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THE FATE OF FERTILISER PHOSPHORUS IN WHAREKOHE PODZOLS

A thesis presented in partial fulfilment of the requirements for the degree of Doctor of Philosophy in Soil Science at Massey University

> Jennifer Kay Edwards 1997

ABSTRACT

During the 1980's and early 1990's, the then Ministry of Agriculture and Fisheries (MAF) Soil Fertility Service used the mass balance Computer Fertiliser Advisory Service (CFAS) model to make phosphorus (P) fertiliser recommendations where P requirements were calculated to replace losses from the cycling P pool via the soil and animals. In the late 1980's, concerns were raised that higher P application rates than those calculated by the CFAS model were necessary to maintain Olsen P levels on Wharekohe podzols. The soil loss factor (SLF) was identified as the model parameter which most likely led to the inability of the CFAS model to predict P requirements on these podzols. The new Outlook model also uses a mass balance approach incorporating a soil P loss parameter to calculate pasture P requirements. In this study the apparent limitation of the CFAS model to predict the maintenance P requirements of the Wharekohe soils, and the appropriateness of the soil loss parameter used in the New Outlook model, was investigated by (a) determining the fate of applied fertiliser P, (b) examining the possible mechanisms for any soil P retention or loss, (c) quantifying the SLF and (d) modeling the fate of applied fertiliser P.

A chronosequence study found that pasture development resulted in an increase in total soil P to the top of the E horizon with increased P movement down the profile with increasing pasture age. The Wharekohe silt loam appears to have a maximum P storage capacity which is reached by 8 years in the 0-3 cm depth (approx. 166 kg applied P/ha) and by 11 years in the 0-7.5 cm depth (approx. 350 kg applied P/ha). The maximum total P storage capacity can mostly be attributed to a maximum inorganic P (Pi) storage capacity. Sodium hydroxide (NaOH) extractable iron and aluminium-Pi was found to be limited in the Wharekohe soil, due to its low sesquioxide content, in comparison to other New Zealand soils. Once the P storage capacity at each depth is reached there is little further accumulation of applied P and much of the P applied in subsequent application is lost from the topsoil in runoff waters. Up to 65% of the applied P could not be accounted for by animal loss or accumulation in the top 7.5 cm of older sites (>30 years).

A glass house leaching study using intact soil cores confirmed that substantial quantities of applied P can be transported in subsurface water movement through Wharekohe podzols. Forty times more P moved through the Wharekohe soil cores than through cores of the yellow brown earth, Aponga clay (\leq 45.6 µg/ml in contrast to \leq 1.07 µg P/ml). In a field study using suction cups, concentrations of up to 18.65 µg P/ml were obtained in soil water sampled under fertilised Wharekohe silt loam plots in comparison to <2 µg P/ml under unfertilised controls. Movement of dissolved P occurred mostly as DIP after the application

i.

of fertiliser P in the glasshouse and field studies. No difference in P movement could be detected in relation to development history in the glasshouse leaching study or in the field study, although the ability of the Wharekohe silt loam to retain added fertiliser P was found to decline with pasture development in a laboratory based P retention study.

Soil loss factors calculated for the Wharekohe podzols from small plot field trials varied enormously (0.04 in the first year to 1.68 over the two year trial period) as a consequence of the large variation in the rate of P required to maintain a steady Olsen P level at each site. Consequently, it was not possible to determine if the SLF of 0.4 used for podzols in the CFAS model was appropriate. The component of the SLF due to non-labile P accumulation, calculated form the chronosequence data, decreased with pasture age. As P applied surplus to animal production requirements and P accumulation is lost from the root zone in runoff, the SLF should be reduced with increasing pasture age or else P runoff losses will increase.

Relationships between pasture age and available Pi, organic P, strongly sorbed/precipitated and residual P, and total P accumulation in the top 7.5 cm of a Wharekohe silt loam were successfully modelled. The annual total soil P accumulation was described in a model which was then incorporated into the Phosphorus in Runoff in High Loss Soils (PRIHLS) model developed to predict potential runoff P losses. Runoff P losses predicted by PRIHLS from the Wharekohe silt loam are nearly 3 times higher from older pasture (>30 years) where the Outlook model is used to calculate P requirements (36 kg P/ha lost in runoff from a calculated P requirement of 44 kg P/ha) compared to the CFAS model (13 kg P/ha lost in runoff from a calculated P requirement of 21 kg P/ha), due to the higher soil loss parameter assigned to the Wharekohe soils in the Outlook model. Such high runoff P losses represent a cost to New Zealand both economically, and environmentally through increased P inputs to water ways leading to possible eutrophication. When runoff P losses have been quantified, through further research, they could be used in the PRIHLS model to predict P requirements and would enable more informed decisions to be made about balanced P fertiliser use on Wharekohe podzols.

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CHAPTER 1 INTRODUCTION

Agriculture is the most important industry financially in the Northland region of New Zealand. The estimated annual total gross farm revenue (before expenses) averaged over the 5 year period from 1992/93 to 1996/97 in Northland is \$334 million (Ministry of Agriculture and Fisheries, 1996). Changes in farm revenue have far more effect on the economy of Northland than any other factor.

Northland has never reached its full potential for agricultural production. A major reason for this is the low natural fertility of the bulk of the pastoral soils in the region. Realising the potential production of these soils requires that the returns from agricultural products must exceed the cost of production (including fertilisers) for an extended period of time. In recent years, increasing costs combined with lower prices for agricultural products have led to a reduction in fertiliser application rates. As a consequence approximately 65% of the Northland farms soil tested by the then MAF Soil Fertility Service (SFS) in 1990 had nutrient levels which were considered below optimum for the maintenance of pasture at 90% of maximum yield (D. Edmeades, pers. comm.).

Most Northland soils have low natural fertility due to the strong weathering and leaching processes created by the mild, humid climate. The least fertile soils are the podzol soil group derived from sedimentary parent material which is low in phosphorus (P). These soils cover 300 000 ha of the 1.2 million ha in Northland (Molloy, 1988). As the podzols are predominantly found on gentle undulating topography, large areas have been bought into agricultural production and are frequently used for intensive pastoral farming such as dairy farms.

The most widespread of the Northland podzols are the Wharekohe soils which cover approximately 60 000 ha (Molloy, 1988). They are derived from mudstone (Wharekohe silt loam) and sandstone (Wharekohe sandy loam) parent materials. However, as weathering is advanced, there is little influence of the original parent material on soil properties except for topsoil texture. Wharekohe soils require large inputs of phosphate, sulphur, potassium, lime and trace elements for establishing pasture successfully (Jackman, 1961; Lambert, 1961; During, 1984). The application of fertiliser P in excess

of 100 kg P/ha (1125 kg superphosphate/ha) is recommended during the first year of pasture establishment (Ballinger, 1953; Lambert, 1961, During, 1984).

Phosphorus accumulates in the soil after development into permanent pasture as a result of the continued addition of P fertiliser to the pasture cycle (Walker et al., 1959; Jackman, 1964a; Perrott and Sarathchandra, 1987; Nguyen et al., 1989). This cumulative build up of P can contribute to pasture growth. Eventually only maintenance applications of P are required to balance any losses from the pastoral system in order to maintain pasture growth at a required relative yield (Karlovsky, 1966, Cornforth and Sinclair, 1982, During, 1984). Until this maintenance situation is reached, high capital dressings of P fertiliser are applied to the Wharekohe soils for up to ten years to realise the production capacity of these soils (During, 1967).

Phosphorus fertiliser is a major cost to the farmer accounting for approximately 20% of variable cash farm expenses (MAF, 1993). Hence, in recent years much effort has been focussed on developing models to predict P fertiliser requirements for pastoral farming.

In 1978 Sinclair and Cornforth, drawing on earlier mass balance models used to calculate the P required for pasture maintenance in a particular pastoral system (Karlovsky, 1966; 1975a&b; 1981) developed the Computer Fertiliser Advisory Service (CFAS) model used by the SFS of the then MAF and more recently AgResearch. The CFAS P model calculates the amount of P required as fertiliser to replace the P lost from the pastoral system to the soil and through animals, in products and in transfer of excreta to unproductive and concentrated areas (Cornforth and Sinclair, 1982). Parameters required in the calculation of the amount of P required to replace these losses in a pastoral system are stocking rate (SR), pasture utilisation (PU), the potential carrying capacity (CC), amount of P lost per stock unit (ALF, dependent on topography and stock type) and the amount of P lost from the pasture cycle to the soil (SLF, expressed as a fraction of the total P uptake by pasture maintained at 90% of maximum yield) (Cornforth and Sinclair, 1982). The calculated maintenance P rate is then corrected to account for the amount of available soil P (measured by the Olsen P soil test) through the use of a modifying factor. In order to overcome the difficulty in

estimating PU and the large errors associated with an incorrect estimation of CC, a modified version of the CFAS model was developed (Sinclair and Cornforth, 1984).

Despite their low P retention, the Wharekohe soils were allocated a high soil loss factor in the CFAS model. All other Northland soils of sedimentary origin require the use of the medium soil loss factor in calculating P requirements. The modified CFAS model calculates that 20 kg P/ha is required to maintain 15 stock units and an Olsen P level of 20 on the flat to rolling Wharekohe soils.

However, in 1989 it came to the attention of scientific and advisory staff at the DSIR, Kaikohe, and MAF, Northland and Ruakura, that higher P application rates than those calculated by the CFAS model were necessary to maintain required Olsen P levels on many of the farms in the district on Wharekohe soils. The model was able to predict, with some certainty, the P requirements of a volcanic soil (also classified as high P loss) on one of the farms on which the P recommendation was insufficient to sustain Olsen P on the Wharekohe soil. Therefore, the underestimation of the ALF can be ruled out. It was concluded that the SLF assigned to the Wharekohe soils in the CFAS model had been underestimated.

Phosphorus can be lost from the pasture cycle via the soil through the accumulation of plant unavailable P or from the soil as particulate and dissolved P in surface and subsurface runoff waters. The Wharekohe soils have a very low capacity to retain added P with Anion Storage Capacities often close to 0%. Hence, losses of P from the soil may form a significant component of the CFAS SLF. Substantial losses of applied P in runoff water represent a cost to New Zealand both economically and environmentally through increased P inputs of water ways leading to their possible eutrophication.

Since the commencement of this PhD, the CFAS model has been replaced by the SFS. The new model, Outlook, has been developed, without the unquantifiable parameters PU and CC and with the ability to evaluate the economics of different P fertiliser strategies using a water soluble P source, and used by the SFS since 1994. Outlook also uses a soil loss parameter to estimate losses of P from the cycling P pool through plant unavailable P accumulation and runoff P losses. Hence, an investigation of soil P loss in Wharekohe podzols is relevant to the use of the Outlook for predicting P requirements on these soils also.

The objective of this research study was to investigate the apparent limitation of the soil loss factor used in the CFAS model to predict maintenance P requirements of the Wharekohe soils, and the appropriateness of the soil loss parameter used in the new Outlook model, further by:

a) determining the fate of applied fertiliser P (Chapters 3 and 4),

b) examining possible mechanisms for any soil P retention or loss (Chapters 5 and 6),

c) quantifying the amount of P lost from the pasture P cycle via the soil (SLF) in Wharekohe soils (Chapter 7),

D) modelling the fate of applied fertiliser P (Chapter 8).

The information derived from this PhD study will be used to improve the economics and reduce the environmental impact of P fertiliser use on Wharekohe soils.

CHAPTER 2 REVIEW OF THE LITERATURE

2.1 INTRODUCTION

This chapter presents a review of the literature relevant to assessing the ability of the CFAS model to predict the maintenance P requirements of pastures growing on the Wharekohe soils. Firstly, a brief outline of the P cycle in grazed pasture systems and the forms and amounts of P found in the soil is provided. Then a review of the chronosequence studies examining the fate of fertiliser P in New Zealand soils under permanent pasture is followed by a discussion of the properties of podzols and the fate of applied P in podzolic soils. Finally, modelling of pasture maintenance P requirements, with particular reference to the CFAS model and the difficulties encountered in using the CFAS model on Wharekohe soils, is discussed.

2.2 THE PHOSPHORUS CYCLE UNDER GRAZED PASTURE

Under grazed pasture, P cycles through both above and below ground pools, summarised in figure 2.1. The chemical form in which P is found changes as it is transferred between these pools. Phosphorus is added to the cycle through the weathering of native parent material and the addition of P containing fertiliser. Phosphorus can be lost from the cycle via animals through the transfer of P in excreta to unproductive sites and concentrated areas within paddocks, and by removal of P in animal products. Losses of P via the soil occur through the accumulation of P in the soil by net organic immobilisation and net precipitation/sorption, and from the soil as particulate and dissolved P in surface and subsurface runoff waters. The loss of significant quantities of P from the soil as dissolved P in subsurface runoff waters is rare in New Zealand soils. As soil losses have been identified as the most likely reason for the CFAS model under predicting the P requirements of Wharekohe soils, much of this literature review will concentrate on the fate of applied P in the below ground component of the P cycle.



Figure 2.1 Phosphorus cycle under grazed, fertilised pasture.

The forms and amounts of P found in the soil have been well reviewed by many authors (Larsen, 1967; Russell, 1973; Ryden et al., 1973; Dalal, 1977; Parfitt, 1978; Sample et al., 1980; Tate, 1984; Rowarth, 1987). A brief description of the forms and chemistry of P found in the soil follows.

Phosphorus is relatively immobile in the soil, it is not added by the atmosphere and so the P status of a virgin soil is dependent on the primary P content of the parent material, most commonly apatite with some iron and aluminium phosphates in acid soils (Norrish and Rosser, 1983). With time, the primary P is weathered through the action of climate and vegetation to give secondary inorganic mineral P, and inorganic P in solution which is in turn converted to solid and solution organic P (Syers and Walker, 1969a&b; Williams and Walker, 1969a&b; Adams and Walker, 1975).

Inorganic P (Pi) in the soil solution provides P for plant uptake. There is no evidence that Po is directly available for plant uptake under field conditions. Soil organic P (Po) derived from plant residues, animal excreta, soil fauna and micro-organisms becomes available for plant uptake following mineralisation into inorganic P (Cosgrove, 1977). Mineralisation of organic P can contribute large quantities of P to the available pool in New Zealand during spring (Saunders and Metson, 1971). P which can easily contribute to the solution P and plant uptake is termed labile.

The type of inorganic P polymers found in solution are governed by protonation and complex formation, and the amount is governed by precipitation and sorption reactions (Larsen, 1967). A very small proportion of the total soil P is found in solution at any time, approximately 0.1 to 1 μ g P/ml in soils which have not been recently fertilised (Larsen, 1967).

Inorganic P reacts with free Ca and Mg (alkaline soils), and Fe, AI, and Mn (acid soils) to form insoluble precipitates (Reviewed by Sample et al., 1980; Brady, 1984). Inorganic P is also adsorbed onto variable charged surfaces of iron oxides, aluminium hydroxides and clay minerals through reactions with short-range order and crystalline hydrous

oxides and short-range order aluminosilicates (Saunders, 1965; Syers et al., 1971). Eventually the adsorbed P can become absorbed as the P slowly diffuses into the soil particles on which it had been adsorbed (Barrow, 1983).

The identification of up to 50% of organic P compounds remains unknown. Known organic P compounds include a large proportion of inositol phosphates, smaller amounts of phospholipids and nucleic acids, traces of sugar phosphates, phosphoproteins, glycerophosphates and phosphonates (Anderson, 1967; Omotoso and Wild, 1970; Tate, 1984). The amount of organic P in the soil is controlled by the processes of immobilisation and mineralisation (Dalal, 1977). Organic P can be stabilised against mineralisation by reactions with soil surfaces as with inorganic P (Williams and Saunders, 1956; Williams et al., 1958; Jackman, 1964b).

Phosphorus fractionation schemes aimed at quantifying the amount of P in various labile and non-labile soil pools are reviewed in chapter 4.

2.4 FATE OF FERTILISER PHOSPHORUS IN NEW ZEALAND SOILS UNDER PERMANENT PASTURE

One way of examining the fate of applied fertiliser P in the soil is by determining changes in the quantity and type of P accumulation in the soil in relation to the application of fertiliser P over time from pasture development, that is chronosequence studies.

Many of the early New Zealand chronosequence studies investigated the accumulation of nutrients into organic matter (OM) due to concerns that the accumulation of nutrients in OM made them unavailable for plant uptake (Jackman, 1951; Walker et al., 1959; Jackman, 1964a&b). As fertiliser P prices escalated and shortages were perceived in the 1980's, emphasis in chronosequence work shifted to examining P requirements for pasture maintenance and the effects of withholding or reducing P (Lynch and Davies 1964; Grigg 1966; Nguyen et al., 1989).

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This section reviews the fate of applied P in New Zealand soils, as determined from chronosequence studies, excluding podzols. The fate of applied P in podzols is reviewed in section 2.5.

2.4.1 Total Soil P

Total soil P accumulates under pasture with time where P application rates exceed losses from the pasture cycle (Doak, 1942; Jackman, 1951; Walker et al., 1959; Saunders 1959a; Jackman, 1964a; Lambert et al., 1988; Nguyen et al., 1989). The rate of soil P accumulation will depend on factors such as soil type, the form of fertiliser P, the P application rate and animal losses (Saunders, 1959a; Lambert et al., 1988; Nguyen et al., 1988; Nguyen et al., 1989; Perrott et al., 1992a).

2.4.2 Inorganic Soil P

As with total P, the application of P fertiliser over time onto permanent pasture results in an increase in inorganic soil P (Pi) (Jackman, 1951; Quin and Rickard, 1983; Perrott and Sarathchandra, 1987; Nguyen et al., 1989; Perrott et al., 1992a), with more Pi accumulating at higher rates of P application (Nguyen et al., 1989; Perrott et al., 1992a).

Any changes in net annual plant available Pi will be dependent on the annual application of fertiliser P in respect to pasture production and utilisation (Grigg, 1966; Nguyen et al., 1989; Perrott et al., 1992a). Olsen P (NaHCO₃ extractable plant available Pi) will increase where the P application rate is in excess of the pasture maintenance requirements to balance losses of P from the cycling P pool (Edmeades et al., 1991a).

Many papers have detailed the mechanisms for Pi retention in New Zealand soils. The following is a brief summary of their findings.

The application of fertiliser P results in an increase in both P associated with Fe and Al (alkali extractable Pi) and Ca-Pi (acid extractable Pi) (Perrott et al., 1989; Condron and Goh, 1989; Perrott et al., 1992a). In acid weathered New Zealand soils, most of the Pi

accumulates as alkali extractable Al- and Fe-Pi, where soluble P fertiliser is applied (Saunders, 1959a; Steele, 1976; Grigg and Crouchley, 1980; Condron and Goh, 1989; Perrott and Mansell, 1989; Perrott et al., 1989; Floate and Enright, 1991; Perrott et al., 1992a; Rowarth et al., 1992a). Most of this alkali P has been found to be associated with Al, rather than Fe, in most acid weathered New Zealand soils (Saunders, 1959b; Saunders, 1965; Syers et al., 1971; Grigg and Crouchley, 1980) as is the case overseas (Williams et al., 1958; Udo and Uzu, 1972; Lopez-Hernandez and Burnham, 1974; Borggaard et al., 1990; Singh and Gilkes, 1991; Gilkes and Hughes, 1994).

The application of phosphate rock (Grigg and Crouchley, 1980; Perrott et al., 1992a), large rates of soluble P fertilisers (Rickard and Quin, 1981) and lime (Condron and Goh, 1989) have been shown to increase the Ca bound Pi fraction in relation to the sorbed P in acid weathered New Zealand soils. Calcium Pi accumulates in the soil as a result of the accumulation of residual Ca-Pi from P fertilisers and the conversion of soluble Pi to Ca-Pi at high pH where the cation exchange complex is saturated with Ca (Laverty and McLean, 1961; Chang and Chu, 1961; Sample et al., 1980).

2.4.3 Organic Soil P

Most of the P applied with pasture development accumulates initially as organic soil P (Po) in New Zealand soils where OM levels are low and C:N ratios are generally high (Jackman, 1951; Walker et al., 1959; Jackman, 1960). As low N levels are overcome by N fixation by pasture legumes, C/N ratios are lowered encouraging the immobilisation of Po and a decrease in the C/Po ratios (Jackman, 1951; Walker et al., 1959; Jackman, 1960). The rate of accumulation of Po, and hence the Po/Pt ratio, decreases over time as the Po content approaches equilibrium (steady state) (Jackman, 1951; Walker et al., 1989). The more labile Po pool reaches equilibrium first (Perrott et al., 1989). The time to Po equilibrium varies and depends on P supply, soil type and pH.

Phosphorus fertiliser application has little impact on Po accumulation provided existing soil P levels, from native P or historic fertiliser P application, are adequate to supply the rate of OM accumulation. Negligible to small increases in organic P, C and N were found

between top dressed and un-top dressed pastures on volcanic (Burgess and Davies, 1951; Saunders, 1959a(uncorrected for bulk density)) and moderately weathered sedimentary (Floate and Enright, 1991; Perrott et al., 1992b(uncorrected for bulk density)) soils and between low P input and high P input farmlets established on 50 year old unfertilised pastures (Lambert et al., 1988). On the South Island Lismore stony loam under irrigation, Po did not increase to the same extent without added P (Nguyen et al., 1989), but cessation of P fertiliser, resulted in continuing Po accumulation with an associated decrease in Pi under pasture (Nguyen et al., 1989).

Non allophanic soils have lower steady state OM and Po contents and reach this steady state more quickly than allophanic soils presumably because AI stabilises OM and Po against mineralisation through sorption and precipitation in a similar way to Pi (Jackman and Black, 1951; Jackman, 1955b; Williams et al., 1958; Jackman, 1964a&b). In a study by Jackman (1964a), Po contents appeared to be independent of C, N, and S contents to some extent, indicating the operation of a separate mechanism for the retention of Po other than accumulation in OM (Jackman, 1964a). The soil Po pool not only includes Po found in OM, but also includes Po complexes with low C:Po ratios which are not part of the bulk OM (Kowalenko, 1978) and can be stabilised against mineralisation through reactions with soil sesquioxides.

Increasing soil pH has been shown to slow the accumulation of Po in favour of Pi accumulation on a Lismore silt loam under irrigation (Quin and Rickard, 1981; Condron and Goh, 1989). Lime, which increased pH from 5.8 to 6.6, would have increased mineralisation of Po by enhancing microbiological activity (Condron and Goh, 1989). However, increasing pH would also have led to increased solubility of some organic P species which are less soluble when they occur as sparingly soluble iron and aluminium salts (at low pH) than when they are sparingly soluble calcium salts (at high pH). Also the desorption rate of some organic P species, reflected by decreasing NaOH extractable Po rather than NaHCO3 extractable Po (Condron and Goh, 1989) may have increased at the higher pH.

The accumulation of Pi and Po in New Zealand soils with pasture development is reviewed in more detail in Chapter 4.

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2.4.4 Losses of Applied P from the Pasture Root Zone

P is considered to be immobile within most NZ soils with applied P generally confined to the root zone (Jackman, 1951; Saunders, 1959a; Walker et al., 1959; Jackman, 1964a; Saggar et al., 1992). However, there is also some indirect evidence for more substantial losses of P through the soil where P accumulated down the profile in other soils (Doak, 1942; Nguyen and Goh, 1992). Phosphorus can be lost from the pasture root zone as particulate and dissolved P in surface and subsurface runoff waters. In addition to the movement of P in runoff waters, P can be physically moved down the soil profile via the transport of dung and higher fertility top soil to lower depths by earthworms (Mackay et al., 1982) and the decomposition of pasture roots in situ. (Batten et al., 1979). The accumulation of P down the profile of New Zealand soils is reviewed in Chapters 3 and 4, while the movement of P in runoff waters is reviewed in Chapter 5.

2.4.5 Other Chemical Characteristics

Carbon, N and S levels rise and C/N and C/S ratios are lowered in the top soil over time under permanent pasture, with the application of fertiliser and lime (Walker et al., 1959; Jackman, 1964a; Perrott and Sarathchandra, 1987). Where the soil is ploughed prior to pasture establishment, an initial fall in both C and N contents, due to the mineralisation of organic matter, may occur (Walker et al., 1959).

Continuous P application results in increasing CEC, as P precipitates with AI and Fe resulting in an increased number of H ions from the phosphate radical available for cation exchange (Saunders, 1959a). Increasing OM, and hence humus levels, also lead to increasing CEC. The pH and base content increase as Ca from the P fertiliser and lime replace the H ions which are then leached from the soil (Saunders, 1959a; Haynes and Williams, 1992). However, acidification also occurs with the development of leguminous pastures, and where lime is not applied, pH levels will fall (Bolan et al., 1991).

2.5 FATE OF FERTILISER P IN PODZOLS

Before reviewing the fate of applied P in podzols, an understanding of podzolisation and how this changes the chemistry of a soil is necessary.

2.5.1 The Podzol

2.5.1.1 Podzol Development

Podzolisation refers to the process whereby sesquioxides and humus are transferred to an illuvial horizon leaving an eluvial horizon high in residual quartz and secondary silica and low in sesquioxides (Taylor and Pohlen, 1970). This process is sometimes, but not necessarily, accompanied by clay illuviation.

Podzolisation occurs throughout the world under acid leaching conditions through the influence of mor humus and high rainfall. In New Zealand, particular tree species which produce mor humus and are associated with podzolisation are kauri (*Agathis australis*), rimu (*Dacrydium cupressinum*), Hall's totara (*Podocarpus cunninghamii*), kaikawaka or pahautea (*Libocedrus plumosa*) and hard beech (*Nothofagus* sp.) (Atkinson, 1980).

2.5.1.2 Characteristics of Podzols

The podzols are characterised by low natural nutrient status, pH, CEC, total base content and Anion Storage Capacities (previously known as the P Retention test, Saunders, 1965) in their A horizons, and high variable charge and Anion Storage Capacities in their B horizons due to the accumulation, at depth, of sesquioxides and organic matter (New Zealand Soil Bureau, 1968; Blakemore, 1980). The A horizon of podzolic soils is more coarsely textured than the less weathered soils derived from similar parent material leading to greater storage of plant available water and hence drought tolerance (Gradwell, 1980; Jackson, 1980). However, in their natural state, some podzolic A horizons, including that of the Wharekohe silt loam, are massive in structure with low porosity and water storage capacities (New Zealand Soil Bureau,

1968; Gibbs, 1980). The dense E and B horizons result in poor drainage and waterlogging of the A horizon during wet months (Jackson, 1980; Molloy, 1988).

2.5.1.3 Podzol Classification

There are still differing view points through the world over the classification of podzols. The term podzol is a Russian word which was adopted by the nineteenth century soil scientist V.V. Dokuchaev to describe soils with a grey or whitish horizon near their surface. Modern Russian classification includes three types of podzols, i) eluvial podzols characterised by the absence of both clay and sesquioxide accumulation, ii) the eluvial clay bearing type characterised by an elevated clay content below the eluvial horizon due to soil weathering in situ and iii) the eluvial-illuvial type characterised by a simultaneous accumulation of clay and sesquioxides in the illuvial horizon, the only Russian definition which fits the western concept of a podzol (Petersen, 1984).

The western classification systems place greater emphasis on the illuvial (B) horizon. In the USA most podzols are classified as Spodosols (Soil Survey Staff, 1975). The chemical criteria for a soil being classified as a spodosol is that the spodic horizon (B horizon) contains pyrophosphate (pH 10) extractable Fe + AI at a level greater than 20% of the clay content, the spodic horizon looses 25% of its CEC after shaking with citrate-dithionate and that pyrophosphate extractable Fe + AI divided by dithionite extractable Fe+AI is greater than 0.5. Where extractable iron is less than 0.1%, extractable carbon is substituted.

The Wharekohe silt loam does not fit the USDA definition of a spodosol due to its low extractable Fe + Al : clay ratio as a result of the very high clay content of the B horizon. It is classified as an Ultisol, Typic Albaquult (Soil Survey Staff, 1975). Some British and Canadian podzols under their respective classification systems are also excluded from the spodosol class due to their not meeting the required chemical criteria (Avery et al., 1977; Wang and Rees, 1980).

In the latest New Zealand soil classification (Hewitt, 1992), podzols are defined as "acid soils with low base saturation having an horizon of accumulation of aluminium occurring as complexes with organic matter and/or as short-range-order minerals (typically with silicon as allophane/imogolite). Iron (typically as ferrhydrite) may or may not be accumulated with aluminium. This horizon is usually associated with an overlying E horizon indicating translocation. The E horizon may be missing as a result of erosion, ploughing or bioturbation or it may be masked by organic matter." Many areas containing Wharekohe soils have been disturbed by Kauri gum digging and pasture establishment so that parts of the E and B horizons are found in the A horizons and the E horizon is often missing. The Wharekohe soils would be classified as densipan podzols in this current New Zealand Soil Classification.

2.5.1.4 The Wharekohe Podzol

The Wharekohe podzols have developed in Northland New Zealand from sedimentary sandstones, siltstones, claystones, greywacke or colluvium and alluvium derived from erosion of these rocks (Gibbs, 1980). They are usually associated with podocarp forests dominated by kauri trees under which H ions from the organic complexes in the leaves replace other cations in the soil promoting the downward movement of the cations, humus and clay particles (Bloomfield, 1953 a&b). Wharekohe soils are often found in a complex with other less weathered and leached soils due to the historic pattern of vegetation distribution. They are characterised by a massive grey A horizon, often only 10 cm deep, overlying a dense, white silica E horizon or pan, underneath which lies the clay and sesquioxide rich B horizon.

The properties of Wharekohe soils which need to be overcome to achieve reasonable production using legume based pastures include very low pH (pH 4-4.5), very high C:N ratios, inadequate amounts of most essential plant nutrients including P, and very poor drainage (Molloy, 1988). The presence of the E horizon pan and the flat to rolling topography result in the A horizon becoming waterlogged in winter. The E horizon also restricts roots from obtaining soil moisture from lower down the soil profile during dry summers.

2.5.2 Phosphorus Chemistry of Podzols

2.5.2.1 Phosphorus in Undeveloped Podzols

Podzols generally contain less P in their undeveloped state than other soils. In an undeveloped Wharekohe podzol (New Zealand Soil Bureau, 1968) under kauri forest, the total P content was three times greater in the surface humus layer than the 100 µg P/g of soil in the A horizon. Total P then increased down the profile so that the B horizon had a higher P content of 150-170 µg P/g. Organic P decreased slightly with depth, while Pi increased accounting for the total P increase down the profile. The A horizon of the Wharekohe silt loam had the lowest total P content of the 54 soils recorded in the New Zealand Soil Bureau Bulletin 26 (1968) and the lowest ever recorded in a topsoil by Deventer (Netherlands) (Jackman, 1960). The Northern podzolised yellow brown earth (Waikare silty clay loam), the other Northern podzol (One Tree Point loamy sand), and the South Island podzol (Okarito peaty loam) described in the New Zealand Soil Bureau Bulletin 26 (1968), also contained low levels of total P and similar patterns of P down their profiles.

In contrast, the undeveloped illuvial-humic ferruginous and gley podzols investigated in a Russian study had different quantities and patterns of P content down the profile (Pereversev and Koshleva, 1991). Amounts of total P in each horizon were up to 30 times higher than those measured in the Wharekohe soil. Both organic and inorganic P increased with depth from the E horizon on the two illuvial-humic ferruginous podzols studied. In contrast, in the gley podzol, a large decrease in organic P overlaying the smaller increase in Pi with depth, resulted in total P decreasing with depth. In the gley podzol, sesquioxide P compounds made up a larger component of total P in the A horizon, however with depth, residual calcium bound P became more important. In these acid Russian podzols on silty, sandy deposits, apatite and residual P were the largest P fractions. Their high total P and Ca-P contents indicate that these Russian podzols may not be as weathered as the Wharekohe podzol due possibly to differences in vegetation and climatic conditions.

Calcium, Al and Fe-Pi, and the more stable Po extractable by NaOH are usually the largest P fractions in less weathered undeveloped New Zealand topsoils (Walker and Syers, 1976; Perrott et al., 1989; Haynes and Williams, 1992). In contrast most of the P in highly weathered sedimentary topsoils is expected to be found in the occluded Pi and more stable Po forms, as weathering of yellow brown earths to podzols leads to a reduction in the amount of non-occluded Fe and AI-P, Ca-P and organic P (Walker and Syers, 1976). In a review of the literature concerning P fractions found in soils in natural ecosystems overseas, most highly weathered spodosols, ultisols and oxisols were also found to have negligible Ca-P. However, the ultisols and oxisols contained the highest proportion of Fe and Al-Pi due to their high sesquioxide content (Cross and Schlesinger, 1995). Most of the highly weathered soils in the survey contained relatively low levels of labile Pi. However, in the spodosols with the lowest total P content (close to that in Wharekohe soils), the labile P pool was larger than the NaOH extractable Fe and AI-Pi (Pare and Bernier, 1989; Trasar-Cepeda et al., 1990). The more stable NaOH Po was the largest Po fraction in all soils in the survey.

The Anion Storage Capacity of New Zealand podzolic A horizons is low, in the range of 0-20% (Molloy, 1988). Wharekohe A horizons generally have very low P retentions closer to 0. In contrast, the Bh and Bms horizons exhibit very high P retention in the vicinity of 80-95% due to the accumulation of iron and aluminium at depth (New Zealand Soil Bureau, 1968; Molloy 1988). Such a difference in Anion Storage Capacity between horizons is not as great in other New Zealand soils (Saunders, 1965).

The retention of P by A horizons samples of Canadian podzols shaken in solution with a range of added P levels has been shown to be related to oxalate-extractable Fe and Al (Laverdiere et al., 1981; Laverdiere and Karam, 1984). Tamm oxalate extractable Al had a higher correlation with Anion Storage Capacity than tamm oxalate extractable Fe for most soils in a study of major New Zealand soil groups including podzols (Saunders, 1965). Anion Storage Capacity in the study by Saunders (1965) was closely related to the chemical composition of the parent material and the degree of weathering and leaching of the soil profile. It is not surprising that the highly weathered and leached Wharekohe podzols, which are very low in sesquioxides in their A horizons, have some of the lowest Anion Storage Capacities in New Zealand.

2.5.2.2 Podzol Pasture P Chronosequence Studies

As with other soils, pasture development on podzols, accompanied by fertiliser and lime application, results in an increase in pH, exchangeable Ca and K, N, P and a reduction in the C:N ratio (Powell and Taylor, 1980; O'Connor, 1980; Lee et al., 1983).

Organic P accumulation with pasture development followed a similar pattern in a Maimai gley podzol (Powell and Taylor, 1980) to that in other soils reviewed in 2.4.3 (Jackman, 1951; Jackman, 1960; Walker et al., 1959; Condron and Goh, 1989). Pasture development resulted in the net accumulation of P solely as organic P in the first two years from development, however both inorganic and organic P increased in the third and final year of the study (Powell and Taylor, 1980).

In a comparison of superphosphate fertilised and unfertilised pasture on the Northern podzol Te Koporu sand, (Jackman, 1955a), 25% of the applied P which had accumulated in the top 15 cm was in the organic form after 9 years. Applied P has been shown to have little impact on the accumulation of Po under pasture provided existing soil P levels are adequate (2.4.3). Inadequate native P combined with the very high C:N and N:Po ratios of the Te Koporu sand in an undeveloped state have most likely resulted in the accumulation of further Po where fertiliser P was applied. Organic P accumulation in a less weathered South Island upland podzol of higher total P content was not enhanced by the addition of fertiliser following pasture development presumably because native P levels were sufficient to supply the accumulation of organic matter (Floate and Enright, 1991).

Podzolic soils low in AI are expected to reach a steady state Po content which is lower and more rapidly obtained than in other soils with higher AI contents which have a greater capacity to stabilise the Po compounds (section 2.4.3).

Lime stimulated the mineralisation of organic P in the Te Koporu podzol (Jackman, 1955a) as was shown for other New Zealand soils (2.4.3).

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The application of 10 and 20 kg P/ha/yr over 5 years has been shown to increase Olsen P levels in the South Island Maungatua upland podzol in a similar manner to 4 upland yellow brown earths of similar parent material (Floate and Enright, 1991). However, where P application was increased to 40 kg P/ha, the resulting increases in Olsen P at all sites were lower for the podzolic soil and the driest yellow brown earth. Leaching of P from the podzolised yellow brown earth and a high P retention in the yellow brown earth may have contributed to lower NaHCO₃ extractable Pi at both sites.

The ability of podzolic soils to retain added P has been shown to reduce as the few available P retention sites become occupied by applied P fertiliser (Jorgensen and Borggaard, 1992).

2.5.2.3 Losses of P from New Zealand Podzols

Large losses of applied P from the top soil have been estimated for New Zealand podzols under pasture. In a P fertiliser form comparison trial on a Te Kopuru podzol soil in Northland, only about 10% of the fertiliser P applied at 34 kg P/ha/yr had been retained in the top 15 cm after 9 years of application (Jackman, 1955a). The author assumed that the remaining P (apart from animal losses) had moved down the profile to the iron pan. Where superphosphate was applied, the proportion of Po increased with depth. Accumulation of Po at depth does not necessarily mean that P is moving as Po to depth, as Pi may be converted to Po in situ. This study of Jackman's did not differentiate these mechanisms.

Losses of applied P from South Island podzols have also been reported. Floate and Enright (1991) only recovered 18% of the 240 kg/ha P applied to a Maungatua upland podzol over 5 years in the top 7.5 cm compared to up to 68% for the upland yellow brown earths in the same study. Sampling to 30 cm failed to recover further P in the podzol but increased recovery in the other soils. Removal of P in clippings could only account for another 4% of the P not recovered at the podzolised site and so either lateral P movement or movement of P beyond 30 cm in runoff waters was the most likely pathway for P loss.

Of the 220 kg P/ha applied over a 5 year period, 82% was recovered in the top 15 cm in an Addison peaty loam whereas only 33% was recovered in the top 15 cm of the areas of Addison silt loam on the same site (O'Connor, 1980). O'Connor concluded that this was most likely due to movement of P from crests (silt loam) to hollows (peaty loam) rather than a greater affinity for P by the peat loam as both soils had low Anion Storage Capacities. In an earlier study, McNaught and During (1970) noted that the inability of 84 kg P/ha/yr to prevent P deficiency in pasture on an Addison soil was most likely due to the very low P retention accompanied by high rainfall inducing lateral movement of water and nutrients on this soil with a shallow pan.

Phosphorus (acid extractable) failed to accumulate in an Okarito silt loam beyond 3 years despite continued application of approximately 40 kg P/ha/yr as superphosphate (Lee et al., 1983). The Okarito silt loam has an impenetrable pan close to the surface, as in Wharekohe soils, which restricts water movement resulting in waterlogging for large parts of the year and lateral movement of runoff water.

Such large losses of P from these New Zealand podzols are unlikely to be accounted for by the physical movement of P alone, and hence losses of P dissolved in surface and subsurface runoff water are likely. Large losses of applied P have been recorded in the laboratory from repacked cores of the Northland podzols, Wharekohe silt loam and Te Kopuru sand (up to 36%) (Hogg and Cooper, 1964) and the South Island Addison gley podzol (42%) (McSweeney and Muller, 1979). Considerable movement of P down repacked cores of an Australian gley podzol has also been recorded (Lefroy et al., 1995). These laboratory studies indicate the potential for subsurface runoff losses of P from the podzols.

The above review of P losses from podzols are not surprising given their low ability to retain added P and the heavy rainfall experienced by the podzolic soils of New Zealand. The potential for subsurface runoff P losses from the Wharekohe podzol has already been demonstrated and if they behave in the field as the other New Zealand podzols examined in this literature review, significant losses of applied P from the profile could be experienced. Large losses of P from the soil profile have a cost not only economically, through inefficient fertiliser use, but also to the environment, through increased P loading
of water ways inducing the potential for eutrophication. Methods for reducing runoff P losses from soils susceptible to large P losses in this way are reviewed in chapter 5.

2.6 MODELLING P FERTILISER REQUIREMENTS

The accumulation of P over time under permanent pasture with fertiliser P application can contribute to pasture growth so that eventually only maintenance applications of P are required to balance any losses from the pasture P cycle and maintain pasture growth at the required relative yield and stocking rate (Karlovsky, 1966; Cornforth and Sinclair, 1982).

Over the past 30 years numerous models for predicting the amount of P required to maintain pasture production have been developed (Karlovsky, 1966; Bowden and Bennett, 1975; Helyar and Godden, 1977; Cornforth and Sinclair, 1982; Metherell et al., 1995).

Most P fertiliser requirement models are based on the Mitscherlich equation.

 $Y = 100 - Be^{-cx}$

where Y = relative yield (%)

100 = maximum yield

B = 100 - production without fertiliser

C = response factor

X = fertiliser addition

The Cornforth and Sinclair (1982) approach differs from other models incorporating the Mitscherlich equation, in that P losses are related to the required relative yield giving a P maintenance requirement curve rather than a pastoral response curve (Helyar and Godden, 1977).

Models used to investigate the cycling of P under grasslands and to predict P requirements for grazed pastures and some of the limitations of these models have been

well reviewed by Rowarth, (1987). This literature review includes a brief description of the Computerised Fertiliser Advisory Scheme (CFAS) model developed by Cornforth and Sinclair (1982) and examines the sensitivity of the model to variation in parameter estimation on maintenance P requirements, in order to determine which aspect/s of the model contribute to the apparent underestimation of P requirements on the Wharekohe podzols.

2.6.1 CFAS Model

The CFAS model has been developed from a balance sheet approach to the calculation of P maintenance requirements originally proposed by Karlovsky (1966; 1975a&b; 1981; 1982). The amount of P required to maintain pasture production is calculated as the amount of P required to replace losses of P from the cycling P pool via soil P accumulation and runoff P losses, and animal products and excretal transfer, where a 'steady state' exists.

A steady state refers to the size of the cycling pool, reflected by Olsen P status, remaining constant from year to year. Cornforth and Sinclair (1982) confined their model to pastures maintained at a 'steady state' so that there was no need to quantify flux rates between various compartments of the cycling P pool or to consider residual value of fertiliser P which are important aspects of other models (Blair et al., 1977; Bowden and Bennett, 1975). However, in podzols and other soils of low Anion Storage Capacity, the retention of added P in the soil decreases with increasing P fertiliser application and pasture age (Weaver et al., 1988; Borggaard et al., 1990). If the net rate of accumulation of non-labile P in the soil decreases with increasing P application and pasture age, the P cycle will not be in a 'steady state', and the calculation of P requirements from the CFAS model would be inappropriate.

The maintenance P equation involves the calculation of i) the total P lost from the cycling pool when the relative yield is 90% of the maximum and ii) the total P loss associated with the required level of production, giving an overall equation of:

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Maintenance P requirement = $\log_{10}\{100/[100 - (8550 \times SR)(CC \times PU)]\} \times CC \times (0.005 \times CC + 0.275) \times (PU \times ALF \times 0.0301 + SLF \times 5.79).$

The parameters used in the calculation of the P maintenance requirement are:

i) stocking rate (SR) - number of stock units ha⁻¹, where each stock unit is considered to consume 550 kg of dry matter annually.

ii) pasture utilisation (PU) - % of pasture grown which is eaten by stock.

iii) potential carrying capacity (CC) - number of stock units ha⁻¹ which can be carried where PU=90% and pasture production is maintained at 95% of Ymax.

iv) animal loss factor (ALF) - amount of P lost per stock unit (kg/SU), in animal products and by transfer of excreta to concentrated and unproductive areas, grazing pasture maintained at 90% of Ymax (dependent on topography and grazing intensity).

v) soil loss factor (SLF) - amount of P lost from the pasture cycle to the soil, by the accumulation of organic and inorganic compounds which are unavailable to plants, erosion, and leaching, expressed as a fraction of the total P uptake by pasture maintained at 90% of Ymax.

(Cornforth and Sinclair, 1982)

Once the maintenance P requirement has been calculated using the model, it is adjusted to account for the amount of available P in the soil (measured by the Olsen P test) through the use of a modifying factor. The modifying factor was calculated using published data for changing Olsen P with P application. The output of the model is then the current P requirement necessary to sustain or gain pasture maintenance at 90% of Ymax. The modifying factor corresponding to a particular Olsen P will depend on the relative yield of the pasture, in relation to current and potential stocking rates, and the P loss category of the soil (Cornforth and Sinclair, 1984). Three P loss categories exist, low, medium and high.

2.6.1.1 Sensitivity of Calculated P Requirements to Incorrect Estimation of Model Parameters

The impact of incorrect estimation of model parameters on the calculation of P maintenance requirements has been investigated by several authors (Parker, 1982; Rowarth, 1987; Scobie and St-Pierre, 1987a). The examples examined by Parker (1982) can be related to a dairy farm on a Wharekohe soil where the CC is considered to be 18 (Cornforth, 1988) and the ALF is 0.9 (Cornforth and Sinclair, 1984).

Stocking Rate

Stocking rate can be difficult to estimate where areas of the farm differ in their development, soil type, topography and stock type. The incorrect estimation of stocking rate can have a large impact on P requirements particularly at higher stocking rates. Changing the SR from 15 to 16 can result in a 35% higher P requirement where CC=18, ALF = 0.90 (Parker, 1982)

Pasture Utilisation

Under hill country and extensive grazing conditions pasture utilisation is difficult to assess (Sinclair and Cornforth, 1984). The incorrect estimation of PU has greater impact when the PU is low. For example, changing the PU form 85% to 80% results in a 10% increase in the maintenance P requirement, whereas changing the PU from 70% to 65% results in a 35% increase in the maintenance P requirement, whereas changing the PU from 70% to 65% results in a 35% increase in the maintenance P requirement, where CC=18, ALF=0.9, SLF=0.4 and SR=13. Pasture utilisation can change markedly on the Wharekohe podzol when heavy rainfall leads to waterlogging, pugging and the loss of pasture which is trampled into the top soil.

Carrying Capacity

In the example given by Parker (1982) changing the CC from 18 to 20 resulted in a 12% decrease in the maintenance P requirement, where SR =13, ALF=0.9, SLF=0.40 and PU=80%. He concluded that an incorrect estimate of CC was shown to have the smallest impact on the P maintenance requirement of all the parameters. However where the SR is increased to 16, a change in CC from 18 to 20 results in a 26% decrease in the amount of P required for pasture maintenance.

Animal Loss Factor

The ALF values used in the model were calculated from a single large grazing trial on hill country (Gillingham, 1980a&b; Gillingham et al., 1980a) and hence these values may have been influenced by any of the aspects of trial design, paddock size or grazing management peculiar to that trial (Rowarth, 1987). Rowarth's data supported the use of a common ALF over a range of stocking rates for a given topography in the CFAS model. However, her estimates of ALF were lower than those used by the model and she attributed this to lower pasture P concentration, animals selectively grazing pasture with a higher P concentration and the topographically flatter nature of her trial area.

The model assumes that the animal loss is linearly related to the pasture P concentration. However, where the P concentration of pasture does not lead to a deficiency, the removal of P in animal products does not increase linearly with pasture P concentration and animals excrete P in excess to their requirements (Bromfield, 1961; Barrow and Lambourne, 1962; Rowarth, 1987). Consequently, where P concentration in pasture is higher than 0.35%, there will be less P transferred per stocking unit than is presently accounted for in the model. Such a discrepancy has a negligible impact on the maintenance P requirement. Even substituting an incorrect ALF in the model has little effect, for example changing the ALF from 0.9 to 1.1 where the SLF=0.40, PU=80%, CC=18 and SR=16, only results in a 10% difference in the calculated P requirement.

Soil Loss Factor

Estimates of SLF values used in the model were calculated, from P rate trial data, where soil loss was determined as the difference between fertiliser P inputs and the amount of P removed in clippings where available P (as measured by Olsen P) was in a steady state. However, due to the scarcity of well conducted and reliable maintenance trials, much of the data was drawn from trials which were not really suitable for the calculation of SLF values (Cornforth and Sinclair, 1982). Little field data was available to determine the SLF for Wharekohe podzols (I. Cornforth, pers. comm.). There was also little data available to determine if differences in trial conduct can influence the calculation of SLF values (Rowarth, 1987). Total reliance was placed on the Olsen P soil test for assessing steady state. The Olsen P test is known to be variable, both spatially and temporally (Edmeades et al., 1988), and some doubt as to its reliability for establishing a 'steady state' exists (Rowarth, 1987).

Soil loss factors determined for the three soil P loss categories were 0.10 (low soil P loss), 0.25 (medium soil P loss), and 0.40 (high soil P loss). The soil P loss categories appeared to be closely related to P retention except for in soils with low P retention capacities under moderate to high rainfall or irrigation where subsurface runoff P losses probably contributed to a higher SLF (Cornforth and Sinclair, 1982). Groupings were tentative and the authors of the model acknowledged the need for further research. Not only may a soil be incorrectly categorised, but a soil placed in the low SLF category could feasibly have a lower SLF than 0.1, while a soil categorised as a high SLF soil may in fact have a higher SLF than 0.4. The northern podzols were initially placed in the high SLF category (Cornforth and Sinclair, 1984), however this has been changed at times by the computer fertiliser advisory service to a medium soil loss as a result of consultant observations rather than any scientific investigations (P. Shannon pers. comm.).

Parker (1982) noted that using the wrong SLF in the model can result in large errors in the calculation of maintenance P requirements. For example, 36% more P is required when a low P loss soil is accidentally classified as a medium loss soil and 26% too much P calculated when a medium loss soil is classified as a high loss soil, where CC=18, ALF=0.9, SR=13 and PU=80%.

Modifying Factor

The modifying factors used to predict current fertiliser requirements have been established from trial data where the optimum Olsen P value to maintain pasture production at a particular RY and the Olsen P value at which no fertiliser P input is required to maintain production are used to establish a linear relationship between the modifying factor and Olsen P for each RY. Problems with applying the modifying factor arise through anomalies in trial data used to calculate the modifying factors and through the use of incorrect estimates of RY or Olsen P. Olsen P is of particular concern as variability of up to 40% can be encountered in its estimation under field conditions (Edmeades et al., 1988), although variability will be less under intensively sampled trial plot conditions.

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The modifying factors used in the CFAS model calculate a current P requirement aimed at obtaining optimum labile P levels. If a farmer is below the optimal labile P level and SR, then the P recommendation is aimed at gradually increasing the soil P to optimum levels over several years making fertiliser costs more affordable for the farmer (P Shannon pers. comm.). However, this approach does not take into account that a more rapid increase in P application rate and hence soil P levels may in fact be more economic as farm finance structures change. Scobie and St-Pierre (1987b) showed that capital dressings to raise soil P levels to optimum in one year are more economic than the approach of Cornforth and Sinclair (1984) where a more gradual build up in soil P is recommended through the use of the modifying factor. Capital P dressings have become more common over the last three years in Northland where soil P levels are frequently below optimum due to a decrease in fertiliser use in recent years.

Economic Impact of Incorrect Parameter Estimation

Scobie and Pierre (1987a) examined the cost of incorrectly determining P maintenance on gross profit margin and determined that an error of 20% would be needed in all parameters to induce a significant economic loss. Economic loss was greatest where P was underestimated rather than overestimated, with a more than 20% error in all parameters resulting in a 10% loss in gross margin of course net loss more. However, the authors used high unit P costs (an average of \$2.50 compared to \$1.66 (superphosphate) and \$1.34 (RPR) per kg P calculated in 1991) and a very low kg butterfat pay out (\$2.50 compared to the \$5.53 averaged over the 5 years from 1989 to 1993) and hence economic losses would be far greater in the 1990s where incorrect parameter estimation leads to an underestimation of required P.

2.6.1.2 Modifications to the CFAS Model

Since its inception, various modifications have been made to the CFAS model and also in the way it is used by consultants to overcome some of the practical problems associated with its use. The rate constant 0.005 used to estimate pasture P concentration at 90% Ymax from the CC was lowered to 0.003 to lower estimated pasture P concentrations, and hence estimated losses of P from the pasture cycle. Where a rate constant of 0.005 previously equated to a pasture concentration of 0.4% at a CC of 25, substituting 0.003 equates to a pasture concentration of 0.35% for a CC of 25. As previously mentioned the SLF allocated to the Wharekohe podzols has been changed at times by the computer fertiliser advisory service from 0.4 (high P loss) to 0.25 (medium P loss).

In order to overcome problems associated with the estimation of PU and CC, which can have a marked effect on the P requirements calculated by the original CFAS version, Sinclair and Cornforth (1984) developed a modified version. The full version has been modified by assuming that relative yield should not be allowed to fall to such low levels that species composition and pasture quality decline. Hence, the following assumptions apply: RY should be maintained at 75% when SR is half CC, when SR=CC then RY should equal 95% and that for other stocking rates RY should be linearly related to SR:CC.

These assumptions result in a modification of the model where PU is substituted by (SR*8550)/(55CC+40SR) and hence:

The impact of incorrect CC estimation has been substantially reduced, for example a CC change from 18 to 20, as given in the earlier example, results in only a 1% decrease in calculated P requirements compared to a 26% decrease when the full version is used. The full version was still advocated when PU and CC could be accurately predicted.

The CFAS model, although having the advantage of simplicity and ease of use in its modified form, suffers from the lack of economic, soil P status, pasture or animal production outcomes with changing fertiliser application strategies (rates, timing of application or form). Consequently, the CFAS model has also been modified to overcome some of these shortcomings.

The CFAS model has been extended to include the economic consequences of fertiliser decisions (Scobie and St-Pierre, 1987a; Sinclair and Rodriguez Julia, 1993), the residual

effects of fertiliser use (Scobie and St-Pierre, 1987b; Metherell, 1988), animal response to pasture consumption and quality (St-Pierre and Scobie, 1987a; Metherell, 1988), and the incorporation of environmental risk (St-Pierre and Scobie, 1987b). Metherell's were the only changes incorporated into the CFAS model by the SFS. Metherell (1988) used the current soil P status and fertiliser input to calculate the expected relative yield, which combined with other parameters from the CFAS model, was used to predict the size of the cycling P pool and fertiliser recommendations for the following three years.

The CFAS model was used by MAF consultants to predict P requirements for New Zealand pastoral systems until March 1994. The present AgResearch SFS is no longer using the CFAS model for the following reasons:

i) misuse of the maintenance model in the pasture development phase where a 'steady state' does not exist,

ii) lack of economic outcome,

and iii) PU and CC parameters being difficult to quantify.

2.6.1.3 Difficulties with the CFAS model on Wharekohe soils

As stated in the Chapter 1, in 1989 it was realised that higher P rates than predicted by the CFAS model were required to maintain appropriate Olsen P levels on many of the farms in Northland on Wharekohe soils. To document the existence of a problem with the CFAS model, soil tests and fertiliser requirements dating back to 1984 from 3 farms on Wharekohe and volcanic soils were examined (Table 2.1). Included in the tables are the maintenance P requirements (calculated from the modified CFAS model (Sinclair and Cornforth, 1984) and current P requirements (maintenance requirement multiplied by the modifying factor based on the Olsen P soil test) for each site.

All of the farms examined in table 2.1 are dairy farms. The Chamberlain and Inverarity properties have been under established pasture for more than 30 years. The sites examined on Baxters' property were on newly established pasture (early 1980s).

The Olsen P values, due to variability (40%) associated with their estimation, cannot be interpreted as infallible estimates of the true mean of the Olsen P for each site in each

Table 2.1Changes in soil Olsen P levels with P fertiliser addition and calculated
maintenance and current P requirements on three properties on
Wharekohe soils in Northland.

a) Baxter's property near Kerikeri

Date	Olsen P	Applied P	Maintenance P	Current P
	(MAF Quicktest)		Requirement	Requirement
		(kg/ha)	(kg/ha)	(kg/ha)
Site A: Wharekohe	silt Ioam	•	•	
1984 spring	26	25	12.5	11.5
1985 autumn	18	24	12.5	19
1985 spring	25	24	12.5	12.5
1986 autumn	17	24	12.5	20
1986 spring	12			
Site B: Wharekohe	silt loam			
1984 spring	35	25	12.5	3
1985 autumn	27	24	12.5	10.5
1985 spring	18	24	12.5	19
1986 autumn	12	24	12.5	45
1986 spring	15			

Where: RY=88.3%; SR=15; CC=18; ALF=0.9; SLF=0.40

b) Chamberlain's property near Taheke

Date	Olsen P	Applied P	Maintenance P	Current P	
	(MAF Quicktest)		Requirement	Requirement	
		(kg/ha)	(kg/ha)	(kg/ha)	
Site A: Wharekohe	sandy loam				
1988 autumn	22	56	28	34	
1989 autumn	14	31	26	49	
1990 autumn	11				
Site B: Wharekohe sandy loam					
1988 autumn	11	56	28	58	
1989 autumn	13	60	26	51	
1990 autumn	18				

Where: RY=90%; SR=16(1988/89), 15.5(1989/90); CC=18; ALF=0.9; SLF=0.40

c) Inverarity's propery near Taheke

Date	Olsen P	Applied P	Maintenance P	Current P
	(MAF Quicktest)		Requirement	Requirement
		(kg/ha)	(kg/ha)	(kg/ha)
Site A: Wharekohe	sandy loam (WK)			
1984 spring	21	52	26	34
1985		52	26	34
1986		52	26	34
1987		95	26	34
1988 autumn	8			
Site B: Ruatangata	friable clay (RT)			
1984 spring	13	52	25	48
1985		52	25	48
1986		52	25	48
1987		95	25	48
1988 autumn	25			

Where: RY=89.4 (WK), 86 (RT); SR=15.5; CC=18 (WK), 20 (RT); ALF=0.9; SLF=0.4 (WK &RT)

year, especially as each soil test result was from a limited, but recommended, number of cores to give a bulk soil sample with no replication. However, the cumulative Olsen P test values measured over time can be used to establish possible trends in the changing availability of P in the soil.

Olsen P levels have fallen, despite P applications in excess of maintenance requirements calculated by the CFAS model, on all of the Wharekohe soils which were initially above or near the optimum Olsen P value of 25. In contrast, Olsen P levels on the volcanic Ruatangata soil on Inveraritys' have increased, from low to optimum Olsen P, with the same amount of P as was applied to the Wharekohe sandy loam on that farm. Where the Olsen P increased from low to medium on the Wharekohe sandy loam site on Chamberlains', inputs of P were greater than on the site where Olsen P values dropped on that farm. Both the Wharekohe soils and Ruatangata soils have the same SLF in the model of 0.40 (although at times 0.25 has been used for Wharekohe soils).

The maintenance P requirements calculated by the CFAS model (Table 2.1) appear to be inadequate to balance the P losses from the system on the Wharekohe soils.

It is unlikely that either an incorrect CC or ALF assessment are contributing reasons for a drop in the Olsen P levels on the Wharekohe soils. The CC of 18 is most likely an underestimation. A value closer to 20 may be more realistic (Lambert et al., 1979; Rumball and Boyd, 1980). However, the use of the modified version of the CFAS model reduced the effects of an incorrect estimation of CC. The ALF was expected to have been similar at both the Wharekohe and volcanic sites on the Inverarity property due to similar topography. Differences in animal loss/ha cannot be discounted fully as stocking rates may have been different for the soil types and small changes in SR can have a large impact on P requirements as described earlier. Each of the dairy farms described in table 2.1 have large areas of volcanic soils. Given the difficulty in grazing Wharekohe soils in wetter months and the higher production usually obtained on volcanic soils (reflected by the higher CC values), SRs are more likely to have been overestimated on the Wharekohe soils on the Chamberlain and Inverarity properties as the SR was calculated as an average over the whole farm. The calculation of stocking rates for each soil type was not possible on these properties. However, the overestimation of SRs would have led to an overestimation of calculated P requirements and so the surveys still indicate that calculated P requirements were most likely insufficient to maintain Olsen P levels in most cases.

Under estimation of the SLF appears to be the major reason for low predictions of P requirements on Wharekohe soils. The other parameters in the model are unlikely to be influential as P fertiliser predictions for volcanic soils have not been of concern on at least one farm in Table 2.1.

2.6.2 P Requirement Models Developed Since the CFAS Model

Other models which have been developed in New Zealand to predict pasture P requirements include the incorporation of the residual effect of applied P (McCall and Thorrold, 1991), the use of reactive phosphate rock (RPR) (Sinclair and Johstone, 1994; Sinclair et al., 1993; Roberts et al, 1994; Metherell, 1994), and the economic impact of fertiliser management strategies (Metherell et al., 1995).

The present AgResearch SFS is now marketing the 'Outlook' model developed by Metherell et al. (1995) to consultants who make fertiliser P recommendations to farmers (Introduced in 1994). The Outlook model uses the mass balance approach where P requirements are calculated to replace P lost from the cycling P pool via non-labile P accumulation and runoff losses, and animal losses in excretal transfer and product removal, similar to the CFAS model. The Outlook model also assumes that the cycling P pool is maintained in a steady state in the calculation of P maintenance requirements. The Outlook model accounts for P added to the cycling pool via soil weathering whereas the CFAS model did not. The animal loss parameter has been assigned different values, divided into product losses and animal transfer rates, than those used in the CFAS model based on trials reviewed by Metherell (1994). The model assumes that soil P loss will be a constant proportion of the labile P pool, estimated from the Olsen P test by a curvilinear relationship for each soil group category. The CFAS model also assumed soil loss was a constant proportion of the labile P pool, but expressed the soil loss factor as a proportion of P pasture uptake. Outlook divides the soil groups into 4 soil loss categories; sedimentary (soil loss 0.04), volcanic (soil loss 0.05), pumice (0.10) and high loss, the podzols (soil loss 0.10). The Outlook model is extremely sensitive to the allocation of soil group categories with maintenance P requirements calculated for the podzol soil group more than twice those calculated for the sedimentary and volcanic soil groups (Metherell et al., 1995). Phosphorus requirements calculated by the Outlook model for northern podzols are more than twice those calculated from the CFAS model. The higher soil losses assigned to the podzols by the Outlook model compared to the CFAS model may address the apparent underestimation of soil P loss found in the case studies in table 2.1 and is investigated in chapter 7.

2.7 SUMMARY OF LITERATURE REVIEW

In a grazed pasture system, P cycles through above and below ground pools.
 Phosphorus is added to the cycling pool from the weathering of minerals in the native parent material and P fertiliser application, and lost from the cycling pool through transfer of excreta to unproductive areas and concentrated areas such as campsites, in animal

products and through soil losses such as net immobilisation, net sorption/precipitation, erosion and runoff waters.

Total P and Pi accumulate in the soil under pasture with time where P application rates exceed losses from the pasture cycle. Inorganic P accumulates mostly as P associated with Fe and AI in the acid, weathered soils of New Zealand. Organic P accumulation dominates in the initial years following pasture development where OM levels are low and C:N ratios are high, as N fixation by pasture legumes leads to a lowering of C/N rations encouraging OM accumulation and the organic immobilisation of P. The rate of Po accumulation slows as an equilibrium is approached with the most labile Po pools reaching equilibrium first. P is considered to be immobile in most New Zealand soils.

 Podzolisation results in low sesquioxide contents and consequently low Anion Storage Capacities, and extremely low natural P contents in the A horizons of the more weathered podzols. The largest proportion of this natural P is found in the labile P pool. Pasture development on podzols leads to P accumulation which initially accumulates as Po. Podzolic soils low in Al are expected to reach an equilibrium Po content which is lower and more rapidly obtained than in other soils with higher Al content which have a greater capacity to stabilise Po compounds. The ability of podzols to retain added P is reduced with increased fertiliser application as the few available P retention sites become occupied with the added P. Large losses of P have been recorded from the A horizons of New Zealand podzols and the potential for subsurface P runoff losses has been demonstrated.

• The accumulation of P over time under permanent pasture with fertiliser P application can contribute to pasture growth so that eventually only maintenance applications of P are required to balance any losses from the pasture P cycle and maintain pasture growth at the required relative yield and stocking rate. Various models have been developed to predict P requirements for pastoral systems in New Zealand. During the 1980's and early 1990's, the then MAF SFS used the Cornforth and Sinclair CFAS model, where P requirements are calculated to replace losses from the cycling P pool, to make fertiliser P recommendations. Investigation of several farms, where the CFAS model was underestimating the amount of P required to maintain soil Olsen P values on Wharekohe

soils, has identified the CFAS SLF as the parameter most likely leading to the inability of the CFAS model to predict P requirements on these podzols. The Wharekohe sandy loam may require a higher SLF than the Wharekohe silt loam.

 The CFAS model is no longer used by the present AgResearch SFS who are now marketing the new Outlook model to fertiliser consultants. Higher soil P losses have been assigned to the podzols in the Outlook model, resulting in calculated P requirements of twice those calculated by the CFAS model, which may address the apparent underestimation of soil P loss determined for the Wharekohe soils in this review.

• This review of the literature has confirmed the need to establish the extent and nature of soil P losses from the Wharekohe podzols so that pasture P requirements can be modified and unnecessary costs, to the farmer economically and to the environment through increased potential for eutrophication, be minimised.

CHAPTER 3 FATE OF APPLIED P

3.1 INTRODUCTION

When a phosphatic fertiliser is applied to pasture the water soluble component is dissolved by moisture from both the air and surrounding soil. The dissolved fertiliser P can either remain in solution, form sparingly soluble initial reaction products, become weakly sorbed, be taken up by plants or be lost from the P cycling pool. Phosphorus is lost from the P cycling pool via the soil through both its accumulation within the soil profile as non-labile P and loss from the soil profile through water movement as surface soil erosion and leaching either vertically or laterally. These P losses constitute the soil loss factor (SLF) used in the CFAS model for New Zealand conditions.

Phosphorus is generally considered to be an immobile anion in most soils and this is certainly the case in most New Zealand soils where a large portion of the applied P is retained in the topsoil (Jackman, 1951; Walker et al., 1959; Haynes and Williams, 1992). However, evidence exists for losses of applied P from podzolic soils both in New Zealand (Jackman, 1955a; O'Connor, 1980; Lee et al., 1983) and overseas (Khanna et al., 1992; Lefroy et al., 1995) suggesting that in these soils P is mobile. In comparison to other mineral soils, the Wharekohe podzols of Northland New Zealand are characterised by very low anion storage capacities, which may eventually limit P accumulation and lead to the movement of applied P down and through the profile and eventually from the soil to the wider environment. Therefore, it is possible that the magnitude and type of soil P losses from the pool of cycling P in Wharekohe podzols may change with time from initial pasture development. Any losses of applied P from the soil represent a cost both to the farmer and to New Zealand society through increased P loading of water ways creating the potential for eutrophication.

Losses of P from the soil can be quantified by directly measuring P loss in erosion material and runoff water. However, such experiments can be time consuming, expensive and do not provide a historic perspective on P losses. Alternatively, where farm fertiliser and stocking history are known, applied P which has been lost from the soil can be calculated as:

P lost from soil = Applied P - (Animal P Loss + P accumulated in the soil).

The original DSIR Grasslands Kaikohe Research Station provided an ideal environment to assess the fate of applied P on Wharekohe podzols at various stages of pasture development, as pastures have been developed over a period spanning 24 years, and reasonably accurate fertiliser and stocking records were available.

3.2 OBJECTIVES

This chapter considers the following specific objectives of the research project:

- The determination of the fate of applied fertiliser P in a pasture development chronosequence on the Wharekohe silt loam at the Kaikohe Research Station by measuring total soil P and, by calculation, P losses. (The accumulation of P into plant unavailable soil fractions in the chronosequence are presented and discussed separately in Chapter 4.)
- The determination of the effect of the stage of pasture development on plant available P (as measured by Olsen P).
- The determination of the effect of the stage of pasture development on pasture production and P uptake.

3.3 MATERIALS AND METHODS

To meet the above objectives, two separate investigations were conducted. Soils for the first study were sampled in the spring of 1990. To confirm and extend the initial findings, further samples were collected in the spring of 1993.

3.3.1 Site Selection

Wharekohe silt loams are found on the rolling areas of the Kaikohe Research station. There are two variants on the station, the Wharekohe silt loam (with pan) and the Wharekohe silt loam (without pan), the pan being the dense pale eluvial (E) horizon. In addition, the Wharekohe silt loams exist in a complex with the podzolised yellow-brown earth Hukerenui silt loam. Most of the Kaikohe station had been dug over by Kauri gum diggers and hence the topsoil, and in some places the E horizon, have been disturbed on all sites including the undeveloped sites. Where areas have been developed to pasture, the process of pasture development involved deep ploughing which has resulted in further inversion of the soil's upper horizons and often disturbance of the E and B horizons. Hence, in some areas, the E horizon has been broken up and bits of E and B horizon have been turned up into the surface soil. Therefore, large uniform areas of Wharekohe silt loam with the pan intact are difficult to find on the Kaikohe Station.

Wharekohe silt loam (with pan) was the soil type chosen for this study because it is the more dominant variant and is considered to be the "typical" Wharekohe podzol in Northland. It is at the extreme end of the leaching scale and hence different sites are expected to behave more similarly in respect to P chemistry than the less leached Wharekohe silt loam without pan. The latter is likely to be more variable and is easily confused with the less weathered Hukerenui and disturbed areas of Wharekohe silt loam with pan.

In spring, 1990, non-campsite areas of Wharekohe silt loam (with pan) on slopes of between 4° and 14°, covering at least 100 square metres were identified over a

range of pasture ages (Table 3.1). The sites had similar annual P fertiliser histories as outlined in 3.2.2.

In order to confirm that the conclusions reached from the individual pits in 1990 were applicable to a wider area, four further sites from each of the areas developed to pasture in 1958, 1960, 1967 and 1982 and the undeveloped area were identified as described above in spring 1993. Sampling sites were spread over 2 to 3 paddocks for each pasture age and a similar area in the undeveloped region.

Year	Pasture Age	Slope	Average Depth to	Average Depth of E
Developed	1990		top of the E Horizon	horizon (cm)
	(years)		(cm)	
Undeveloped	Undeveloped	5° 40'	12.8	10.0
Undeveloped	Undeveloped	11° 30'	14.0	7.1
1982	8	6° 20'	17.5	11.0
1967	23	14°	10.1	8.9
1965	25	4° 20'	13.0	15.4
1960	30	9°	14.4	8.6
1958	32	6° 10'	23.8	11.8

 Table 3.1.
 Descriptions of Wharekohe silt loam sites selected in 1990.

3.3.2 Fertiliser and Lime History

Fertiliser History

The total amount of P applied since initial pasture development at the sites selected in 1990 and 1993 are presented in Table 3.2.

Approximately 1000 kg/ha of superphosphate was commonly applied in the first year of pasture development at all pasture age sites except the youngest area, developed in 1982, where 800 kg/ha superphosphate was applied initially.

Table 3.2P application history of pasture chronosequence sites selected in 1990(additional sites selected in 1993 in brackets).

Year Developed	Pasture Age	Total P	Pasture Age	Total P
	1990	Application	1993	Application
	(years)	to 1990	(years)	to 1993
-		(kg P/ha)		(kg P/ha)
Undeveloped (1)	Undeveloped	0	Undeveloped	0
Undeveloped (2)	Undeveloped	0	-	-
1982	8	394	11	540
				(526)
1967	23	910	26	1056
				(1037)
1965	25	908	-	-
1960	30	947	33	1095
				(1074)
1958	32	1010	35	1156
				(1142)

In the years leading up to the 1980's, the annual P application rate varied between pasture age sites due to different trial requirements but averaged 24 kg P/ha, except on the area developed in 1967 which received an average of 33 kg P/ha in each of the 10 years to 1978. In later years all sites received approximately 30 kg P/ha/year, except the area developed in 1960 which received 26 kg P/ha/year.

Until 1986, P was applied as superphosphate normally on an annual basis. From the spring of 1986 until 1990, P was applied as "Longlife", a product containing 30% reactive phosphate rock and 70% superphosphate (11% P).

All the original sites selected in 1990 received 70 kg P/ha in 1991, 37 kg P/ha in 1992 and 39 kg P/ha in 1993. This was applied as superphosphate in 1991 and 1992, and RPR in 1993. All P was applied as RPR from 1991 to 1993 to the rest of the Kaikohe Station including the additional sites selected in 1993 at 51-56 kg P/ha in 1991, 37 kg P/ha in 1992 and 39 kg P/ha in 1993.

The most recent fertiliser applications to each sampling time were March, 1990 and January, 1993.

Lime History

The total amount of lime applied in the 7 years from initial pasture development and in the 10 years prior to sampling at the sites sampled in 1990 are presented in Table 3.3.

The amounts of lime applied to each developed site during the initial pasture development stage were 2.24 tonne/ha (1960 site), 5 tonne/ha (1967 site) and 6 tonne/ha (1958 and 1982 sites).

Lime was last applied to all sites in autumn 1989 at 2 tonne/ha. No further lime had been applied to any sites from 1989 to the 1993 sampling.

Table 3.3Lime application history of selected pasture chronosequencesites sampled in 1990.

Year	Pasture Age 1990	Total Lime Application	Total Lime Application
Developed	(Years)	in 7 years From Initial	1981-1990
		Pasture Development	(tonne/ha)
		(tonne/ha)	
1982	8	9.1	11.1
1965	23	unknown	5.0
1967	25	10.6	7.2
1960	30	4.5	5.0
1958	32	15.3	5.0

All of the sites sampled in 1993 from the 1982 and 1967 developed sites had similar lime histories to the sites sampled in 1990. However, lime application varied enormously over the areas developed to pasture in 1958 and 1960 in the first years following initial pasture development, due to the requirements of lime application rate trials. The sites developed to pasture in 1960 and sampled in 1993 received a higher average lime rate than the 1960 site sampled in 1990, while the sites developed to pasture in 1993 had received a lower average lime rate than the 1990.

3.3.3 Soil Sampling

Spring 1990

Initially one 10×10 m site was selected for each of the pasture age sites (described in 3.2.1) to determine if the low anion storage capacity of the Wharekohe soil limits the accumulation of applied P leading to P movement down or from the soil profile.

Four soil pits were dug at each site, one pit on each side of a 10×10 m area. A typical soil profile is shown in plate 1. Soil was sampled down a transect line of the profile on one side of each pit where the E horizon was greater than 5 cm thick (marked by an arrow on each plate). Approximately one kilogram of soil was removed with a knife at each of 6 depths: 0-3 cm, 3-7.5 cm, 7.5 cm to the top of the E horizon, E horizon, 0-10 cm below the E horizon and 20-30 cm below the E horizon, shown in Plate 1. Soil bulk density was determined at each depth by removing 3 intact soil cores (4.8 cm diameter by 2.3 cm) which were dried overnight at 105°C and weighed.

Spring 1993

In spring 1993, 10×10 m areas were selected from within the 4 additional sites (described in 3.2.1) for each pasture age and the original sites were resampled in order to investigate whether the original sites were representative of a wider area.



Plate 1 Profile of an undeveloped Wharekohe silt loam.

20 soil cores (2.5 cm diameter by 7.5 cm depth) were removed from each site and bulked. Soil bulk density was determined by removing 5 intact soil cores (7.1 cm diameter by 7.5 cm) which were dried overnight at 105°C and weighed.

All soil samples collected were air dried and sieved to <2 mm particle size to remove rocks and roots. Sub-samples for chemical analysis were removed by successive mixing and halving. The sub-samples used for total P were ground to <150 μ m particle size in a ring grinder.

3.3.4 Soil Analysis

3.3.4.1 Total P

Total P was measured after digestion in a tri-acid mixture of concentrated HNO_3 : HCI: HCIO₄ (5:5:7) (Bolan and Hedley, 1987). One gram of soil was digested with 25 ml of tri-acid in a 250 ml Erlenmeyer flask at 260°C until white fumes appeared. The digest was made up to 50 ml in volume and allowed to settle before an aliquot was removed for inorganic P determination colorimetrically by the phosphomolybdate method of Murphy and Riley (1962).

3.3.4.2 Olsen P

Olsen P was extracted using the MAF Olsen P Quicktest method (modified from Olsen et al., 1954) where soil was shaken with 0.5 M NaHCO₃ (pH 8.5) in a 1:20 (v/v) ratio at 25°C for 30 minutes. The suspension was filtered (Advantec Toyo No.2) and the inorganic P determined colorimetrically by the phosphomolybdate method of Murphy and Riley (1962) with an autoanalyser.

3.3.5 Pasture Sampling and Analysis

Pasture samples were collected regularly from beneath animal exclusive cages for two years from December 1990-1992 at the 1990 soil sampling sites. Fresh caged areas were pretrimmed to mower height at the start of each growth period. Dry matter yield and chemical analysis samples were collected at intervals determined by pasture growth over a two year period. Pasture botanical composition samples were also collected at seven of the growth periods.

3.3.5.1 Dry Matter Yield

Samples for dry matter yield were collected with a mower set to approximately 3.5 cm above ground level cutting strips 0.46 m wide and 2.25 m long. The samples were dried overnight at 65°C before weighing.

3.3.5.2 Botanical Composition

Pasture botanical composition samples were also collected with hand shears at mower height. Botanical composition was determined by hand sorting each pasture sample into its grass, clover, lotus, weed and dead matter components which were then dried overnight at 65°C and weighed.

3.3.5.3 N and P Concentration

At the same time as yield measurements were made, samples for N and P analysis were collected with hand shears at mower height, oven dried at 65°C and stored in airtight plastic bags until grinding to <2 mm. Herbage N and P concentration were determined after Kjeldahl digestion (McKenzie and Wallace, 1954) by analysis with an autoanalyser (Twine and Williams, 1971).

3.3.6 Statistical Analysis

Soil Data

Olsen P and total P results were subjected to analysis of variance using Genstat to determine differences between sites for each depth and between depths for each site. Statistical analysis of total P was conducted on log transformed results using the unbalanced analysis of variance program REML in Genstat.

Herbage Data

The relationship between each of dry matter yield, N and P concentration and uptake, and botanical composition with pasture age were determined using FLEXI (Upsdall, 1994), a Bayesian smoothing program which produces curves representing each relationship and their 95% confidence intervals..

Trial Design

Pasture was established on the Kaikohe Research Station in large blocks at a time, starting from the road frontage in the late 1950's. Consequently the study of pasture age effects could not be approached as a conventional trial design. There is effectively no replication of pasture age. Hence, the analysis of variance indicates differences between sites rather than pasture ages and it is only possible to say that soil data from one site was significantly different from another site. Although replicates for the spring 1993 soil sampling were sampled over a wider area from sites spaced further apart in different paddocks, this second sampling still did not overcome the problem of a lack of randomisation of pasture age.

3.4 RESULTS AND DISCUSSION

3.4.1 Effect of Pasture Development on the Fate of Applied P

3.4.1.1 Total P

Spring 1990

Total P concentration decreased significantly (P<0.05) with depth to the E horizon on all sites (Figure 3.1). Other New Zealand studies, where fertiliser P was applied over time, have also shown decreasing total P with depth down the profile (Doak, 1942; Jackman, 1951; Jackman, 1955a; Walker et al., 1959, Saunders, 1959a, Haynes and Williams, 1992). Total P concentration of the samples taken from the E and B horizons (0-10 cm and 20-30 cm below E) were lower than in the A horizon and showed little variability between the three lower depths at each site.

Despite problems with the interpretation of site data, some clear trends with pasture development are evident. Low natural total P content and its low variability in undeveloped Wharekohe top soils, combined with the number of older developed sites, mean that some confidence can be placed in any changes in P status reflecting pasture age and hence applied lime and P.

Total P concentration increased with pasture development at all sampling depths above the E horizon (Figure 3.1) indicating that P moved down the profile to the top of the E horizon. There was no significant difference in the total P concentrations for the 0-3 cm depth of the developed sites. In the 3-7.5 cm depth, total P concentration in the 8 year old site was significantly lower (P<0.001) than in the four older developed sites. A similar pattern occurred at the 7.5 cm - E depth where the total P concentration in the 8 year old site was significantly lower (P<0.001) than all the older developed sites except the oldest 32 year old site.



Figure 3.1 Effect of pasture age on soil total P concentration (S.E.D.s varied, Table in Appendix 3.1).

The lower total P concentration of the oldest site at the 7.5 cm - E horizon depth was most likely due to the dilution effect of the significantly higher depth (23.8 cm) to the top of the E horizon at this site rather than pasture age. When the results were expressed as kg P/ha (Table 3.4), the oldest site contained the highest total P of any site at this depth.

Some of the developed sites had significantly higher total P concentrations than the undeveloped sites for the two B horizon samples (0-10 and 20-30 cm below the E horizon), although the magnitude of differences in total P concentration in and below the E horizon between all the sites were small. The higher P concentrations at some sites may have been due to the downward movement of applied P and its subsequent accumulation in the B horizon. Variation in the continuity and thickness of the E horizon was evident at pit sites and may have influenced the variation in the downward movement of applied P.

When the results are expressed in kg/ha (Table 3.4) a substantial portion of applied P could be accounted for in the B horizon of some of the developed sites, at least 20% of the P applied to the 23 year old site. However, the higher P contents of the B horizon of some developed sites may not have been due to downward movement of applied P and its subsequent accumulation in the B horizon as natural variation in native P content between the sites may also have accounted for the higher P concentrations recorded in the B horizon of some developed sites. Variation in native P content is most likely to be high in the B horizon of Wharekohe podzols. An anion storage capacity of 95% and total P concentrations, ranging from 150-170 ug P/g were recorded in the B horizon of an undeveloped Wharekohe silt loam site (New Zealand Soil Bureau, 1968), yet in the present study much lower P levels were recorded (85 ug P/g measured in the 20-30 cm below E horizon depth of the 23 and 30 year old sites).

Pasture	0-3 cm	3-7.5 cm	7.5-E cm	E	0 -10 cm	20-30 cm
Age				horizon	below E	below E
					horizon	horizon
0	20	23	28	33	11	21
8	167	128	92	55	24	23
23	221	267	93	92	95	115
25	187	220	140	92	26	49
30	174	191	167	48	87	98
32	185	234	247	44	20	14

Table 3.4 Total P content (kg P/ha) of Wharekohe silt loam samples.

Accumulation of applied P in the A horizon, from which pasture nutrients are drawn, is presented in table 3.5. Pasture roots draw most of their nutrients from the upper 7.5 cm of soil (the effective root zone) (Horne, 1985; Gillingham et al., 1980b) with the 7.5 cm - E horizon depth contributing nutrients to a lesser degree. The accumulation of P in the E and B horizons effectively represents a loss of P from the pasture cycle.

Site	P Applied	P Acc.	P Acc.	P Acc.	% applied P	% applied P	% applied P
age	(kg/ha)	0-3 cm	3-7.5	7.5 cm-	accumulated	accumulated	accumulated
-		(kg/ha)	cm	E*	0 - 7.5 cm	7.5 cm - E*	0 - E*
			(kg /ha)	(kg /ha)			
8	394	147	105	64	64	16	80
23	910	201	243	65	49	12	61
25	908	167	196	112	40	12	52
30	947	154	168	139	34	15	49
32	1010	165	210	219	37	22	59

Table 3.5 Accumulation of applied P at each depth to the top of the E horizon.

* E horizon.

The substantial quantities of applied P accumulating below 7.5 cm to the top of the E horizon in the Wharekohe silt loam, up to 22%, are not unusual for a sedimentary soil. Applied P has been shown to accumulate to depth in even greater quantities in other sedimentary soils, including a podzol, in New Zealand, but not in volcanic soils. In P fertiliser comparison trials of 4.5 years duration (Jackman, 1955a) over a range of soils, the largest increases in P accumulation at depth were in the sedimentary soils compared to volcanic soils.

In contrast to the sedimentary soils, applied P was generally restricted to the top sampling depth of central North Island volcanic soils, 5 cm in a yellow brown pumice soil (Jackman, 1951), 10 cm in a yellow brown pumice soil (Walker et al., 1959) and 5 cm in a yellow brown loam with only minor accumulation of applied P to 12.5 cm (Saunders, 1959a).

However, of the 35 kg P/ha/yr applied over a 35 year period to the surface of an irrigated yellow grey earth at Winchmore, 283 kg P/ha (23%) and 129 kg P/ha (11%) had accumulated in the 7.5-15 cm and 15 -22.5 cm depths respectively (Nguyen and Goh, 1992). In a yellow grey earth near Marton receiving 45 kg P/ha as superphosphate for 9 years, only 119 ug P/g and 62 ug P/g had accumulated in the

10-15 and 15-25 cm depths, respectively. In the West Coast Okarito podzol (Lee et al., 1983), surface applied P at \approx 30 kg P/ha/yr had moved downward to accumulate in the 5-10 cm depth on sites developed to pasture for 3, 5 and 13 years. However, only the 13 year old site was significantly different from the undeveloped site, 108 µg/g more 0.5 M H₂SO₄ extractable P. The authors considered that the lack of differences was due to large variability in the P contents of the samples taken from each site.

The greater percentage accumulation of applied P at depth in the above mentioned sedimentary soils does not necessarily indicate greater movement of applied P through the profile in comparison to the Wharekohe silt loam. The low Fe and Al contents and associated low anion storage capacity of the A horizon in the Wharekohe silt loam and a maximum P capacity to accumulate P, may be restricting P accumulation in this horizon leading to large losses of applied P.

Most of the applied P which accumulates as Pi in New Zealand soils has been shown to be associated with Fe and AI (Saunders, 1959a; Steele, 1976; Grigg and Crouchley, 1980; Condron and Goh, 1989; Perrott et al., 1989; Perrott et al., 1992a; Rowarth et al., 1992a). However, some Pi accumulates in the soil as Ca-P from relatively inert fertiliser residues (Rowarth, 1987; Condron and Goh, 1989; Perrott et al., 1992a). Hence RPR and insoluble PR residues from superphosphate were probably accumulating at each developed site in the present study. As RPR use continued beyond 1990, the rate of net Ca-P accumulation is likely to have decreased from 1991 as the dissolution of RPR in the soil approaches RPR application rates with continued application (Edmeades et al., 1991b). Fertiliser P residues were likely to be accumulating evenly over the older sites due to similar site characteristics and the application of similar quantities and forms of P. It is highly unlikely that any other P fraction would have continued to accumulate evenly over all of the developed sites. Hence, as small quantities of fertiliser P residues are likely to continue accumulating in the soil, the maximum P storage capacity referred to in this text applies to the capacity of the soil to sorb inorganic and organic P onto/into soil surfaces and form new insoluble P compounds in situ. The extent of accumulation of applied P into various inorganic and organic P fractions is investigated further in chapter 4.

The low P storage capacity of the Wharekohe silt loam topsoil is limiting the accumulation of applied P leading to P movement down the soil profile. Although it is difficult to determine the significance of differences between sites, total P accumulation at each depth appeared to be delayed until the depth immediately above had reached a maximum total P content. Hence, P may only move down the profile of the Wharekohe silt loam in large quantities, to accumulate at depth, once the P content of the topsoil is near a maximum P storage capacity. In this study the maximum P storage capacity appears to be reached by 8 years under pasture in the 0-3 cm depth, and between 8 and 23 years for the 3-7.5 cm depth. The consequence of such a low maximum P storage capacity would be large losses of applied P from the topsoil of the older developed sites (explained further in 3.4.1.2).

Doak (1942) also found that P (measured as HCl soluble P_2O_5) moved slowly down the profile of a yellow grey earth over a 9 year period. Applied P initially accumulated only in the top 5 cm of the soil in Doak's study, with applied P only accumulating at 5-10 cm after 2 years, at 10-15 cm after 4 years, and at 15 to 25 cm after 5 years. In the present study, pasture ages within 0 and 8 years or within 8 and 23 years were not available to determine more precisely when P started to move into each depth in the Wharekohe silt loam.

Spring 1993

Interestingly the concentrations of total P in the top 0-7.5 cm of the additional 26 and 33 year old sites sampled in spring 1993 (Figure 3.2) were similar to the 750 μ g/g measured in a Wharekohe silt loam by Perrott and Sarathchandra (1987) in a survey of soils which had been in pasture for at least 20 years.

Comparison of the total P content (kg P/ha) of samples collected in both spring 1990 and 1993 revealed that the 23 and 30 year old sites selected in 1990 may not be that representative of wider areas of similarly aged pastures on the Wharekohe silt loam on the Kaikohe Research Station (Table 3.6). The original 23 year old site (developed in 1967), and another site selected in the same paddock in 1993, had far higher total P contents than the other 3 additional sites despite the additional sites receiving all their applied P in RPR form (RPR would be expected to increase total P initially through the accumulation of undissolved RPR residues). Such high P contents in the original site indicate that a different fertiliser history at the site may have occurred. The paddock has a large, steep area (30% of paddock) that fertiliser trucks may have avoided and hence increased application rates in the vicinity of the sampling sites. The original 30 year old site (developed in 1960) had a lower total P content than the other sites developed for at least 23 years that were selected in 1990 or the additional sites of similar age due to its reduced Ca-Pi accumulation (related to its early liming history), explained further in Chapter 4.

A comparison of the total P content of the sites sampled in 1990 with samples from the same sites collected in 1993, at which point an additional 146 kg P had been applied to each site, reveal that P has continued to accumulate at all sites (Table 3.6). As expected P continued to accumulate at a greater rate in the top 7.5 cm of the youngest site. Continued accumulation of large quantities of applied P on the 26 year old site was unexpected, however, this site does not seem to be representative of other sites of similar age as explained above. Accumulation of applied P was clearly lowest in the two oldest sites. The application of RPR and associated increases in undissolved phosphate rock residues would account for a large proportion of the total P increase in the older sites, and is investigated further in Chapter 4. Hence these results, in relation to the accumulation of P, support the hypothesis that the older sites on the Wharekohe silt loam on the Kaikohe Research Station are approaching or have reached a maximum P storage capacity.

The spring 1993 samples from the additional sites also confirmed that the Wharekohe silt loam on the Kaikohe station has a maximum P storage capacity, as there was no difference in the amount of applied P in the 0-7.5 cm depth between the developed sites despite the much higher P inputs to the older pasture sites

(Table 3.7). These results indicate that the maximum P storage capacity is reached by 11 years in the top 7.5 cm of soil.

Table 3.6Accumulation of P applied from spring 1990 -1993 in the top 7.5 cm oforiginal sites (Additional sites in brackets).

Year Developed	Total P in top 7.5 cm	Total P in top 7.5 cm	P accumulated 1990-
	1990 (kg/ha)	1993 (kg/ha)	1993 (kg/ha)
Undeveloped	43	44 (52)	-
1982	295	424 (449)	129
1967	488	660 (526)	172
1960	365	393 (498)	28
1958	419	451 (444)	32

Table 3.7 Accumulation of applied P in the top 7.5 cm of soil sampled from the additional sites in 1993.

Site	P Applied (kg/ha)	P accumulated in top 7.5	% applied P accumulated in
Age		cm (kg/ha)	the soil to 7.5 cm.
11	526	396	75
26	1037	470	45
33	1074	458	43
35	1142	369	32

A comparison of the total P measured in the additional sites to those sites originally sampled in 1990 (Figure 3.2) reveals a higher average total P content than in the original sites. The greater total P recorded (55 kg P/ha as the difference in average applied P accumulated, original 23 year old site removed as outlier) can be attributed to the application of P solely as RPR on the additional sites. The RPR residues were expected to have accumulated reasonably evenly across the developed sites. This aspect is investigated further in chapter 4.



Figure 3.2 Comparison of total P measured in original 1990 sites (◊) and total P measured in additional sites in 1993 (♦).
 (Vertical bars = standard errors of the means).

A low maximum P storage capacity appears to be a feature of podzol topsoils and not a feature of most other agricultural soils in New Zealand. Evidence from a chronosequence study of P (extracted by 0.5 M H2SO4) in Okarito soils (West Coast gley podzols) also found that, while applied P accumulated with pasture development in the top 10 cm of the soil, there was no significant difference between the P contents of the top 5 cm of the developed sites (3, 5 and 13 years) (Lee et al., 1983).

In contrast to the podzols, long term studies of P changes over time in sedimentary yellow grey earths have found that P was still increasing in the topsoil (7.5 cm) after 8 (Doak, 1942), 15 (Lambert et al., 1988) and 35 years (Nguyen et al., 1989). Evidence collected from several studies indicates that P also accumulates to very high levels in yellow brown loams and yellow brown pumice soils high in allophane (Jackman, 1951; Saunders, 1959a; Walker et al., 1959; Perrott et al., 1989).

3.4.1.2 Losses of Applied P

A large proportion of the P applied to the chronosequence sites could not be accounted for in the top 7.5 cm of the soil (the effective root zone), to greater depth (0- E horizon) or when losses associated with the grazing animal were included in the calculation (Figure 3.3, Table 3.8).

The amount of P not accounted for in the top 7.5 cm of the soil increased with pasture age to over 40% of the applied P. When P accumulation to the top of the E horizon is included, nearly all of the P applied to the 8 year old site could be accounted for (Figure 3.3 b). 16 -27% of the applied P is still unaccounted for in the older developed sites even when all the P accumulated above the E horizon is included in the calculation. Such large losses indicate that P is lost from the system by lateral movement down slope above the E horizon and/or to below the E horizon.

Some of the lost P may have accumulated in the E and B horizons (Figure 3.3 c, Table 3.8a). However, given the low permeability of the E horizon, large losses via vertical leaching are unlikely. High variability of native P in the B horizons could account for the larger P at this depth in some of the developed sites rather than the accumulation of applied P. P has most likely been lost through either lateral movement of soil water above the impermeable E horizon or has moved beyond the sampled B horizon where vertical leaching has occurred. The former is the most likely scenario as little applied P accumulated in the B horizon samples despite their high P retention capacity. Lateral movement of P in soil water above impermeable horizons has been suggested to account for the high losses of P from other New Zealand podzols (O'Connor, 1980; Lee et al., 1983) and from Australian soils (Lewis et al., 1987; Khanna et al., 1992).

For each developed site, the percentage soil loss of applied P was calculated over the entire period from development. However, soil losses of P in the years following initial pasture development are low, and hence, soil losses of P will be much higher in later years. The soil losses of P applied to the original sampling sites between 1990 and 1993 were calculated as 65% and 62% for the 33 and 35 year old sites

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b) Fate of applied P from the soil to the top of the E horizon.



c) Fate of applied P from the soil profile to 30 cm below the E horizon.



Figure 3.3 Fate of applied P showing losses from each depth with time from pasture development, a) 0-7.5 cm, b) 0 cm -Top of E Horizon, c) Soil Profile to 30 cm below E Horizon.

Table 3.8Losses of applied P from different aged pastures on theWharekohe silt loam.

Site Age	P Applied (kg/ha)	% Applied P lost from the soil (ie not accounted for by					
(Years)		animal loss* or accumulation in varying soil depths)					
		To 7.5 cm To Top of E		To 30 cm Below			
			Horizon	E Horizon ^o			
) () () () () () () () () () ((full sampling			
				depth)			
8	394	20	4	0			
23	910	31	24	12			
25	908	38	26	19			
30	947	41	27	2			
32	1010	38	16	16			

a) Spring (1990) Sampling

b) Spring (1993) Sampling

Site	P Applied (kg/ha)	% Applied P not accounted for by		
Age		animal loss* or accumulation in soil to 7.5 cm		
11	526	8		
26	1037	35		
33	1074	35		
35	1142	42		

*Animal loss calculated as 0.5 kg P/yr/SU (Cornforth and Sinclair, 1984), SR=15.6 SU/ha. °Calculation included an estimate for P in the unsampled 20-30 cm below E depth.

respectively. If soluble P fertiliser, such as superphosphate, had been used throughout this period, higher P losses than recorded would be expected. Much of the P accumulating on each site in later years could be attributed to the accumulation of RPR residue as RPR was applied in 1993.

High losses of applied P have also been reported in other studies on podzolic soils in New Zealand. It is not possible to estimate the amount of applied P which remains unaccounted for in the soil or by animal loss in these studies on other podzols, as stocking rate data is not available, and hence, applied P accumulation figures are presented. The accumulation of applied P was only 10% in the top 15 cm of a Te Kopuru sand after 9 years of superphosphate application averaging 34 kg P/ha/yr (Jackman, 1955a), 43% in the top 7.5 cm after 5 years where an average of 48 kg P/ha/yr was applied to a Maungatua podzol (Floate and Enright, 1991) and 33% in the top 15 cm after 5 years of P application averaging 44 kg P/ha/yr to an Addison silt loam (O'Connor, 1980). Losses of P from the root zone, 0-7.5 cm, were possibly even greater in the Te Kopuru and Addison soils.

The above studies of P loss from New Zealand podzols have been conducted on mostly young pasture of less than 10 years. In most of these studies, losses of P have been far higher than those recorded in the 8 and 11 year old Wharekohe silt loam pastures sampled in the present study where a large proportion, 64% and 75% respectively, of the P was recovered in the top 7.5 cm (80% of P accumulated in the soil above the E horizon (0-17.5 cm) in the 8 year old site).

The reasons for far greater accumulation of applied P in the early years following initial pasture development in the Wharekohe silt loam in comparison to the above mentioned podzols are not clear. Phosphorus was applied at an average rate of 48 kg P/ha on the Wharekohe silt loam, and hence, is similar to rates applied to the The other podzols may have had lower maximum P storage other podzols. capacities than the Wharekohe soil. Higher annual rainfall (>2500 mm) may have led to higher P losses in the South Island podzols compared to the Wharekohe soil (1630 mm). However, Powell and Taylor (1980) also reported little loss of applied P from the top 10 cm of the South Island Maimai gley podzol 3 years after development due mostly to the organic immobilisation of applied P. The Maimai trial was very short term and it is not possible to know if losses from the soil would have been similar or greater in the ensuing years. The coarser texture and higher rainfall of the Te Kopuru sand podzol, in comparison to the Wharekohe silt loam, may have created larger losses of applied P through greater porosity and water movement. Differences in nitrogen fixation may also have effected differences in organic P accumulation. Increased nitrogen fixation leads to greater accumulation of organic matter and organic P (Walker et al., 1959; Perrott and Sarathchandra, 1987).

Phosphorus losses from the sedimentary yellow grey earths under pasture are variable but generally lower than losses from the podzols. Most of the P applied to a North Island vellow grev earth was accounted for in the top 15 cm of soil after 13 years (Saggar, 1990b). Of the P applied as dairy effluent over a 3 year period, 90% had accumulated in the top 5 cm of a yellow grey earth (MacGregor et al., 1982). Only 40 % of the applied P had accumulated in the top 5 cm of another North Island yellow grey earth after 9 years of P application but most was accounted for by animal losses and sampling to 25 cm (Doak, 1942). However, larger losses have been calculated for the South Island yellow grey earth Lismore stony silt under irrigation at Winchmore. Only 27% of the applied P had accumulated in the top 7.5 cm of the Winchmore soil following 35 years of 35 kg P/ha/yr in comparison to 34% of the P applied to the 35 year age site on Wharekohe silt loam. However a lower rate of P averaging 32.5 kg P/ha/yr had been applied to the 35 year age site on the Wharekohe silt loam possibly accounting for the lower losses. When animal loss of P was included, >53% of applied P could not be accounted for in the top 7.5 cm of the Winchmore soil (calculations made using data presented by Nguyen and Goh, 1992). Inclusion of P recovered to 30 cm soil depth reduced the amount of applied P which could not be accounted for to 30%.

The losses of P from the top 30 cm of the yellow grey earth under irrigation are similar to the losses of P from above the E horizon of the Wharekohe soils recorded in this study. However, the pattern of loss was different to that in the Wharekohe silt loam. As P has accumulated in the soil at Winchmore at a fairly steady rate and is still accumulating, P losses over time may also have been at a steady 30%. In contrast, P loss increased with time, from pasture development, from an average of 4% for the first 8 years on the Wharekohe silt loam. The downward movement of irrigation waters may be a factor facilitating P losses at Winchmore, where the anion storage capacity of the soils is approximately 25% (Perrott et al., 1992a). In particular, the movement of dry faecal pellets in flood irrigation waters may lead to losses. However, losses via irrigation water would not be expected to be large where irrigation is carried out correctly.

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Accurate figures for the accumulation of applied P are difficult to determine on the volcanic soils. The chronosequence trials on volcanic soils have included a limited number of different sites differing in pasture age rather than ongoing measurements on the same sites and the soils have larger native P content and variability than sedimentary soils. Little loss of P has been recorded from the top sampling depth in studies on volcanic soils. All of the P applied over a 25 year period to a Taupo sandy silt (yellow brown pumice soil) under pasture could be accounted for by animal loss and accumulation in the top 10 cm of soil (Walker et al., 1959). 88% of applied P was accounted for by animal loss and accumulation in the top 7.5 cm of soil under 7 and 25 year old pastures on a yellow brown loam (Saunders, 1959a).

Overall, applied P initially accumulates in the topsoil of the Wharekohe silt loam, following pasture development, and soil losses of P are low. However, once the maximum P storage capacity of the topsoil is reached, P can no longer accumulate and soil losses of applied p become high. Soil losses of applied P from older sites were measured up to 65%. Lateral movement of P in soil water above the E horizon is the most likely pathway for P loss. High losses of applied P have also been recorded from other New Zealand podzols, but in earlier stages of development.

3.4.2 Effect of Pasture Development on Olsen P

Olsen P decreased significantly (P<0.05) with depth on all sites (Figure 3.4). This finding was consistent with the findings of other New Zealand studies which investigated the effects of P application on P availability (Floate and Enright, 1991; Rowarth et al, 1992a).

Olsen P values in the undeveloped sites were very low, averaging 4 in the top 7.5 cm. Olsen P increased significantly (P<0.05) with pasture development at all depths as a result of fertiliser P application (Figure 3.4). In the soils sampled above the E horizon in 1990, Olsen P was related to total P (R^2 =0.87). Hence, Olsen P values showed a similar pattern to total P values at each depth. There was no significant difference between the Olsen P values for the 0-3 cm depth of the developed sites sampled while Olsen P increased with increasing pasture age and applied P until



Figure 3.4 Effect of pasture age on Olsen P (MAF Quicktest) for each depth and a calculated value for the 0-7.5 cm depth.
(Vertical bars=S.E.D.s for developed sites sampled to 0-3 cm, 3-7.5 cm and 7.5 cm to the E horizon)

between 23 and 25 years below 3 cm. Floate and Enright, (1991) found increases in Olsen P with pasture development and P application in a series of South Island upland yellow-brown earths and a podzolised yellow brown-earth to at least 100 mm over the five years from development.

Where the P application rate is greater than animal and soil losses, Olsen P values can be expected to increase (Floate and Enright, 1991; Nguyen et al., 1989; Perrott et al., 1992a; Rowarth et al., 1992a). In the present study, where approximately 30 kg P/ha/yr has been applied, Olsen P values appear to rise with pasture development in the top 7.5 cm to approximately 26 on the 3 oldest sites. The desired range of Olsen P to maintain pasture production at 90% of Ymax on this soil is considered to be between 20 and 25 (Edmeades et al., 1991a). Hence, 30 kg P/ha/yr would appear to be sufficient to maintain the appropriate Olsen P levels on the Wharekohe soils at Kaikohe. However, assuming an ALF of 0.5, a SLF of 0.4,

CC of 18, and a SR of 15.6, the modified CFAS model predicts that only 21 kg P/ha would be sufficient to maintain a stocking rate of 15.6 SU/ha. If 30 kg P/ha were to be applied annually, the model would predict a progressive increase in Olsen P. Despite these relatively high P inputs, Olsen P seems to have reached an asymptote of 26.

Resampling of a wider area at the study site in 1993 confirmed that Olsen P does not increase despite higher than calculated maintenance inputs of applied P, as Olsen P increased from initial pasture development reaching an asymptote of 22 in the older developed sites (Appendix 3.2).

If practice suggests that 30 kg P/ha is required for maintenance, then it appears that the model is underestimating the amount of P required for maintaining a stocking rate of 15.6 SU/ha on these soils, the SLF of 0.4 is too low for Wharekohe soils. However, if there is a maximum P storage capacity in the root zone of older sites, it is also possible that no matter how much P is applied above animal losses, the Olsen P may not increase beyond current levels due to high soil losses. Hence, it would be counterproductive to increase the SLF used in the model, therefore increasing requirements for carrying 15.6 SU/ha, if the extra P was only going to be lost from the pasture cycle to the wider environment. The SLF is investigated more fully in Chapter 7.

3.4.3 Effect of Stage of Development on Pasture Production and Composition.

Statistical analysis, using FLEXI, of the relationship between pasture age and dry matter yield, N and P concentration and uptake, and botanical composition are presented in appendix 3.3.

3.4.3.1 Dry Matter Yield

Over the 2 years of measurement, pasture age did not impact on pasture growth (Fig 3.5). On the 10/2/92 the 30 and 32 year old sites grew slightly more pasture and on

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Figure 3.5 Effect of pasture age on dry matter yield in 1991 and 1992.



Figure 3.6 Effect of pasture age on P uptake in 1991 and 1992.

the 18/8/92 the 23 and 25 year old sites grew slightly more pasture than the other sites (Appendix 3.3a). Other factors unrelated to pasture age may have influenced yield differences on these two occasions. For example, the two older sites retained more water, due to poor drainage, which may have depressed growth in winter.

The lack of a relationship between pasture yields and pasture age was surprising as available P in the root zone of the sites increased over time and the Olsen P of the youngest site, 16 in the top 7.5 cm, is considered to be below the optimum range for pasture growth (Edmeades et al., 1991a) on these soils. However, herbage P concentrations (Appendix 3.3b) were considered adequate for pasture growth at all sites including the youngest.

Other factors besides P influence pasture growth. pH was less than optimal for pasture growth on all but the youngest site and N is likely to be limiting pasture growth at all sites 3.4.2.3. Climatic factors had a large influence on pasture growth during the trial period, with the annual dry matter yield measured in the second, more favourable, year (13000 kg DM/ha) over twice that measured in the first at some sites. Extremely dry conditions were recorded in the first year of the trial. Hence, these factors which are limiting pasture growth at all sites may be masking any response to soil chemical factors which may differ with pasture age.

Examination of pasture growth measurements recorded continuously for 11 years on the pasture developed in 1982 revealed no pasture yield relationship with pasture age (AgResearch, unpublished data). Also the annual pasture yields were closely related to rainfall with low pasture production during very dry and very wet years. Pasture growth is severely restricted by animals pugging Wharekohe soils during wet years. Other authors have also recorded no dry matter yield relationship with pasture age (up to 35 years) from initial pasture development (Nguyen et al., 1989) and after oversowing to create improved pasture (Suckling, 1976) on hill country where P was applied at a constant rate annually.

3.4.3.2 Botanical Composition

Pasture age had no effect on the botanical composition with respect to grass, legume or dead matter content (Appendix 3.3c). The 23 and 25 year old site recorded a lower summer weed content than the other sites. In contrast, another study has found that pasture composition deteriorates with time from initial sowing, resulting in an increased summer weed content with increasing pasture age although dry matter yield was not effected (Nguyen et al., 1989).

In the present study, the grass to clover ratio was highest in spring when nitrogen is more freely available in the soil, while the proportion of dead matter increased in summer to 20-40% due to lack of rainfall. The proportion of clover in the swards on each of the developed sites was low, generally below 20% and as low as 3 - 9% in the first spring, in comparison to other New Zealand sites on a range of soils where clover content was approximately 30% where P fertiliser was applied (Morton et al., 1994). Such low clover content has implications for the N status of the pasture on these Wharekohe silt loam as described in more detail in 3.4.2.3.

3.4.3.3 Pasture N and P Concentration and Uptake

Overall, pasture N and P concentration and uptake did not vary with pasture age except for small differences recorded on the 10/2/92 harvest (Figure 3.6, Appendix 3.3b). The N concentration declined and P uptake increased in the 30 and 32 year old pastures in line with the slightly higher dry matter yield recorded at this sampling.

Both N and P concentration were highest in autumn, winter and early spring and lowest in late spring and summer each year as has been noted by other authors for P (McNaught, 1970; Metson and Saunders, 1978; Rowarth, 1987). The highest recorded N and P concentrations were 3.5 - 4.7% N in the first autumn sampled on 20/5/91 and 0.48 - 0.56% P in the 2nd winter sampled on 18/8/92. The lowest recorded N and P concentrations were 2.1 - 2.7% N in the early summer at the end of the two years on the 14/12/92 and 0.28 - 0.35% P in the first summer sampled on

11/2/91. A lack of water would have restricted the diffusion of nutrients to plant roots in summer. However, a very high proportion of dead matter, 20-40%, in summer would also have contributed to such low N and P concentrations and the N and P concentrations in the living component of the herbage would have been higher.

Herbage N concentrations of<4% in ryegrass and<4.5% in clover at active growth are considered limiting to plant growth (Cornforth, 1984). As herbage N concentrations were generally far below these levels, even in spring 1991 when the pasture was cut regularly ensuring the sampling of active growth, a lack of N from N fixing legumes is most likely limiting pasture growth on the Wharekohe silt loam. Some reduction in herbage N concentration may have occurred during sample storage, however such losses are not expected to have accounted for such low herbage N concentrations. The proportion of clover in the pasture swards was found to be very low in comparison to other soils (Morton et al., 1994). Herbage P concentrations were generally higher than the 0.34%, 0.34%, 0.46% and 0.49% P, considered to be limiting to pasture growth in a mixed sward in spring, summer, autumn and winter, respectively (Cornforth, 1984). Therefore factor/s, other than P concentration, are limiting clover growth and hence N fixation on the Wharekohe silt loams on the Kaikohe station. pH may be one of these limiting factors, as pH had fallen as low as 5.3 - 5.6 by 1993 on the older developed sites. However, it is not the only limiting factor as pH was considered optimal at the youngest site while the proportion of clover and herbage N concentration were not. Molybdenum is not considered to be limiting clover growth on the Wharekohe station. Although Mo had not been applied to the Wharekohe soils since 1982, herbage analysis in 1984, 1988 and 1989 revealed high Mo status on the Kaikohe Research Station.

The total P uptake for the two years was 90 kg P/ha (38 kg P/ha in year one and 52 kg P/ha in year two) and was marginally lower than the 100 kg of P applied as superphosphate and RPR during this period. This relationship is similar to the findings of Rowarth (1987) where pasture P uptake was found to be similar to a P application rate of 50 kg P/ha applied as superphosphate. In Rowarth's study, P uptake was higher than P application on gentle slopes at low P application rates (<50 kg P) and lower at high P application rates. However, Perrott et al. (1992b)

found that P uptake was similar to P applied at 22.5 kg P/ha on a central yellow brown earth. The lower availability of P from RPR in the present study on the Wharekohe silt loam may have resulted in slightly lower P uptake than for similar rates of applied superphosphate.

The values for soil P and pasture P uptake measured over the two years are used in a model showing the fate of applied P in Wharekohe podzols presented in chapter 8.

3.5 CONCLUSIONS

• Pasture development and the associated application of fertiliser P on Wharekohe podzols results in an increase in total soil P to the top of the E horizon with applied P accumulating to a higher concentration in the top 3 cm.

• Evidence has been presented which supports an increase in the movement of applied P down the profile with increasing pasture age. The Wharekohe silt loam appears to have a finite ability to retain P (referred to as the maximum P storage capacity), which is reached by 8 years in the 0-3 cm depth and by 11 years in the 0-7.5 cm depth. Once the P storage capacity at each depth is reached, there is little further accumulation of applied P, apart from small quantities as fertiliser P residue. Much of the P applied in subsequent applications moves through the soil resulting in large soil losses of P from the pasture cycle.

 Soil losses of applied P from older sites of up to 65% were measured. As little of the lost P could be accounted for to a depth of 30 cm below the E horizon, lateral movement of P in soil water above the E horizon is the most likely pathway for P loss.

• Pasture development on Wharekohe podzols results in an increase in Olsen P levels to the top of the E horizon. Olsen P reached an asymptote of 26 in the root zone of the oldest sites despite annual applications of P estimated to be in excess of the maintenance requirements calculated by the CFAS model. • Calculated large losses of applied P, combined with an apparent maximum Olsen P for the Wharekohe soil, despite P application in excess of the amount calculated by the CFAS model to maintain current stocking rates, indicate that the SLF used in the CFAS model may be too low. However, if P applied in excess of animal losses is lost from the soil, a high SLF would be counterproductive, increasing P losses from the pasture cycle to the wider environment.

 Pasture production, botanical composition and herbage N and P concentrations were not effected by pasture age in this chronosequence study. Legume content was low at all sites which impacted on the N nutrition of the pasture. Herbage P concentrations were considered adequate for maximum pasture production at all sites, however, low N concentrations would have been restricting pasture growth at all sites.

• Large losses of P from these Wharekohe soils are of economic importance and could impact on the environment through increased P loading of waterways. Clearly further studies are required to investigate mechanisms for P retention and P loss in the Wharekohe podzols (Chapters 4-7).

CHAPTER 4

CHANGE IN P FRACTIONS IN A PASTURE DEVELOPMENT CHRONOSEQUENCE ON A WHAREKOHE PODZOL.

4.1 INTRODUCTION

Over time, applied phosphorus has been shown to be lost from the root zone of a Wharekohe silt loam (Chapter 3). In addition to P lost by physical movement and leaching of dissolved P from the root zone, the other component of the Soil Loss Factor (SLF) is the loss of P from the pasture cycle through the net accumulation in the soil of non-labile inorganic and organic P. The accumulation of applied P into various P fractions is known to be effected by several factors including pasture age, soil depth, lime application, the rate and type of fertiliser application, the origin of soil parent material and the degree of weathering of soil minerals.

Various P fractionation schemes have been developed to characterise the distribution and availability of Pi and Po in soils based on their solubility in chemical extracts (Chang and Jackson, 1957; Williams et al., 1967; Hedley et al., 1982; Perrott et al., 1989, Tiessen and Moir, 1993). The methods of Chang and Jackson (1957) and Hedley et al. (1982) were well reviewed by Tiessen and Moir and the main points were: The method of Chang and Jackson (1957), which was later modified by Williams et al. (1967), involved the extraction of labile P (by NH₄CI), followed by the extraction of AI-Pi (by NH₄F), Fe-Pi (by NaOH), "occluded Pi" (by dithionite-citrate), Ca-Pi (by HCl) and residual P (after Na₂CO₃ fusion). Organic P was determined separately as the difference between acid-extractable Pi before and after ignition. This early fractionation procedure was limited by the precipitation of Pi in the fluoride extraction, the unreliability of AI and Fe separation and the "occluded Pi" pool being ill-defined (Williams and Walker, 1969a). Consequently, an alternative fractionation procedure was developed by Hedley et al. (1982) which divided soil P into labile Pi and Po (extracted by Resin P and NaHCO₃), Fe & Al-Pi and stable Po (extracted by NaOH), Ca-Pi (extracted by HCI) and residual P.

This fractionation procedure of Hedley et al. (1982) has been further modified by Perrott et al. (1989), to include a preliminary NaCl extraction to remove exchangeable Ca which precipitates with P in the alkali extracts, and by Tiessen and Moir, (1993) to include a concentrated acid extraction to distinguish between Po and Pi in the residual P. A modified version of these latter three fractionation procedures is used in this study to indicate the extent of P accumulation into non-labile P compounds and possible reasons for P loss from the soil profile.

In acid soils, P usually accumulates as alkali extractable Pi in Fe and Al phosphates, and as Pi and Po sorbed on the surfaces of sesquioxides (Saunders, 1959a; Condron and Goh, 1989; Perrott et al., 1989; Floate and Enright, 1991; Perrott et al., 1992a), while in calcareous soils, P usually accumulates as Ca bound P (Hedley et al., 1982; Tiessen et al., 1983). The Wharekohe soils are acid soils, but, due to extreme weathering, they contain very little iron and aluminium, and have extremely low Anion Storage Capacities (<10%) in the rooting zone (New Zealand Soil Bureau, 1968). Hence, a low level of accumulation of Pi and Po associated with Fe and Al in the Wharekohe soils, in contrast to less weathered soils derived from similar parent material, may account for the high loss of P recorded from the Wharekohe silt loam over time.

Accumulation of P in specific fractions with depth may also provide an indication of how P moves through the profile of Wharekohe soils. Alone, however, fractionation data cannot confirm how P moves in a Wharekohe podzol, in comparison to other New Zealand soils, as P can move down the profile in one form to change in situ. to another (as inferred by Haynes and Williams, 1992).

4.2 OBJECTIVES

The objectives of this P fractionation study were to assess:

 The effect of pasture age on the accumulation of applied P into various P fractions in a pasture development chronosequence on Wharekohe silt loam.

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- 2. The contribution of applied P accumulation into plant unavailable fractions to the SLF for use on the Wharekohe silt loam.
- Possible reasons and pathways for P loss from the Wharekohe silt loam.
- 4. The influence of lime history and fertiliser P form on the accumulation of applied P into various fractions in the Wharekohe silt loam.
- The effect of parent material on P fractions in Wharekohe podzols to determine possible reasons for the higher apparent P requirement of the Wharekohe sandy loam in comparison to the Wharekohe silt loam.
- 6. The effect of the degree of weathering of the silt parent material on P chemistry by characterising P fractions in the soil under pasture on the yellow brown earth, Aponga clay, compared with the Wharekohe silt loam.

4.3 MATERIALS AND METHOD

4.3.1 Soils

The Wharekohe silt loam soils, used for the P fractionation analysis, were sampled from the pasture development chronosequence to the top of the E horizon in spring 1990 as described in Chapter 3. In order to confirm conclusions reached from the soil P data collected in 1990 and to investigate the effect of RPR application on P fractions, the original sites and an additional four sites were resampled in 1993 as described in Chapter 3.

The Wharekohe sandy loam and Aponga clay soils were sampled in 1991 from plots within the trial areas which had been under pasture for at least 30 years as described in chapter 8.

4.3.2 Soil Treatment

All soils were air dried and sieved to <2 mm particle size and then ring ground to <150 um.

4.3.3 Soil Analysis

4.2.3.1 *P* Fractionation

Soil P in the 1990 samples was divided into 10 fractions using a sequential extraction procedure modified from the methods of Hedley et al. (1982), Perrott et al. (1989) and Tiessen and Moir (1993) and outlined in Figure 4.1. Soil P in the additional Wharekohe silt loam samples, Wharekohe sandy loam and Aponga clay was divided into 8 fractions, NH_4CI Pi & Po, $NaHCO_3$ Pi & Po, NaOH Pi and Po, H_2SO_4 Pi and Residual P.

The extraction solutions removed the following P fractions:

1 M NH₄Cl - The first solution in the fractionation procedure is considered to extract available P in soil solution and P from the death of micro-organisms when the soil is dried prior to fractionation (Chang and Jackson, 1957; Sparling et al., 1985). NH₄Cl also extracts exchangeable Ca²⁺ which could precipitate phosphate in the alkali extracts leading to an underestimation of alkali extractable Pi and Po and an overestimation of Ca-P and Hot HCl extractable Po (Chang and Jackson, 1957; Perrott, 1992; Mackay et al., 1986).

0.5 M NaHCO3, pH 8.5 - changes the solution in a similar way to roots (Tiessen and Moir, 1993) and therefore extracts available Pi adsorbed onto the surfaces of crystalline compounds, sesquioxides, or carbonates (Mattingly, 1975; Bowman and Cole, 1978) and easily mineralisable Po which contributes to plant available P (Bowman and Cole, 1978).



Figure 4.1. Flow chart of sequential P extraction.

1 M NaOH - extracts less labile Pi in iron and aluminium phosphates, Pi and Po held by chemisorption on sesquioxides and Po associated with humic and fulvic acids (Chang and Jackson, 1957; Perrott and Mansell, 1989). NaOH Pi can contribute to plant P especially where fertiliser P is withheld, whereas NaOH Po is not readily available to plants even where fertiliser P is withheld (Hedley et al., 1982; Goh and Condron, 1989; Condron and Goh, 1989).

 $NaHCO_3$ and NaOH extractable Pi are not considered to be discrete pools, representing instead a continuum of Fe and Al associated P extractable with increasing pH from the original pH of the soil to 8.5 to 13 (Tiessen and Moir, 1993).

0.5M H₂SO₄ - extracts mostly Pi held in calcium phosphates (apatite) and a small quantity of P released upon the partial dissolution of secondary more crystalline sesquioxides (occluded Pi) (Hedley et al., 1982; Tiessen and Moir, 1993). The dilute acid extractable fraction usually contains little or no Po (Perrott et al., 1989) and this was confirmed on the Wharekohe soil in a preliminary fractionation where less than 2% of the total P was recovered in the HCl Po fraction. Dilute HCl is most commonly used in fractionation procedures however H₂SO₄ has been shown to be more effective at extracting P from highly weathered soils although the reasons for this are not clear (Tambunan, 1992). Some Ca-Pi can be made available to plants as the pH in the vicinity of plant roots falls leading to the dissolution of Ca-Pi (Hedley et al., 1982).

Hot Conc. HCI - extracts Pi and Po in very stable residual pools (Tiessen and Moir, 1993). Some of the Po may be available Po from organic matter which is not alkali extractable (Tiessen and Moir, 1993). Other fractionation procedures commonly use a second NaOH extraction to remove this P pool. However, in highly weathered soils hot HCI is preferable as i) Hot HCI extracts more P (Tiessen and Moir, 1993) and ii) NaOH following acid extraction removes silicon which interferes with colour development in the phosphomolybdate method of Murphy and Riley (1962) (H.Tiessen, personal communication).

Tri-acid digest - extracts residual P which is unlikely to contain anything but recalcitrant Pi (Tiessen and Moir, 1993).

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Supernatant solutions from cold extractions were filtered through 0.45 um millepore filter papers. The hot HCI solutions were filtered through Whatman No. 40 filter papers.

Inorganic P was determined in each extract and digest colorimetrically by the phosphomolybdate method of Murphy and Riley (1962). Interference to absorbence readings by discolouration from extracted organic matter in the alkali extracts was accounted for by reading the absorbence of the extracts with Murphy and Riley solution without the addition of ascorbic acid. Total P in each extract was determined after digestion in 2 ml of concentrated H₂SO₄ overnight at 360°C followed by the addition of 1 drop of H₂O₂ and reheating for 30 minutes to clear the digest. Organic P was determined as the difference between Pt and Pi.

4.2.3.2 рН

Ten grams of soil was stirred with 25 ml of distilled water and left overnight. pH was measured in the soil solution with a glass electrode.

4.2.3.3 Cation Exchange Capacity and Exchangeable Cations

Exchangeable calcium in the original Wharekohe silt loam samples was removed by leaching with 1 M ammonium acetate method (Blakemore et al., 1987). An atomic absorption spectrophotometer was used to measure the calcium content of the leachates. Cation Exchange Capacity (CEC) and exchangeable Ca, Mg, K and Na were determined using the silver thiourea method (Searle, 1986) for the additional Wharekohe silt loam samples collected in 1993 and the bulked Wharekohe sandy loam and Aponga clay samples.

4.2.3.4 Total Calcium

Total calcium was measured in the soils sampled from the original sites in 1990 after digestion in a tri-acid mixture of concentrated HNO_3 : HCI: HClO₄ (5:5:7) (Bolan and

Hedley, 1987). One gram of soil was digested with 25 ml of tri-acid in a 250 ml Erlenmeyer flask at 260°C until white fumes appeared. The digest was made up to 50 ml in volume and allowed to settle before filtering through 0.22 µm millepore filters and total Ca determined by atomic absorption spectrophotometry.

4.3.3 Statistical Analysis

As in Chapter 3, results from each P extraction, the sum of the inorganic and organic P fractions (sumPi and sumPo), pH, exchangeable Ca and total Ca for the spring 1990 soils were subjected to analysis of variance using Genstat to determine differences between sites for each depth and between depths for each site. For the soils collected in spring 1993, the relationships between each fraction, sumPi, SumPo, pH, CEC, exchangeable cations and total Ca, and pasture age were determined by using the computer program FLEXI (Upsdall, 1994).

4.4 RESULTS AND DISCUSSION

4.4.1 Effect of Pasture Age on the Accumulation of Applied P into Soil Fractions in a Wharekohe silt loam

4.4.1.1 Inorganic P

Inorganic P accumulation levels (Figure 4.2) followed a similar pattern to total P accumulation (Figure 3.1). Pasture development resulted in an increase in Pi as was found in other New Zealand studies (Jackman, 1951; Walker et al., 1959; Perrott and Sarathchandra, 1987; Condron and Goh, 1989; Nguyen et al., 1989) and Pi concentration decreased with depth on all sites (Figure 4.2).

All of the developed sites had similar Pi concentrations in the top 3 cm, except the 30 year old site where Pi was significantly lower. In the 3-7.5 cm depth, the inorganic P concentrations of the 8 and 30 year old sites were significantly lower than the other developed sites. (The early liming history had influenced Pi



Figure 4.2 Effect of pasture age on inorganic and organic P concentration in each depth of a pasture chronosequence on a Wharekohe silt loam.

accumulation at the sites. Lower lime application on the 30 year old site had led to lower Ca-Pi accumulation, explained further in 4.4.4).

As was the case with total P data, interpretation of Pi levels in the 7.5 cm to E horizon samples was complicated by large differences in soil depth to the E horizon. Pi concentration in the 8 year old site was significantly lower than that of the 23 and 25 year old sites. Pi concentrations in the 30 and 32 year old sites were not significantly different from the 8 year old site. However, the amount of inorganic P (kg/ha) increased with pasture age at this depth below 7.5 cm (Table 4.1).

Table 4.1Inorganic and organic P content (kg P/ha) of Wharekohe silt loam
samples.

	Inorganic P			Organic P		
	(kg/ha)			(kg/ha)		
Age	0-3 cm	3-7.5 cm	7.5 cm-E	0-3 cm	3-7.5 cm	7.5 cm-E
0	11	14	21	14	19	24
8	117	82	59	50	49	56
23	134	157	58	84	106	33
25	113	110	73	74	106	75
30	89	82	72	79	104	110
32	106	109	105	77	126	162

As with total P, the ability of the Wharekohe silt loam to sorb Pi appears to reach an asymptote at 8 years in the 0-3 cm depth, and between 8 and 23 years for the 3-7.5 cm depth. Hence, the accumulation of Pi into non-labile Pi cannot be contributing significantly to the SLF in the older developed sites, apart from the likely accumulation of a small quantity of Pi as insoluble Ca-Pi residues from annual P fertiliser additions. It is also possible that Ca-Pi decreases with pasture age in older sites as Ca-P, which was associated with the initial heavy lime applications with pasture development, is lost as Ca is leached from the soil. The calculation of Pi accumulation over time from pasture development was restricted to differences

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between the sites, rather than continual actual measurements over time, the extent of the small amount of Pi accumulation was impossible to quantify for the soils sampled in 1990. The impact of the change to less soluble superphosphate and RPR on soil P fractions is discussed further in 4.4.4.

Pi accumulation in the Wharekohe silt loam followed a different pattern to that reported for other New Zealand soils. Other New Zealand studies (Condron and Goh, 1989; Nguyen et al., 1989; Perrott et al., 1992a; Rowarth et al., 1992a) have shown that with continued P application, Pi continues to accumulate in the soil with increasing pasture age. The rate of Pi accumulation is dependent on soil type, the rate and type of applied P and the rate of Po accumulation. Pi accumulates at a greater rate where P is applied at rates surplus to pasture requirements, where P fertiliser contains low soluble Pi or where Po accumulation has slowed or stopped.

The reduction in Pi accumulation in the older sites in the present study cannot be explained by differences in P application or pasture P requirements between the youngest and older sites. Similar rates of P were applied to all the developed sites in recent years, except the site developed in 1960 which had received marginally lower rates of P in the 10 years prior to the 1990 sampling. Pasture production and herbage P concentration on the developed sites were similar over a 2 year period (Chapter 3). Although pasture production and herbage P figures prior to 1990 are not available for all the sites in this study, P requirements are likely to have been similar for the developed sites once pasture maintenance had been reached.

The rate of organic P accumulation did not increase with increasing pasture age in the top 7.5 cm (4.4.1.2) and so this can be discounted as a reason for such a drastic reduction in Pi accumulation.

Discussion of the fate of applied P in chapter 3 indicated that applied P not held in the topsoil was lost from the effective root zone of the soil in the older developed sites (Chapter 3).

4.4.1.2 Organic P

As with inorganic P, pasture development resulted in an increase in organic P with organic P concentration decreasing with depth on all sites (Figure 4.2). Organic P has also been found to increase with pasture development in other New Zealand studies (Jackman, 1951; Walker et al., 1959; Perrott and Sarathchandra, 1987; Condron and Goh, 1989;).

Organic P concentration increased at each depth with increasing years from development. Po concentration in the 7.5 cm - E depth dropped in the 32 year old site, however once again this drop was a function of depth to the top of the E horizon and expressing results in kg Po/ha indicated a higher level in the 32 year old site than the other developed sites (Table 4.1). Hence, it appears that the soil's capacity to retain P as organic P has not been reached by 32 years at any depth and the accumulation of applied P as less labile Po (extracted by NaOH and Hot HCI) may be contributing to the SLF (discussed further in 4.4.2).

Despite increasing Po and a constant Pi, the combined effect of Pi and Po accumulation was a constant total P concentration beyond 8 years in the top 0-3 cm and beyond 23 years in the 3-7.5 cm depth (Chapter 3). The maximum P storage capacity discussed in chapter 3 can be solely attributed to a maximum Pi storage capacity as Po continued to accumulate.

The accumulation rate of Po is initially higher than the accumulation of Pi after initial pasture development from native vegetation in New Zealand soils including some podzols where OM levels are low and C:N ratios are generally high (Jackman, 1951; Jackman, 1960; Walker et al., 1959; Powell and Taylor, 1980). In the present study on Wharekohe soils there was a large increase in Pi in the top 7.5 cm in the first 8 years after pasture development. However, it is not possible to precisely assess the Po accumulation pattern in the first years following pasture development due to the lack of developed sites of less than 8 years. It is possible that applied P may have accumulated as Po at the expense of Pi initially in the Wharekohe soils as was the situation in a South Island podzol (Powell and Taylor, 1980). Applied P accumulated

solely as Po in the first two years after pasture development in the Maimai gley podzol with both Pi and Po accumulating in the third year.

Provided soil Pi levels are sufficient to support pasture growth, Po accumulation is more dependent upon the growth rate of pasture and the associated inputs of nitrogen than the application of P (Burgess and Davies, 1951; Saunders, 1959a; Simpson et al., 1974; Lambert et al., 1988; Nguyen and Goh, 1989; Floate and Enright, 1991; Perrott et al., 1992b). However, Wharekohe soils contain very little native Pi and pastures cannot be established without applied fertiliser P, so Po is unlikely to accumulate at any depth until the Pi levels are raised by the application of fertiliser P.

After the high initial immobilisation rate, the rate of Po accumulation during pasture development usually decreases with time from pasture development in the top soil of New Zealand soils (Jackman, 1951; Walker et al., 1959; Jackman 1964a; Perrott et al., 1989). The average rate of Po accumulation (µg Po/g) was slower in the older sites in comparison to the 8 year old site in the top 3 cm which is in agreement with the findings of the other New Zealand studies. However, at the 3-7.5 cm depth, the average rate of Po accumulation was similar in the 8 and 23 year sites with Po increasing at a slower rate at this depth than in the top 3 cm indicating that Po is likely to reach equilibrium closer to the soil surface first.

The rate of Po accumulation was expected to be higher in the 3-7.5 cm depth of the 8 year old site than in the older sites, as was the case in the 0-3 cm depth, because applied P is rapidly immobilised in soils with low OM and high C:N ratios in the first years following pasture development. Possible explanations for the lower than expected Po accumulation in the years following initial pasture development are i) restricted movement of applied P to this depth before the top 3 cm reaches its P storage capacity, combined with ii) the recent heavy liming history of the 8 year old site as lime can encourage the mineralisation of Po (Condron and Goh, 1989; Nguyen et al., 1989; Condron and Goh, 1990) (discussed further in 4.4.4). The average rate of Po accumulation per gram of soil was lower in the 7.5 cm - E horizon depth of the 8 year old site than at a similar depth in the 23 year old site confirming

that limited movement of applied P to depth restricts P immobilisation in the early years following initial pasture development.

Interestingly the amount of Po accumulating, up to 267 µg Po/g soil for the top 7.5 cm of the 32 year old site receiving on average 32 kg P/ha, was similar to the amount of Po (240 µg Po/g) which had accumulated over 32 years in the top 7.5 cm of a weakly weathered yellow grey earth at Winchmore under irrigation (Nguyen and Goh, 1989) at two application rates (17.5 and 35 kg applied P/ha). Hence, Po accumulation within 32 years does not appear to be restricted when compared to a less weathered sedimentary soil with higher sesquioxide content (New Zealand Soil Bureau, 1968). However, Po accumulation in the Wharekohe soil is expected to reach equilibrium earlier than in the less weathered soil due to its lower content of Al and Fe complexes for soil organic matter stabilisation.

The comparison of the extent of Po accumulation in the development of Wharekohe silt loam in the present study with Po accumulation in soils in other studies is restricted by these other studies having i) unknown times from initial pasture development, ii) the use of different soil sampling depths and iii) differing P application rates.

4.4.1.3 Po/Pi Ratio

The Po concentrations measured may be at their lowest annual level in all sites due to mineralisation in spring leading to lower Po/Pi ratios (Perrott et al., 1992b).

Organic P was higher than inorganic P in all depths of the undeveloped sites with Po/Pi ranging from 53:47 to 58:42 (Figure 4.3). Pasture development with its associated application of fertiliser P resulted in a decrease in the Po/Pi ratio in all depths to as low as 30/70 in the top 0-3 cm of the 8 year old site. However, once Pi reached a peak, organic P continued to accumulate and hence the Po/Pi ratio increased at each depth with more than 50% of the soil P as organic P below 3 cm in the 2 oldest sites.



Figure 4.3 Effect of pasture age on organic P content (%) at each depth.

The Po/Pi ratios obtained for the highly modified Wharekohe soils, where Pi reaches equilibrium before Po due to a low maximum Pi storage capacity, are different from the ratios obtained on other New Zealand soils. Most undeveloped soils have very high Po/Pi ratios which decrease over time under developed pastures as the Po content approaches equilibrium and the applied P continues to accumulate as Pi (Jackman 1951, Walker et al., 1959; Condron and Goh, 1989; Perrott and Sarathchandra, 1987; Nguyen et al., 1989). The Wharekohe soil had been highly disturbed by gum diggers and the cut over manuka vegetation was not the climax-equilibrium vegetation cover, but the result of the felling of native timber trees, which may have led to a lower Po:Pi ratio on undeveloped soils.

4.4.1.4 Changes in P Fractions

Over half the P extracted at all depths from the undeveloped sites was found in the most labile and easily extractable NH_4Cl and $NaHCO_3$ Pi and Po fractions (Figure 4.4). Hence much of the P in the undeveloped podzol under Manuka vegetation



Figure 4.4 Comparison of inorganic and organic P fractions measured in each site at each depth.



b) 3-7.5 cm (Fig. 4.4)



Years of Development

appears actively involved in the cycling pool. The high labile Po was unexpected as Po usually exists as more stable Po in highly weathered soils (Cross and Schlesinger, 1995). However, as the Wharekohe podzols are amongst the most weathered soils in the world, their extremely low sesquioxide contents may not be conducive to the stabilisation of very much Po. The high proportion of Pi as labile Pi was similar to that of other spodosols with very low total P contents (Pare and Bernier, 1989; Trasar-Cepeda et al., 1990).

Calcium-P extracted by H₂SO₄ was the smallest fraction in all undeveloped samples as predicted for a highly weathered soil (Walker and Syers, 1976; Cross and Schlesinger, 1995), with only 0-1.6 µg P/g being measured. Highly residual Pi, as extracted by the hot HCI and Tri-acid digest, was a larger fraction than either the Fe and Al-P extracted by NaOH or the acid extractable Ca-P at each depth in the spring 1990 samples in agreement with the findings of Walker and Syers (1976) on other highly weathered soils.

All inorganic and organic P fractions increased with pasture development in the top 7.5 cm of the soils (Figure 4.5). Other New Zealand studies have also shown increases in all P fractions in the top soil following initial pasture development (Perrott et al., 1989; Haynes and Williams, 1992). Except the most residual Pi, which was a very small fraction of the inorganic P, all inorganic and organic fractions decreased with soil depth (Figure 4.3).

Inorganic P Fractions

There was little difference between the Pi extracted from the developed sites for most fractions in the top 0-3 cm. Exceptions were where NH_4CI Pi was lower in the 23 year old site, NaOH Pi was lower in the 8 and 30 year old sites and H_2SO_4 Pi was lower in the 30 year old site. The very low H_2SO_4 Pi concentration measured in the 30 year old site was not related to pasture age but was instead peculiar to that particular site and related to early liming history (explained further in 4.4.4).

In the 3 - 7.5 cm depth the Pi extracted in each fraction was lower in the 8 year old site than in the older developed sites, except the H₂SO₄ Pi fraction in which there



Figure 4.5 Effect of pasture age on each P fraction at each depth. (Vertical Bars = S.E.D., A for comparison of ages within depths, B for comparisons of depths within ages.)

was no significant difference between any of the developed sites. Inorganic P continued to accumulate in each of the other fractions until some time/s between 8 and 23 years in the 3-7.5 cm depth. Hence, only the sites older than 23 years had similar or larger concentrations of alkali Pi than H₂SO₄ Pi.

The largest Pi fraction in both the 0-3 cm and 3-7.5 cm depths of the developed sites was the H_2SO_4 Pi, accounting for up to 41% of the total P in the top 7.5. The accumulation of applied P as Ca-Pi is effected by fertiliser type and lime application explained further in 4.4.4.

Once again, analysis of P fractions below 7.5 cm was complicated by the depth to the top of the E horizon. Increases in each inorganic P fraction with development in the 7.5 cm - E horizon were much smaller than in the top soil. All of the Pi fraction concentrations increased with pasture development below 7.5 cm. However, only the NH₄Cl, NaHCO₃ and H₂SO₄ Pi fractions were significantly greater in the 8 year old site compared to the undeveloped site. Therefore, only the sites developed for at least 23 years had NaOH, Hot HCl and residual extractable Pi concentrations which were significantly different from those extracted in the undeveloped sites.

Inorgnaic P appears to accumulate initially below 7.5 cm in a fraction extractable by NaHCO₃. After 8 years small amounts of NaHCO₃ Pi continued to accumulate with associated small increases in NaOH Pi and residual Pi, while a far larger proportion of applied P accumulates at this depth as H_2SO_4 Pi. Hence, the proportion of Pt as H_2SO_4 Pi below 7.5 cm increased initially to 23 years before dropping again as H_2SO_4 Pi decreased and Po continued to accumulate. The 23 year old site was the only site where H_2SO_4 Pi was larger than NH_4CI + alkali Pi at this depth. When the depth to the E horizon was taken into account, the 32 year old site had the greatest Pi content in each fraction except H_2SO_4 Pi recovered in the 23 year old site.

Haynes and Williams (1992) also found increases in all Pi fractions, calculated as the difference in P fractions recovered in fertilised plots compared to unfertilised controls, in the 10-20 cm depth of irrigated Lismore stony silt at Winchmore. H_2SO_4 Pi increased the most followed by NaOH Pi in their study. However, interference of exchangeable Ca in the fractionation procedure would have underestimated the accumulation of NaOH Pi and overestimated the accumulation of H_2SO_4 Pi in the Winchmore soil. Saunders (1959a) on the other hand, found that P accumulated as Al and Fe-P rather than Ca-P in the 5-12.5 cm depth of a yellow brown loam high in Fe and Al complexes where the Chang and Jackson (1957) procedure was used to fraction soil P.

The implication of P accumulation in various fractions at depth to P movement in the Wharekohe silt loam is discussed in 4.4.3.

Fertiliser P has also been shown to accumulate mostly as Fe and Al-P in the top sampling depth of a wide range of acid soils in New Zealand (Saunders, 1959a; Steele, 1976; Grigg and Crouchley, 1980; Condron and Goh, 1989; Perrott and Mansell, 1989; Perrott et al., 1989; Floate and Enright; 1991; Perrott et al., 1992a; Rowarth et al., 1992a) and overseas (Sainz and Arines, 1988; Sattell and Morris, 1992) studies where superphosphate had been applied using fractionation procedures modified from the methods of either Chang and Jackson (1957) or Hedley et al. (1982). However, the fractionation of soil P in the Wharekohe silt loam has confirmed that little applied P accumulates as Fe and Al-P extractable by NaOH, despite the acid nature of the soil.

It is the lack of alkali extractable Pi accumulation, rather than unusually high Ca-P accumulation, which has resulted in such a high proportion of total P being extracted by H_2SO_4 in the top 7.5 cm of the Wharekohe silt loam, as the amounts of Ca-Pi in the Wharekohe soils are not high in comparison to other New Zealand soils (Table 4.2) (Perrott et al., 1992a). Alkali P accumulation was also limited in the top 7.5 cm of two Northern podzolised yellow brown earths in a two part fractionation, NaOH Pi and HCl Pi following removal of Ca with a NaCl buffer, in contrast to 6 other soils in the study (Perrott et al., 1992a).

The concentrations of NaOH Pi in the developed sites on the Wharekohe silt loam were even lower than the more available Pi (NH₄Cl Pi + NaHCO₃ Pi) at all depths (Figure 4.4). The NH₄Cl extractable Pi was surprisingly large, up to 64 μ g P/g in the top 0 - 3 cm of the developed sites, illustrating how weakly P is held in the soil under

pastures on Wharekohe silt loam. Readily available Pi as measured by NH₄Cl and NaHCO₃ extraction was considered to be ample to meet pasture requirements on all of the Wharekohe silt loam developed sites as herbage P concentrations were above levels which are likely to limit pasture growth (Cornforth, 1984).

The accumulation of applied P into the plant unavailable hot HCl Pi and residual Pi fractions was very low (only 3% of the total accumulated P) in the top 3 cm of the 32 year age site.

Organic P Fractions

The increase in the sum of the Po fractions with pasture development was reflected in all of the Po fractions in all soil samples (Figure 4.5). The rate of Po accumulation in each fraction appeared to slow with pasture age in the top 3 cm. NH₄Cl Po appeared to reach equilibrium at some point between 23 and 25 years in the top 7.5 cm. Perrott et al., 1989 also found that the least stable Po fractions reach equilibrium first. The remainder of the P fractions were still accumulating by 32 years.

NaOH Po and to a lesser extent NH₄Cl Po increased initially with pasture development and pasture age in the 7.5 cm - E horizon depth. NaHCO₃ Po accumulation occurred after 8 years.

NaOH Po accumulated at a faster rate and made up the largest proportion of Po at all depths in the developed sites (Figure 4.5). As inorganic P accumulation had most likely ceased by 23 years after pasture development on the Wharekohe silt loam in the present study, with the exception of small quantities of Ca-P from fertiliser residues, the proportion of total P as NaOH Po increased with time. Other studies have also shown that most of the Po accumulates in New Zealand (Condron and Goh, 1989, Perrott et al., 1989) and overseas (Sattell and Morris, 1992) soils as the more stable NaOH Po after initial pasture development
4.4.1.5 Spring 1993

The later sampling (to 7.5 cm) in spring 1993 of additional sites which had been developed in 1967, showed that the 23 year old site, sampled in spring 1990, was not representative of other similarly aged sites due to its having a higher level of H_2SO_4 extractable Pi (Appendix 4.1).

Samples collected from both the original and additional sites in 1993 confirmed the conclusions reached from the original 1990 samples (Appendix 4.1).

A maximum Pi storage capacity was reached by 11 years in the top 7.5 cm of the additional sites. Organic P concentration increased with years from development. The 33 and 35 year old additional sites had similar Po concentrations, however, it is not possible to determine if the Po capacity was reached between 33 and 35 years due to a lack of sites beyond 35 years to confirm the trend. Although a significant difference was not detected, the sum of the inorganic P fractions appeared to be lower in the oldest developed site than in the younger sites, explaining why total P did not increase with increasing pasture age although organic P did. Despite the less comprehensive extraction procedure used for the 1993 samples, the sum of the extracted Pi and Po fractions indicate a similar pattern of increasing Po/Pi ratios with pasture age for the developed sites.

Both sets of 1993 samples from the undeveloped sites confirmed that a large portion of P (41 - 42%) was involved in the active cycling pool, while no H_2SO_4 Pi was recovered. Once again, all inorganic and organic P fractions increased with pasture development. NaOH Po was confirmed as the largest Po fraction and H_2SO_4 Pi as the largest Pi fraction.

Comparison of applied P accumulation into various fractions between years is complicated by seasonal effects on the flux of P between different fractions. However, comparison of the P recovered in the original sites sampled in 1990 with the P recovered from the same sites in 1993 revealed that the continued accumulation of applied P recorded for those years and reported in chapter 3 was

due mostly to its continued accumulation as H_2SO_4 Pi. The accumulation of much of the applied P as H_2SO_4 Pi in the older sites confirms that applied P accumulates as a fertiliser P residue once the maximum P storage capacity has been reached,.

Phosphorus continued to accumulate in small quantities in all other measured Pi fractions on all of the original sites, although the results from the 1990 sampling indicated that all inorganic P fractions had reached equilibrium in the older sites. However, the small increase in each of the Pi fractions (aside from H_2SO_4 Pi) may have been effected by the large increase in P application rates from approximately 30 kg P/ha per year to an average of 49 kg P/ha per year between 1990 and 1993.

A comparison of the P fractions accumulating on the original sites between 1990 and 1993 with the pattern of P accumulation in the soils in the National Series study by Perrott et al. (1992a) supported the earlier conclusion that the high proportion of H_2SO_4 Pi in the developed sites on the Wharekohe silt loam was due to low alkali P accumulation rather than excessive H_2SO_4 Pi accumulation (Table 4.2).

The accumulation rate of H₂SO₄ Pi in the Wharekohe soils was within the range of accumulation rates for the soils in Perrott et al.'s study where RPR had been applied. However, H₂SO₄ Pi accumulation was very high in the youngest Wharekohe site compared to the sites in Perrott et al.'s study where TSP had been applied. By 32 years, H₂SO₄ Pi accumulation had dropped markedly on the Wharekohe silt loam. Some of the H₂SO₄ Pi would have accumulated in the youngest Wharekohe developed site from the 37 kg of RPR applied in 1993. However, much of the 54 kg H₂SO₄ Pi/ha which had accumulated over the 3 years would have been derived from superphosphate. Although H₂SO₄ Pi accumulation may be very high in the early years following pasture development (related to high lime inputs leading to high Ca content and pH, explained further in 4.4 and chapter 7), H₂SO₄ Pi accumulation is very much reduced in older sites.

Table 4.2Estimated alkali and acid Pi accumulation in the original 8 and 32 yearsites for a 3 year period compared to estimated accumulation for a 3 year period inMAF 'National Series' soils, TSP and RPR applied at twice maintenance.

Soil	Soil group	Anion	Alkali Pi	Acid Pi
		Storage	(µg/g)	(µg/g)
		Capacity (%)		
Wharekohe silt loam	Northern Podzol	<10	28	105
(8 year old site)				
Wharekohe silt loam	Northern Podzol	<10	30	40
(32 Year old site)				
Hukerenui silt loam*	Podzolised NYBE	15	29	20
			36**	108**
Warkworth clay*	Podzolised NYBE	34	30	41
			22**	74**
Whangaripo clay*	NYBE	22	74	25
			68**	61**
Waitoa silt loam*	Gley	70	172	40
			84**	192**
Te Kuiti silt loam*	Yellow brown	98	302	38
	loam		80**	300**
Lismore stony silt loam*	Yellow grey earth	25	32	5
			20**	41**
Monowai stony silt loam*	Yellow brown	75	111	19
	loam		44**	189**
Waikoikoi silt loam*	YBE/YGE	28	70	15
			35**	49**

NYBE=Northern yellow brown earth YGE=Yellow grey earth

* Data from National Series Trials (Perrott et al., 1992a).

** RPR applied

The estimates of applied P accumulating in each fraction over a 3 year period in the soils of Perrott et al.'s study were calculated as half the difference between their values in the fertilised plots and the unfertilised control plots. Calculation of accumulated Pi in this way would most likely have resulted in an overestimation of both H₂SO₄ Pi and, to a greater extent, NaOH Pi which may have been utilised by pasture growth in the control plots receiving no fertiliser, but comparisons are still valid.

The alkali Pi accumulation in the Wharekohe silt Ioam (Anion Storage Capacity <10%) was considered low and ranked with those calculated for other soils with low Anion Storage Capacities, Hukerenui silt Ioam (Anion Storage Capacity 15%), Warkworth clay (Anion Storage Capacity 22%) and Lismore stony silt (Anion Storage Cpacity 25%) where either TSP or RPR was applied. Such low alkali Pi accumulation confirms that the high proportion of H_2SO_4 Pi in the Wharekohe silt loam was due to limited alkali Pi accumulation rather than excessive H_2SO_4 Pi accumulation in the older sites.

4.4.2 Contribution of P Fractions to the SLF for the Wharekohe silt loam

The net accumulation of P into less available fractions under pasture in a 'steady state' constitutes a component of the SLF (Cornforth and Sinclair, 1982).

The P fractions extractable by NH₄Cl and NaHCO₃ in the sequential fractionation procedure employed in this study are considered to form the labile P pool (Chang and Jackson; 1957; Mattingly, 1975; Bowman and Cole, 1978, Hedley et al., 1982; Tiessen and Moir, 1993). Net accumulation into the inorganic and organic NaOH, H₂SO₄, Hot HCl or Residual P fractions would therefore be considered to be a component of the SLF even though they can contribute to plant available P in the long term if a steady state is lost or through cycling where no net change in each fraction occurs (Sattell and Morris, 1992).

The CFAS and Outlook models assume a 'steady state' so that the flux rates between the different compartments of the P cycling pool do not need to be

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considered (Cornforth and Sinclair, 1982). However, examination of the P fractions in the samples collected in 1990 and 1993 reveal that the net accumulation of applied P into less available plant fractions changes with time from pasture development. Consequently, a steady state does not exist on the Wharekohe silt loam while P is accumulating in the soil, as the flux rates between the different compartments of the P cycling pool do change with pasture age and need to be considered in models used to predict P fertiliser levels required to maintain pasture production.

As little P was lost from the youngest site and P was still accumulating in all fractions in the top 7.5 cm, the SLF consists mostly of net P accumulation at 8 years. However, in the oldest sites, losses of P from the top 7.5 cm were large and little P appeared to be accumulating apart from H_2SO_4 Pi from fertiliser residues and some organic P, mostly NaOH extractable. Hence, in the older sites, net accumulation of P into unavailable fractions may play a minor role in the SLF compared to P loss from the soil.

In contrast to other acid New Zealand soils which have been under pasture for some time, little applied P accumulated as Fe and Al-P extractable by NaOH and so the net accumulation of Fe and Al P does not contribute large amounts to the soil P loss. The accumulation of applied P into the plant unavailable hot HCl Pi and Residual Pi fractions was only 3% of the total accumulated P in the top 3 cm of the 32 year aged site and so these fractions do not contribute significantly to soil P loss in the Wharekohe silt loam either.

Calculation of the contribution of the net accumulation of applied P into each fraction to soil loss parameters appropriate for use in the Outlook and CFAS models is complicated by the use of RPR in later years, the lack of sites ranging in age from 0 to 8 years and changing P application rates over time. However, if it is assumed that i) a maximum amount of P can accumulate in each P pool in any one year and P applied surplus to this soil accumulation and production requirements is lost from the soil via runoff, and ii) P was applied at rates surplus to soil accumulation and production requirements in each year, the contribution of net accumulation of applied P into each fraction to soil loss parameters can be determined for various periods

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from the chronosequence data. The contribution of soil P accumulation to the CFAS SLF is investigated further in chapter 7, while chapter 8 presents models for the accumulation of applied P into various soil P pools and discusses the development of a future fertiliser P requirement model which would take into account changes soil P accumulation rates with pasture age.

4.4.3 Movement of P Through the Profile of a Wharekohe silt loam

Results from this P fractionation study support the theory that the low P storage capacity characteristic of the top soil of the Wharekohe silt loam has contributed to the high loss of P recorded in this soil.

In this study, it is not possible to determine the form (fraction) in which P is moving through the profile of the Wharekohe silt loam. The initial accumulation of P mostly as H₂SO₄ Pi in the 3-7.5 cm depth, does not necessarily imply that P is moving as Ca-P. Phosphorus can move through the soil profile in one form to be transformed into another form in situ. Haynes and Williams (1992) attributed the movement of P through the South Island yellow grey earth, Lismore stony silt, under irrigation at Winchmore to physical movement of P through the incorporation of dung and surface soil by earthworms, along with the movement of particulate matter in water through macropores. They considered that incorporated Ca-P was then converted to alkali extractable Pi in situ. The results of P accumulation in both the 3-7.5 cm and 7.5 cm - E horizon depths of the Wharekohe silt loam and noticeable earthworm activity support a similar pathway for P movement through Wharekohe podzols.

However, physical movement of P alone cannot account for all of the very large loss (up to 65%) of P from the top 7.5 cm of the Wharekohe silt loam (Chapter 3). As P is so weakly held in Wharekohe soils, the movement of dissolved P in subsurface runoff water must be contributing significantly to the movement of P both down the profile and laterally through the top soil. Haynes and Williams (1992) also found that although the highest percentage increase in Po was in the labile NaHCO3 Po, the highest absolute increases were in the NaOH extractable fractions. They therefore concluded that labile NaHCO₃ Po may have leached down the profile to be

converted to more stable NaOH extractable Po in situ. Such movement of labile Po and also Pi is also possible in Wharekohe topsoils with their extremely low Anion Storage Capacities.

Increases in accumulated NaHCO₃ and H₂SO₄ Pi below 7.5 cm were much larger in the Wharekohe soil than below 10 cm in the Lismore stony silt. Some of the extra P measured at depth in the Wharekohe soil, in comparison to the Lismore soil, can be attributed to the Wharekohe samples being taken closer to the soil surface (ie 7.5 cm - E horizon rather than 10-20 cm for Lismore) and to the movement of RPR fertiliser P particles in soil water or by earthworms. However, such large levels of accumulated P to depth in the Wharekohe silt loam indicates large levels of dissolved P movement down the profile of this soil.

Chapters 5 further investigates the movement of P in soil water through Wharekohe profiles

4.4.4 The Influence of P Fertiliser Form and Liming History on P Fractions in a Wharekohe silt Ioam

Both P fertiliser form and lime applications have influenced the accumulation of P into soil fractions, in particular H_2SO_4 Pi, in the pasture development chronosequence on the Wharekohe silt loam.

It is likely that some of the H_2SO_4 Pi in the Wharekohe soils accumulated as fertiliser P residues in the years prior to soil sampling on all the developed sites. Acid extractable Pi accumulation in acid soils low in Ca is often attributed to insoluble P fertiliser residues (Condron and Goh, 1989; Rowarth et al., 1992a). The use of 30% RPR in the fertiliser applied in the 5 years prior to the 1990 sampling would have increased the proportion of P recovered in the H_2SO_4 Pi fraction on the Wharekohe silt loam in the present study (Grigg and Crouchly, 1980; Perrott et al., 1992a; Kumar et al., 1993). A further 3 years of 100% RPR application on the additional sites resulted in higher H_2SO_4 Pi accumulation than was recorded for the original sites in 1993, where P was applied mostly as superphosphate in the previous 3 years. Acid

extractable Pi was also substantially higher than alkali Pi in the 8 soils in the study by Perrott et al. (1992a) where RPR (Sechura) had been used annually for 6 years.

Although the actual amount of H_2SO_4 Pi did not change with pasture age, the proportion of Pt as H_2SO_4 Pi decreased with age in the developed sites in the top 7.5 cm at both sample times. The younger sites had received a higher proportion of their applied P as RPR and less soluble Ca-P in the low solubility superphosphate used in New Zealand from the late 1960's. The decreasing proportion of H_2SO_4 Pi was balanced mostly by an increasing proportion of Pt as Po.

Changes in the nature of Pi accumulation in a Lismore stony silt over the 35 years from pasture development followed the sequence of initially accumulating as NaOH Pi, then as NaHCO₃ and NaOH Pi, and finally as HCI Pi (Condron and Goh, 1989; Haynes and Williams, 1992). Although the change to HCI extractable Pi may have been enhanced by exchangeable Ca levels interfering with the fractionation procedure, Condron and Goh (1989) cited two other possible reasons for the change to acid extractable Pi accumulation, namely i) changes in P fertiliser to less water soluble P and ii) lime addition.

Trends towards the accumulation of P as acid P with the addition of lime have also been noted by Pratt and Shoemaker (1955), Laverty and McLean (1961) and Chang and Chu (1961). In contrast, lime resulted in a decrease in NaHCO₃ Pi and 0.1 M NaOH I Pi and no change to H_2SO_4 Pi in the top 2.5 cm of Kokotau silt loam near Masterton (Perrott and Mansell, 1989) where the pH of 5.9 was lower than the pH of 6.6 recorded after the addition of lime at Winchmore (Quin and Rickard, 1981).

The accumulation of H_2SO_4 Pi in the Wharekohe silt loam in this study appears to be closely related to lime history (Lime History outlined in 3.3.2) particularly their lime history in the early years following pasture development. The sites which had received the highest rate of lime in their first 7 years (8, 23 and 32 year old sites) had the highest H_2SO_4 Pi in the top 7.5 cm. The site (30 years) which had received the lowest rate of lime in the first 7 years had the lowest H_2SO_4 Pi in the top 7.5 cm. The site (30 years) which had received the lowest rate of lime in the first 7 years had the lowest H_2SO_4 Pi in the top 7.5 cm. The site and the extremely high lime application rate in the first seven years on the 32 year old site was also

reflected in the higher pH (Figure 4.6), CEC, exchangeable Ca and total Ca contents of these two sites (Appendix 4.2).



Figure 4.6 Effect of pasture age on pH at each depth.

The lower Pi in the oldest sites compared to the younger sites in spring 1993 can mostly be attributed to lower H_2SO_4 Pi, although there was no significant difference between the developed sites for each fraction (Figure 4.4). Liming history may also account for the higher and lower H_2SO_4 Pi measured in the 1993 samples from the sites developed in 1960 and 1958 respectively compared to the sites sampled in 1990. Lime application varied enormously over the areas developed in those years due to the requirements of lime trials. The 1960 sites sampled in 1993 received a higher average lime rate than the site sampled in 1990, while the 1958 sites sampled in 1993.

The accumulation of H_2SO_4 Pi in the top 7.5 cm of the developed sites most likely results from reactions of applied soluble monocalcium phosphate with the undissolved CaCO₃ from the applied lime to produce less soluble Ca-P compounds, which become more stable over time, combined with the accumulation of low

solubility fertiliser Ca-P residues. Some of the H₂SO₄ extractable Pi would contribute to plant available P through the dissolution of Ca-P over time, particularly from RPR residues. However, Ca-P residues from the unreactive phosphate rock used in the manufacture of superphosphate and more stable Ca-P formed in situ., are not likely to contribute significantly to plant growth.

Organic P accumulation has been shown to cease where the application of lime increases pH values to above 5.9 (Condron and Goh, 1989; Nguyen et al., 1989; Condron and Goh, 1990). Soil pH increased with pasture development from 4.0 in the top 7.5 cm of the undeveloped sites, reflecting the large lime inputs (Figure 4.6). Increases in pH occurred at all depths, but were generally greater in the top 7.5 cm where the surface applied lime had the greatest influence. A similar result was found in a pasture development chronosequence on the South Island Okarito podzol where increases in pH with pasture development were confined to the top 10 cm and greatest in the top 5 cm (Lee et al., 1983). There was no significant difference in pH between the 0-3 cm and 3-7.5 cm depths on the Wharekohe sites.

The highest pH was recorded in the top 7.5 cm of the youngest site developed in 1982 at both sampling times (pH 5.95 in spring 1993). This result was consistent with the more recent, large application of lime with pasture development on the youngest site as lime may have a shorter term effect on pH in podzols in comparison to other sedimentary soils. Surface applied lime had a shorter-term effect (lasting 5 years) on the pH of a Maungatua podzol in the South Island in comparison to the yellow brown earths in the study (Floate and Enright, 1991).

Historic pH measurements reveal that the youngest site developed in 1982 had a pH in the top 7.5 cm of over 5.9 for the two years prior to sampling (Appendix 4.3), although this had fallen below 5.9 by 1990. Hence, Po accumulation may have been suppressed at this site during that time in both the 0-3 cm and 3-7.5 cm depths providing an explanation for the similar average rates of Po accumulation recorded in the 3-7.5 cm depth of the 8 and 23 year sites, which was unexpected. Historic pH values were not available for other sites, but it is possible that if the pH of the other sites had remained below 5.9 in recent years (which was likely due to the lower

recent lime history of the older sites), Po accumulation may not have been impeded by the pH level.

Lime induced changes in the retention of added P are discussed further in chapter 6.

4.4.5 Effect of Parent Material on P Fractions in Wharekohe Podzols

Comparison of the P partitioning in a Wharekohe silt loam with a Wharekohe sandy loam, both under pasture for at least 30 years, provides an insight into the effect of parent material on the accumulation of P into various fractions.

The Wharekohe sandy loam contained less total P than the Wharekohe silt loam soil (Table 4.3). Unfortunately an accurate P fertiliser history was not available for the Wharekohe sandy loam site and so calculations of the quantity of applied P which had accumulated in the soil and consequently losses of applied P from the top 7.5 cm could not be made. However, the site was on a dairy farm which had received regular high dressings of P fertiliser (Table 2.1) and as the total P content was low, some P would have been lost from the soil.

A larger proportion of total P, 11.5% (63 μ g P/g), was measured in the NH₄Cl Pi fraction in the Wharekohe sandy loam compared to the Wharekohe silt loam (Table 4.3, Figure 4.7). The sandy loam had received only one dressing of RPR and NH₄Cl Pi is expected to be lower where RPR is used (Kumar et al., 1993). The slightly lower surface area of the sandy loam may also have contributed fewer sites for the sorption of applied P. The high proportion of Pi in the NH₄Cl fraction illustrates just how weakly available P is held in both Wharekohe soils, in particular the sandy loam, and therefore how prone the available P is to leaching. A high proportion of the P applied in superphosphate, 9 to 15%, was also extracted as NH₄Cl Pi in the top 10 cm of three sandy soils in Western Australia known to leach P where a modified Chang and Jackson procedure (Williams et al., 1967) was used to fractionate P (Kumar et al., 1993).

Site	Wharekohe silt loam	Wharekohe sandy loam
Olsen P	22	26
NH₄Cl Pi (µg/g)	32 (5%)	63 (12%)
NaHCO₃ Pi (µg/g)	47.5 (7%)	23 (4%)
NaOH Pi (µg/g)	53 (8%)	42 (8%)
H₂SO₄ Pi (µg/g)	183.5 (28%)	121 (22%)
NH₄CI Po (µg/g)	25 (4%)	31 (6%)
NaHCO₃ Po (µg/g)	71.5 (11%)	55 (10%)
NaOH Po (µg/g)	168.5 (26%)	143 (25%)
Residual P (µg/g)	77.5 (12%)	67 (12%)
Total P (µg/g)	658.5	545

Table 4.3Effect of parent material on the P fractions measured in Wharekohepodzols (% in brackets).



Figure 4.7 Effect of parent material on inorganic and organic P fractions in Wharekohe podzols.

The proportion of total P as NaHCO₃ Pi was much lower in the sandy loam than in the silt loam. However, the sum of the easily extractable NH₄Cl and NaHCO₃ Pi

fractions was similar for both soils. Hence, available Pi appears to be more weakly held in Wharekohe sandy loam.

In both soils NaOH Pi was low, only 8% of the total P, indicating how few Fe and Al P retention sites are available in the Wharekohe soils. The actual amount of NaOH Pi was lower in the Wharekohe sandy loam supporting a lower number of sites in the sandy loam for P sorption.

Calcium-P extracted by H_2SO_4 was the largest fraction in both the Wharekohe soils. However, once again this was not due to an unusually high affinity for Ca-P peculiar to Wharekohe soils but rather to a lack of alkali extractable Pi accumulation. The higher proportion of P extractable by H_2SO_4 in the Wharekohe silt loam was most likely a reflection of the RPR use on those sites.

Organic P differences showed a similar pattern to available Pi between the two Wharekohe soils although the differences were not quite as pronounced as for Pi. Most of the organic P was in the NaOH Po fraction for each soil. As Po stabilisation is directly related to P sorption sites (Saunders, 1959a), limited sorption sites are restricting Po accumulation in both Wharekohe soils. A lower number of sorption sites in the Wharekohe sandy loam due to a lower surface area may have resulted in the lower Po accumulation recorded in the sandy loam.

At such an extreme degree of soil weathering, parent material has had only a minor influence on the accumulation of P into various fractions. However, it is likely that P losses from the soil would be slightly higher from the sandy loam due to the easily extractable nature of the available P and to less sites for the sorption of Pi and stabilisation of Po.

The ability of both Wharekohe soils to retain added P is investigated further in Chapter 6.

4.4.6 Effect of the Degree of Weathering of Silt Sediments on P Fractions

The degree of soil weathering has had a marked effect on the P chemistry of the two soils derived from similar parent materials under older pasture, the yellow brown earth, Aponga clay, and the podzol, Wharekohe silt loam.

The Aponga clay contained substantially more total P, more than twice that found in the Wharekohe silt loam (Table 4.4). As an accurate P fertiliser history was not available for the Aponga clay site, calculations of the quantity of applied P which had accumulated in each soil and consequently losses of applied P from the top 7.5 cm could not be made. Once again the use of RPR on the Wharekohe silt loam and sampling time complicates comparisons of P fractions between the two different soils. However, differences are large and a greater proportion of the P measured in each fraction in the Aponga clay was likely to be derived from native soil P rather than P fertiliser application in comparison to the more strongly weathered Wharekohe soil (Table 4.4, Figure 4.8).

Table 4.4 Effect of the degree of soil weathering on the P fractions measured in the moderately leached yellow brown earth, Aponga clay, and the podzol, Wharekohe silt loam, derived from similar silty parent material (% in brackets).

Site	Wharekohe silt loam	Aponga clay
Olsen P (MAF)	22	25
NH₄Cl Pi (µg/g)	32 (5%)	0.9 (trace)
NaHCO₃ Pi (µg/g)	47.5 (7%)	61 (4%)
NaOH Pi (µg/g)	53 (8%)	437 (27%)
H₂SO₄ Pi (µg/g)	183.5 (28%)	346 (22%)
NH₄CI Po (µg/g)	25 (4%)	8 (0.5%)
NaHCO ₃ Po (µg/g)	71.5 (11%)	95 (6%)
NaOH Po (µg/g)	168.5 (26%)	482 (30%)
Residual P (µg/g)	77.5 (12%)	168 (10.5%)
Total P (µg/g)	658.5	1597



Figure 4.8 Effect of degree of weathering of silt sediments on inorganic and organic P fractions in the soil.

Only 0.86 μ g P/g or 0.05% of the total P recovered in the yellow brown earth Aponga clay was in the NH₄CI Pi fraction, in contrast to the 32 μ g P/g measured in the Wharekohe silt loam. The proportion of total P as NaHCO₃ Pi was lower than in the Wharekohe silt loam, although the actual amount was higher. Phosphorus is much more tightly held in the Aponga clay than in the Wharekohe soil. This was confirmed by the much larger size of the NaOH Pi extractable Pi in the less weathered Aponga clay due to the presence of more Fe and Al sorption sites, than in the Wharekohe silt loam.

The Ca-P measured in the Aponga clay was far higher than the amount measured in the Wharekohe silt loam, despite RPR application in the latter. The presence of residual primary Ca-P in the less weathered soil is the most likely explanation of the difference.

The Aponga clay contained a larger quantity of organic P than the Wharekohe soil. Most of the organic P was in the NaOH Po fraction for each soil and although the proportions in the NaOH fraction were similar, the amount in the Aponga clay was far higher than in the Wharekohe soil (9x). Such high levels of NaOH Po in the less weathered soil are most likely due to the stabilisation of Po against mineralisation by Al and Fe complexes. Consequently, as was the case with Pi, weakly held NH₄CI Po was very low in the Aponga clay compared to the Wharekohe soil.

The degree of weathering on the silty sediments has resulted in large differences in P accumulation, with both Pi and Po held more strongly through reactions with and sorption on the surface of Fe and Al complexes, in the less weathered Aponga clay in comparison to the Wharekohe silt loam. The accumulation of non-labile P would contribute much more to the SLF in the Aponga clay than in the Wharekohe silt loam.

The ability of the Aponga clay to retain added P in comparison to the Wharekohe silt loam is investigated further in Chapter 6.

4.5 SUMMARY AND CONCLUSIONS

4.5.1 Effect of Pasture Age on the Accumulation of Applied P into Soil Fractions in a Wharekohe silt loam

• The maximum P storage capacity reported in chapter 3 can be attributed solely to a maximum Pi storage capacity. Inorganic P accumulation had stopped by 8 years in the top 3 cm and by 11 years in the 3-7.5 cm depth of the Wharekohe silt loam, apart from the continued accumulation of small quantities of Ca-P from insoluble fertiliser residues. The Pi accumulation in the Wharekohe silt loam followed a different pattern to other New Zealand soils where Pi continues to accumulate where P is applied surplus to pasture requirements.

 In contrast to Pi, Po continued to accumulate over time to at least 32 years at each depth to levels similar to those recorded by other researchers in a less weathered South Island yellow grey earth. Restricted movement of applied P under young pasture contributed to delayed organic P immobilisation at depth.

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 Initially pasture development resulted in a decrease in the Po/Pi ratio. However, in contrast to other New Zealand soils, the Po/Pi ratio increased with time after 8 years as Pi had stopped accumulating while Po continued to accumulate.

• Over half of the P extracted from all depths of the undeveloped sites was in the plant available and easily extractable NH₄Cl and NaHCO₃ Pi and Po fractions indicating that a large proportion of the total P is actively involved in the cycling pool. The amounts of Pi extracted in the other inorganic fractions were as expected for a highly weathered soil, with occluded P extracted by hot acid larger than both the negligible Ca-P extracted by H₂SO₄ and the small quantity of NaOH Pi associated with Al and Fe. In contrast to other highly weathered soils, the more stable NaOH Po fraction was low in comparison to the more labile Po, which was perhaps due to the low Fe and Al content of the Wharekohe silt loam.

• All inorganic and organic P fractions increased with initial pasture development. In contrast to other acid New Zealand soils, Ca-P extracted by H₂SO₄ was the largest fraction in the top 7.5 cm of all the developed sites. Calcium-P was still accumulating in the top 7.5 cm of the Wharekohe silt loam sites from the accumulation of P fertiliser residues and reactions of soluble monocalcium P over time with Ca added to the soil in lime. Such a high proportion of P as Ca-P was not due to the preferential accumulation of Ca-P peculiar to Wharekohe soils, but rather to a limit to the accumulation of P associated with Fe and Al (NaOH Pi) in the Wharekohe soil in comparison to other New Zealand soils including the Aponga clay in the present study.

 The Wharekohe silt loam contained a large quantity of easily available Pi of which a large amount was very weakly held in the soil (NH₄Cl Pi) and therefore prone to leaching in comparison to other less weathered soils.

 The rate of Po accumulation decreased over time in the top 3 cm. By 25 years, the most labile Po fraction extracted by NH₄CI had reached equilibrium. Organic P accumulated predominantly as NaOH extractable Po, that is Po stabilised against mineralisation by sorption on sesquioxides and Po associated with humic and fulvic acids, at all depths. The low Fe and Al content of the Wharekohe soils should result in a limit to the amount of Po which can be stabilised against mineralisation, and hence Po is expected to reach equilibrium sooner than in other soils.

4.5.2 Contribution of P Fraction to the SLF for a Wharekohe silt loam

• The relative contribution to the SLF of P accumulation into non-labile P fractions decreases with time from initial pasture development. The quantity of applied P accumulating in plant unavailable compounds in the rooting zone (top 7.5 cm) of Wharekohe silt loam is not large in comparison to the losses recorded from the soil profiles of the older developed sites (Chapter 3). Hence, non-labile P accumulation only forms a minor component of the SLF on soils which have been under pasture for more than 11 years where further P accumulation is mostly small amounts of insoluble Ca-P fertiliser residues and the more stable forms of Po. The amounts of accumulated P recorded in this chapter are used to calculate values for the SLF in chapter 7 and to model the fate of P in chapter 8.

4.5.3 Movement of P Through the Profile of a Wharekohe silt loam

• It is the limit to the accumulation of applied P as Fe and AI phosphates and P sorbed on the surfaces of sesquioxides which has led to the high P losses recorded from the Wharekohe silt loam in comparison to other soils.

• Phosphorus accumulates initially in the first 8 years as NaHCO₃ Pi and NaOH Po, then predominantly as Ca-Pi and NaOH Po to 23 years and then as NaHCO₃ and NaOH Po after 23 years below 7.5 cm in the Wharekohe silt loam. It is not possible to determine in which form P is moving through the profile of the Wharekohe silt loam due to possible changes in P forms in situ. The results of P accumulation in both the 3-7.5 cm depth and 7.5 cm - E horizon support the theory that some P moves physically as Ca-P and Po in dung and surface soil particles (including RPR) via earthworms and soil water, some of which is then converted to alkali Pi at depth. Physical movement of P alone cannot account for the vary large losses of P

recorded in the Wharekohe silt loam. As P is so weakly held in Wharekohe soils, the movement of dissolved P in soil water must be contributing significantly to the movement of P both down the profile and laterally through the top soil. Chapter 5 investigates whether P is moving in soil water as Pi or Po.

4.5.4 Influence of P Fertiliser Form and Historic Lime Application on P Fractions in Wharekohe Podzols

• The use of RPR and lime history have contributed to H₂SO₄ extractable Ca Pi accumulation.

• Calcium-Pi, extractable by H₂SO₄, was closely related to liming history, in particular the lime application in the years immediately following initial pasture development.

• The more recent heavy lime application on the youngest site has led to a higher pH which may have restricted Po accumulation in recent years.

4.5.5 Effect of Parent Material on P Fractions in Wharekohe Podzols

• At such an extreme degree of weathering, parent material has had only a small influence on the accumulation of P into various fractions in Wharekohe soils with available Pi and Po held less strongly in the soil derived from sandy sediments. It is likely that P losses from the soil would be slightly higher from the sandy loam due to the easily extractable nature of the available P and to less sites for the sorption of Pi and stabilisation of Po.

4.5.6 Effect of Degree of Weathering of Silt Sediments on P Fractions

• The degree of weathering on the silty sediments has resulted in large amounts of P in the slowly available and unavailable P fractions in the less weathered Aponga clay in contrast to the Wharekohe silt loam. Applied P accumulation, particularly as

NaOH extractable Fe and Al Pi, would be expected to make a greater contribution to the SLF of the Aponga clay in comparison to the Wharekohe silt loam.

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CHAPTER 5 P MOVEMENT IN SUBSURFACE RUNOFF

5.1 INTRODUCTION

Runoff from intensively grazed pastoral systems has resulted in the eutrophication of many lowland and coastal lakes in New Zealand (Wilcock, 1986). Much of the research into nutrient losses in runoff water has focused on P as the key nutrient limiting eutrophication, as C and N can exchange with the atmosphere, but greater control can be exerted over P enrichment (Sharpley et al., 1995). Although P is considered to be relatively immobile and losses of P from New Zealand soils are generally considered to be low from an agronomic point of view, the application of fertiliser to pastures has resulted in losses of P in runoff waters well in excess of the 0.02 to 0.035 µg P/mI (OECD, 1982; Vollenweider, 1968) considered limiting to eutrophication (McColl et al., 1977; Bargh, 1978; Lee et al., 1979; McColl and Gibson, 1979 a&b; Sharpley and Syers, 1979a&b; Close and Woods, 1986; Sharpley and Syers, 1983; Lambert et al., 1985; Cooper and Thomsen, 1988). Such losses appear to be similar to those reported overseas (Olness et al., 1975; Jawson et al., 1982; Schepers and Francis, 1981).

However, data presented in Chapter 3 shows that P losses from Wharekohe soils are so large as to not only possibly impact negatively on eutrophication, but to also represent a large economic loss to the farmer. Up to 65% of P applied over a 3 year period (an average of 32 kg P/ha/yr) could not be accounted for in the top 7.5 cm and up to 27% (8.5 kg P/ha/yr) of P applied since pasture development could not be accounted for above the E horizon in older developed sites on Wharekohe soils. As little P was found to accumulate at depths below the E horizon, P is most likely being lost in water movement down slope, and most likely into the wider environment.

Both inorganic and organic P were found to accumulate at depth in the Wharekohe silt loam (Chapter 4). However, due to possible transformations of P fractions in situ., it was not possible to determine from the fractionation data presented in

chapter 4, whether P was moving in soil water as dissolved inorganic P, organic P or both forms.

Phosphorus is lost from the soil in surface runoff, in subsurface runoff and in groundwater runoff. The relative contribution of subsurface and surface flow to P losses depends on both the concentrations of P and the volume of water in each (Sharpley et al., 1976).

Surface runoff usually contributes the greater proportion of P losses from finely textured mineral soils, despite contributing lower volumes of water (Burwell et al., 1974; Hanway and Laflan, 1974; Baker et al., 1975; Sharpley et al., 1976, 1995; Sharpley and Syers, 1979a).

Subsurface losses of P are usually low in both New Zealand and overseas except in sandy soils with low P sorption capacities (Ozanne, 1961; Hogg and Cooper, 1964; Diggle and Bell, 1984; Ruprecht and George, 1993; Gilliam et al., 1994) and in organic soils (Hogg and Cooper, 1964; Fox and Kamprath, 1971; Cogger and Duxbury, 1984; Deal et al., 1986). The low concentration of total P in subsurface waters in finely textured mineral soils is due to the greater soil contact leading to increased sorption of dissolved P and the filtering nature of the soil removing particulate P (Sharpley and Syers, 1979a). In developed Wharekohe soils, however, the soluble P concentration should be higher in subsurface runoff than in other New Zealand soils, due to a lack of P retention sites in the A horizon. The loss of P in subsurface runoff is expected to be higher from older developed sites than from younger sites on Wharekohe soils. The older sites have become saturated with P to a greater depth, containing P close to their maximum P storage capacities through the soil profile above the E horizon, where subsurface runoff is likely to flow. Consequently, there are few remaining sites for P storage, while at the younger sites, the lower soil P concentration at depth is likely to lead to the more effective removal of P from subsurface runoff water.

5.2 OBJECTIVES

The main objectives of this study were to determine:

1. If freshly applied P can move through Wharekohe soils as dissolved P in subsurface water movement and whether this is effected by;

- i) time under developed pasture,
- or ii) differences in parent material.

2. If dissolved P movement occurs as inorganic and/or organic P

5.3 MATERIALS AND METHOD

5.3.1 Glasshouse Trial

5.3.1.1 Collection and Preparation of Soil Cores

Sixteen intact soil cores, 14 cm in diameter by 9 cm deep, were collected from each of the following soils using the method of Cameron et al. (1990) and illustrated in figure 5.1;

Wharekohe silt loam	(10 years under developed pasture),
Wharekohe silt loam	(32 years under developed pasture),
Wharekohe sandy loam	(>30 years under developed pasture),
Aponga clay	(>30 years under developed pasture),

Aponga clay cores were included for comparative purposes. It is a soil with parent material similar to the Wharekohe but has a significantly higher anion storage capacity. The anion storage capacities at each of the sites were 10 % for the Wharekohe silt loam, 7 % for then Wharekohe sandy loam and 54% for the Aponga clay.



Figure 5.1 Intact soil cores, with petrolatum (vaseline) seal between galvanised casing and soil, and the dual leachate collection system.

Perennial ryegrass and white clover were the dominant pasture species at each site. Pasture was initially trimmed to 2 cm height and then trimmed to this height at regular intervals during the leaching trial to avoid excessive transpiration in the glasshouse.

The bottom of each core was carefully picked with a nail to expose an uncut surface and to open the pores which had been smeared when cut by the knife. The bottom was then covered with nylon gauze to prevent sediment falling into the leachate.

The soil cores were well watered over several days and then left to drain for 2 hours before weighing to establish a watering weight close to saturation but from which no soil water would drip from the base of the cores.

100 kg P/ha (superphosphate <2 mm) was applied to 8 cores of each soil leaving 8 cores of each soil as 0 kg P/ha (controls) on Day 0. The soil cores were arranged randomly in four blocks, 2 cores of each soil x treatment in each block.

5.3.1.2 Leaching Technique

The cores were watered to weight prior to each leaching event and between leaching events to prevent soil water loss from over watering. Adjustments were made to the watering weight during the trial to account for a reduction in the hydraulic conductivity of some of the soils and their increased water retention.

11.4 mm of simulated rain was applied on four separate occasions (3, 5, 10 and 13 days from P application) over a four hour period (35 ml container of water spread over the core surface each hour). Water did not accumulate on the surface except in a very few cores where hydraulic conductivity had markedly deteriorated. The cores were then kept watered for a further 40 days before 3 further leaching events on days 53, 81 and 94. The cores had become dry during the 40 days and required resealing with vaseline and re-wetting before further leaching events. Some water (not more than 200 ml) had passed through the cores during this period and was discarded.

Leachate samples were collected via a dual collection system (shown in Figure 5.1) to check for preferential flow down the sides of the cores after each rainfall event. A 13.5 cm diameter container collected leachate from the bulk of the cores while a second container collected leachate from the 0.25 cm perimeter.

Conditions in the glasshouse for the duration of the trial in summer were hotter than experienced in the field.

Initial leaching events, prior to fertiliser application, revealed that most of the cores collected from the Wharekohe soils displayed substantial flow from the 0.25 cm perimeter, particularly those cores collected from the Wharekohe sandy loam site and the 10 year old Wharekohe silt loam site. In order to investigate reasons for this preferential flow, a core from each of these two sites was leached with a bright pink marker dye and then dissected to examine water movement before the trial commenced.

At the end of the leaching trial, methylene blue was applied to four cores from each soil in the same manner as the simulated rainfall. The soil cores were then removed from the cylinders and the vaseline peeled back to examine macropores. Each soil core was sliced at one centimetre intervals from the top and an acetate grid divided into 1 cm squares was used to determine soil water penetration cover at each depth.

5.3.1.3 Chemical Analysis of Leachate

Leachate was filtered through a <0.45 μ m millepore filter. Dissolved inorganic P (DIP) was measured in the leachate colorimetrically by the phosphomolybdate method of Murphy and Riley (1962). Dissolved organic P (DOP) was determined as the difference between total dissolved P (TDP), measured after H₂SO₄ /H₂O₂ digestion (Thomas et al., 1967) and dissolved inorganic P.

Leachate was analysed straight away, except those collected on day 13. These were filtered and then approximately 30 ml samples were frozen overnight after the addition of one drop of concentrated HCl.

5.3.1.4 Statistical Analysis

Differences and similarities between the quantities of P leached through the different soils were readily apparent and consequently analysis of variance of the data was unnecessary. Mean standard error bars are included where appropriate.

5.3.2 Field Trial

5.3.2.1 Field Sites and Fertiliser Treatments

Six 25 m² plots, with slopes of 9°, were selected at 2 Wharekohe silt loam sites, 11 and 33/35 years under developed pasture, on the Kaikohe Research Station. The plots were fertilised with 100 kg P/ha (superphosphate) on the 5th of September (Day 0).

5.3.2.2 Soil Solution Collection

Porous ceramic cups were used to collect water samples at two depths, 2-7.5 cm and 7.5-13 cm, within and at 3 distances away from the fertilised plots (10 cm down slope, 20 cm down slope and 10 m away from fertilised plots (control)). Soil solution was sampled, from each cup, 6 days prior to fertiliser application and after each of five major natural rainfall events by placing the cups under suction for 24 hours.

To minimise P sorption on the surface of the ceramic cups, cups were soaked in a P solution prior to use and then rinsed thoroughly in distilled water.

5.3.2.3 Chemical Analysis of Soil Solutions

DIP in filtered water samples (<0.45 um) was measured colorimetrically straight away using the phosphomolybdate method of Murphy and Riley (1962). DOP was determined as the difference between TDP, measured colorimetrically after H_2SO_4 /H2O2 digestion (Thomas et al., 1967) and dissolved inorganic P.

5.3.2.4 Statistical Analysis

Differences between DIP in the control and each of the other three distances were tested for significance (P=0.95) at each sampling using Dunnett's procedure after log transformation.

DOP was only a small proportion of TDP in the 2-7.5 cm depth under the fertilised plots and often below the limits of detection. A comprehensive statistical analysis was not possible due to unequal variances which could not be overcome by transformation. T-tests (unequal variance) were used to test for the significance of differences measured between the control and under fertilised plots on the first day after fertiliser application.

5.4 RESULTS AND DISCUSSION

5.4.1 Glasshouse Trial

5.4.1.1 Amounts of DIP and DOP Lost by Leaching

Movement of DIP through Wharekohe soils after superphosphate application was substantial. Concentrations of DIP in the Wharekohe leachate 3 days after P application were very high, 37.5, 45.6 and 31.2 µg/ml for the 11 year silt loam, 33/35 year silt loam and >30 year sandy loam sites respectively. After just four, 11.4 mm rainfall events, a total of at least 8% of the applied P had leached through each of the three Wharekohe soils as DIP (Figure 5.2).



Figure 5.2 Sum of dissolved inorganic P leached through soil cores after four 11.4 mm rainfall events on days 3, 5, 10 and 13.

The application of fertiliser P resulted in no additional movement of DOP (Figure 5.3). The proportion of TDP leached as DOP in the Wharekohe soils where fertiliser P had been applied was low ranging from 0 to 5.5%. The proportion of TDP leached as DOP was higher in the unfertilised sites where little P movement occurred. Both New Zealand and overseas studies have found DIP to be the major component of TDP in subsurface (Sharpley and Syers, 1979b; Turner et al., 1979; Culley et al., 1983; Heckrath et al., 1995) and surface (Sharpley and Syers, 1978; Sharpley et al., 1982) runoff from mineral soils where fertiliser P has been applied. McColl (1978) found that 93 % of the TDP was lost as DIP in post-fertiliser floods from a podzolised yellow brown earth catchment, which included Wharekohe soils in Northland.

In contrast to the Wharekohe soils, P equivalent to less than 0.27% of the P applied (1.07 μ /ml) had leached through the yellow-brown earth, Aponga clay, as DIP. Negligible P movement has also been measured through repacked soil cores in a

a) Day 3



b) Day 13



c) Day 94

7 2



Figure 5.3 DIP and DOP leached through cores after three 11.4 mm rainall events, a) 3, b) 13 and c) 94 days after P fertiliser application.

range of laboratory and field studies on New Zealand soils including yellow brown earths, yellow brown pumice soils, granular brown loams and yellow brown loams despite high P application rates ranging from 45 to 79 kg P/ha/yr (Elliott, 1973; Muller and McSweeney, 1974; McSweeney and Muller, 1979).

Studies on repacked cores can lead to lower nutrient losses from P sorbing soils than would be found by using intact soil cores or in the field, as naturally occurring macropores, which result in preferential flow, are removed (Cassel et al., 1974; White, 1985; Scotter and Kanchanasut, 1981). The effect of preferential flow on P leached from soils with low P sorption capacities is discussed further in 5.4.1.4. The repacked cores used in the above studies were also longer, 30 cm, than the cores used in the present study allowing for greater soil contact and hence P sorption (Gerritse, 1995). However, despite the removal of macropores and the use of long cores, large losses of applied P have been recorded through repacked cores of the New Zealand podzols Wharekohe silt loam, Te Kopuru sand (up to 36%) and an Addison gley podzol (42%), and through a Northland peat soil (Hogg and Cooper, 1964, McSweeney and Muller, 1979). In an Australian study, considerable movement of P occurred in repacked columns of a gley podzol in comparison to no recorded P movement in a red earth (Lefroy et al., 1995).

Freezing can reduce the amount of DIP measured in both filtered and unfiltered runoff samples (Nelson and Romkens, 1972; Klingaman and Nelson, 1976; Haygarth et al., 1995). In the present study, DOP in the leachate sampled on day 13, which had been frozen, was higher than in leachate sampled on days 3 and 94. As DOP is calculated as the difference between TDP and DIP, some loss in recovery of DIP may have occurred in the day 13 samples upon freezing. However, any such changes were not large enough to impact significantly on the results.

The results from the podzol leaching experiments described above, combined with those of the present study, illustrate how readily P is leached from podzolic soils with low anion exchange capacities such as the Wharekohe podzols.

5.4.1.2 Effect of Pasture Age on P Leaching

Time under developed pasture had no significant effect on P movement in either the unfertilised or fertilised Wharekohe silt loam (Figure 5.2). In contrast, an Australian laboratory leaching study found that more P was leached through a sandy soil collected from a site which had been under pasture for 20 years, receiving on average 33 kg P/ha/yr, compared to a soil collected from a site 10 years under pasture, receiving on average 18 kg P/ha/yr (Weaver et al., 1988). However, it is difficult to conclude from the Australian study if the higher P loss in the soil collected from the older developed site was a function of fertiliser application rate or pasture age.

The rapid movement of water through macropores in the present trial may have masked differences in P movement with pasture age which may occur in the field, where the presence of the pan leads to much slower movement of subsurface runoff. Rapid movement of water preferentially through macropores allows for less contact of P in subsurface runoff with the soil surface and hence lowers P sorption. Alternatively, small (but undetected) differences in flow rates between the two pasture ages in the glasshouse study may have masked differences in P loss which may occur under field conditions. The effect of preferential flow on the retention of P and hence leaching losses is discussed more fully in 5.4.1.5.

Pasture age in relation to P saturation and P losses is discussed further in 5.5.2.

5.4.1.3 Effect of Parent Material on P Leaching

There was no detectable difference between the amount of P leached from the Wharekohe sandy loam and Wharekohe silt loam cores for the duration of the trial. The sandy loam at the collection sites was not particularly more coarse textured than the silt loam. The texture is strongly influenced by a few large quartz particles and the matrix is a silt loam. Hence, differences in porosity may not be as marked as one would expect between a silt and sandy loam leading to more similar infiltration and flow rates. Certainly no difference in infiltration rate and water flow through the

soil cores was observed between the two Wharekohe variants, although the rate of water movement was not measured directly. However, once again, small (but undetected) differences in flow rates between the two Wharekohe variants in the glasshouse trial may be masking differences in P loss which may occur under field conditions.

5.4.1.4 Effect of Time on P Leaching

The amount of DIP leached per leaching event decreased exponentially with time from fertiliser application (Figure 5.4). An exponential decline in P leached from soil cores was also found by Weaver et al. (1988) in sandy soils with low anion storage capacities. A greater proportion of freshly applied P will be susceptible to leaching in soils with low anion storage capacities resulting in large initial P losses. P losses are reduced dramatically over time as the P which was susceptible to leaching has already been lost from the soil. Hogg and Cooper's (1964) Te Kopuru sandy loam leaching results support a decline in the amount of P leached over time in soils with low P sorption capacities. The amount of P leached each week only reduced with time in the highest P leaching soil with the lowest P retention. Interestingly, the amount of P leached increased with time from the higher P retention soils collected from all other Te Kopuru sites where P losses were much lower. Assumed loss of soil structure with continued leaching may have led to waterlogging in the repacked cores. Increased waterlogging over time leads to both an increase in pH and the reduction of Fe (III) to Fe (II), and consequently the release of increasing quantities of P from these higher P retention soils (Ponnamperuma, 1972; Gotoh and Patrick, 1974; Khalid et al., 1977; Kirk et al., 1990). The effect of waterlogging on the retention of P is discussed further in the general discussion in 5.5.3.

The concentration of DIP leached from the fertilised Wharekohe cores was approaching the concentration leached from the unfertilised cores after 94 days (Figure 5.5), although it was still higher. As much of the freshly applied P remained in the soil, the P must have been becoming less accessible for leaching with time from application as an equilibrium concentration was approached. If the equilibrium concentration was approached through the cores,



Figure 5.4 Effect of time on the amount of DIP leached from fertilised cores during each 11.4 mm rainfall event. (Vertical bars = S.E.D.s for Day 3).

greater rainfall would not have led to substantially higher losses of P. The amount of simulated rainfall applied in the glasshouse study was low in comparison to that encountered in the field in the months following an autumn P application. However, if the equilibrium concentration was time dependent, greater rainfall during the period of the trial would have led to larger losses of applied P. The latter scenario is the most likely as time allows for the diffusion of solution P into soil aggregates and away from preferential water flow, reducing P losses in low P sorbing soils as discussed in 5.4.1.4.



Figure 5.5 Comparison of DIP leached from fertilised and unfertilised cores with time from P application for the cores collected from each site.

5.4.1.5 Water Movement Through Intact Cores

Water had broken through the soil cores almost immediately after simulated rainfall at each leaching event. The leachate would not only consist of freshly applied water, but may also have contained older displaced water higher in solution P.

In the two soil cores through which pink marker dye flowed prior to trial commencement, the water was found to have penetrated evenly into the top 2 cm and then flowed preferentially down earthworm channels. The earthworms had moved down through the cores coming out to the sides in the top 6 cm and then turning back into the soil core when they encountered the vaseline lining the cores. However, where the earthworms had burrowed to the sides of the soils cores in the bottom 3 cm, where there was no vaseline to hinder them, they had burrowed straight down the edge of the cores to the bottom resulting in most of the water being collected from the perimeter. There was no flow of soil water between the soil, vaseline and container sides apart from through the earthworm channels. There was little flow from the perimeter of the Aponga clay cores as any macropores located down the perimeter of the cores had been filled with vaseline when the cores were collected and earthworm activity was limited.

At the end of the trial, the methylene blue stained simulated rainfall initially penetrated evenly, and was recorded in 44 and 62% of the centimetre squares at 1 cm depth (Table 5.1). At the 2 cm depth, applied water penetration was only recorded in 13-25% of the squares. By 4 cm depth, water movement was mostly restricted to pores. The number of pores conducting water decreased with depth so that by the base of the cores, the bulk of the water movement was restricted to just a few macropores as was found in lysimeter studies conducted by Scotter and Kanchanasut (1981) and Munyankusi et al. (1994).

Hence, leachate collected from the bottom of the cores had moved through the cores via preferential flow through macropores, mostly earthworm channels. Preferential flow through macropores occurs when the soil is sufficiently saturated or when macropores are open at the soil surface and the application of water exceeds the
infiltration rate (Scotter and Kanchanasut, 1981; Beven and Germann, 1982; Munyankusi et al., 1994). The soils in the present study were close to saturation and received simulated rainfall at a rate faster than infiltration due to the method of application.

Table 5.1Pattern of methylene blue stained water infiltration through intact soilcores at the end of the leaching trial.

	Water Infiltration			
	(% squares (1&2 cm from surface) or mean no. of			
	pores (4 cm - core base) occupied by methylene blue)			
Distance from	Aponga clay	Wharekohe silt	Wharekohe silt	Wharekohe
core surface		loam 10 yr	loam 32 yr	sandy loam
(cm)				
1	54	44	53	62
2	25	19	13	25
4	7.25	7.75	5.75	8.75
6	3	2.25	3.34	4
8	0.75	3	1.67	3.5
10 (base)	0.75	1.75	3.75	5

Relating P movement through the soil cores to the field situation is complicated by several factors including the effect of preferential flow through soils with low anion storage capacities, the removal of the pan influence when the intact cores were collected and the methods of simulated rainfall application employed in the trial.

Phosphorus adsorption below 6 cm may have been slightly restricted in cores where water flowed from the perimeter, as some of the earthworm channels were edged with PVC resulting in less soil contact for sorption of P from the leaching solution. However, little difference between the movement of non-sorbed and adsorbed ions occurs during preferential flow (Scotter, 1978; Kanchanasut et al., 1978; Scotter and Kanchanasut, 1981) and hence, the reduced soil contact at depth for soil water flowing down the perimeter of cores is expected to have little impact on the amount

of P leached. Cameron et al. (1990) did not find perimeter flow as their leaching experiment was conducted shortly after core collection. This limited time did not allow earthworms, if present, to create fresh channels by burrowing.

Rapid movement of P through macropores does not allow for very much soil contact for sorption of P from the flowing water as a limited surface area is exposed to moving water and the water is moving faster than it would through the remainder of the soil mass (Scotter and Kanchanasut, 1981). This explanation is used to indicate the reason for varying nutrient losses from surface applied fertilisers in soils with high anion storage capacities. However, in soils with very low anion storage capacities and/or those soils which are P saturated, such as the Wharekohe soils, preferential flow may eventually reduce P losses. Freshly applied P which has diffused into soil aggregates would largely be protected from the water flowing preferentially through macropores (McClay et al., 1991). In contrast, where water moves through the soil mass, soil solution of high P concentration, due to little P retention, may be displaced from the soil mass and lost from the soil.

The removal of the pan influence from the base of the intact cores has most likely led to greater preferential flow through the Wharekohe soil cores than would be observed in the field. Therefore, it is not possible to extrapolate the quantity of P leached through cores in the laboratory to the field situation.

The method of leaching employed in the present study may have led to lower losses than would have been encountered with other methods used. As P is so easily desorbed from Wharekohe soils, the delayed and intermittent rainfall application would have decreased losses compared to immediate or continuous rainfall application. Upon application, P had time to diffuse into soil aggregates in which it would have been protected from leaching with the bulk of the water flowing through macropores. Losses of P in surface runoff have also been found to be higher when leaching is commenced closer to P application (Sharpley, 1982). The intermittent leaching employed in the present study would have resulted in lower losses of P than continuous leaching, as P would have been able to diffuse into aggregates between 'rainfall' applications where it would be protected from subsequent 'rainfall' events as shown for S and N on a yellow grey earth silt loam with low S adsorption (McClay et al., 1991).

5.4.2 Field Trial

5.4.2.1 Movement of Applied P

Rainfall recorded for the duration of the field trial is presented in Figure 5.6.

Freshly applied P (as DIP) moved to the 2-7.5 cm depth at both sites from the first day after P application when 10 mm of rain had been recorded (Figure 5.7a). DIP concentrations were high, 18.65 μ g/ml and 13.87 μ g/ml for the 11 and 33/35 year old sites, respectively.

McAuliffe et al. (1979) also measured high initial concentrations of DIP from pasture irrigated with casein waste applied at 144 kg total P/ha (95 kg DIP/ha) on an alluvium soil derived from greywacke material and volcanic ash. The top soil had become saturated with P resulting in downward movement of the applied P and DIP concentrations of up to 20 ppm were recorded at 60 cm depth. Interestingly, the highest DIP measurements were at 60 cm depth in this free draining soil.

Heavy rainfall on day 16 resulted in freshly applied P moving down slope in the 2-7.5 cm depth on the younger site (Figure 5.7a). In contrast no movement of P down slope at this depth was recorded on the older site (Figure 5.7 b).

Inorganic P also moved down the profile to the 7.5-13 cm depth and down the slope at that depth on the younger site after the heavy rainfall on day 16 (Figure 5.8 a). Only slight movement of freshly applied P was recorded down the profile or the slope at the lower depth on the older site (Figure 5.8 b). Concentrations of DIP were lower in the 7.5 to 13 cm depth. Wheeler and Edmeades (1995) also found P concentration in soil solution extractions generally decreased with depth in a range of pastoral soils which had not received P fertiliser for 4.5 years.







Figure 5.7 Dissolved inorganic P measured in water samples collected from 2-7.5 cm depth, a) 11 years under developed pasture, and b) 33/35 years under developed pasture.

(s-significantly different from control).

a) 11 year old sites



Figure 5.8 Dissolved inorganic P measured in water samples collected from 7.5-13 cm depth, a) 11 years under developed pasture, and b) 33/35 years under developed pasture.

(s-significantly different from control).

Movement of P to the 7.5-13 cm depth may have been restricted by the water saturated nature of the soils at the time of P application which could have led to much water and applied P being lost as surface runoff. Hence, less movement of P both to depth and laterally could have been recorded in the present study than if the trial had commenced in autumn when P is normally applied. However, lower DIP concentrations below 7.5 cm may not necessarily indicate low levels of DIP movement to this depth. It is quite likely that the soil at the 7.5-13 cm depth is yet to be saturated with P (Chapter 3). Hence, DIP which moves below 7.5 cm may have been removed from solution through soil P retention at both sites.

The application of P appeared to result in an initial flush of DOP at least to the 2-7.5 cm depth in both sites (Figures 5.9 and 5.10). However, examination of data reveals that the flush was restricted to only one out of the 6 replicates at both sites and t-tests showed that the difference was not significant. Once again the amount of DOP was generally small in relation to DIP under fertilised plots (<5% of TDP for the 2-7.5 cm depth, Day 1).

Dissolved organic P may still play a role in P leaching as the DIP concentration reduces with time after P application (Figure 5.11), and for a large part of the year, DOP is likely to form a large proportion of TDP. However, as P is mostly applied in autumn before the wettest part of the year, the bulk of the TDP lost from sites is expected to be DIP at the Kaikohe station. McAuliffe et al. (1979) also found that the DIP concentration decreased with time following the initial increase encountered while the freshly applied P was moving to the depths where DIP concentration was measured. Dissolved inorganic P concentrations in the field may not necessarily decrease exponentially, as occurs in laboratory leaching studies where simulated rainfall is generally applied at a constant level at each rainfall event. In the field solution P concentrations over time will be effected by changes in soil water volume, due to natural variation in the rainfall pattern.

Although the areas surrounding the suction cups were protected by pasture cages (2 x 1 m), rotational grazing by cattle may have influenced P concentration to depth. Grazing has been shown to increase losses of P substantially in surface and

135

a) 11 year old sites



Figure 5.9 Dissolved organic P measured in water samples collected from 2-7.5 cm depth, a) 11 years under developed pasture, and b) 33/35 years under developed pasture.



Figure 5.10 Dissolved organic P measured in water samples collected from 7.5-13 cm depth, a) 11 years under developed pasture, and b) 33/35 years under developed pasture.



Figure 5.11 Effect of time on DIP concentration in the 2-7.5 cm within the fertilised plots and 10 m away (controls).

subsurface runoff both in New Zealand (Sharpley and Syers, 1976; Turner et al., 1979; McColl and Gibson, 1979a; Lambert et al, 1985) and overseas (Olness et al., 1975; Schepers and Francis, 1981; Jawson et al., 1982). Grazing by cattle has been found to have a greater impact on P concentrations in runoff waters than grazing by sheep (Lambert et al., 1985). As surface pugging and destruction of drainage channels by animals reduces infiltration, total losses of fertiliser P (kg/ha) via subsurface water will not be increased by as much as the P concentrations. Grazing animals increased P concentration in tile drainage 150 times for DIP and 400 times for PP but the actual amounts only increased by 50 and 100%, respectively, in a Tokomaru silt loam (Sharpley and Syers, 1979b).

5.4.2.2 Effect of Pasture Age on P Movement

On the basis of P concentration data, P appeared to move down slope from the trial sites and to greater depth after heavy rain on day 16 in the youngest site, compared

to little movement of P in the oldest site, suggesting greater movement of applied P at the young site. This result contrasts with the expectation that the movement of P in soil water would be greater at the oldest site. However, volumes of runoff waters were not measured and may effect both the total P movement and P concentrations at each depth and each site. Therefore, it is not possible to use the soil water P concentration field trial data directly as a basis for comparing the extent of P movement in subsurface runoff between the two sites.

5.5 GENERAL DISCUSSION

Results from the glasshouse leaching experiment and field trials indicated that the movement of dissolved inorganic P through Wharekohe soils, after superphosphate application, appeared to be substantial. Inorganic P added to the soil from sources such as living pasture, litter and dung are expected to undergo the same the fate. Some of the P which moved through the Wharekohe soils in the above experiments would have been freshly applied fertiliser P, while some may have been derived from the store of accumulated soil P displaced by the freshly applied P.

In most other New Zealand soils, P movement is not large enough to warrant concerns from an agronomic point of view, although they are still considered to have considerable impact environmentally (Gregg et al., 1993). However, in the Wharekohe soils and other New Zealand podzols, losses of P were so high that, not only may the lost P play a role in the eutrophication of water bodies, but the losses of P in soil water reduces the potential effectiveness of the applied P, representing a significant economic loss to the producer.

5.5.1 Comparison of the P Concentration in Leachate from the Intact Soil Core and Soil Solution Collected in the Suction Cups

Phosphorus concentrations were higher in the leachate collected from the intact cores in the glasshouse study (up to 45.6 μ g/ml) than in the soil solution collected in the suction cups in the field study (up to 18.65 μ g/ml). This difference may be due to

differences in soil moisture at the time of P application. The amount of simulated rainfall applied to the intact soil cores in the days prior to leachate collection was lower than the rainfall recorded in the days prior to the collection of soil solution from suction cups in the field study.

Suction cups have been found to provide a better estimate of the stagnant soil solution, while field lysimeters provide a better estimate of mobile solution in soils which exhibit preferential flow (Magid, 1991). In Magid's study, the solutions collected by the field lysimeters contained 4.6 times more inorganic P and 2 times more organic P on average than the suction cup solutions in the field. The removal of the pan influence in the present glasshouse trial would have initiated greater preferential flow, than occurs in the field, resulting in the higher P concentrations observed in the glasshouse trial. The rapid movement of soil water from the soil surface, where P concentrations are high, through macropores reduces soil contact with solution P and hence, opportunities for P retention. At the time of the present field study, movement of soil water in the Wharekohe soil was expected to be very slow, due to poor drainage. Therefore suction cups may provide a better indication of the concentration of P moving through the soil subsurface than the leachate collected in the glasshouse study (where flow rates were artificially increased) or in the suction cups in Magid's study of a free draining soil.

5.5.2 Effect of Pasture age and P Saturation on P Losses

New Zealand podzols generally have very low anion storage capacities. The application of fertiliser P fills the available P sorption sites so that, with time under developed pasture, the soil P content approaches a maximum P storage capacity and P saturation (Chapter 3). Both overseas (Logan and McLean, 1973; Adriano et al., 1975; van Riemsdijk et al., 1987; Lefroy et al., 1995) and New Zealand (Doak, 1942; McAuliffe et al., 1979) studies have demonstrated that P moves through soil profiles once P saturation has occurred). Lefroy et al. (1995) demonstrated that ³²P movement through repacked cores was increased in a gley podzol in contrast to no P movement recorded for a red earth (which had a considerable higher capacity to sorb P) where the soils had received previous fertiliser P applications.

Even in coarse textured podzols, P leaching is very much dependent on the soils ability to retain P. In a laboratory study using the Te Kopuru podzol collected from six dairy farms, the amount of applied P leached through columns of sieved soil, which had been sampled to 3 cm, after the application of 400 mm of simulated rainfall over 4 weeks, varied from <1% to 36% of the applied P (Hogg and Cooper, 1964). The amount of P leached was indirectly proportional to the P retention ability of each soil sample. Less than 1% of applied P was lost from the soil with the highest anion storage capacity, 47%, while 36% of the applied P was lost from the soil with an anion storage capacity of 0%.

It was expected that the amount of P leached would be greater in the older developed Wharekohe site which has reached saturation than in the younger 10 year old site. No significant effect of pasture age on P movement could be detected in the glasshouse experiment in the present study for the two pasture sites examined. The Wharekohe silt loam was shown to be close to P saturation in the top 7.5 cm by 11 years under developed pasture (Chapter 3). The rate of applied P in the leaching experiment was most likely too high to detect the small differences in the ability of the soils to retain added P (reported in chapter 6). In addition, P loss via surface runoff may have been a more important component of soil loss than subsurface runoff losses in the field. The P movement field trial results were inconclusive in relation to the effect of pasture age as explained in 5.4.2.2.

Results from a catchment study in Northland on podzolised yellow brown earths and Wharekohe soils (McColl et al., 1975; McColl, 1978) supports low P loss from freshly developed pastures on these soils. These losses which were very low included both surface and subsurface runoff losses. Only 1.44% and 0.55% of the superphosphate (applied at 48 kg P/ha/yr) was lost from the smallest catchment after the first and second applications respectively, and negligible losses were reported for the larger catchments. Phosphorus losses from the whole basin were lower during the first 2.5 years from development than in some natural and undisturbed catchments. Much of the P lost from the smallest catchment could be accounted for by the direct application of fertiliser P to the waterways, which only contained water

in the months with high rainfall. The soils in the catchment study would not have reached P saturation and hence P losses were negligible. Losses of P from this catchment would be expected to be considerably higher once the soils become saturated with P after continued fertiliser P application.

5.5.3 Effect of Waterlogging on P Loss

Waterlogging is a soil forming process which can eventually lead to lower anion storage capacities. Hogg and Cooper (1964) attributed differences in the P sorption capacity recorded between the Te Kopuru podzols in their laboratory P leaching study to the varying degree of waterlogging experienced at the soil collection sites.

In addition, P leaching has been shown to increase where soils become water logged (Hingston, 1959). Waterlogging a previously dry soil results in a decrease in the anion storage capacity and hence an increase in water soluble P as a) the increase in pH bought about by the reduction of soil compounds leads to the hydrolysis of Fe (III) and AI phosphates, and the release of P held by anion exchange on clay and hydrous oxides of Fe (III) and AI, and b) Fe(III) is reduced to Fe(II) releasing sorbed and chemically bonded P (Ponnamperuma, 1972; Gotoh and Patrick, 1974; Khalid et al., 1977; Kirk et al., 1990).

Wharekohe soils are naturally poorly drained due to the presence of both the silica pan (E horizon) found within 30 cm of the soil surface, and a poorly structured topsoil. Waterlogging will have contributed to the low anion storage capacities recorded for these soils. Prolonged waterlogging in winter could result in the above mentioned processes further reducing the already low ability of the soil to retain P while the soil is saturated, resulting in the release of P into the soil solution from which it would be prone to loss in runoff waters. Although the soil cores in the glasshouse study were kept well watered, they would not have been as waterlogged as in the field in winter and hence, P losses may not have been so great.

Most New Zealand podzols are prone to waterlogging and hence P losses are expected to be enhanced by the reduction of soil compounds including Fe in winter.

5.5.4 Loss of P in Subsurface and Surface Runoff

As already mentioned, the relative contribution of subsurface and surface flow to P losses depends on both the concentrations of P and the volume of water in each component of runoff. Poor drainage and the relatively flat to rolling areas on which the Wharekohe soils have developed results in waterlogging and most likely very slow lateral movement down slope (M. Richardson, pers. comm.). Hence, surface runoff may contribute a greater portion of P loss in Wharekohe soils in comparison to other soils. Losses of P via surface runoff from Wharekohe soils would be expected to be far higher than the 5.63 kg P/ha/yr reported for a Tokomaru silt loam (Sharpley and Syers, 1979a) as the Wharekohe soils have lower anion storage capacities, receive a higher rainfall, have low surface infiltration rates, are more waterlogged, and are more prone to pugging leading to surface sealing and higher sediment losses. Concentrations of DIP in surface runoff collected 6 months after the application of 51-56 kg RPR in 1991 on the Kaikohe Station during this research project were high, ranging from 0.24 to 0.54 µg/ml during heavy rainfall. In contrast, concentrations of applied P in surface runoff from a Maimai podzol under high rainfall conditions 6 months after the application of 42 kg of P as superphosphate were low, <0.1 µg/ml (only 6% of applied P had been lost in runoff to 5 months) (Lee et al., 1979). However, the lower than expected P loss was attributed to a higher anion storage capacity (39%) at the trial site than is normal (5%) for this podzol.

In contrast to the findings of McAuliffe et al. (1979), surface applied P did not appear to penetrate very deeply into the soil in the present field study. Although the low DIP concentrations could be explained by the removal of DIP from the solution by soil P retention at depth (5.4.2.1), it is likely that little downward movement of water occurred at either site. The Wharekohe soil was already saturated with water at the commencement of this field study and consequently surface runoff was likely to be high for the trials duration. A similar pattern of soil water movement and P loss exists on duplex soils where 10-20 cm of sand overlies an impermeable clay horizon, in Western Australia. Surface runoff contributes 75% of the P lost from shallow duplex soils, as lateral subsurface drainage is slow and approximately 80% of the drainage is surface runoff (Ruprecht and George, 1993). The relative contribution of surface and subsurface flow to P losses in the duplex soils changes with position on the slope. Lateral flow is more important up-slope and mid-slope, whereas down slope, overland flow becomes more important as the soils are more saturated. Position on a slope is likely to effect runoff from Wharekohe podzols in the same way and may have influenced the results in the present field trial, although it was not specifically studied.

5.5.5 Loss of Particulate and Dissolved P

Losses of total P in subsurface runoff would be underestimated in this study as particulate P was not measured. Subsurface runoff is dominated by dissolved P but can still contain significant quantities of particulate P (Sharpley and Syers, 1979a&b).

Eroded soil is usually richer in P than non eroded soil due to the selective removal of finer particles which have a greater ability to sorb P (Sharpley, 1980). However, Wharekohe soils are high in fine siliceous material which are prone to movement but do not have a great ability to sorb P. Particulate P is not expected to play as large a role in P losses from Wharekohe soils compared to other soils, although much P is still likely to be lost as PP in surface runoff. TDP (mostly as DIP) is likely to be the more important mechanism for P losses from Wharekohe podzols in both subsurface and surface where soluble P fertilisers are applied.

5.5.6 Predicting Runoff P Losses from Soil P Tests

Loadings of dissolved inorganic P in surface runoff waters have not only been found to be closely related to P storage capacity (Hogg and Cooper, 1964), but also to various measures of soil P status: 0.1 M NaCl extractable P (Sharpley et al., 1977, 1978), Olsen P (Heckrath et al., 1995; Greenhill et al., 1983), water extractable P (Romkens and Nelson, 1974; Sharpley et al., 1977, 1978, 1982), Bray-I P (Olness et al., 1975; Romkens and Nelson, 1974; Schreiber, 1988; Sharpley et al., 1985), Mehlich-3 P (Sharpley, 1995), iron oxide resin strip extractable P (Weaver et al., 1988; Sharpley, 1995), total inorganic P (Weaver et al., 1988) and total P (Greenhill et al., 1983; Sharpley et al., 1985). The amount and concentration of P in surface runoff is well correlated to the P status of surface soil, while P in subsurface runoff is well correlated to P status at depth (Sharpley et al., 1977; Hanway and Laflan, 1974).

No soil P status data was collected in the present studies at the time of soil core or soil water collection. However, comparison of various P fractions extracted from the soils sampled in the chronosequence study (Chapters 3 and 4) revealed that the differences in P lost between the unfertilised moderately leached yellow brown earth, Aponga clay, and the Wharekohe soils in the glasshouse study was better correlated with differences in the easily extractable NH₄Cl Pi fraction than any other fraction or Olsen P. Thirty six times more NH₄Cl Pi was extracted from the top 7.5 cm of the two oldest Wharekohe silt loam areas than from the Aponga clay, while 33 times more applied P was leached from the oldest Wharekohe silt loam cores compared to the Aponga clay cores. Hence, NH₄Cl extractable Pi is likely to provide a better indication of potential runoff P losses than many other soil tests, as it extracts P which is in solution and very weakly held in the soil, and therefore prone to loss in runoff water.

5.5.7 Minimising P Losses

Clearly it is very important to minimise P losses from Wharekohe podzols to reduce losses of P to the wider environment and the uneconomic use of P by the farmer.

Effective measures to reduce losses of P in runoff waters from pastures include the application of a small amount of soluble P more frequently, the application of slowly soluble P fertilisers (Weaver et al., 1988), the application of P at levels which meet plant requirements but do not result in surplus P (Weaver and Prout, 1993; Yeates, 1993), drainage to reduce surface runoff (where surface runoff contributes the greater amount of P to runoff P losses), riparian zones and buffer strips (Smith 1989; Chambers et al., 1993; Weaver and Prout, 1993), impoundments or small

reservoirs (Weaver and Prout, 1993) and the addition of soil amendments such as the red mud waste (derived from the production of alumina from bauxite) to increase P adsorption (Ho et al., 1989; Vlahos et al., 1989, Summers et al., 1993; Scheffer et al., 1986; Summers et al., 1996)

Modifying fertiliser practices would most likely have the largest impact and be the most cost effective means of reducing P losses on Wharekohe soils. On these soils farmers are currently applying P at rates surplus to plant requirements and, as little P accumulates in the soil (Chapter 3),much of the applied P is being lost in runoff water. Phosphorus is usually applied as one autumn dressing on sheep and beef farms. At this time the soil is dry enough for spreading and the application time takes advantage of the flush of autumn growth with the first seasonal rains while the ground is still warm. Alternatively, P is applied in split dressings (in autumn and spring), which is the more common practice on dairy farms. The application of a large amount of P just before winter most likely leads to large losses of P in winter runoff, while the application of P to largely saturated soil in early spring could lead to large losses of applied P in surface runoff.

Applying smaller quantities of soluble P more frequently may help to meet plant demands while avoiding such large losses of applied P. Alternatively the use of less soluble P fertilisers may achieve the same purpose, meeting plant requirements through slow dissolution but restricting the amount of soluble P available for leaching or loss as dissolved P in surface runoff. Slowly soluble P fertilisers have been found to reduce the quantity of P leached through sandy soils and New Zealand podzols (Ozanne et al., 1961; Hogg and Cooper, 1964; Gillman, 1973; McSweeney and Muller, 1979). Of the 30 kg of concentrated superphosphate applied to repacked cores of Addison gley podzol, 36% had leached from the cores in 21 weeks. In contrast, none of the Chatham Rise phosphorite or Reno Hypophosphate (proprietary granulated Gafsa phosphate rock from North Africa) and only 3% of the superphosphate/ Calciphos mix (18% Calciphos added to superphosphate at den cut) had been leached (McSweeney and Muller, 1979). Phosphorus losses by leaching from repacked cores of Te Kopuru sandy loam were much lower where

basic slag (P lost 6%), serpentine super (P lost 5%) or Gafsa PR (P lost 0%), rather than superphosphate (P lost 15%), were applied (Hogg and Cooper, 1964).

While the use of slowly soluble P may reduce P losses dramatically in the short term, reductions in P losses may not be so marked in the long term if P application in these form exceeds plant requirements. Weaver et al. (1988) found in a laboratory experiment that, while superphosphate treated cores lost more P in initial leaching cycles (one cycle representing one years rainfall), losses from coastal superphosphate were greater in the 4th to 7th leaching cycles because the superphosphate had already been leached. The total amount of P leached from the coastal superphosphate treated laboratory cores never equalled the amount leached form the superphosphate treated cores. However, continual annual application of slowly soluble P in the field could result in the annual amount of less soluble P becoming available for plants and leaching, through slow dissolution, eventually being equal to the amount applied annually as soluble P. Therefore, P application at rates which do not exceed plant requirements would be more important in reducing P losses than the form of applied P. Less soluble P fertilisers may still reduce P losses in the field, as the P released by slow dissolution over the year may be taken up by plants, in comparison to a once a year large application of soluble P which is prone to leaching before being required for plant uptake.

The effectiveness of less soluble P in comparison to soluble P in restricting P losses from Wharekohe soils may depend on the relative role of surface and subsurface runoff. While the application of P as less soluble dicalcium phosphate reduced DIP in surface runoff compared to superphosphate in plot trials on Tokomaru silt loam, losses as PP were much higher as the less soluble fertiliser particles were in the surface runoff component (Sharpley et al., 1978). A total of 7.09 kg P/ha/yr was lost in surface runoff from the dicalcium phosphate plots in comparison to 5.63 kg P/ha/yr from the superphosphate plots. Losses amounted to 11.5% and 8.8% of the dicalcium phosphate and superphosphate applied, respectively. The slowly soluble dicalcium phosphate was not expected to offer any advantage over superphosphate, as the subsurface movement of P was not a major loss on this soil. Even if surface runoff contributed the larger part of P loss from Wharekohe soils, less soluble P may

still restrict P loss in comparison to more soluble P forms, as dissolved P may dominate P loss in surface runoff where soil P retention is so low.

Results from field studies investigating the agronomic effectiveness of slowly soluble P fertilisers also support larger losses of P from soluble P fertiliser on high P leaching soils. Herbage P concentrations declined over a three year trial period on an Addison podzol to below adequate levels for pasture maintenance (0.35%) where 50 kg P/ha was applied as superphosphate or lime-reverted superphosphate (Morton and Quin, 1980). These results indicated that these P fertiliser forms were inadequate to maintain pasture production at this site, where leaching losses of P were substantial, compared to the preceding annual applications of less soluble serpentine superphosphate. Herbage P concentrations and Olsen P levels in Sechura Phosphate Rock (SPR) treated plots were equal to or higher than those recorded in triple-superphosphate (TSP) treated plots over a five year period from the second year of a field trial on an Okarito silt loam, where P leaching is likely to have occurred (Smith et al., 1990, 1991a) (although higher dry matter yields were measured under TSP than under either SPR or North Carolina Phosphate Rock (NCPR) until year 4).

Western Australian studies have found that low solubility P fertilisers are as agronomically effective as superphosphate on highly leached sands, including podzols, in contrast to the low effectiveness of RPR on other Western Australian soils (Wright, 1975; Yeates et al., 1984; Yeates et al., 1986; Bolland et al., 1995b). Even unreactive Florida phosphate rock has been found to be equally as effective as superphosphate on a high P leaching sandy podzol (Alston and Chin, 1974).

Australian studies have also found that the low solubility P fertilisers can stimulate pasture production to a greater extent than superphosphate on high P leaching sands (Yeates and Clarke, 1993; Bolland et al., 1995b). The relative response of the low solubility PAPR ("Coastal Super") has been found to vary from year to year, depending on climatic conditions (Bolland et al., 1995b). "Coastal Super" was considered to be more effective than superphosphate in wet years at stimulating plant growth while in dry years, superphosphate was considered to be the more

effective P fertiliser. However, runoff losses from RPR may still be high where RPR is applied surplus to plant requirements where particulate P losses are high and dissolved P from RPR dissolution is lost. High runoff losses of P have even been reported from an Australian sandy podzol fertilised with unreactive Florida rock (Alston and Chin, 1974). Hence, even with an RPR it is necessary to accurately calculate the P requirements to minimise P losses in runoff.

Studies are needed to investigate strategies for minimising P losses in runoff water from Wharekohe podzols. Such studies should include the determination of the relative role of surface runoff and subsurface runoff to P loss, the contribution of less soluble P fertilisers or frequent small applications of soluble fertilisers to meet plant demand but reduce losses, and the determination of the amount of P required annually to meet plant requirements but avoid application surplus to requirements. Plant P requirements and the contribution of less soluble fertilisers to reducing P losses are considered more fully in chapter 7.

5.6 CONCLUSIONS

 The leaching study indicated that substantial quantities of P can be transported in subsurface water movement through Wharekohe podzols (up to 45.6 µg/ml) in contrast to the yellow brown earth, Aponga clay (up to 1.07 µg/ml). The levels of P which move through Wharekohe podzols are so high, that it is likely that they contribute significant quantities of P to waterways creating the potential for eutrophication. Additionally the losses may represent a large economic cost to the producer.

• The large differences in P lost between the Wharekohe soils and the yellow brown earth, Aponga clay, were more closely related to the large difference in the easily extractable NH₄Cl Pi fraction (32 μg/g vs 0.9 μg/g, for the Wharekohe silt loam and Aponga clay, respectively) rather than either Olsen P (22 vs 25) or other soil P fractions.

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 Movement of dissolved P occurs mostly as DIP after the application of fertiliser P.
DIP concentrations decreased with time from P application in both the glasshouse and field trials with the amount of P leached through intact cores at each leaching event decreasing exponentially with time from fertiliser P addition.

 No difference in P movement could be detected in relation to development history in these trials. The younger site may have been close to P saturation and the rate of P application was most likely too high to detect the small differences in P retention recorded between the soils and reported in chapter 6. In addition differences in P loss via surface runoff between the two sites may have been a more important component of soil loss.

• No difference in the amount of P leached could be detected between the Wharekohe sandy loam and Wharekohe silt loam in the glasshouse trial.

• Further field studies aimed at quantifying P losses in both surface and subsurface run off, determining the effect of less soluble P fertilisers in reducing P loss and determining the optimum amount of P required for plant uptake are required if appropriate fertiliser practices are to be developed to minimise such losses.

CHAPTER 6 P RETENTION IN WHAREKOHE SOILS

6.1 INTRODUCTION

The precipitation and adsorption of P from freshly applied soluble P fertiliser will occur simultaneously in the soil following dissolution of P fertiliser and its diffusion outwards from the fertiliser granule. Precipitation reactions dominate at high P concentrations in the vicinity of the freshly applied fertiliser granules, while adsorption reactions become dominant at low P concentrations (between 0.0001 and 0.001 molar P) further from the fertiliser granule (Sample et al., 1980; Holford, 1989). Initially, only a small portion of the fertiliser P will be adsorbed in the soil compared to retention in products of precipitation reactions. However, with time, as the concentration of P in the vicinity of the P fertiliser granule slowly declines, a larger proportion of the fertiliser P will be adsorbed (Holford, 1989).

In acid weathered soils, P retention is most closely related to the presence of high surface area amorphous inorganic and organic Fe and, in particular, AI compounds (Williams et al., 1958; Saunders, 1965; Syers et al., 1971; Laverdiere and Karam, 1984; Borggaard et al., 1990; Singh and Gilkes, 1991; Gilkes and Hughes, 1994). Although P will also be sorbed on the surfaces of silicate clays, the ability of the alumino-silicates such as kaolinite and vermiculite, found in the Wharekohe soils, to retain P is very low in comparison to amorphous Fe and AI compounds (Molloy, 1988). The Wharekohe soils have extremely low Fe and AI contents and mineralogical analysis of Wharekohe silt loams from the Kaikohe Research Station revealed that they contained over 90% quartz, with small quantities of crystophilite, vermiculite and anatase (J.Whitton, pers. comm.). This explains their lower Anion Storage Capacity in comparison to other less weathered sedimentary soils. Hence, the maximum P storage capacity of Wharekohe soils will be reached sooner than in other soils.

The capacity of the Wharekohe silt loam to retain added P has been shown to decrease substantially with pasture age (Chapter 3). Initially, most of the applied P

is retained in the top soil (0-7.5 cm), but by 11 years under developed pasture, only a small proportion of applied P is retained in the top 7.5 cm as the soil appears to reach a maximum P storage capacity. As there is a limit to the soils capacity to retain P, it is likely that over time the amount of applied P required to maintain production will be reduced. P applied surplus to soil accumulation and production losses will be lost from the soil via runoff waters. Several studies have related P retention characteristics of soils to plant P requirements (Woodruff and Kamprath, 1965; Morris et al., 1992; Bolland et al., 1994) and the susceptibility of applied P to loss in soil water runoff (Sawhney, 1977; Diggle and Bell, 1984; Sharpley, 1995).

The ability of a soil to retain added P over a range of P concentrations in solution (known as "P sorption isotherms" in the literature) can be used to illustrate differences in the P storage behaviour of different soils. "Phosphorus sorption isotherms" provide a useful tool for investigating, under controlled conditions, the P retention characteristics of the Wharekohe podzols.

Although studies of the nature presented in this chapter are often termed "P sorption isotherms" in the literature, the term is inappropriate for the description of the relationship between solution P concentration and the amount of P sorbed. Firstly, the term has been adopted from surface chemistry where it is used to describe adsorption that depends only on temperature and concentration, which is clearly not the case with soils (Barrow, 1989). Secondly, P sorption may not be the only mechanism operating for the retention of added P.

At the low concentrations usually employed in studies investigating P retention over a range of P concentrations, the adsorption of P is considered to be the dominant mechanism for the retention of added P. However, in the present study, the highest P addition was in the order of 0.004 M P at which significant precipitation may also be occurring (Holford, 1989). The present study was not designed to differentiate between the mechanisms for P retention in Wharekohe soils, but rather to investigate differences in P retention between soils of different type and pasture age. The term used in this discussion of results is P retention to reflect that added P is retained in the soil by not only adsorption and absorption, but also by precipitation.

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6.2 OBJECTIVES

The objectives of this part of this PhD study were to:

i) confirm that the ability of the Wharekohe silt loam to retain added P decreases with pasture age,

and ii) investigate the effect of parent material texture and degree of weathering on P retention characteristics.

6.3 MATERIALS AND METHODS

The soils used in this study were the Wharekohe silt loam (0, 11 and 35 years under developed pasture collected in 1993), Wharekohe sandy loam and Aponga clay samples described in Chapters 3 and 4. The four replicate Wharekohe silt loam samples collected for each of the three pasture ages were bulked, taking into account the bulk density of each replicate.

Duplicate 0.9 g samples of soil were shaken with 36 ml solutions of 0.01 M CaCl₂ containing chloroform and increasing amounts of P (0, 250, 500, 1000, 5000 µg P/g soil) in 40 ml polypropylene centrifuge tubes on an end over shaker at 20°C for 3 periods (16, 40 and 136 hours). 0.03 M NaCl was also included as a background electrolyte at 40 hours. The soil solutions were then centrifuged at 9000 rpm for 10 minutes before the supernatants were filtered through 0.45 µm millepore filter papers.

Inorganic P was determined in the solutions colorimetrically by the phosphomolybdate method of Murphy and Riley (1962). The amount of P sorbed by the soil was calculated as the difference between the amount of P added to the solutions per gram of soil prior to shaking and the amount of inorganic P in the solutions per gram of soil after shaking.

pH was also measured in the supernatants, after filtering, with a glass electrode.

6.4 RESULTS AND DISCUSSION

6.4.1 Effect of Pasture Age on P Retention

The amount of added P retained by the Wharekohe soil decreased with increasing pasture age after 16 and 40 hours of shaking in 0.01 M CaCl₂, except at the highest P concentration in the samples shaken for 16 hours (Figures 6.1 a & b and 6.2). Although the differences in P retention between sites were small they were consistent across all concentrations (except the highest) and laboratory duplicate errors were negligible. Differences in P retention could not be detected in the highest final P concentrations. Caution should be taken in interpreting the results obtained at the highest added P concentration.

The release of P from the soils at 0 added P indicates that the undeveloped soil contained little releasable inorganic P and that inorganic P was more strongly retained in the soil from the 11 year old pasture than in the soil from the 35 year old pasture (Figure 6.2) despite the higher inorganic P content of the younger soil. Not surprisingly, the pattern of P release was similar to that encountered in the NH₄Cl extracts in the P fractionation study (Chapter 4).

The results from the 16 and 40 hour shaking periods support the hypothesis that the ability of the Wharekohe silt loam to retain added P declines with pasture development as the P retention sites are filled with applied P. Anion storage capacity has also been shown to decline with increasing pasture age in New Zealand yellow brown loams. During (1968) found that while P retention remained high on two sites which had been under pasture for 6 and 8 years, the P retention of similar soils with much longer histories of intensive farming and fertiliser application were medium to low. However these differences in P retention could possibly have been explained by natural variation in anion storage capacity between sites. In another yellow brown loam study investigating P retention over a range of pH levels, the amount of added P retained at low pH (pH 1.5 - 3.5) decreased with increasing P status in soil collected from 3 sites of varying farming history on New Plymouth black loam, including an undeveloped site (Saunders, 1959b). The amount of added P



b) 40 hours



c) 136 hours



→ Wh. silt 0 Yrs → Wh. silt 11 Yrs → Wh. silt 35 Yrs · · · · · Wh. sandy

Figure 6.1 Effect of increasing solution P concentration and shaking time on the retention of added P from 0.01 M $CaCl_2$ by Wharekohe silt loam developed for 0, 11 and 35 years and Wharekohe sandy loam during a) 16 hour, b) 40 hour and c) 136 hour shaking periods.



Figure 6.2 Effect of pasture age on P storage by Wharekohe silt loam at various solution P concentrations.

(436 µg/g soil) in Saunder's study was too low to detect differences in P retention between the soils at the pH range usually encountered in soils. Further evidence for a changing P retention with fertiliser P application can be found in P retention studies on a range of Australian soils (Barrow, 1984), where the retention of added P was lower when the soils had been incubated with lime and P than when they were incubated with lime alone, suggesting that some of the previously added P was occupying P retention sites and blocking them from retaining further P.

The soil from the 11 year old pasture in the present study has the potential to retain more added P than the soil from the 35 year old pasture, indicating that applied P

may continue to accumulate in topsoils which have been under pasture for up to at least 11 years. However, the greater retention of added P by the soil from the 11 year old pasture than by the soil from the older developed site was surprising given that both soils appeared to have reached a similar maximum total P content (Chapter 3 and Appendix 3.2). After 136 hours, the amount of P retained by the soil from the 11 year old pasture was even marginally higher than that retained by the undeveloped soil at final P concentrations in excess of 5 µg P/ml (Figure 6.1c). Although changes in the amount of P retained with time were small, the soil from the 11 year old pasture appeared to retain P with continued shaking beyond 40 hours at a slightly higher rate than the other Wharekohe silt loam soils (Figure 6.3). The effect of prolonged shaking time on P retention is discussed further in 6.4.1.1.

The present study investigates the retention of added inorganic P. However, organic P molecules could well be retained by similar mechanisms and are likely to compete with inorganic P for P retention sites in the field. Likewise, added inorganic P may have displaced organic P in the present study, leading to an overestimation of P retention, as organic P was not measured in the final shaking solution.

6.4.1.1 Possible Explanations for Differences in P Retention Between Developed Site

While the present study was not designed to determine the specific mechanisms (sorption or precipitation) involved in P retention, some possible mechanisms for the increase in the amount of P retained by the soil from the 11 year old pasture in the present study are described below.

The greater than expected P retention of the soil from the 11 year old pasture may be due to a combination of factors induced by the higher pH and exchangeable Ca content of the younger developed soil as a result of its more recent heavy liming history, an integral part of the development procedure for a podzol (Chapters 3 and 4). The application of lime with pasture development can affect P retention in several ways.



Figure 6.3 Influence of shaking time on the storage of added P by a) Wharekohe silt Ioam, 0 years, b) Wharekohe silt Ioam, 11 years, c) Wharekohe silt Ioam, 35 years, d) Wharekohe sandy Ioam and e) Aponga clay.

Rising pH increases the negative charge on soil surfaces reducing P sorption (Bowden et al., 1980; Uehara and Gillman, 1981; Barrow, 1984; Naidu et al., 1990a). However, rising pH in very acid soils can also increase P retention through the precipitation of exchangeable Fe and Al as Al or Fe phosphates (White and Taylor, 1977) and amorphous Al and Fe compounds capable of both sorbing P (Amarasiri and Olsen, 1973; White et al., 1976; Robarge and Corey, 1979; Haynes and Ludecke, 1981), and increasing surface charge (Rengasmy and Oades, 1978; Oades, 1979). At higher pH levels increasing the pH above 6 can lead to increased P retention through the precipitation of calcium phosphates (Naidu et al., 1990b; Condron et al., 1993).

Increases in exchangeable Ca concentration will increase P sorption as the adsorption of divalent cations leads to the charge on soil surfaces becoming less negative (Ryden and Syers, 1975; Barrow and Shaw, 1979a; Barrow et al., 1980; Stoop, 1983; Curtin et al., 1992). Calcium, in particular, stimulates P sorption on oxide surfaces (Helyar et al., 1976; Barrow et al., 1980). Increased P sorption where Ca is the dominant exchangeable cation is supported by the higher P retention recorded when the soils in the present study were shaken with CaCl₂ in contrast to NaCl of equivalent ionic strength (Figure 6.4). The greater pH recorded in the NaCl shaking solutions (Figure 6.5) will also have contributed to reduced P sorption. Increased exchangeable Ca also increases the precipitation of calcium phosphates (White and Taylor, 1977; Barrow et al., 1980; Sanchez and Uehara, 1980; Naidu et al., 1990b) and discourages the dissolution of existing calcium phosphate products at high pH (Mackay et al., 1986).

An increase in the ionic strength of the soil solution, induced by liming, may also lead to increased P sorption (Ryden and Syers, 1975; Helyar et ., 1976).

The effects of liming on P retention in the soil are usually small and dependent on the relative roles of each of the above processes and the measuring method employed. Liming of acid soils has been shown to both increase (Fox et al., 1974; Haynes, 1983; Holford, 1983; Haynes and Swift, 1985) and decrease (Lopez-Hernandez and Burnham, 1974; Friesen et al., 1980; Smyth and Sanchez, 1980; Haynes, 1983; Holford et al., 1994) the retention of P. Much of this variability in

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Figure 6.4 Effect of cation species on the storage of added P by a) Wharekohe silt Ioam, 0 years, b) Wharekohe silt Ioam, 11 years, c) Wharekohe silt Ioam, 35 years, d) Wharekohe sandy Ioam and e) Aponga clay. results has been attributed to the use of air dried soil compared to field moist soils (Haynes, 1982).

Liming of soils followed by air drying has been shown to decrease P retention in contrast to the increase in P retention encountered when field moist soils were used to investigate P retention (Haynes, 1983). This difference was attributed to the crystallisation, upon drying, of the amorphous-Al polymers which had formed in the moist soil upon liming as gibbsite, and hence a reduction in P sorptive surface area (Oades, 1979; Sims and Ellis, 1981; McLaughlin et al., 1981; Haynes, 1983). On the other hand, Baskaran et al. (1994) found an increase in P retention upon air drying in a yellow brown loam and yellow grey earth collected from undeveloped and non-limed pasture, respectively. In the present study, the retention of P in both the soils collected from under developed pasture, which had received lime, was lower than that in the undeveloped soil. Reduced P sorbing surface area due to crystallisation of amorphous Al compounds upon air drying is unlikely to have had much impact in the present study due to the extremely low Al content of the Wharekohe soil.

The precipitation of AI and Fe compounds with increasing pH will have contributed to increased P sorption when the soils were limed during pasture development, as the pH of the undeveloped Wharekohe soil is very low (pH 4.25).

Some of the possible increase in P retention upon liming with pasture development will have been offset by the retention of applied P over the years in both of the developed sites. The fractionation study revealed that the effect of the more recent heavy liming history of the 11 year old sites was the greater accumulation of calcium phosphates rather than any increase in sorbed P compared to the 35 year old sites. The lack of difference in sorbed P between the two developed sites indicates that differences in exchangeable Ca (which decreases negative charge) may not have had a large impact on P sorption or have been offset by the high pH (which decreases negative charge) in the field. The pH of an 11 year old pasture had exceeded 6 in recent years encouraging the precipitation of calcium phosphates and discouraging the dissolution of fertiliser P and initial calcium reaction products.

However, in the present P retention study, the pH of the shaking solution did not rise above 6 where P was added (Figure 6.5). Despite the use of CaCl₂ as the background electrolyte, increased P sorption, due to decreasing negative charge on soil surfaces (induced by greater exchangeable Ca adsorption), may have played a larger role than precipitation in the higher P retention recorded in the soil sampled from the 11 compared to the 35 year old pasture. Barrow (1984) found that the use of 0.01 M CaCl₂ overwhelmed differences in P retention which could have been attributed to Ca status differences between the soil treatments in his study. This did not appear to be the case in the present study where exchangeable Ca levels were much higher than those reported in Barrow's study.

Greater ionic strength in the shaking solution of the developed soils may also have increased P sorption and some precipitation of calcium phosphates may still have occurred. Whichever of the liming effects induced the higher P retention in the soil from the 11 year old pasture, they had a greater effect on P retention than the effect of the higher pH which would have increased negative charge and lowered P sorption.

The increased P retention at higher added P concentrations encountered in the soil from the 11 year old pasture after 136 hours is most likely a function of the longer shaking time combined with the effects of the higher pH of the shaking solution and exchangeable Ca content of the soil. Prolonged shaking can lead to the breakdown of soil particles exposing a greater surface area for P sorption (Barrow and Shaw, 1979b). The higher exchangeable Ca content of the soil from the 11 year old pasture may have resulted in greater exchangeable Ca adsorption on the freshly exposed surfaces leading to a decrease in negative surface charge. Hence, the increase in P retained with prolonged shaking was greater than in the other soils. For the sorption of added P to have increased, the decreasing negative charge induced by the exchangeable Ca adsorption must have been greater than the increasing negative charge induced by the small rise in pH with continued shaking.

The differences in P retention measured between the soils of different pastoral age in the present study were not reflected in the results from the laboratory leaching study, reported in chapter 5. The amounts of P leached through the intact soil cores



Figure 6.5 Effect of added P, pasture age and soil type on the final pH of the shaking solution in a) CaCl2 shaken for 16 hours, b) CaCl2 shaken for 40 hours, c) CaCl2 shaken for 136 hours, and d) NaCl shaken for 40 hours.

collected from 10 and 32 year old pasture were similar. The high concentration of applied P in the leaching study may have prevented the detection of the small measured differences in P retention between the Wharekohe silt loam soils of different pasture age. Alternatively, the added P retained by the developed soils in the present P retention study may be retained in a form susceptible to loss under leaching conditions.. These factors may also have accounted for the lack of an expected difference in the amount of P leached between the Wharekohe silt and sandy loam despite large measured differences in P retention between the two soils and reported in 6.4.2.

6.4.1.2 Implications of Decreasing P Retention with Pasture Age on Modelling P Requirements

Changing P retention, with pasture development, has important ramifications for modelling P fertiliser requirements, from the points of view of meeting plant P requirements, using applied P efficiently and minimising potential losses of P in runoff.

Decreasing P retention with increasing pasture age is not taken into account in New Zealand models (CFAS or Outlook) used to calculate P fertiliser requirements. Both the accumulation of P into plant unavailable compounds in the soil and P lost from the soil via runoff waters contribute to the soil loss parameters used in the models. The decrease in P retention in the Wharekohe soils, as they become saturated with P with increasing pasture age, results in an increasing proportion of applied P and the total soil P loss being lost via runoff water to the wider environment (Chapters 3 and 5). If the P surplus to soil P accumulation and plant requirements is washed from the soil, it is inefficient to continue applying P at a constant annual rate as pasture age increases. To reflect the decreasing P retention and to reduce the loss of applied P from the soil, the soil loss parameters used in both the CFAS and Outlook models should be reduced as the soils approach P saturation.

Phosphorus accumulation is maximised at even lower levels in the top 7.5 cm of soil following pasture development in another New Zealand podzol, Okarito silt loam
(Lee et al., 1983). Hence, reducing the soil loss parameters with increasing years pasture age and associated annual P application is also likely to be necessary on this podzol also.

In the Netherlands, an estimate of P saturation, determined as the ratio between exchangeable soil P and the P sorption maximum, is used as a factor in models used to calculate applied P fertiliser rates for free draining, low P retention soils in order to limit P loss to runoff waters (Sharpley, 1995). In non-calcareous soils, extractable soil P and P sorption maximum are determined from oxalate extractable P, AI and Fe (Sharpley, 1995). In the free draining soils in the Netherlands, a P saturation level of 25% has been identified as the critical ratio above which P application should not exceed crop removal rates.

In laboratory studies, Sharpley (1995) used a similar approach to that used in the Netherlands to relate P saturation to P lost in surface runoff from Okalahoma soils. For each soil, exchangeable soil P was measured as Mehlich-3 P and the P sorption maximum was calculated from "P sorption isotherms" using the Langmuir equation (P sorption maximum = the reciprocal of the slope of the plot of the final P concentration against final P concentration/amount of P sorbed (Olsen and Watanabe, 1957)). Currently in the United States, runoff P losses are predicted by simple soil tests for exchangeable P such as Mehlich-3 P or resin-P (Gartley and Sims, 1994). Loadings of dissolved inorganic P in surface runoff waters have also been found to be related to other measures of soil P status including Olsen P (see 5.5.6). Sharpley (1995) found that P saturation better described differences in runoff P losses than either Mehlich-3 P or Resin-P.

An investigation of historic Olsen P levels on the youngest and oldest pastures on the Kaikohe Research station (Appendix 4.3) reveals that Olsen P does not provide a good indication of potential leaching losses from the Wharekohe silt loam. Olsen P levels varied between consecutive years and there was no trend for increasing Olsen P levels with fertiliser application rates or increasing pasture age on the youngest pasture once developed. Nor was there a consistent difference between the pastures of different age despite large differences in potential runoff P losses as predicted from the chronosequence study in chapter 3. Likewise, Olsen P did not provide a good indication of expected leaching losses between contrasting soil groups (Chapter 5). These losses were more closely related to the various chloride extracts used in the chronosequence and present P retention study (NH₄Cl, CaCl₂ and NaCl).

Total P would provide a better indication of the potential for P losses from the Wharekohe silt loam than Olsen P, but its application in a fertiliser P requirement model is restricted by variation in the maximum total P levels which would be reached with continued P application between sites and soils. The use of soil P fractions in predicting P saturation, and hence runoff P losses, is also restricted by variation in maximum P levels between sites and soils. The inclusion of a measure of P saturation in New Zealand models that predict fertiliser requirements is considered the most suitable indice of P status for improving P recommendations on low P retention soils, such as podzols.

The calculation of P saturation for use in New Zealand models from "P sorption isotherms" using the Langmuir equation is restricted by several factors. Firstly, the procedure is time consuming and a faster and cheaper method would be required. Secondly, the validity of the Langmuir equation to describe "P sorption isotherms" has been guestioned by several authors (Bowden et al., 1977; Parfitt, 1978; Sample et al., 1980; Barrow, 1989). The sorption of P changes surface charge affecting the rate of further P sorption and P retention may not necessarily be restricted to sorption reactions. It also implies an equilibrium condition rarely encountered in soil P retention studies, that adsorption is reversible (some of the P is nearly always irreversibly adsorbed), and that a single sorption mechanism steadily adsorbing P in a monolayer across the soil surface exists (obviously not the case in soils). Other authors have suggested the use of two and three term Langmuir equations to describe the different sorption regions encountered in soils (Holford et al., 1974; Rajan and Fox, 1975; Ryden et al., 1977a&b) and soil constituents (Muljadi et al., 1966) over a wide final P concentration range to overcome the last problem. However, these are still not a suitable means for determining an absolute P sorption maximum or P storage capacity for a soil.

An absolute measure of P storage capacity is not necessarily required to predict P runoff losses. A more simple extraction method may result in an arbitrary measure of P storage capacity which can then be calibrated for the prediction of runoff P losses from at risk soil groups, such as the approach used in the Netherlands where 3 elements, P, Al and Fe, are measured from a single oxalate extraction procedure and used to estimate the P storage maximum and P saturation.

Phosphorus retention is closely related to oxalate extractable AI in acid soils including Canadian podzolic soils (Laverdiere and Karam, 1984) and New Zealand podzols (Saunders, 1965), and to the amount of aluminium and iron oxyhydroxides on the surface of quartz grains in heavily weathered Australian sands, including a podzol, which were prone to leaching (Diggle and Bell, 1984). Therefore, the oxalate extraction which extracts amorphous Fe and AI and the P retained by these Fe and AI compounds could also be used to estimate P saturation in New Zealand soils prone to P losses in runoff waters. When determining the degree of P saturation in podzols, it is important that oxalate extractable Po is also measured. In contrast to many other soils, Po continues to accumulate in the Wharekohe silt loam once inorganic P accumulation has ceased.

Another approach to predicting the susceptibility of a soil to P runoff losses would be the inclusion of a measure of the soils ability to retain added P. The standard anion storage capacity test (previously called the P retention test) used in New Zealand, where 5000 µg of P is shaken with 1 gram of soil, is not sensitive enough to indicate changes in P retention in low P retention soils where P saturation is most likely to be encountered. The use of a lower level of added P to measure P retention, such as the P Retention Index (PRI) used by the Australians (200 µg P/g soil) (Bolland et al., 1994), may be a more suitable measure as P retention from a low added P solution concentration will change with pasture development as soil P approaches saturation levels.

Alternatively, a simple Pasture Development Index (PDI) could be incorporated into the model based on pasture age where regular topdressing of P has occurred at levels equal to or in excess of soil P accumulation and animal production. Pasture age could be calibrated with runoff P losses. However, P saturation is likely to be site and fertiliser P history dependent and so a PDI is unlikely to be as sensitive an indicator of P saturation as that measured by an oxalate extraction. The main advantage of a PDI is that it does not require a soil test to gain an estimate of P saturation. Such an approach is employed to model the fate of P in the Wharekohe silt loam in Chapter 8.

As already mentioned, the ability of other New Zealand soils to retain applied P may also decrease with increasing pasture age and fertiliser applications. However, in contrast to podzols, applied P becomes less strongly retained and the continued application of P surplus to production requirements is likely to result in an increase in the Olsen P. Hence, a low P requirement will result. Decreasing P retention with pasture development may become increasingly important in New Zealand soils of lower P retention such as the brown grey earths, yellow grey earths, strongly leached and podzolised yellow brown earths, recent and organic soils in future years with time under developed pasture. The latter two soil groups are expected to be particularly prone to P losses in runoff waters.

Clearly, further investigations of P retention and runoff P losses in New Zealand soils would be required to relate any measure of P saturation with expected runoff P losses. Only then could appropriate P saturation levels be determined for each soil and the P saturation factor be incorporated into New Zealand models. A P saturation factor would be incorporated into the models not only to reduce the quantity of P applied as P saturation is approached, but would also indicate when the more frequent application of small quantities of soluble P fertiliser or the application of slowly soluble P fertiliser, such as RPR, would be required to reduce runoff P losses and increase P fertiliser efficiency.

The modelling of P requirements for Wharekohe podzols is discussed in more detail in chapters 7 and 8.

6.4.2 Effect of Soil Weathering and Parent Material on P Retention

The Aponga clay retained substantially more P than either of the Wharekohe soils across the final P concentration range (Figure 6.6). Such a result is not surprising given the higher Fe and Al content of the less leached yellow brown earth.

The Wharekohe sandy loam retained less P than the Wharekohe silt loam of similar pasture age (Figures 6.1 and 6.6). Both the Wharekohe soils retained substantially less P than other New Zealand soils in similar studies where 0.01 M CaCl₂ was used as the background electrolyte (Ryden and Syers, 1975; Baskaran et al., 1994). The Wharekohe silt loam, which had been under pasture for 35 years, retained approximately half the amount of P retained by a Tokomaru silt loam across a similar final concentration range. Tokomaru soils have been recorded as loosing up to 5.63 kg P/ha/yr in surface runoff (Sharpley and Syers, 1979a) and 1.2 kg P/ha/yr in accelerated subsurface runoff (Turner et al., 1979). The much lower retention of added P by the Wharekohe soils supports the potential for much higher P losses from the Wharekohe soils.

The Aponga clay, on the other hand, sorbed substantially more P than the Tokomaru silt loam (Baskaran et al., 1994) or the sedimentary subsoils in the study of Ryden and Syers (1975), but far less P than the allophane containing volcanic soils in both studies.

The finding in this study that Wharekohe soils retain only small amounts of P relates to other studies outside New Zealand. The amounts of P retained by the Wharekohe soils were similar to that retained by Australian podzolic soils of low P retention in a similar P retention study (Holford et al., 1994). The Wharekohe sandy loam in the present study retained similar quantities of P to those recorded from a range of P concentrations by the A horizon material from Queensland sands which leached substantial quantities of P from repacked soil cores (Diggle and Bell, 1984).

An indication of the P retention figures which would be expected from the standard New Zealand anion storage capacity test can be obtained from the percentage of



Figure 6.6 Effect of increasing solution P concentration on the storage of added P from 0.01 M CaCl2 by Wharekohe silt loam, Wharekohe sandy loam and Aponga clay during a) 16 hour, b) 40 hour and c) 136 hour shaking periods.

added P retained by the soil at 5000 µg P/g soil. 4.2%, 5.0%, 4.3% of the added P was retained by the undeveloped, 11 year old and 35 year old Wharekohe silt loam soils, respectively, and 1.3% and 28.6% by the Wharekohe sandy loam and Aponga clay in the present study confirming the extremely low P retention of the Wharekohe soils, in particular the sandy loam. These values are likely to differ from those which would be obtained from the standard Anion Storage Capacity test. The standard Anion Storage Capacity test involves the shaking of soil samples at a 1:5 soil:solution ratio in a background solution of NaOAc-HAc buffered at pH 4.6 for 24 hours (Saunders, 1965). A higher retention of added P is expected in the presence of CaCl₂ whereas the higher pH of the shaking solutions in the present study would have led to increased negative charge on soil surfaces reducing P sorption. The higher solution to soil ratio employed in the present study would have resulted in less soil breakdown lowering the amount of P retained in comparison to the 5:1 ratio employed by the standard Anion Storage Capacity test. Soil breakdown has been shown to be the major factor influencing differences in the amounts of P sorbed by soils in different solution to soil ratios (Barrow and Shaw, 1979b).

Phosphorus was only released at 0 µg added P/g soil from the Wharekohe silt loam. In contrast, P was being released at up to 500 µg added P/g soil in the Wharekohe sandy loam after 16 hours of shaking and at up to 1000 µg P/g soil after 40 and 136 hours. The fact that P was released from the Wharekohe sandy loam at all rates of added P in the NaCl solutions (Figure 6.3) illustrates just how weakly P is held by the sandy loam.

These P retention results would seem to indicate that P would be more prone to leaching from the sandy loam than from the silt loam. However, although the leaching column results presented in chapter 5 reflected the large difference in the P storage capacity of the Aponga clay in comparison to the Wharekohe soils, substantial amounts of P could be leached from intact soil cores of both Wharekohe soils with little difference in the amounts leached between soil types. At such a large number of years from initial pasture development, and consequently high level of P saturation, both soils were expected to retain little further added P.

Factors which may have influenced the differences in measured P retention between the two Wharekohe soils include i) a larger surface area in the Wharekohe silt loam leading to greater P sorption in the artificial conditions of the present study, ii) a lower pH in the Wharekohe silt loam leading to a smaller negative charge and hence greater P sorption and iii) higher exchangeable Ca in the Wharekohe sandy loam which should have resulted in higher P sorption as Ca was sorbed onto new surfaces freshly exposed by shaking. In particular, the use of considerable RPR on the Wharekohe silt loam soils in recent years has most likely reduced the amount of easily released P in comparison to the sandy loam where P was continually applied as soluble superphosphate and monocalcium phosphate.

6.5 CONCLUSIONS

• The ability of the Wharekohe silt loam to retain added fertiliser P declines with pasture development as the P retention sites become filled with applied P. The greater retention of added P by the soil under the 11 year old pasture was surprising given that both developed soils appeared to have reached the same maximum total P content. This effect was attributed to the more recent heavy liming history of the youngest developed sites.

 Changing P retention with pasture development has important ramifications for modelling P fertiliser requirements in relation to the quantity required and effects on water quality. It was suggested that a P saturation factor, as used overseas, could be included in New Zealand P recommendation models to reduce P application to levels which meet plant requirements but limit losses in soil water as the ability of the soil to retain added P diminishes with increasing pasture age and P application.

 Further research is required to relate any measure of P saturation to expected runoff P losses in order to determine appropriate P saturation levels for use in models to restrict P losses from at risk soil groups such as podzols, recent gley soils and organic soils.

• A P saturation factor could be incorporated into the P fertiliser requirement models, not only to reduce the quantity of P applied as P saturation is approached,

but also to indicate when the more frequent application of small quantities of soluble P fertiliser or the application of slowly soluble P fertiliser, such as RPR, would be required to reduce runoff P losses and increase P fertiliser efficiency.

• The Aponga clay, with its higher Fe and Al content, retained substantially more P than both Wharekohe soils.

• The Wharekohe silt loam retained more P than the Wharekohe sandy loam which released P to the shaking solution at quite high rates of added P, especially when the background electrolyte was NaCI. The use of RPR on the Wharekohe silt loam in comparison to the soluble P applied to the sandy loam may have led to the release of a higher amount of P to the shaking solutions from the latter.

• The far greater P retention recorded in the Aponga clay in comparison to the Wharekohe soils was reflected by the substantially higher quantity of P leached from the latter and recorded in chapter 5. However, the smaller differences in P retention between the Wharekohe silt loams of different pasture age and the Wharekohe sandy loam were not reflected in differences in P leaching in the study presented in chapter 5.

CHAPTER 7

QUANTIFYING THE SLF FOR WHAREKOHE SOILS

7.1 INTRODUCTION

Olsen P levels have been found to fall on some Northland paddocks containing Wharekohe podzol soils, despite annual P inputs being higher than the estimated maintenance rates calculated by the CFAS model (Chapter 2). In contrast, Olsen P levels increased on at least one adjacent paddock containing volcanic soil. It was concluded that the SLF (0.4) for the podzol used in the CFAS model underestimates the soil P loss on the highly-weathered, low P retention, Wharekohe podzols.

The maintenance P rates for any level of pasture production, calculated by the CFAS model, are sensitive to change in the SLF. For example, a change in the SLF from 0.25 to 0.4 would result in a change in the calculated P requirement to maintain 15.6 stock units, on the Kaikohe Research station, from 16 to 21 kg P/ha, a 32% increase. The use of an SLF which is too low for a site can lead to a loss in production, while overestimating the soil loss parameter, and consequently the P requirement, is likely to lead to large losses of applied P in soil water from the low P retention Wharekohe soils. From both an economic and environmental view point, it is important that the SLF can reliably predict potential soil P losses on the Wharekohe podzols.

Soil P is lost from the cycling P pool as P accumulates in the root zone in non-labile forms (such as strongly adsorbed and absorbed P, Fe-, Al- and Ca-P precipitates and stable organic P compounds), or is lost from the root zone in runoff waters. Both these types of soil P loss comprise the soil loss factor in the CFAS model. As the Wharekohe topsoils are low in Fe and Al, the accumulation of strongly sorbed P and Fe- and Al-P precipitates is lower than in less weathered soils. Therefore, the component of the SLF which can be attributed to soil P accumulation (SLF_{SPA}) is expected to be lower on the podzols than on the less weathered sedimentary soils. However, the potential for runoff P losses is much higher from the podzols (chapter 5).

It has generally been assumed that P losses in runoff from New Zealand soils are small and, although they may impact on the environment, are of little on farm economic productive significance (McColl et al., 1977; Bargh, 1978; Lee et al., 1979; McColl and Gibson, 1979a&b; Sharpley and Syers, 1979a; Close and Woods, 1986; Sharpley and Syers, 1983; Lambert et al., 1985; Cooper and Thomsen, 1988). Situations where the soil P loss is likely to be dominated by losses of P in runoff have not been fully considered in the CFAS model. In these situations, the concept of using a constant SLF regardless of pasture age in determining P fertiliser requirements is inappropriate if non-labile soil P accumulation decreases with an increase in pasture age. As less P accumulates in non-labile forms with increasing pasture age on the Wharekohe silt loam (Chapter 4), the amount of P required to maintain a particular pasture production level decreases, provided the fertiliser P strategy can maintain an adequate available P pool over the year. Consequently, the SLF should decrease with increasing pasture age.

Much of the P applied surplus to animal losses and soil P accumulation in the root zone is lost from the soil via runoff. A small quantity is likely to accumulate in the soil profile below the rooting zone. If P is applied annually at the same maintenance rate, despite increasing pasture age and decreasing SLF_{SPA}, runoff P losses will increase with pasture age. Some runoff P loss is unavoidable under present P fertiliser application strategies. Even where the SLF and P application rates are reduced with pasture age, runoff P loss will still contribute to the SLF constituting a greater proportion of the SLF as soil P accumulation decreases.

Phosphorus has been demonstrated to be less strongly retained in the Wharekohe sandy loam compared to the Wharekohe silt loam (Chapters 4 and 6). Local farmer experience has indicated the possibility of higher P requirements to maintain similar levels of pasture production on the sandy loam podzols compared to the silt loam podzols. Consequently the SLF may differ between these two Wharekohe soils of differing parent material.

The use of slowly soluble P fertilisers have been shown to reduce runoff P losses on soils prone to P leaching (Ozanne et al., 1961; Hogg and Cooper, 1964; Gillman, 1973; McSweeney and Muller, 1979). Therefore, the SLF and consequently the

calculated P requirements may be less under P fertilisers of lower solubility, such as RPR, on the Wharekohe podzols.

The SLF values were originally determined from pasture P response trials by dividing annual soil P loss, calculated from the rate of P required to maintain a steady Olsen P level minus simulated animal P loss, by pasture P uptake at 90% of maximum yield for each trial site (Cornforth and Sinclair, 1984). The initial fertility of trial sites used to determine the SLF values does not appear to have been considered as a factor which may influence calculated SLF values. The initial soil nutrient fertility status of the trial sites used to determine SLF values for each soil group may have influenced yield response to applied P, P uptake, animal P loss and consequently the calculated SLF value.

A soil loss parameter is also used in the new Outlook model to calculate maintenance P requirements (Metherell et al., 1995). The Outlook soil loss parameter represents losses of P from the cycling P pool due to non-labile P accumulation in the root zone and losses of P from the root zone in runoff water. This soil loss parameter is a constant proportion of P which will be lost from the labile P pool for each of four categories of soil P loss (as opposed to the proportion of pasture P uptake which will be lost from the soil in the CFAS model). The Outlook soil loss parameters were also determined from pasture P response trials. The factors which effect the calculation of CFAS SLF values, and therefore P requirements, which have been described in this introduction, will also impact on the Outlook model's soil P loss parameter and consequently calculated P requirements.

7.2 OBJECTIVES

The objective of the study reported in this chapter was to determine if the SLF (0.4) assigned to podzols, in the CFAS model, was appropriate for calculating the P fertiliser requirements of the Wharekohe soils by examining the effect of:

- i) soil fertility status on the SLF for the Wharekohe silt loam.
- a difference in parent material (silt vs sandy loam) on the SLF for Wharekohe soils.

- iii) the degree of soil weathering (YBE vs Podzol) on the SLF.
- iv) fertiliser solubility (soluble P in MCP vs slowly soluble P in P RPR) on the SLF on the Wharekohe silt loam.
- v) pasture age on the SLF for the Wharekohe silt loam.

7.3 MATERIALS AND METHODS

The SLF was determined by two methods in the present study. The first method utilised four small-plot field trials to determine the SLF associated with the use of a soluble P fertiliser for Wharekohe soils varying in fertility and the physical nature of the parent material. The degree of soil weathering was assessed by comparing SLF values for the Wharekohe silt loam and the yellow brown earth, Aponga clay. The effect of the solubility of P fertiliser (MCP vs SPR) on the SLF was also investigated at one site. The second method utilised data presented in the chronosequence study (Chapters 3 and 4) to calculate the SLF_{SPA} for various periods of pasture development on the Wharekohe silt loam.

7.3.1 Small-Plot Field Trials

7.3.1.1 Trial Sites

The small-plot field trial sites were selected on a Wharekohe silt loam with a history of continuous P fertiliser application (Ft), a Wharekohe silt loam which had not received P fertiliser for the previous three and a half years (NFt), a Wharekohe sandy loam, and an Aponga clay. Sites were selected on the basis that they had good quality pasture and, with the exception of the NFt site, Olsen P levels considered optimum for maintaining pasture production at 90% of Ymax, 20-25 on Northland sedimentary soils (Edmeades et al., 1991a).

None of the sites had received any fertiliser in 1991 prior to becoming trial sites. The two Wharekohe silt loam sites were located on the Kaikohe AgResearch Station. Both had been under developed pasture for 31 years at the trials' commencement and had similar P fertiliser histories up until 1988, which included Longlife superphosphate from 1986. The Ft site was in the same paddock and adjacent to the 30 year old pasture site sampled in 1990 in the chronosequence study (Chapters 3 and 4). The NFt site was 200 m up slope in a separate paddock. The Wharekohe sandy loam site was located on Rakawahia Road, near Taheke, 9 km west of Kaikohe and the Aponga clay site was located on the Hupara Road near Moerewa, 18 km east of Kaikohe. Both of these latter sites had been under pasture for at least 30 years but their fertiliser histories were unknown.

At each field trial site a uniform area, with respect to the physical surface and pasture composition (ryegrass/white-clover) was selected. Some paspalum (<5% of total grass growth) was present on the Aponga clay site.

Some characteristics of each trial site are outlined in Table 7.1.

Table 7.1 Soil properties and slope at each small-plot field trial site, samples collected in May 1991 (pH and anion storage capacity) and in late July 1991 (Olsen P).

Site	Olsen P	рН	Anion Storage	Slope
	(MAF	in H₂0	Capacity (%)	
	Quicktest)			
Aponga clay	23	6.0	54	7°
Wharekohe sandy loam	24	5.9	7	<1°
Wharekohe silt loam NFt	18	5.7	Not Determined	9°
Wharekohe silt loam Ft	22	5.8	9	9°

7.3.1.2 Trial Design and Establishment

The field trials were designed to run for two years. Fertiliser P was applied at each trial site in late July 1991 and August 1992. Phosphorous was applied at all 4 field

sites as monocalcium phosphate (MCP), the main form of P in superphosphate, at the rates outlined below:

Site	M	CP A	ppli	catio	on r	ates	(kg	P/ha	I)
Aponga clay	0	20	30	40	50	60	80	100	
Wharekohe sandy loam	0	20	30	40	50	60	70	80	100
Wharekohe silt loam NFt	0	20	30	40	50	60	70	80	100
Wharekohe silt loam Ft	0	20	30	40	50	60	70	80	100

To investigate the effect of P solubility on the SLF, Sechura phosphate rock (SPR) was applied at 20, 40, 60, 80 and 100 kg P/ha on the Wharekohe silt loam Ft site.

Each rate of P was replicated 4 times in a randomised complete block design (Figure 7.1). Fertiliser was applied to plots 3.86 m long and 2.75 m wide at the Wharekohe silt loam NFt, Wharekohe sandy loam and Aponga clay sites and 2.42 m wide at the Wharekohe silt loam Ft site. Pasture and soil sampling was restricted to a 3 x 2 m area within each plot.

All plots received a basal fertiliser (Table 7.2) in 1991 and 1992 at both P application times. Additional dressings of potassium and sulphur, as potassium sulphate at 62.5 kg/ha, were applied in late spring and autumn in the first year and in the summer of the second year.

Animals were excluded from the field trial sites. The trial areas were mown to 3.5 cm above ground level at the commencement of the trials before fertiliser treatments were applied. Following the trials' commencement, when P fertiliser was applied in 1991, pasture growth was measured at intervals determined by growth rates. At each harvest, each plot was mowed to 3.5 cm above ground level and 46% of the pasture clippings (herbage samples and discarded clippings) removed to represent animal loss. The remaining 54% of clippings were returned to each plot. Initially the pasture clippings were returned evenly to half the plot to avoid the accidental sampling of

(1) Calculated to represent animal P loss on a dairy farm with a stocking rate of 16 SU on the basis of predicted herbage P concentrations of 0.35% and an average annual dry matter production of 9000 kg.

a) Aponga clay site

0	30	80	40	20	100	50	60
1 m buf	fer strip						
100	50	40	0	80	60	30	20
20	60	80	50	40	0	100	30
40	80	30	50	20	0	100	60

b) Wharekohe sandy loam

0	70	100	50	80	60	40	30	20
1 m buf	fer strip							
50	20	100	40	60	70	80	0	30
30	50	100	80	20	70	40	0	60
30	80	0	100	70	20	60	50	40

Figure 7.1 Layout of small-plot field trials.

(Fig 7.1)

c) Wharekohe silt loam Ft

30	0	100	50	40	100	60	40	80	80	70	20	20	60
MCP		MCP	MCP	SPR	SPR	SPR	MCP	SPR	MCP	MCP	SPR	MCP	MCP
1 m bu	fer strip												
20	80	100	80	60	50	60	0	70	100	30	20	40	40
MCP	MCP	MCP	SPR	SPR	MCP	MCP		MCP	SPR	MCP	SPR	SPR	MCP
								_					
40	100	60	60	80	100	70	30	20	50	40	20	0	80
SPR	MCP	MCP	SPR	SPR	SPR	MCP	MCP	MCP	SPR	MCP	MCP		MCP
100	80	70	40	50	100	30	20	60	20	0	60	80	40
SPR	SPR	MCP	SPR	MCP	MCP	MCP	MCP	MCP	SPR		SPR	MCP	MCP

d) Wharekohe sil loam NFt

30	20	100	60	70	80	40	0	50
1 m buff	er strip							
50	0	100	70	40	20	60	30	80

0	100	40	80	60	70	30	50	20
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0	20	50	30	70	40	100	60	80
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Fertiliser:	Rate (ha ⁻¹)
Elemental Sulphur	25 kg
Calcium sulphate	90.5 kg
Muriate of Potash	80 kg
Magnesium Sulphate	50 kg
Borax	15 kg
Zinc sulphate	10 kg
Copper sulphate	5 kg
Cobalt	100 g
Sodium molybdate	50 g

dead pasture in the following harvest. However, the pasture beneath the returned clippings grew at a greater rate in the following period, which may have been due, at least in part, to a possible P response (detected in Autumn 1992 by herbage P analysis) from P released upon the decay of the returned clippings and would probably have resulted in an underestimation of P uptake. Hence, from harvest 5, in late Autumn 1992, the clippings were returned evenly to the whole plot areas. Shading (mulch effect) and the return of other nutrients may also have influenced greater pasture growth under the returned clippings. No differences in pasture N status was detected.

7.3.1.3 Pasture Sampling and Analysis

Pasture samples were collected from each plot for the two years of the trial. There was little dead pasture present in the pasture samples taken at each harvest.

Pasture dry matter yield samples were collected with a rotary mower (to 3.5 cm above ground level) cutting a single strip 0.46 cm wide down the 3 m length of each plot, at intervals determined by pasture growth. Sub-samples were taken, weighed and dried overnight at 65°C before weighing, to assess dry matter content.

Herbage N and P analysis samples were collected at each harvest with hand shears at mower height in a strip parallel to the pasture yield samples. All samples were oven dried at 65°C and stored in airtight plastic bags. Chemical analysis was restricted to samples collected at the rates of applied P closest to the rate of P estimated to maintain a steady Olsen or Resin P test value. Herbage N and P concentrations were determined as described in 3.3.5.3.

Botanical composition samples were collected in a similar manner to herbage N and P analysis samples at five (six for the Wharekohe sandy loam site) of the pasture sampling times. Botanical composition was determined as described in 3.3.5.2.

Statistical Analysis

Pasture dry matter yield and botanical composition were subjected to an analysis of variance using Genstat to determine if effects of rate and solubility of applied P were significant. The data was transformed (angular transformation) where appropriate. The analysis of variance was adjusted for covariates (position in block) on the Wharekohe silt loam Ft site to take into account the variation in the site from one side to the other across the slope (one side was noticeably wetter in winter).

7.3.1.4 Soil Sampling and Analysis

Soil Sampling

Soil samples were collected prior to the application of fertiliser (July 1991), in early February 1992, late July 1992, early February 1993 and late July 1993. 20 soil cores (2.5 cm diameter by 7.5 cm depth) were removed from each plot and bulked at each sampling. The soil samples were then air dried and sieved to < 2 mm. Soils were stored at room temperature in airtight plastic bags until analysis at the end of 1993.

Soil Analysis

Olsen P was determined for each sample as described in 3.3.4.2. P extractable by a dual resin system (Resin P (Saggar et al., 1990a)), incorporating both cation (CER) and anion (AER) exchange resin strips, was determined for the samples collected from plots on the Wharekohe silt loam Ft site where 0 P and SPR were applied. One gram samples of soil were shaken in 30 ml of deionised water containing CER and AER strips for 16 hours. The AER strips were rinsed in deionised water and the P retained determined colorimetrically after shaking them directly in the Murphy and Riley (1962) reagent.

Statistical Analysis

At each site, the relationship between the change in Olsen P with the rate of applied MCP and SPR was determined for each sampling period using the Baysian smoothing program, Flexi (Graphs presented in Appendix 7.1). At the Wharekohe silt loam Ft site, the relationship between the change in Resin P with the rate of applied SPR was also determined for each sampling period. The dotted lines represent the 95% confidence intervals for each relationship. Flexi estimated the rate of applied P for which there was no change in Olsen P or Resin P, and the standard deviation of this estimate, for each period, at each site.

7.3.1.5 Calculation of the SLF

The soil loss factor at each site was calculated for each soil sampling period, July 91-92, Feb 92-93, July 92-93 and July 91-93 as:

SLF = <u>(Applied P - Simulated Animal P Loss</u>) = <u>Soil P Loss</u> P Uptake P Uptake

Where:

Applied P is the annual rate of applied P (kg/ha) estimated to maintain a steady Olsen P soil test for each period,

P Uptake is the amount of P (kg/ha) taken up by pasture annually at the rate of applied P closest to that which maintained a steady Olsen P during each period (%P x Dry Matter Yield),

Simulated Animal P Loss was the amount of P (kg/ha) which was lost via clipping removal annually during each period (0.46 x P Uptake).

Soil P Loss includes P lost from the cycling P pool due to the accumulation of nonlabile P in the soil and the loss of P from the rooting zone in runoff waters (kg/ha).

7.3.2 Chronosequence Trial

In order to determine the effect of pasture age on the component of the SLF which is due to the accumulation of non-labile P in the rooting zone (SLF_{SPA}), data presented in the chronosequence study (Chapter 4) was used. The SLF_{SPA} for various periods since pasture development was calculated as:.

SLF_{SPA} = <u>Unavailable P Accumulation</u> P Uptake

Where:

SLF_{SPA} is the component of the SLF which can be attributed to the accumulation of non-labile P in the rooting zone,

Unavailable P Accumulation is the annual accumulation/depletion of P in the top 7.5 cm into P fractions considered to be unavailable to plants (kg P/ha) for each period.

P Uptake is the annual P uptake (kg P/ha) for each period.

Changes in unavailable P for various periods were calculated from the soil P fractionation results obtained for the 1990 original sites, the 1993 additional sites and changes in the three year period from 1990-1993 for the original sites. Two versions of unavailable P accumulation/depletion were calculated: i) change in NaOH Pi, H_2SO_4 Pi and Residual Pi & Po (Residual Pi and Po included hot HCl Pi & Po where measured separately),

and ii) change in NaOH Pi & Po, H₂SO₄ Pi and Residual Pi & Po.

P uptake was determined as the mean annual P uptake of the developed sites over the 2 year monitoring period on all chronosequence sites for the SLF values calculated from the original 1990 and additional 1993 sites. The annual P uptake appropriate to each site was used to calculate the SLF_{SPA} over the three year period on the original sites.

7.4 RESULTS AND DISCUSSION

The primary aim of the present study was to quantify the SLF for the Wharekohe podzols and the effect of various factors listed in 7.2 on this SLF. However, in order to evaluate the SLF results, an understanding of pasture P response and the effect of applied P on the soil P test values is required.

Therefore the results are presented and discussed in 3 main sections investigating:

a) the effect of applied P on pasture growth response in the small plot field trial,

b) the effect of applied P on soil P test values in the small-plot field trial,

c) the SLF values calculated from the small-plot field trial and the SLF_{SPA} values calculated from the chronosequence study.

7.4.1 Effect of Applied P on Pasture Growth

Pasture growth was monitored in the present small plot field trial to determine P uptake at 90% of maximum yield for use in calculating the CFAS SLF. Limited pasture response to applied P on each site (Figure 7.2) prevented the accurate determination of P uptake at 90% maximum yield.

7.4.1.1 Effect of Applied MCP on Pasture Growth

The existing pool of available P was sufficient to maintain maximum pasture production in the first year on all sites (Figure 7.2, Appendix 7.2a). An exception was at the Wharekohe silt loam NFt site where in the autumn there was a significant

a) Wharekohe silt loam NFt







Figure 7.2 Effect of applied MCP on annual pasture yield for years 1 and 2 for a) Wharkekohe silt loam NFt, b) Wharekohe silt loam Ft, c) Wharekohe sandy loam and d) Aponga clay. (vertical bars=S.E.D.)

c) Wharekohe sandy loam



linear trend for increasing % clover with increasing P (P<0.05) (Appendix 7.2b) and P fertilised plots grew significantly more pasture than the controls (P< 0.01) (Appendix 7.2a). The subsequent likely higher N input to the pasture cycle on the NFt site in the following spring after the return of the autumn clippings high in clover with increasing P application, led to a significant trend for increasing % grass and an associated depression in % clover with increasing P application rate (P<0.05).

Pasture production was substantially higher in the second year of the trial on the two Wharekohe silt loam and Aponga clay sites. The higher rainfall recorded in the late spring and autumn of the second year (Appendix 7.3), in comparison to the first year, was the most likely reason for the substantially higher growth rates during those periods on the three sites (Appendix 7.2a). The initial sampling procedure, where clippings were only returned to half the area of each plot at each harvest, may also have underestimated pasture production in the first year. In contrast, pasture growth was slightly lower in the second year of the trial on the Wharekohe sandy loam. Factors which may have contributed to the lower pasture growth recorded in the second year include higher losses of nutrients from this flat, poorly drained site when the fertiliser was applied in the second wetter winter and during the extremely wet autumn at the end of the second year and prolonged waterlogging.

Total pasture dry matter production (Figure 7.2a&b)on the unfertilised plots on both the Wharekohe silt loam sites was significantly lower than the fertilised plots for the second year (Ft (P<0.05) and NFt (P<0.001)). However, there was no significant difference in dry matter yield between rates of applied P.

In the second year of the small plot field trial, the unfertilised plots on the Wharekohe silt loam NFt site grew consistently less pasture than the fertilised plots from January 1993, but the difference was only significant (P<0.01) in the two autumn harvests (Appendix 7.2a). The fertilised plots also grew more pasture than the unfertilised plots from October 1992 on the Wharekohe silt loam Ft site with differences significant in the October and April harvests (P<0.05). Reductions in pasture production, due to with-holding fertiliser P, were also highest in spring and autumn in a series of Northland field trials on a range of soil types including a podzolised yellow brown earth (P. Shannon, pers. comm.).

Due to fertiliser history, pasture had been expected to respond to higher rates of applied P (>20 kg P/ha) on the NFt site in comparison to the Ft site. While the Wharekohe silt loam NFt site had not received any P fertiliser for 3 and a half years prior to trial commencement, its Olsen P level was only slightly lower than the Ft site, 18 compared to 22, although this difference was significant (P<0.001). Dry matter yields were much lower on the NFt site for each rate of applied P (Figure 7.2a&b). Factors other than Olsen P levels, such as N deficiency and depressed legume growth, are also likely to have limited pasture growth at the NFt site, especially in the first year. At 20 kg P/ha P uptake was lower in the first year on the NFt site than on the Ft site which will increase the calculated SLF as described in 7.4.3.1.

Differences in pasture response to applied P may have become more apparent if the trial had continued beyond 2 years as the existing available P pool on the control plots became depleted. Alternatively, differences in pasture response to applied P may also have been more apparent at rates of applied P below 20 kg P/ha during the two year trial period. In the long term, both trial sites would be expected to behave similarly to fertiliser P application, as the fertility of the NFt site is raised under higher rates of applied P and the pool of available P becomes depleted on the Ft site at rates of P insufficient to maintain pasture production.

A similar pattern of pasture response to applied P, as was encountered in the present trial, was also recorded in a trial on a South Island Addison gley podzol which had been under pasture for 9 years (Morton and Quin, 1980). No significant response to applied P was detected in early stages of the first year. The lack of pasture response to applied P was attributed to the residual effect of previous P applications, as was probably occurring in the present small-plot field trial. In the second year of the South Island trial, there was a significant response to applied P, although there was no significant difference between rates. However, by the third year of the South Island trial, dry matter yield increased significantly with increasing applied P.

No response to applied P was measured on the Wharekohe sandy loam in either year (Figure 7.2c, Appendix 7.2). The existing pool of available P may have been

sufficient to maintain pasture production in the sandy loam for the first two years of the trial.

There was a significant response to applied P on the Aponga clay site in late Autumn 1993 (Appendix 7.2a). The mean dry matter production values in years 1 and 2 were lower on the unfertilised plots, with a t-test revealing that the difference between the unfertilised plots and the pooled fertilised plots was significantly different (P<0.01) in the second year (Figure 7.2d). The Olsen P levels in all treatments were above the minimum of 20 required to maintain 90% of maximum yield on sedimentary soils (Edmeades et al., 1991a) at the end of the trial. Therefore, available soil P would most likely have buffered against any pasture response to increasing P application and the trial would have had to continue for a longer period to establish the effect of increasing P application rates on pasture growth and if the degree of soil weathering effects differences in the SLF and pasture response to applied P. Limited P response has also been noted in the early years of P response trials on a range of other New Zealand soils including podzols and yellow brown earths (Sinclair et al., 1994).

Clearly the present small-plot field trials would need to have been continued beyond two years to determine P uptake corresponding to 90% of Ymax as required in the calculation of the CFAS SLF. Even in trials of longer duration than the present study, large variations in pasture response to applied P and soil P test values at individual sites, both between seasons within a year, and between years, have been reported (Saunders et al., 1987a; Bolland and Gilkes, 1992; Sinclair et al., 1994), making it difficult to relate pasture yield to Olsen P or applied P. Pooling data from trials on similar soils can help to overcome this variability so that estimates of yield parameters can be obtained for use in P fertiliser requirement models (Sinclair et al., 1994). However, pooling data is likely to be less precise in relating to certain specific sites.

7.4.1.2 Effect of P Fertiliser Solubility on Pasture Growth

Except for one harvest in year 1 (harvest 5) when the combined MCP rate treatments produced more pasture (P<0.05) growth than the combined SPR treatments (Figure 7.3, Appendix 7.2a), there was no detectable effect of P fertiliser form on pasture growth at the Wharekohe silt loam Ft site in the two years of measurement. The SPR treated plots had a higher percentage weed content in early spring 1992 (harvest 7) than the MCP plots (Appendix 7.2b). However, these effects did not persist.



Figure 7.3 Effect of fertiliser solubility on annual pasture yield for years 1 and 2 for Wharekohe silt loam Ft, adjusted for covariates (0P not included). (Vertical bars=S.E.D.).

Although RPR has also been found to be as agronomically effective as soluble P on a range of New Zealand soils under pasture (Karlovsky, 1958; Mackay et al., 1984; Gregg et al., 1988; Mackay and Wewala, 1990), several other New Zealand studies have found the initial pasture growth to be slower with RPR application, compared to soluble P, due to the slow dissolution of the former (Grigg and Crouchley, 1980; Sinclair et al., 1990b; Rajan and Watkinson, 1992). Edmeades et al (1991b) noted that the lag effect of RPR dissolution on pasture growth "may or may not be observed by the farmer, or measured in an experiment, depending on the initial P status of the site." Ledgard and Jones (1991) found that the relative response of pasture and ewe live-weights to RPR was higher at an Olsen of 11 than at an Olsen of 8 on a hill country yellow brown loam site. The initial Olsen P level of 22 on the Wharekohe silt loam Ft site was within the optimum range for pasture production and although there was a small response to added P in the second year, the high P status of the soil is most likely to have masked any response to P form.

It is also possible that differences in dry matter yield response between MCP and SPR may have been detected had rates of applied P below 20 kg P/ha been included in the small-plot field trials. Although the present trial was inconclusive with regard to pasture response to the solubility of P fertiliser on the Wharekohe silt loam, it is possible that the use of low solubility P fertiliser may reduce runoff P losses and hence soil loss parameter values as discussed further in chapters 5 and 8.

Since the pasture response to applied P was limited at each site, the calculation of P uptake at 90% Ymax was not possible. Pasture P uptake measured at the P application rate closest to that determined to maintain a constant Olsen P level was used to calculate SLF values.

Summary of section 7.4.1:

• Pasture response to applied P was limited during the 2 year trial period. The existing pool of available P appeared sufficient to maintain pasture production in the first year of the trial at all sites, except on the Wharekohe silt loam NFt site in autumn where applied P stimulated clover growth leading to a significant increase in dry mater yield. The subsequent likely higher N input to the pasture cycle under applied P stimulated grass growth in the following spring on the NFt site, depressing

clover growth. In the second year of the trials, dry matter yield on both the Wharekohe silt loam sites and Aponga clay site responded to applied P but no difference in pasture growth between the rates of applied P could be detected. There was no response to applied P on the Wharekohe sandy loam site in either of the 2 years.

 There was no sustained difference in pasture response between applied SPR and MCP on the Wharekohe silt loam Ft site. The high P status of the Ft site and limited P response may have masked any possible response to P solubility.

• As P uptake at 90% Ymax could not be accurately assessed, pasture P uptake measured at the rate of P closest to that determined to maintain a constant Olsen P level was used to calculate the SLF values for each period.

7.4.2 Effect of Applied P on Available P Soil Tests

7.4.2.1 Effect of MCP Application Rate on Maintaining Olsen P Levels

The effect of applied MCP on Olsen P levels over the two years in the small-plot field trials are presented in Figure 7.4. A marked difference in Olsen P levels were found between years 1 and 2 on the podzols. Compared to year 1, when increasing P application led to increasing Olsen P levels, Olsen P levels fell dramatically in the second year of the trial at all rates of applied P. On poorly buffered soils, such as the Wharekohe podzols, where the accumulation of P is limited and runoff P losses are large, the temporal variation would be expected to be large from year to year, compared to a well buffered soil, like the Aponga clay.

The amount of P, applied as MCP, calculated to maintain a steady Olsen for each time period are presented in Table 7.3. (The Flexi graphs used to calculate the rate of P at which the change in Olsen P or Resin P would have been 0 for each site and period are in Appendix 7.1).

a) Wharekohe silt loam NFt







Figure 7.4 Effect of applied MCP on Olsen P levels over time for a) Wharekohe silt Ioam NFt, b) Wharekohe silt Ioam Ft, c) Wharekohe sandy Ioam and d) Aponga clay. Arrows indicate P fertiliser application times.

c) Wharekohe sandy loam



Sampling Date



d) Aponga clay

The rates of MCP required to maintain a steady Olsen P on the Wharekohe soils over the two year trial period (7/91 - 7/93) were high (in excess of 80 kg P/ha) (Table 7.3). However, as previously mentioned, seasonal variability in Olsen P limits the confidence that can be associated with any conclusions, especially as a much lower rate of P (20 kg/ha) maintained Olsen P levels in the first year on both the Wharekohe silt loam sites.

Table 7.3 Rate of applied P as MCP required to maintain a constant Olsen P test at each site for each time period (standard deviations in brackets).

Rate of P Required to Maintain a Constant Olsen P Test									
(kg P/ha)									
Site	7/91 - 7/92	2/92 - 2/93	7/92 - 7/93	7/91 - 7/93					
Wharekohe sandy loam	72	79.9	ND	ND					
	(8)	(4.5)							
Aponga clay	9.4	Olsen P	64.7	34					
	(5.4)	Not Determ.	(4.3)	(1.9)					
Wharekohe silt loam NFt	21.4	24	ND	ND					
	(9)	(8)							
Wharekohe silt loam Ft	21.2	ND	ND	83					
	(3.6)			(1.8)					

ND Rate of P required to maintain a constant Olsen P test could not be determined as Olsen P levels fell at all rates of applied MCP.

As all rates of applied MCP were insufficient to maintain the Olsen P test values on the Wharekohe soils in the second year of the small plot field trial, it was not possible to calculate the rate of P corresponding to a steady Olsen P level for the Wharekohe soils for that period. On the Aponga clay, the amount of P required to maintain a steady Olsen P level also rose dramatically in the second year from 9.4 kg P/ha to 64.7 kg P/ha.

Although there was no difference in the rate of P required to maintain Olsen P levels between the two Wharekohe silt loam sites of differing P fertiliser history in the first year, it appeared that a lower rate of applied P was required to maintain the Olsen P level on the Ft site in the second year, as even 100 kg P/ha was insufficient to do so on the NFt site over the two year period.

The rate of P required to maintain a constant Olsen P level in the first year on the Wharekohe sandy loam site (72 kg P/ha) was higher than on the Wharekohe silt loam sites (21 kg P/ha), implying larger losses of P on the former. Previous studies, presented in this research study, support this finding. Phosphorus is less strongly retained in the Wharekohe sandy loam compared to the silt loam (Chapters 4 and 6).

Clearly the amount of fertiliser P required to maintain a constant Olsen P value for each period was far higher on the Wharekohe soils than on the Aponga clay, indicating lower P losses from the less weathered yellow brown earth. Large losses of applied P have been recorded from the topsoil of the Wharekohe podzols (Chapters 3 and 5). Losses of P in water runoff are presumed to account for the large difference in the rate of P required to maintain a steady Olsen P test between the Wharekohe and Aponga soils in the present study.

Assessments of the rate of P required to maintain constant Olsen P levels, on other New Zealand podzols, are limited in number and also restricted by the variability inherent in the Olsen P test and trial conduct (extent of clipping removal). Olsen P values in the Okarito podzol included in the MAF "national series" trial were extremely variable over the 6 year trial period. Olsen P levels were lower after 6 years at all rates of annually applied TSP up to 40 kg P/ha (twice calculated maintenance from the CFAS model) than the initial recorded levels (Smith et al., 1991b).

However, in contrast to the Wharekohe and Okarito podzols, only 16.5 kg P/ha appeared to be required to maintain Olsen P levels on the podzolised Hukerenui silt loam (Smith et al., 1991b). On the two less weathered Northland yellow brown earths, Whangaripo and Warkworth clays, included in the "national series" trial, 33 kg P/ha appeared to be required to maintain a constant Olsen P level (Smith et al, 1991b). These results indicate that higher rates of P may not necessarily be

required to maintain a particular Olsen P level as the degree of soil weathering increases.

Olsen P Variability

The large variability between the 1991/92 and 1992/93 years in Olsen P values would appear to limit the use of Olsen P as an appropriate indicator of soil P loss. Large temporal variability in Olsen P data between years has also been observed at many other well controlled, field trial sites where the effect of P rate on Olsen P has been monitored (Smith et al., 1990; Rowarth et al., 1991; P. Shannon et al., 1985). Environmental conditions influence the amount of P in the available soil pool at any one time by influencing reactions rates of P with the soil, runoff P losses, plant growth and microbial activity, and therefore contribute to temporal variability.

Factors which may have effected the lower Olsen P levels recorded in the second year of the present small-plot field trials include higher P runoff losses of applied P in the wetter winter and autumn of the second year (Appendix 7.3). The wetter and warmer autumn of the second year also resulted in increased pasture growth, and hence greater simulated animal P loss on the Wharekohe silt loam and Aponga clay sites. The wet winter and autumn of the second year, and the extremely dry month prior to sampling at the field trial conclusion may have influenced microbial P contents. Much of the P extractable by NaHCO₃ is likely to be derived from P due to the death of microbes in the Wharekohe soils. The proportion of total soil P found in the microbial biomass in a Wharekohe silt loam was by far the largest (11.7%) of any of the 21 soils surveyed by Perrott and Sarathchandra (1989). Consequently, Olsen P levels will be more effected by environmental factors influencing the microbial population in the Wharekohe soils than in most other soils. (Rainfall data is presented in Appendix 7.3)

The large year to year variability in Olsen P levels recorded in the present field study illustrates the necessity of multiple years of data to establish with confidence the rate of applied P at which available P will remain constant over time for determining the SLF. Calculations of soil loss parameters for use in fertiliser P requirement models by AgResearch (and MAF) staff have been restricted to trials which have run for at

least 5 years with frequent herbage P and Olsen P analysis (Metherell et al., 1995). Even so, the determination of soil loss in this way from long term trials is still complicated by the highly variable nature of the Olsen P and is therefore questionable. Rowarth et al (1992b) were unable to determine a rate of annual P addition which maintained a steady Olsen P level over a four year period in New Zealand hill country. Data from individual sites in the MAF 'National Series' trials was variable and considered of limited value in determining the change in Olsen P as a function of the rate of applied P (Roberts et al., 1994). Pooling data from similar sites enables patterns to be more clearly defined (Roberts et al., 1994), but raises doubts about the integrity of soil loss parameters determined for soil groups where trial numbers are limited.

Despite the problems with Olsen P variability, the method of determining soil loss parameters from average changes in the available P pool over a long period of time is sound, provided a 'steady state' situation exists (as in older Wharekohe podzols where soil P accumulation has ceased. The 'steady state' concept has been described in 2.6.1 and 4.4.2). It may be more appropriate, however, to determine the SLF by monitoring changes in a more comprehensive set of soil P fractions across a range of P application rates over a longer period. This would enable the identification of whether a 'steady state' exists and the rate of P required to maintain the average 'steady state' over time, and hence the appropriate SLF, so that calculated P requirements would be more likely to reflect the P required for an average year.

Variability in the Olsen P test for a farm block, where a fertiliser P application rate is recommended, may also lead to large errors in calculated P requirements. In order to help compensate for the spatial and temporal variability inherent in the Olsen P soil test, the Outlook Manual (Soil Fertility Service, AgResearch, 1996) recommends that the start Olsen P be obtained from the average of four or more samples from each block and that results then be averaged over the last two to three sampling dates where fertiliser has been regularly applied at approximately maintenance rates.

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Variation in the length of time that soils were stored is not expected to have effected the soil P test variability. Bolland and Allen (1996) could detect no change in Olsen P with storage times of up to 180 days at room temperature in Australian soils, while no change in bicarbonate extractable Colwell P could be detected in soils stored for up to 17 years (Bolland et al., 1994).

7.4.2.2 Effect of P Fertiliser Solubility on Maintaining Available Soil P Levels

Olsen P levels were lower where SPR was applied than where MCP was applied at similar rates in the first year of the present trial. Olsen P levels only increased over time where 80 and 100 kg of P/ha as SPR were applied on the Wharekohe silt loam Ft site in the first year (Figure 7.5). Consequently, the amount of P required to maintain a constant Olsen P level was greater where SPR was applied than where MCP was applied (Table 7.4).

Other studies have also found that Olsen P levels are lower where RPR has been applied compared to soluble P fertilisers at similar P application rates (Mackay et al., 1984; Saggar et al., 1992; Roberts et al., 1994). Where data from 13 sites in the MAF 'National Series' forms of phosphate fertiliser trials was pooled, Olsen P levels remained steady at the maintenance TSP application, declining at all rates below maintenance and increasing at twice maintenance over the 6 years of the trial. In contrast, Olsen P values decreased over the 6 years at all rates of applied SPR including twice maintenance (Roberts et al., 1994). Such a result is not surprising given the slow dissolution rates of the SPR in the surveyed soils (Edmeades et al., 1991b) in comparison to the highly soluble TSP.

However, at two sites in the 'National Series' which were not included in the pooled data presented by Roberts et al (1994), a South Island gley podzol (Okarito silt loam) and a recent gley soil on the West Coast of the South Island, where runoff P losses are expected to be high, the Olsen P values were similar and at times higher where SPR was applied compared to MCP at the same application rates, 10 - 40 kg P/ha/yr (Smith et al., 1991b). Where soluble P is prone to large losses in runoff,





b) SPR



Figure 7.5 Effect of P fertiliser solubility on Olsen P levels over time where a) MCP and b) SPR were applied on the Wharekohe silt loam Ft site. Arrows indicate P fertiliser application times.

 Table 7.4 Effect of fertiliser P solubility on the rate of applied P required to maintain

 a constant available P soil test for each period (standard deviations in brackets).

Rate of P Required to Maintain a Constant Soil P Test						
(kg/ha)						
Site	7/91 - 7/92	2/92 - 2/93	7/92 - 7/93	7/91 - 7/93		
Wharekohe silt loam Ft,	21.2	ND	ND	83		
MCP, Olsen P	(3.6)			(1.8)		
Wharekohe silt loam Ft,	43	55	ND	ND		
SPR, Olsen P	(13)	(11)				
Wharekohe silt loam Ft,	ND	25.3	ND	35.1		
SPR, Resin P		(4.5)		(8)		

ND Rate of P required to maintain a constant Olsen P or Resin P test could not be determined as soil P test levels fell at all rates of applied P.

RPR may 'drip feed' the available P pool so limiting P losses and leading to higher or more sustained available P levels with time following P application. This situation as appears to have occurred on the above mentioned South Island soils. Colwell bicarbonate P test values have also been found to be lower under ordinary superphosphate use than under the lower solubility coastal superphosphate applied to humic sandy podzols in Western Australia from which leaching of high solubility P fertiliser occurs (Bolland et al., 1995a).

As Wharekohe soils loose substantial quantities of P in runoff (Chapters 3 and 5), they would be expected to behave in the same way as the two South Island soils. Although Olsen P values where SPR was applied were lower than where TSP was applied in the first year of the present trial and Olsen P levels fell at all rates of both applied MCP and SPR in the second year, the fall in Olsen P was greater under MCP than under SPR applications (Figure 7.5, Appendix 7.1). Hence, runoff losses of P may influence the relative performance of MCP and SPR in maintaining Olsen P levels on the Wharekohe soils also. Relative losses of P from MCP and SPR could depend on the relative roles of surface and subsurface runoff, and dissolved and particulate P in P runoff losses (Chapter 5).

The lower Olsen P values recorded in most soils where SPR has been applied can partially be attributed to the slow release nature of the RPR in the soil leading to a reduction in available soil P relative to the same quantity of soluble P fertiliser (Perrott et al., 1992a). However, the Olsen P test also underestimates available soil P status associated with the use of RPR (Mackay et al., 1984; Saggar et al., 1992; Roberts et al., 1994). The dual Resin P test, has been found to better predict the relative pasture yield of ryegrass in a glasshouse study than the Olsen P test, which underestimated the relative yield where RPR was applied (Saggar et al., 1992). A field evaluation of soils fertilised with SPR and TSP also found that resin P was a better indicator of relative yield than Olsen P (S. Saggar pers. comm.).

In contrast to the effect of RPR application on Olsen P values in the first year (7.5b), Resin P increased at all rates of applied SPR in the first year (Figure 7.6). Some of this increase may have been due to seasonal variation, as the increase in Resin P measured on the 20 and 80 kg P/ha plots was similar to that recorded on the control plots. As was the case with Olsen P, resin P values fell at all rates of P in the second year of the trial, indicating that Resin P is also prone to spatial and temporal variability and the factors which effect these.

The amount of P applied as SPR required to maintain the same steady Resin P test was far less than the amount of P applied as MCP required to maintain a steady Olsen P on the Wharekohe silt loam Ft site over the 2 year trial period (Table 7.4).

The implications of these findings in terms of P fertiliser strategies for minimising P runoff losses are discussed in chapter 8.



Figure 7.6 Effect of applied SPR on Resin P levels over time on the Wharekohe silt loam Ft site. Arrows indicate P fertiliser application times.

Summary of section 7.4.2:

• Olsen P and Resin P soil test values displayed large year to year variability making it difficult to identify a constant available P level.

• Both the Wharekohe silt loam Ft and NFt sites required 21 kg P/ha to maintain a steady Olsen P level in the first year. Over the two year period 83 kg P/ha was required to maintain a constant Olsen P level on the Wharekohe silt loam Ft site. A higher rate of applied P, in excess of 100 kg P/ha, appeared to be required to maintain the Olsen P level on the NFt site.

• A higher rate of applied P was required to maintain the Olsen P level on the Wharekohe sandy loam (72 kg P/ha) in the first year, in comparison to the silt loam sites (21 kg P/ha) indicating greater P losses in the sandy loam.

• The amount of MCP required to maintain Olsen P levels was much higher on the Wharekohe silt loam sites (>83 kg P/ha) than on the Aponga clay site (34 kg P/ha) over the two year period, indicating greater P losses on the former.

 Olsen P levels were lower where SPR was applied after the first year. However, in the second year, Olsen P levels under SPR did not fall to the same extent as those under MCP, possibly indicating lower losses of available P in the second year where SPR was applied. As dissolution of SPR approaches application rates, the Olsen P levels could become higher than under an equivalent application of MCP on these high P loss podzols.

• The rate of applied SPR required to maintain a steady Resin P test over the two years (35.1 kg P/ha) was substantially lower than the rate of MCP required to maintain a steady Olsen P test (83 kg P/ha). It was difficult to determine if SPR would offer advantages over MCP, in terms of minimising soil p losses, in the long term due to the short duration of the trial.

The implications of the results presented in this first section are discussed in terms of the SLF values and soil P losses in 7.4.3.

7.4.3 Quantifying the SLF

Calculated SLF values for use in the CFAS model are presented in Table 7.5.

Table 7.5	Soil Loss	Factors determine	d for each sa	ampling pe	eriod at each site.
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Period	Estimated	Pasture P Uptake	Simulated Soil		SLF	
	Rate of P	(kg/ha)	Animal P	Loss		
	To maintain	(In brackets:	Loss	(kg /ha)		
	Steady	P treatment used to	(kg/ha)			
	Olsen P	estimate P Uptake)				
Wharekohe	silt Ioam Ft			In		
7/91 - 7/92	21	42.3 (20 MCP)	19.5	1.7	0.04	
7/92 - 7/93	100*	64.1 (100 MCP)	29.5	70.5	1.10	
7/91 - 7/93	83	50.4 (80 MCP)	23.2	59.8	1.19	
7/91 - 7/92	43	42.3 (40 SPR)	19.4	23.6	0.56	
7/91 - 7/93	35.1(Resin P)	49.1 (40 SPR)	22.6	12.5	0.25	
Wharekohe	silt Ioam NFt					
7/91-7/92	21	30.2 (20 MCP)	13.9	7.5	0.25	
2/92 - 2/93	24	32.3 (20 MCP)	14.9	9.1	0.28	
7/91 - 7/93	100*	46.8 (100 MCP)	21.5	78.5	1.68	
Wharekohe sandy loam						
7/91 - 7/92	72	52.7 (70 MCP)	24.2	47.8	0.91	
2/92 - 2/93	80	53.3 (80 MCP)	24.5	55.4	1.04	
7/91 - 7/93	100*	59.5 (100 MCP)	27.4	72.6	1.22	
Aponga clay						
7/91 - 7/92	9.4	33.9 (20 MCP)	15.6	-6.2	-0.18	
7/92 - 7/93	64.7	51.6 (60 MCP)	23.7	41	0.79	
7/91 - 7/93	34	41.6 (30 MCP)	19.1	14.9	0.36	

* No rate of applied P sufficient to maintain Olsen P levels, 100 kg P/ha used to calculate minimum SLF values.

The calculated SLF varied greatly between sampling periods on the Wharekohe silt loam Ft site, from 0.04 in the first year of the trial to 1.19 over the two year trial period (Table 7.5). This large difference in calculated SLF values was due to the large increase in the rate of P required to maintain a steady Olsen P level in the second year of the small plot field trial. Such a large difference in the SLF would create a range of calculated P requirements to maintain 15.6 stock units from 8.6 kg P/ha to 47.5 kg P/ha for a change in the SLF from 0.04 to 1.19, respectively. This large range of calculated P requirements illustrates the importance of reliably predicting soil P loss.

Because of the large variation in the calculated SLF in the present trial, it is difficult to determine if the SLF of 0.4 used in the CFAS model (which calculates 21 kg P/ha to maintain 15.6 SU) is inappropriate for use in the CFAS model for determining maintenance P requirements for a given level of production on the Wharekohe silt loam. Another approach where part of the SLF factor is calculated from a soil loss derived from the accumulation of P into plant unavailable P compounds, as per Rowarth et al. (1992b), is presented in 7.4.3.7.

7.4.3.1 Effect of Soil Fertility Status on the SLF

The calculated SLF values for each period were higher for the Wharekohe silt loam NFt site than for the Ft site exposed to the same climatic conditions (Table 7.5). The much higher SLF, despite similar rates of P required to maintain a constant Olsen P level, were a result of the much lower P uptake on the NFt site. The low P uptake led to lower simulated animal losses, and consequently higher soil P loss for a similar rate of P required to maintain a constant of P negative to maintain a constant Olsen P level.

Such a large difference in calculated SLF values (0.04 to 0.25 in the first year for the Ft and NFt sites, respectively) serves to illustrate how the initial fertility of a site can have a large impact on the calculated SLF. The SLF values used in the CFAS model were derived by dividing the estimated soil P loss by the P uptake corresponding to 90% of maximum yield for that soil group. In theory, if all other limiting factors associated with the initial lower fertility are overcome, the maximum yield should be similar on both Wharekohe silt loam sites and eventually the rate of P required to maintain a constant Olsen P will be similar leading to similar calculated

SLF values regardless of initial P fertility. However, trials rarely continue for long enough for this to occur and initial soil fertility is likely to impact on the calculation of the soil loss parameters even in the 6 year trials used by previous MAF and present AgResearch staff.

7.4.3.2 Effect of Parent Material on the SLF

The calculated SLF values were much higher on the Wharekohe sandy loam than either of the Wharekohe silt loam sites, 0.91 compared to 0.25 and 0.04 in the first year of the trial for the sandy and two silt loam sites, respectively (Table 7.5). This finding is consistent with observations that the Wharekohe sandy loam appears to have a higher requirement for fertiliser P than the silt loam (P. Shannon pers. Comm.) at similar stocking rates and that P is less strongly retained in the sandy loam. The higher SLF is due to the higher rate of P required to maintain a steady Olsen P level and consequently higher calculated soil losses. However, the large variability in Olsen P levels, and therefore SLF values, in the present trial reduces the confidence that can be placed in the sandy loam requiring a higher SLF to calculate P requirements than the silt loam.

7.4.3.3 Effect of Degree of Soil Weathering on the SLF

The calculated SLF values were much lower on the Aponga clay soil than the Wharekohe silt loam sites for each sampling period (Table 7.5). In the first year of the trial, the SLF was negative, implying that the provision of P from existing soil P was greater than P losses from the cycle. However, in later periods the SLF was much higher. Once again variability in the SLF between periods makes it difficult to decide upon an appropriate SLF for use in the CFAS model for the yellow brown earth. In the first year of the trial, the calculated SLF was well below 0.25 which was used in the CFAS model for this soil group, but in the second year and over the two year period, the calculated SLF was higher than 0.25.

7.4.3.4 Effect of P Fertiliser Solubility on the SLF

When the change in Olsen P level was used as an indicator of P loss, the calculated SLF was higher under SPR than MCP in the first year due to the higher rate of SPR required to maintain a steady Olsen P level (Table 7.5). However, when a change in Resin P was used as an indicator of soil loss where SPR had been applied, the calculated SLF was substantially lower (0.25) than under MCP (1.10) for the two year period (Table 7.5). Continuation of the trial beyond 6 years, by which time SPR dissolution should allow for a 199% effective P application rate, would be needed to confirm if the SLF calculated in this way would be lower under applied SPR compared to MCP.

7.4.3.5 Sensitivity of the SLF

Rate of P Required to Maintain a Steady Available Soil P Level

The large variation in the calculated SLF values between time periods was mostly due to the large variation in the rate of P required to maintain a steady available soil P rather than the much smaller variation in P uptake (and hence also simulated animal loss) between the two periods. The large temporal variability found in the Olsen and Resin P values led to a large variation in calculated soil P losses, and hence SLF values. A small error in the rate of P required to maintain a particular available soil P soil test can lead to large changes in the calculated SLF value, especially at lower SLF values (Table 7.6). For example, a 10% error in the estimation of the rate of P required to maintain a steady Olsen P value leads to a 28% change in the calculated SLF value on the Wharekohe silt loam NFt site using the first year results.

As previously mentioned in 7.4.1.2, variability in Olsen P has made it impossible to calculate soil P loss in trials of longer duration (4 years on hill country at Whatawhata (Rowarth et al., 1992b) and up to 6 years in the range of trial sites included in the "National Series" (Roberts et al., 1994)).

Period	Rate of P To Maintain Steady Olsen	P Uptake (kg/ha)	SLF	Effect of changing P uptake on SLF		Effect of incorrect estimation of The rate of P required to maintain a steady Olsen combined with incorrect estimation of P uptake.					
	(kg/ha)			- 10% +10%		-10% Rate P		+10% Rate P			
						-10% P	-0% P	+10% P	-10% P	-0% P	+10% P
						Uptake	Uptake	Uptake	Uptake	Uptake	Uptake
					Aponga clay	/					
7/91 - 7/92	9.4	33.9	-0.18	-0.15	-0.21	-0.18	-0.21	-0.23	-0.12	-0.15	-0.18
7/92 - 7/93	64.7	51.6	0.79	0.93	0.68	0.79	0.67	0.57	1.07	0.92	0.79
7/91 - 7/93	34	41.6	0.36	0.45	0.28	0.36	0.28	0.21	0.54	0.44	0.36
	Wharekohe sandy loam										
7/91 - 7/92	72	52.7	0.91	1.06	0.78	0.91	0.77	0.66	1.21	1.04	0.91
2/92 - 2/93	79.9	53.3	1.04	1.21	0.90	1.04	0.89	0.77	1.37	1.19	1.04
7/91 - 7/93*	100	59.5	1.22	1.41	1.07	1.22	1.05	0.92	1.59	1.39	1.22
	Wharekohe silt loam NFt										
7/91-7/92	21.4	30.2	0.25	0.33	0.18	0.25	0.18	0.12	0.41	0.32	0.25
2/92 - 2/93	24	32.3	0.28	0.37	0.22	0.28	0.21	0.15	0.45	0.36	0.28
7/91 - 7/93*	100	46.8	1.68	1.91	1.48	1.68	1.46	1.29	2.15	1.89	1.68
Wharekohe silt loam Ft											
7/91 - 7/92	21.2	42.3	0.04	0.10	0	0.04	-0.01	-0.05	0.15	0.09	0.04
7/92 - 7/93*	100	64.1	1.10	1.27	0.96	1.10	0.94	0.82	1.45	1.26	1.10
7/91 - 7/93	83	50.4	1.19	1.37	1.04	1.19	1.02	0.89	1.55	1.35	1.19
7/91 - 7/93	43	49.1	0.42	0.51	0.34	0.42	0.33	0.26	0.61	0.50	0.42
7/91 - 7/93	35.1(Resin P)	49.1	0.25	0.33	0.19	0.25	0.18	0.12	0.41	0.33	0.25

 Table 7.6
 Sensitivity of the SLF to an incorrect estimation of the rate of P to maintain a steady Olsen P level and P uptake.

P Uptake

It was also not possible to accurately determine P uptake at 90% Ymax, at any of the sites in the present study as they were not particularly P responsive. Consequently, the actual P uptake measured at the rate of applied P closest to that determined to maintain a steady Olsen for each period was used in the calculation of the SLF. A small error in P uptake leads to a similar change in the calculated SLF to the change which is encountered for a similar error in the rate of P required to maintain a steady Olsen 7.6). An increase in P uptake will result in a decrease in the calculated SLF.

Other researchers (Rowarth et al., 1992b; Sinclair et al., 1994) have also encountered difficulties in determining the P uptake which corresponds to 90% of maximum yield. Rowarth et al. (1992b) were unable to determine maximum yield in their study of a range of P treatments encompassing 4 years on hill country at Whatawhata. In their calculations of the SLF they used the P uptake for each rate of P, as was done in the present study. Mitscherlich response curves fitted to pasture dry matter yields on the MAF "National Series" trial sites fitted the data poorly and the large variability in the curves' parameters made it impossible to predict the rate of P required for any specific yield at individual sites (Sinclair et al., 1994). Only when data from all sites were combined, could a mitscherlich curve be defined.

The mowing regime, used in the present study may not be appropriate for determining the SLF to determine pasture P requirements under grazing. Mowing produced similar dry matter yields to yields measured under grazing between July 91 and July 92 on the Wharekohe silt loam Ft site when pasture growth adjacent to the trial site was monitored under grazing. However, dry matter yields were 11% lower in the mown SLF trial than in an adjacent unfertilised area under grazing on the Wharekohe silt loam NFt site. Pasture production was 21-37% less under mowing compared to grazing at three other New Zealand sites, although the relative response to applied P was similar under both mowing and grazing (Morton et al., 1995). If pasture yields occurring under grazing were underestimated by mowing, P uptake is also likely to be underestimated and mowing will result in a lower estimation of the SLF than would be estimated under grazing.

P Uptake and the Rate of P Required to maintain a Steady Olsen P Level

Small errors in both parameters required to calculate the SLF can lead to very large changes in the calculated SLF values and hence maintenance P requirements. The combined effect of a 10% change in both parameters can result in a greater than 50% change in the calculated SLF value on the Wharekohe silt loam NFt site in the first year (Table 7.6). The 64% increase in the SLF factor from 0.25 to 0.41, when the P rate was increased by 10% and the P Uptake decreased by 10%, leads to a 34% increase in the amount of P required to maintain a stocking rate of 15.6 SU on rolling topography, that is 15.7 kg P/ha to 21.1 kg P/ha. This difference serves to illustrate why the calculation of the SLF from P response trials can lead to large errors in maintenance P rates, even from pooled site data.

Simulated Animal Loss

Apart from the Wharekohe silt loam NFt site (where dry matter yield was under 8000 kg/ha in the first year), the simulated animal losses in the present mowing trial were high in comparison to what would be expected under grazed pasture, due to the removal of 46% of the pasture and higher than expected herbage P concentrations and dry matter yields. For example, at a stocking rate of 16 SU/ha, only 14.4 and 8 kg P/ha would be expected to be removed by animals on an intensive dairy and sheep farm, respectively, on rolling topography. Yet the simulated animal losses via clippings removal in the small-plot field trials varied from 46% of 42 to 64 kg P/ha (19.3 to 29.5 kg P/ha).

Grazing animals excrete consumed P which is surplus to their requirements. Phosphorus returned in dung therefore increases with increasing herbage P concentrations (Bromfield, 1961; Barrow and Lambourne, 1962; Rowarth, et al., 1988). Hence, although animal transfer losses are higher under high herbage P concentrations (Mackay et al., 1987), losses via animal products will not increase greatly. However, the mowing regime removed 46% of the P taken up by pasture regardless of P concentration or dry matter yield. Consequently, lower amounts of P were returned to the plots than what would have been returned under grazing

animals, and hence the mowing regime simulates lower rates of P than were actually applied. For example, where 80 kg P/ha was applied in the present trial, the greater simulated animal loss simulated rates of P closer to 71.2 and 64.8 kg P/ha for grazed intensive dairy farms and sheep farms, respectively, on the Wharekohe silt loam Ft site for the two years. Theoretically, soil loss is independent of animal loss and consequently soil losses would have been similar if simulated animal losses had been lowered to more realistic levels. Therefore the higher than expected simulated animal losses should not have impacted on the calculated SLF values.

7.4.3.6 Effect of Pasture Age on the SLF

When the component of the SLF which can be attributed to the accumulation of nonlabile soil P (SLF_{SPA}) was calculated from the chronosequence study results, by the equation described in 7.3.2, the SLF_{SPA} decreased with increasing pasture age (Table 7.7).

The reduction in the SLF_{SPA} with increasing pasture age was the result of little further accumulation of P in the top soil beyond 11 years (Chapters 3 and 4). The negative SLF_{SPA} values are the result of a decrease in the unavailable P for those periods due to either measurement error or loss from the unavailable P pools.

The calculated SLF_{SPA} values were increased by the inclusion of organic P up until 33 years (Table 7.7). However, Rowarth et al. (1992b) did not consider the accumulation of P into organic compounds as a soil loss, as their inclusion resulted in far higher SLF_{SPA} than had been derived from P response trial data for sedimentary soils. For the oldest site in the present study, the inclusion of P o accumulation made little difference to the calculated SLF_{SPA}, as little Po accumulation had occurred. Although the SLF_{SPA} values all declined with increasing pasture age, the higher SLF_{SPA} values calculated from the 1993 soil data in comparison to the 1990 soil data can probably be attributed to increasing P accumulation associated with the use of RPR during the intervening period.

The interpretation of the SLF_{SPA} values with increasing pasture age at each sampling time is complicated by large differences in the average rates of P applied during each time period. The decrease in the SLF_{SPA} with increasing pasture age was also associated with a decrease in P application rates which may have influenced the SLF_{SPA} values. Rowarth et al. (1992b) have found that the SLF_{SPA} generally decreases with decreasing rate of applied P.

 Table 7.7
 Effect of pasture age on the SLF_{SPA} for use in the CFAS model

Period	Average Annual	SLF _{SPA}	SLF _{SPA}			
	P Application	(Unavailable Pi + HCl Po)	(Unavailable Pi + Po)			
	(kg/ha)					
1990 Data						
0-8 years	49	0.40	0.53			
0-32 years	32	0.11	0.19			
8-32 years	26	0.02	0.08			
25-32 years	34	0.03	0.09			
1993 Data						
0-11 years	48	0.53	0.66			
0-35 years	33	0.12	0.19			
11-35 years	28	-0.07	-0.03			
33-35 years	38	-0.11	-0.18			
Difference Between 1990 and 1993 Sampling of Original Sites.						
8-11 years	49	0.56	0.74			
30-33 years	49	-0.05	0.11			
32-35 years	49	-0.05	-0.04			

However, comparison of the SLF_{SPA} calculated from changes in P fractions on the original sites between 1990 and 1993, where P application was the same on each

site reveal that the decrease in the SLF_{SPA} does result from an increase in pasture age rather than decreasing P application (Table 7.7).

Runoff losses from rates of soluble P which would be required to maintain pasture production are unavoidable, although they may be minimised by alternative fertiliser P strategies (discussed in Chapter 5). Consequently, the SLF must also include a runoff P component. The SLF_{SPA} values presented in Table 7.7 indicate that no soil P loss via accumulation of non-labile P is occurring in the root zone in the older sites leading to SLF_{SPA} values close to or even lower than 0. Consequently, the SLF would consist mostly of the runoff P component in older developed sites on the Wharekohe silt loam. It is inefficient to continue applying P at the constant rates calculated by using a constant SLF in the CFAS model, if P surplus to production requirements and soil P accumulation is going to be lost from the soil and runoff losses are increased with pasture age (as demonstrated in Chapter 3). It is therefore very important that the overall SLF, and consequently calculated P requirements, are reduced as pasture age increases from development, and that the minimum P runoff losses, which are unavoidable for a given fertiliser P strategy, are included in the SLF.

Until the minimum runoff P losses for various fertiliser strategies are identified, it is impossible to determine if the CFAS SLF of 0.4 underestimates soil loss on the older developed Wharekohe sites in the chronosequence study. It appears, however that the SLF appropriate for younger pastures (<11 years) on the Wharekohe silt loam has been underestimated, as the SLF_{SPA} values were greater than 0.4 and runoff P losses have yet to be added to the SLF_{SPA} to give the overall SLF.

A 'steady state' has yet to be achieved in younger pastures (0-11 years) on the Wharekohe silt loam, as the net accumulation of non-labile P in the root zone changes with pasture age. Consequently, the use of small-plot field trials, where the average rate of P required to maintain a constant available P pool over a long period is estimated, would be inappropriate for determining SLF values on young pastures which are not in a 'steady state' and where the soil P loss will be changing with time. On such sites, the monitoring of P uptake and a wider range of P fractions, total P and runoff P losses (by difference, that is P runoff = Applied P - (Animal P loss +

Accumulated soil P)) across a range of P application rates should give a more reliable estimate of soil loss and SLF values as pasture age increases. Such trials should continue for at least 6 years once a 'steady state' has been identified so that an average SLF can also be determined which would reliably predict soil loss from a pasture in a 'steady state' for an 'average' year. Alternative fertiliser strategies, such as the more frequent application of small dressings of soluble fertilisers and the use of slowly soluble P fertilisers such as RPR, to minimise runoff P losses could also be investigated in this way and appropriate SLF values for such strategies be determined.

As pasture age and fertiliser history are often unknown variables when making fertiliser recommendations, a measure of P saturation (Chapter 6) may be a more appropriate means for determining an appropriate soil loss factor value. Soil loss factors would need to be determined for a range of P saturation values on soils where P saturation is likely to lead to large runoff P losses.

Evidence for reducing the magnitude of the soil P loss parameters, with increasing pasture age, are not only restricted to podzols. Higher fertiliser P inputs and Olsen P levels have been noted to be required to maintain pasture yields at a relative yield of 90% of Ymax in trials on yellow brown pumice soils under pastures established for less than 15 years, than under pastures which had been established for 30 to 40 years (Saunders et al., 1987b). The change in P requirements with pasture age were attributed to a decrease in soil P loss as the accumulation of organic matter and the net organic immobilisation of P slows with increasing pasture age leading to a greater contribution of P from the organic P pool for plant uptake. Likewise, it has been noted that lower rates of applied P are required to increase Olsen P levels on sedimentary soils at Ballantrae (G. Lambert pers. comm.) and Winchmore with increasing pasture age (A. Metherell pers. comm.).

7.4.3.7 Implications of Soil Loss Estimation on P Fertiliser Requirements

Each of the factors discussed in sections 7.4.3.1 to 7.4.3.6 will also impact on the determination of the soil loss parameter used in the calculation of P requirements by the Outlook model. The soil loss parameters currently employed in the CFAS and Outlook models both assume that the quantity of P lost from the cycling P pool via soil loss will be a constant proportion of the P available for plant uptake (that is, a constant proportion of pasture P uptake in the CFAS model and a constant proportion of labile soil P estimated by Olsen P in the Outlook model). This means that increasing P additions above maintenance requirements is expected to lead to an increase in available soil P and therefore an increase in non-labile soil P and P lost via runoff waters equal to a constant proportion of the applied P. However, results in this research project indicate that an increasing proportion of the P applied in excess to animal loss is lost in runoff from the Wharekohe soils, as pasture age increases, because net P accumulation in the soil declines. Consequently, the proportion of applied P which will be lost from the soil also increases with increasing P application rate. A similar pattern has been observed on a high P leaching sandy soil in South Western Australia in contrast to other West Australian soils (Bolland and Barrow, 1991).

Although podzols have been allocated a high soil loss factor (0.4) in the CFAS model, scientific evidence for using such a high value is lacking. Even higher soil P losses have been included for the podzols in the Outlook model in comparison to the older CFAS model (Metherell et al., 1995) because very high soil P losses were estimated on the associated podzolised yellow brown earth, Hukerenui silt loam site used to calculate soil loss parameters, despite the measurement of very low soil P loss on the true podzol, Okarito silt loam (Metherell, 1994). Whereas the CFAS model previously calculated that 21 kg P/ha was required to maintain an Olsen P level of 20 and a stocking rate of 15.6 on a Wharekohe silt loam on rolling topography (SLF 0.4), the Outlook model now calculates that 44 kg P/ha is required to maintain the same level of production on a Wharekohe podzol (Soil Loss 0.1). An application of 44 kg P/ha is very high and is likely to lead to large losses of P in

runoff from older Wharekohe sites (Chapter 8). In contrast, the maintenance P rates calculated by the Outlook model for the same stocking scenario and initial Olsen P level on a sedimentary soil is 19 kg P/ha (Soil Loss 0.04), which is similar to the 21 kg P/ha calculated by the CFAS model to maintain the same production levels on a podzol.

The use of high soil loss parameters in calculating P requirements for Wharekohe podzols is highly questionable if most of the P applied surplus to animal losses is going to be lost from the soil under older and regularly topdressed pasture. Evidence presented in this research project supports the application of a declining soil P loss parameter in both the CFAS and Outlook models as pasture age increases on Wharekohe podzols. Modified P application strategies, where smaller quantities of P enter the available P pool more frequently, should also be investigated to reduce runoff P losses. It is likely that a similar pattern of P loss is occurring in other NZ podzols and consequently, very low soil P loss parameters and modified P application strategies should also be applied on other podzols under older pastures as well. A P saturation factor (as described in Chapter 6) could be incorporated into the model to assess the likelihood of P loss via accumulation in the soil and an appropriate soil loss parameter value for each individual farm site on soils where large runoff P losses are likely.

7.5 CONCLUSIONS

• Calculated SLF values varied enormously from 0.04 in the first year of the trial to 1.19 over the two year trial period on the Wharekohe silt loam Ft site. This variation is a consequence of the large variation in the rate of P required to maintain a steady Olsen P level at each site. It was not possible to determine if the SLF of 0.4 used for podzols in the CFAS model was appropriate from the SLF trial presented in this study due to this large variation.

• The SLF was higher on the Wharekohe silt loam NFt site (0.25) compared to the Wharekohe silt loam Ft site (0.04) in the first year, despite similar rates of applied P required to maintain a steady Olsen P. This large difference was due to the much

lower P uptake in the former. Such a large difference in calculated SLF values between sites of different fertility illustrates how the initial fertility of a site can have a large impact on the calculated SLF value.

• The calculated SLF values were higher on the Wharekohe sandy loam site than on the Wharekohe silt loam sites reflecting that P is less strongly retained in the sandy loam.

• The calculated SLF values were higher on the Wharekohe silt loam sites than on the Aponga clay site.

• SLF values calculated from the change in Resin P under applied SPR (0.25) were substantially lower than those calculated from the change in Olsen P under applied MCP (1.10) for the two year trial period. A longer trial period would be required to determine if the soil loss determined from changes in Resin P reflects soil losses under SPR.

The highly variable nature of the Olsen and Resin P soil tests has led to large variability in the calculated SLF values which are very sensitive to incorrect estimation of both the rate of P required to maintain a constant Olsen P level and P uptake. The calculation of a soil loss parameter whose reliance is placed on the ability of the highly variable Olsen P test to determine soil P losses is questionable. A 10% increase in the rate of P required to maintain Olsen P levels accompanied by a 10% decrease in P uptake led to a 64% increase in the SLF and an associated 34% increase in the amount of P required to maintain 15.6 SU on rolling topography on the Wharekohe podzol.

• The SLF_{SPA} calculated from the chronosequence data decreased with pasture age. As P applied surplus to animal production requirements and P accumulation in the root zone is lost from the root zone in water runoff, the SLF should be reduced with increasing pasture age or else P runoff losses will increase. In order to determine the SLF appropriate for a particular pasture age, the minimum runoff losses which are unavoidable for a given fertiliser P strategy must be determined and included in the SLF.

• Until the minimum runoff P losses for various fertiliser strategies are identified, it is impossible to determine if the CFAS SLF of 0.4 underestimates soil loss on the older developed Wharekohe sites in the chronosequence study. It appears, however that the SLF appropriate for younger pastures (<11 years) on the Wharekohe silt loam has been underestimated, as the SLF_{SPA} values were greater than 0.4 and runoff P losses were not included to give the overall SLF.

• The use of the current soil loss parameters in the CFAS, and particularly, the Outlook model is likely to lead to very high runoff P losses from older pastures on the Wharekohe silt loam. It is important that soil loss parameters used in both the CFAS and Outlook models reflect the decrease in non-labile soil P accumulation with increasing pasture age in association with improved P application techniques on the podzol soils to minimise costs to the farmer and the environment.

CHAPTER 8

MODELLING THE FATE OF P IN A WHAREKOHE SILT LOAM

8.1 INTRODUCTION

In New Zealand, simple mass balance models, CFAS and Outlook, have been used to predict the P requirements of grazed pastures (Cornforth and Sinclair, 1982, 1984; Metherell et al., 1995). Annual P requirements are calculated to replace animal and soil P losses from the cycling P pool in order to maintain pasture production and stocking rates. These models assume that the fluxes of P between the soil P pools, within the pasture P cycle, are in a steady state. Once the desired available P and pasture production levels are reached, it is assumed that the amount of soil P loss is a constant proportion of the available P each year, and therefore a constant soil loss parameter is used in each model. Pasture age is However, as already described (Chapters 3 and 4), the rate of disregarded. accumulation of P into various soil pools in the Wharekohe silt loam decreases with pasture age. If the soil loss parameters do not reflect this decreasing soil P accumulation rate, P application rates surplus to soil P accumulation in the root zone and production requirements will be calculated by the models and surplus P will be lost in runoff waters from the root zone and ultimately to the wider environment.

In most New Zealand soils, soil P loss is generally considered to be predominantly non-labile P accumulation rather than runoff losses (Saggar et al., 1990b; Rowarth et al., 1992b), as only small runoff P losses have been recorded from most New soils (Chapter 5). A model developed to predict Ρ Zealand soil accumulation/depletion in hill country sedimentary soils (where predicted P accumulation in the top 15 cm = P applied - animal gain/loss) was found to account for most of the applied P (Saggar et al., 1990b). However, substantial quantities of P were lost via soil loss from a yellow grey earth at Winchmore under irrigation, >53% from the top 7.5 cm and 30% from the top 30 cm (calculated from data presented by Nguyen and Goh, 1992). These losses of P from the soil at Winchmore exceeded the P losses recorded from a similarly aged Wharekohe silt loam site (Chapter 3). In contrast to the Wharekohe soil, the pasture system at Winchmore appeared to be in a 'steady state' as soil P accumulation (Quin and Rickard, 1981; Nguyen et al.,

1989), and therefore runoff P losses (by difference), occurred at a constant rate and a constant soil loss parameter was appropriate for calculating P requirements during the 35 year period from pasture development.

Total P and organic P accumulation have also been found to accumulate linearly with both pasture age and the amount of superphosphate applied in the top 10 cm of sandy soils overlying clay in Australia over a 25 year period, despite large losses of applied P presumably in lateral runoff (Lewis et al., 1987). These results imply a constant soil loss and that P saturation had not occurred within 25 years. The sandy texture of the soils was the most likely reason for the high P loss from the top soil, rather than the soils approaching P saturation. As would be expected, exchangeable P (Bray 1) increased quadratically with the amount of superphosphate applied.

An Australian model used to calculate pasture P requirements predicts a decline in Pi 'fixation' over the first 10 years following the pasture development of P deficient soils as available P and pasture production increase (development phase) (Blair et al., 1977). However, P fixation was then predicted to remain at a constant level of 20% of applied P, rather than approaching 0.

Soil P accumulation declines with pasture age in Wharekohe soils at pasture production levels which reached the maintenance phase. Consequently, it is important that any models developed to predict the fate of applied P and fertiliser P requirements for the Wharekohe soils account for this decline in P accumulation with pasture age.

8.2 OBJECTIVES

The objective of this study was to model the fate of P in a Wharekohe silt loam with pasture development in respect to the fluxes which contribute to soil P loss, namely: i) accumulation of P into non-labile soil pools (available P, organic P and total P accumulation were also investigated), and

ii) losses of P in runoff.

The fate of P in a Wharekohe podzol can be described by a simple diagram (Figure 8.1).

8.4 MODEL DEVELOPMENT

The total P and P fractionation data from the chronosequence study presented in chapters 3 and 4 can be used to model the rate of P accumulation in a Wharekohe silt loam with increasing pasture age. The work presented earlier in this research project suggests that P which is applied surplus to soil P accumulation and animal requirements is lost from the soil via runoff waters. Once P accumulation in the Wharekohe podzol has been modelled, this could be incorporated into a separate model to predict runoff P losses.

8.4.1 Soil P Accumulation

The soil P pools were estimated from the following chemical P fractions. The chemical nature of each P pool has already been described in 4.2.3.2.

Soil P Pool:

Estimated by the fraction/s:

 Readily available Pi 	NH₄CI and NaHCO₃ Pi
Organic P	NH₄Cl, NaHCO₃ and NaOH Po
• Calcium Pi	H₂SO₄ Pi
 Strongly sorbed/precipitated Pi 	NaOH Pi, Hot HCl Pi & Po and
and Residual P	Residual P

Data collected from the original chronosequence sites sampled in spring 1990 and 1993 was used to establish a relationship between pasture age and the net accumulation of P into each soil P pool in the rooting zone (0-7.5 cm) (where net P accumulation was calculated as the difference in each P pool between each



Figure 8.1 Fate of fertiliser P in a grazed Wharekohe podzol (Note: SsrpP includes a small quantity of residual organic P extracted by hot HCl).

developed site and the undeveloped sites). The mathematical equation which best describes the relationship was derived as follows:

Rate of P Accumulation = K - a. P(t)

or
$$\frac{d P(t)}{d(t)} = K - a. P(t)$$
(1)

Where:

- P(t) is the amount of P which has accumulated in the soil following pasture development for a given pasture age (kg/ha).
- t is the pasture age (years).
- *K* is a constant corresponding to the rate of P accumulation at age 0.
- *a* is the rate constant.

Assuming that:

i) P is applied in excess to or equal to animal loss plus soil accumulation each year, and ii) the accumulation of P in the soil in each year is proportional to the amount already accumulated in the soil.

Equation (2), which describes the relationship between pasture age and the amount of P which has accumulated in the soil, can then be derived from equation (1) (derivation outlined in Appendix 8.1).

$$P(t) = G(1 - e^{-a.t})$$
 (2)

Where:

G is the maximum amount of P which can accumulate in the soil following pasture development (kg/ha).

The amount of P which can accumulate in the soil in the year following each P application can then be determined as the difference between the total amount of P which is predicted to have accumulated in the soil at the time of P application and

the total amount of P which is predicted to have accumulated in the soil one year later (that is pasture age plus 1).

$$P(t+1) - P(t) = G(1 - e^{-a(t+1)}) - G(1 - e^{-a.t})$$

that is: Annual $P_{acc.}(t) = Ge^{-a.t}(1-e^{-a})$

Where:

Annual P_{acc.} is the amount of P which accumulates in the soil in the year following P application (kg/ha).

Equation 2 can be used to determine the relationship between pasture age and each of the soil P pools, shown in the simple diagram of the P cycle presented in Figure 8.1, and the total soil P accumulation. Equation 3 can then be used to predict the amount of P accumulation into each soil P pool for the year following each P application.

A non-linear least squares regression procedure using the statistics package SAS was used to determine values for *G* and *a* for the relationship between pasture age and each of the soil P pools and total P accumulation (Equation 2). These relationships are presented graphically along with their 95% confidence intervals (dotted lines). Data collected from the additional sites in spring 1993 was then used to validate each model.

The use of pasture age as a parameter in a model predicting the fate of applied P presents several problems. Accurate development history, site and soil type information is not always available to consultants making fertiliser P recommendations for farmers. A P saturation factor, as discussed in chapter 6, may be a more appropriate indicator of the soils ability to retain, and hence lose, added P. The relationships of P accumulation and runoff loss with pasture age are likely to be site and soil specific and the need for accurate site information would be bypassed by the use of a soil test for P saturation rather than pasture age.

(3)

8.4.2 Runoff P Losses

The following model can be used to predict the amount of P which would be lost from the root zone (0-7.5 cm) via runoff in the year following P fertiliser application, that is Phosphorus in Runoff in High Loss Soils (PRIHLS):

Where:

- *P Runoff* is the amount of P lost in runoff water in the year following P application (kg/ha).
- Applied P is the amount of fertiliser P applied in that 1 year period (kg P/ha).
- *Annual Ptace.* is the amount of total P which accumulates in the soil in the year following P application (kg/ha).
- *SR* is the stocking rate (Stock Units/ha, where 1 SU consumes 550 kg DM/ha/yr).
- *ALF* is the animal loss factor which is the amount of P lost via excretal transfer and animal products per stock unit (kg P/SU).

Values for the ALF can be used from either the CFAS or Outlook model.

Some of the runoff P lost from the root zone may accumulate in the soil profile below 7.5 cm. However, much of the P which was unaccounted for was likely to have been lost from the soil altogether (chapter 3).

8.5 PREDICTING P ACCUMULATION IN EACH SOIL P POOL

A relationship could be established between pasture age and available Pi (AvPi), organic P (Po), and strongly sorbed/precipitated and residual P (SsprP) accumulation in the top 7.5 cm, (Figure 8.2). The models for predicting available Pi and organic P accounted for 90 and 96% of the variation in accumulated P with pasture age, respectively. However, the model used to predict the sum of strongly



Figure 8.2 Effect of pasture age on predicted and measured a) Available Pi, b) Organic P, c) Calcium Pi and d) Strongly sorbed and precipitated and residual P accumulation in the top 7.5 cm of a Wharekohe silt loam.

> X -P accumulation in original sites sampled in 1990 and 1993 from which each model was derived. ----- P accumulation in top 7.5 cm predicted by models. - - - 95% confidence intervals for predicted P accumulation values. • -P accumulation measured in additional sites sampled in 1993. Vertical lines = standard errors.

sorbed/precipitated and residual P only accounted for 72% of the variation encountered, and the 95% confidence intervals for the fitted curve were much wider than for the other two P pools.

The models for both available Pi and strongly sorbed/precipitated and residual P show a rapid initial increase in accumulated P, but the rate of increase slows so that the predicted value for available Pi and strongly sorbed/precipitated and residual P are close to maximum by 11 years. Organic P, on the hand, also increased rapidly with pasture age but continued to accumulate beyond 11 years, as the rate of increase in organic P declined more slowly compared to the other two P pools.

The lack of data for pastures younger than 8 years limits confidence in the models for predicting P accumulation in the period up to 8 years. It is possible that available Pi and strongly sorbed/precipitated and residual P pools are much closer to their maximum values earlier than the models indicate. If this was so, P accumulation would be underestimated by the models during this period.

It was not possible to model a relationship between pasture age and calcium P as calcium P accumulation is effected more by liming history than pasture age (chapter 4). Calcium-P can be expected to show a dramatic increase where large quantities of lime are applied during the initial stages of pasture development. However, where lime application is not continued at high rates, little further Ca-P is expected to accumulate apart from unreactive fertiliser P residues, and P derived from Ca-P may even be leached from the soil with the Ca over time resulting in a possible net depletion in Ca-P in older sites.

The data collected from the additional chronosequence sampling to 7.5 cm in spring 1993 was used to validate the models. The observed values for each of the accumulated soil P pools measured fell within the 95% confidence intervals for the models, despite the use of RPR in the past 3 years on the additional sites. The use of RPR compared to superphosphate can lower available Pi as measured by bicarbonate P (Olsen P) on many soils (Mackay et al., 1984; Saggar et al., 1992; Roberts et al., 1994). Therefore, the models can be used to predict the accumulation of applied P under pasture on a Wharekohe silt loam into the available

Pi, organic P and strongly sorbed/precipitated and residual P pools with some confidence.

The validation data was measured on sites located on the Kaikohe Research station where the samples used to derive the models were taken. It would have been preferable to validate the models with data collected from other areas containing Wharekohe soils. However, the collection of further validation data was restricted by the lack of knowledge of development history at other sites. It is likely, due to the very low capacity to retain added P and little natural variability in the P chemistry of the topsoil of Wharekohe silt loams, that P accumulation on other sites would follow a similar pattern under similar climatic conditions.

The models to predict the accumulation of P in the root zone into the 3 soil P pools for which relationships with pasture age could be established in the year following P application for a given pasture age are:

Annual AvPiacc. (t) =
$$44e^{-0.2145t}(1-e^{-0.02145t})$$
 (5)

Annual
$$Po_{acc.}(t) = 195 e^{-0.0581 t} (1 - e^{-0.0581})$$
 (6)

Annual Sspr
$$P_{acc.}(t) = 60 e^{-0.1556 t} (1 - e^{-0.1556})$$
 (7)

8.6 PREDICTING TOTAL P ACCUMULATION

A relationship between pasture age and total P accumulation in the root zone (0-7.5 cm) could be effectively modelled (Figure 8.3). The model was able to account for 90% of the variation in total P encountered on the original sites. The total P values for the validation data measured on the 1993 additional sites fell within the 95% confidence intervals for the model, despite the application of P solely as RPR in the preceding three years on the additional sites. The application of RPR is likely to have resulted in the greater accumulation of P as Ca-P than would be expected under more soluble P fertiliser. The model predicted a maximum accumulation of 380 kg P/ha on this Wharekohe silt loam which is very low compared to other New

Zealand pastoral soils (Saunders, 1959a; Walker et al., 1959; Nguyen and Goh, 1992).



Figure 8.3 Effect of pasture age on predicted and measured total P accumulation in the top 7.5 cm of a Wharekohe silt loam.
X Total P accumulation in original sites sampled in 1990 and 1993 from which model was derived. — Total P accumulation in top 7.5 cm predicted by the model. ---- 95% confidence intervals for predicted values for total P accumulation. • Total P accumulation measured in additional sites sampled in 1993. Vertical lines = standard errors.

The following equation can then be used to model the accumulation of total P in the root zone (0-7.5 cm) in the year following P application for a given pasture age:

Annual
$$Pt_{acc.}(t) = 380 e^{-0.1881t} (1 - e^{-0.1881})$$
 (8)

This model can then be incorporated into models for the prediction of runoff P losses (8.7) and fertiliser P requirements (8.8).

8.7 PREDICTING RUNOFF P LOSS

The model presented in equation 8 predicts total soil P accumulation for an average year. In drier than average years, less P is likely to be lost from the soil via runoff and hence annual P accumulation will be greater than predicted. However, it is possible that any extra P surplus to predicted P accumulation will be only loosely held in the soil and therefore may be susceptible to runoff P loss in future wetter than average years.

Annual P losses in runoff from the root zone of a Wharekohe silt loam can be predicted for a given pasture age from the PRIHLS model as follows:

Annual P Runoff = Applied P - 380
$$e^{-0.1881 \text{ age}}(1 - e^{-0.1881}) - (SR \times ALF)$$
 (9)

8.7.1 Validation of the PRIHLS Model

The 95% confidence intervals for predicted P runoff loss for each of the additional sites were calculated from the PRIHLS model (equation 9) using Annual Pt_{acc.} values calculated for the 95% confidence intervals of equation 8 and an ALF of 0.5 from the CFAS model (Figure 8.4). The estimated cumulative runoff P losses from each site from pasture development are represented in figure 8.4 by the solid circles. Runoff P loss increased with pasture age as P was applied at rates surplus to animal loss and soil P accumulation at each of the additional sites. The 95% confidence intervals for predicted runoff P loss at each site were wide, approximately 250 kg of P. Hence, the PRIHLS model cannot accurately predict runoff P loss but can be

used to gain an estimate of runoff P loss for a particular P application rate at a given pasture age and a comparison of runoff losses between different application rate strategies.



Figure 8.4 Predicted and measured P runoff losses for additional sites sampled in 1993.

Runoff P (Chapter 5) and P retention (Chapter 6) measurements also supported runoff P losses where P is applied at rates surplus to animal loss and soil P accumulation. During the period spring 1990 to spring 1993, no P was estimated to have been lost from the youngest site developed in 1982 (11 years in 1993). In contrast, 91.2 and 94.6 kg P/ha were unaccounted for by either estimated animal loss or accumulation in the top 7.5 cm of the original sites developed in 1958 and 1960, respectively (35 and 33 years old in 1993). During this period, there was a

surplus of 1660 mm of rain to evapo-transpiration. Therefore, the average P loading of runoff waters from the top 7.5 cm was estimated to be 5.5 to 5.7 μ g P/ml over the 3 years in the oldest developed sites.

A P concentration of 5.5 µg P/ml is extremely high for an average P loading of runoff waters from pastoral soils. Phosphorus concentrations as high as 1.94 µg/ml and 1.8 µg P/ml have been reported in surface runoff from a Tokomaru silt loam (Sharpley and Syers, 1979a) and in catchment runoff (surface plus subsurface runoff) from a freshly developed catchment in Northland which included Wharekohe soils (McColl et al., 1975), respectively, where approximately 50 kg P/ha/yr had been applied. Substantially lower average P loadings in runoff waters have been recorded from other New Zealand soils (McColl et al., 1977; Lee et al., 1979; Sharpley and Syers, 1979a&b; Lambert et al., 1985). However, the measurement of very high DIP concentrations in runoff waters collected from intact soil cores in the glasshouse study (Chapter 5), up to 45.6 µg/ml, and suction cups in the field, 18.65 µg/ml, where 100 kg P/ha was applied in both studies, support high average P loadings in runoff waters from Wharekohe soils where P surplus to production requirements and soil P accumulation is applied.

In the P retention study (Chapter 6) the amount of P retained by the soil sampled from the 11 year old pasture was approximately five times greater than the amount of P retained by the soil sampled from the 35 year pasture, at a final solution P concentration of 5.5 μ g/ml. This serves to support the greater loss of P in runoff from the Wharekohe silt loam under older in comparison to younger pastures.

8.7.2 Effect of Fertiliser and Stocking Rates on Runoff P Losses

The model can be used to examine the effect of P fertiliser and stocking rates on the amount of soil P accumulation and runoff P losses for the Wharekohe silt loam at different stages of development. Predicted total P accumulation (from equation 8) and runoff P losses (from the PRIHLS model, equation 9) with increasing pasture age for a Wharekohe silt loam are presented for two P application rates (40 and 50 kg P/ha) and two stocking regimes (intensive sheep and dairy) in figure 8.5. The P

application regimes included capital applications of fertiliser P for 6 years (as outlined in Figure 8.5) followed by the constant application of either 40 or 50 kg P/ha/yr. The capital application rates approximate rates commonly used on developed pastures on the Wharekohe podzols.





The annual P runoff loss varied initially while changing capital P applications were made. Clearly, where P is applied at a constant rate, the amount of P lost from the
soil in runoff increases with pasture age as the amount of P which accumulates in the soil decreases (Figure 8.5). The rate of increase in P runoff declines over time approaching an asymptote as the accumulation of P in the soil approaches 0. Obviously, the more P which is applied, the greater the predicted P runoff losses. Runoff P losses are expected to be lower from a dairy farm than from an intensive sheep farm at a given P application rate, due to higher loss from the pasture cycle via animals on the dairy farm. Hence, less P is applied that is surplus to animal requirements, and soil P accumulation, and therefore susceptible to loss in runoff.

The CFAS model calculates that 21 kg P/ha is required to maintain 15.6 SU (sheep) on the rolling topography of the Kaikohe Research Station with an Olsen P level of 20 (SLF=0.40). Approximately 13 kg of this applied P is predicted to be lost from an older pasture (>30 years) in runoff. The newer Outlook model, currently used for P fertiliser recommendations in New Zealand, recommends a very much larger application of 44 kg P/ha/yr to maintain the same level of production on the Kaikohe station. Predicted runoff P losses from an older pasture (>30 years) on a Wharekohe silt loam where 44 kg P/ha is applied annually are substantial, 36 kg P/ha. The application of such large quantities of P, which result from the high soil loss parameter assigned to the podzols in the Outlook model, is highly questionable as gains in pasture production are unlikely to outweigh this extremely inefficient use of fertiliser P and its loss to the wider environment.

The PRIHLS model presented in this chapter can be used to predict soil P accumulation and runoff P losses when applied P is greater than the sum of the animal losses and soil P accumulation. The application of P at rates below the sum of animal losses and total soil P accumulation is likely to result in both a drop in production and the amount of P which accumulates in the soil. Runoff P losses are also likely to be reduced but are not likely to be stopped altogether, particularly where soluble P is applied in one annual dressing. As P accumulation rates are proportional to the amount of P which has already accumulated in the soil (which is now lower than predicted due to inadequate P application), the effect of pasture age on P accumulation will be delayed. Once P application rates are returned to required levels, P will accumulate in greater quantities than would be predicted by the model for that pasture age.

8.8 USING THE PRIHLS MODEL TO PREDICT P REQUIREMENTS

The PRIHLS model could also be used to predict the amount of P required to maintain pasture production, for a given fertiliser P application strategy, once minimum runoff P losses for that strategy have been determined. Further research would be required to investigate minimum runoff P losses under different P fertiliser strategies such as the more frequent application of soluble P fertiliser or the use of slowly soluble P fertiliser (Chapter 5). It is highly unlikely that runoff P losses can be reduced to negligible levels in the Wharekohe soil with such a low anion storage capacity. Even if P was applied at rates equalling animal losses, runoff P losses would still be expected, and hence pasture production would be likely to be reduced. Once minimum runoff P losses are determined under alternative P application strategies, they could be incorporated into the PRIHLS model to determine the P application rates required to maintain production as follows:

As runoff P will be dependent on pasture age and the amount of P applied, *Annual P Runoff* would be represented by an equation and *P Requirement* determined as the amount of applied P for which runoff losses are minimised but an adequate level of production maintained. Further research is required to determine the effects of runoff P losses on the environment in areas where Wharekohe soils are found so that an acceptable balance can be obtained between losses of P to the environment and agricultural production. In the Netherlands, where runoff P losses have a large negative impact on the environment, P application levels are determined which result in acceptable P losses rather than optimum agricultural production (Sharpley, 1995).

A P saturation factor could also be incorporated into the model. Phosphorus saturation may be a better indicator of the ability of a soil to retain P than pasture age as the results obtained from its use are less reliant on accurate development history, site and soil type information.

8.9 CONCLUSIONS

Relationships between pasture age and available Pi, organic P, strongly sorbed/precipitated and residual P and total P accumulation in the top 7.5 cm of a Wharekohe silt loam, where P application rates exceed soil P accumulation rates, were successfully modelled. It was not possible to model a relationship between pasture age and calcium P as calcium P accumulation is effected more by liming history than pasture age. The validation data fell within the 95% confidence intervals of the models.

• The annual soil accumulation of total P in the year following P application

for a particular pasture age was described by a model which was then incorporated into a model to predict annual P runoff losses, the PRIHLS model. Phosphorus runoff losses were predicted as the sum of the soil P accumulation and animal loss subtracted from the amount of applied P. Predicted runoff P losses increase with pasture age, where P is applied at a constant rate. The rate of increase declines over time as soil P accumulation approaches zero. Runoff P losses will be higher at higher P application rates for a similar farming regime and on farms with lower animal losses per SU, such as sheep farms compared to dairy farms, for a similar P application rate and SR.

 Predicted runoff losses from the Wharekohe silt loam are nearly 3 times higher from older pasture (>30 years) where the Outlook model is used to calculate P requirements compared to the CFAS model, due to the higher soil loss parameter assigned to the Wharekohe soils in the former.

Further research is required to quantify runoff P losses under alternative P application strategies, where such losses are minimised, to determine the effects of runoff P losses on the environment and to investigate the use of a P saturation test as an alternative to the pasture age parameter. Once minimum runoff P losses have been determined they could be incorporated into the PRIHLS model to determine appropriate P application rates to maintain production. The P requirement could be calculated as the sum of the minimum runoff P, soil P accumulation and animal P loss.

CHAPTER 9 SUMMARY AND CONCLUSIONS

Background

 The accumulation of P over time under annually fertilised permanent pasture can contribute to pasture growth so that eventually only maintenance applications of P are required to balance any losses from the pasture P cycle and maintain pasture growth at the required relative yield and stocking rate. Various models have been developed to predict P requirements for pastoral systems in New Zealand. During the 1980's and early 1990's, the then MAF SFS used the mass balance, Cornforth and Sinclair CFAS model, where P requirements are calculated to replace losses from the cycling P pool via animals and the soil, to make fertiliser P recommendations.

In the late 1980's, concerns were raised that higher P application rates than those calculated by the CFAS model were necessary to maintain required Olsen P levels on many Northland farming properties on Wharekohe podzols. Consultant experience also indicated that to maintain a similar Olsen P value, the Wharekohe sandy loam may require higher P inputs than the Wharekohe silt loam. The podzol soil group covers 300 000 ha of the 1.26 million ha in Northland, with the Wharekohe silt and sandy loams the most widespread, covering approximately 60 000 ha, much of which is used for intensive pastoral farming. Preliminary investigation on several farms, where the CFAS model was underestimating the amount of P required to maintain the required soil Olsen P values on Wharekohe soils, identified the SLF as the parameter most likely leading to the inability of the CFAS model to predict P requirements on these podzols.

• Since the commencement of this PhD, the CFAS model has been replaced with the new model, Outlook, by the SFS. Outlook also uses a soil loss parameter to estimate losses of P from the cycling P pool through non-labile P accumulation and runoff P losses. Hence, an investigation of soil P loss in Wharekohe podzols is also relevant to the use of the Outlook for predicting P requirements on these soils.

• The review of the literature revealed that podzolisation results in low sesquioxide contents and consequently low Anion Storage Capacities, and extremely low natural P contents in the A horizons of the more weathered podzols, such as the Wharekohe soil. The largest proportion of the natural P found in the A horizon of the most weathered podzols is in the labile P pool with much smaller quantities of strongly sorbed and precipitated Fe- and Al-Pi and negligible quantities of calcium P. Pasture development with P fertiliser addition on podzols leads to P accumulation which initially accumulates as Po. Podzolic soils low in Al are expected to reach an equilibrium Po content which is lower and reached more rapidly than in other soils with higher Al content, which have a greater capacity to stabilise Po compounds. The ability of podzols to retain Pi is also reduced with increased P fertiliser application, as the few available P retention sites become occupied with the added P. Large losses of P have been recorded from the A horizons of New Zealand podzols under pasture and the potential for subsurface P runoff losses exists.

• The main objective of this thesis was to investigate the apparent limitation of the CFAS model to predict the maintenance P requirements of the Wharekohe soils, and the appropriateness of the soil loss parameter used in the new Outlook model, further by (a) determining the fate of applied fertiliser P, (b) examining possible mechanisms for any soil P retention or loss, (c) quantifying the amount of P lost from the pasture P cycle via the soil (SLF) and (d) modelling the fate of applied fertiliser P.

Determining the Fate of Applied Fertiliser P

 A chronosequence study was conducted to determine the fate of applied P in a Wharekohe silt loam under pastures of different age. Pasture development and the associated application of fertiliser P on Wharekohe podzols resulted in an increase in total soil P to the top of the E horizon with applied P accumulating to a higher concentration in the top 3 cm. Evidence has been presented which supports an increase in the movement of applied P down the profile with increasing pasture age. The Wharekohe silt loam top soil appears to have a finite ability to retain P (referred to as the maximum P storage capacity), which is reached by 8 years in the 0-3 cm depth and by 11 years in the 0-7.5 cm depth.

• The maximum P storage capacity can mostly be attributed to a maximum Pi storage capacity. Calcium-Pi extracted by H₂SO₄ was the largest fraction in the top 7.5 cm of all the developed sites. The high proportion of P as Ca-P was due to a limit on the accumulation of P associated with Fe and AI in the Wharekohe soil, due to its low sesquioxide content in comparison to other New Zealand soils. The Wharekohe silt loam contained a large quantity of readily available Pi of which a large amount was very weakly held in the soil (extractable by NH₄CI), and therefore prone to leaching in comparison to P held in other less weathered soils. In contrast to Pi, Po continued to accumulate over time to at least 32 years at each depth to levels similar to those recorded by other researchers in a less weathered South Island yellow grey earth. The rate of Po accumulation slowed with age in the top 3 cm with the most labile Po fraction extracted by NH₄CI reaching equilibrium by 25 years.

• Once the P storage capacity at each depth is reached, there is little further accumulation of applied P, apart from small quantities as fertiliser P residue. Much of the P applied in subsequent applications moves from the topsoil resulting in large soil losses of P from the pasture cycle, of up to 65% from the top 7.5 cm of older sites (>30 years). As little of the lost P could be accounted for to a depth of 30 cm below the E horizon, lateral movement of P in runoff waters above the E horizon is the most likely pathway for P loss from the A horizon. It was not possible to determine in which form P is moving through the profile of the Wharekohe silt loam from the chronosequence study, due to possible changes in P forms in situ.

Possible Mechanisms for Soil P Retention and Loss

 A glasshouse leaching study using intact soil cores demonstrated that substantial quantities of P can be transported in subsurface water movement through Wharekohe podzols (≤ 45.6 µg/ml) in contrast to the yellow brown earth, Aponga clay (\leq 1.07 µg/ml). Movement of dissolved P occurs mostly as DIP after the application of fertiliser P. The levels of P which move through Wharekohe podzols are so high, that it is likely that they contribute significant quantities of P to waterways creating the potential for eutrophication. Additionally the losses may represent a large economic cost to the producer. Fertiliser application strategies aimed at minimising P losses were suggested and included the more frequent application of small quantities of soluble P fertiliser or alternatively the use of slowly soluble P such as reactive phosphate rock (RPR).

 No difference in P movement could be detected in relation to development history in the glasshouse leaching study or in a field study where P in soil water was sampled using porous ceramic cups under suction. The younger site may have been close to P saturation and the rate of P application was most likely too high to detect the small differences in P retention recorded between the soils in a laboratory P retention study. The ability of the Wharekohe silt loam to retain added fertiliser P was found to decline with pasture development, as the P retention sites become filled with applied P.

Quantifying the SLF

• Soil loss factors calculated from small-plot field trials varied enormously as a consequence of the large variation in the rate of P required to maintain a steady Olsen P level at each site, from 0.04 in the first year of the trial to 1.68 over the two year trial period on the Wharekohe silt loam sites. From the small-plot field trial data it was not possible to determine if the SLF of 0.4 used for podzols in the CFAS model was appropriate, due to large variation in Olsen P levels. The calculation of a soil loss parameter, whose reliance is placed on the ability of the highly variable Olsen P test to determine soil P losses is questionable.

• The initial fertility of a Wharekohe trial site had a large impact on the calculated SLF values, with larger values determined for a lower fertility site. The calculated SLF values were higher on the Wharekohe sandy loam site than on the Wharekohe silt loam sites, reflecting that P is less strongly retained in the sandy loam. This

conclusion is supported by the findings of the P fractionation and laboratory P retention studies, but not by the glasshouse leaching study where no differences were found between the silt and sandy loams. SLF values calculated from the change in Resin P under applied SPR (0.25) were substantially lower than those calculated from the change in Olsen P under applied MCP (1.10) for the two year trial period. A longer trial period would be required to determine if the soil loss determined from changes in Resin P reflects soil losses under SPR.

• The component of the SLF due to non-labile P accumulation (SLF_{SPA}), calculated from the chronosequence data, decreased with pasture age. As P applied surplus to animal production requirements and P accumulation is lost from the root zone in water runoff, the SLF should be reduced with increasing pasture age or else P runoff losses will increase. Until the minimum runoff P losses for various fertiliser strategies are identified, it is not possible to determine if the CFAS SLF of 0.4 underestimates soil loss on the older developed Wharekohe sites in the chronosequence study. It appears, however that the SLF appropriate for younger pastures (<11 years) on the Wharekohe silt loam has been underestimated, as the SLF_{SPA} values were greater than 0.4 and runoff P losses were not even considered. In order to determine the SLF appropriate for a particular pasture age, the minimum runoff losses which are unavoidable for a given fertiliser P strategy must be determined and included in the SLF.

Modelling the Fate of Applied Fertiliser P

• Relationships between pasture age and available Pi, organic P, strongly sorbed/precipitated and residual P and total P accumulation in the top 7.5 cm of a Wharekohe silt loam were successfully modelled, where P application rates exceed soil P accumulation rates. It was not possible to model a relationship between calcium P and pasture age as calcium P accumulation is effected more by liming history than pasture age.

• The annual total soil P accumulation in the year following P application

for a particular pasture age was described by a model which was then incorporated into the Phosphorus in Runoff in High Loss Soils (PRIHLS) model developed to predict runoff P lossess. Phosphorus runoff losses can be predicted by the PRIHLS model, for a known rate of applied P, as the sum of the annual total soil P accumulation and animal loss, subtracted from the amount of applied P. Predicted runoff P losses increase with pasture age, where P is applied at a constant annual rate. The rate of increase in runoff P loss declines over time as soil P accumulation approaches zero. Runoff P losses will be higher at higher P application rates for a similar farming regime, and on farms with lower animal losses per SU, such as sheep farms compared to dairy farms, for a similar P application rate and SR. The PRIHLS model could also be used to predict the amount of P required to maintain pasture production, for a given fertiliser P application strategy, once minimum runoff P losses for that strategy have been determined.

• The use of the current soil P loss parameters in the CFAS, and particularly the new Outlook model, is likely to lead to very high runoff P losses from older pastures on the Wharekohe silt loam. Predicted runoff losses from the Wharekohe silt loam are nearly 3 times higher from older pasture (>30 years) where the Outlook model is used to calculate P requirements compared to the CFAS model, due to the higher soil loss parameter assigned to the Wharekohe soils in the former model. It is important that soil loss parameters used the new Outlook model reflect the decrease in non-labile soil P accumulation with increasing pasture age in association with improved P application techniques on the podzol soils to minimise costs to the farmer and the environment.

Suggestions for Further Research

• Losses of P from the root zone of older pastures on Wharekohe podzols are high under current fertiliser application strategies where an annual predominantly soluble P dressing is applied. Therefore, field studies which quantify runoff P losses from alternative P fertiliser strategies aimed at minimising such losses, which investigate application frequency, application rate and P fertiliser form are required. The PRIHLS model could then be further developed to include a function which describes minimum runoff P losses for a range of P fertiliser strategies in order to predict P requirements for maintaining pasture production. Such runoff P studies should also investigate the relative roles of subsurface and surface runoff in P loss, as losses of slowly soluble P may still be high if surface erosion of particulate P plays a major role in P loss to the wider environment.

 A phosphorus saturation test may be a better indicator of the ability of a soil to retain P than pasture age, as the results obtained from its use are less reliant on accurate development history, site and soil type information. Consequently, further research is required to determine the relationship between P saturation and runoff P losses in order to determine appropriate P saturation levels to restrict P losses from the podzols by reducing application rates and/or using alternative application strategies.

 The environmental impacts of runoff P losses need to be established for areas where Wharekohe soils are found to enable more informed decisions to be made about balanced fertiliser use. This would allow the PRIHLS model to be further developed to maintain an acceptable balance between losses of P to the environment and the need for maintaining a high level of agricultural production for pastures of different age.

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GLOSSARY OF TERMS

Anion Storage Capacity - percentage of P removed from a solution of NaOAc-HAc containing 1000 μ g P/ml buffered at pH 4.6 by soil shaking at a 1:5 soil:solution ratio for 24 hours (Saunders, 1965). Soil to P ratio is therefore 1 g of soil to 5000 μ g P. Previously known as the P Retention Test.

Maximum P Storage Capacity - maximum amount of added P which can be retained by the soil in the field by such processes as P sorption, P precipitation and organic P immobilisation.

P Sorption - refers to both adsorption (sorption on the surface of soil particles) and absorption (incorporation into soil particles).

P Retention - refers to the retention of added inorganic P by the soil through both P sorption and precipitation

Runoff P Loss - the loss of P from the topsoil in both surface and subsurface runoff waters.

Subsurface Runoff - the movement of water beneath the soil surface including both lateral movement (across the top of the pan in the case of the Wharekohe soils) and deeper percolation to the B horizon (considered to be limited in the Wharekohe soils). Subsurface waters may reach the surface and be measured as surface runoff and vice-versa.

Surface Runoff - the movement of water across the soil surface. Surface runoff will often penetrate the soil to a depth of at least 1 cm as the water moves across the surface in waves.

Appendix 3.1

Table of log transformed total P concentration values

depth	0-3 cm	3-7.5 cm	7.5 cm-E	E	E-10 ↓E	20-30 ↓E
Age						
0	4.294	3.816	3.606	3.170	2.074	2.584
8	6.738	5.479	4.359	3.276	2.870	2.783
23	6.660	6.297	5.640	3.837	4.119	4.368
25	6.772	6.263	5.539	3.487	2.855	3.585
30	6.533	6.090	5.437	3.552	3.981	4.168
32	6.898	6.432	4.744	3.190	2.445	2.175

S.E.D.s for comparison of log transformed total P concentration values at each depth of the undeveloped site with other depths at all sites.

Age	Depth	0-3 cm	3-7.5 cm	7.5 cm-E	E	E-10 ↓E	20-30 ↓E
0	0-3 cm	*	*	*	*	*	*
0	3-7.5 cm	0.1226	*	*	*	*	*
0	7.5 cm-E	0.1226	0.1226	*	*	*	*
0	E	0.1548	0.1548	0.1548	*	*	*
0	E-10 ↓E	0.1723	0.1723	0.1723	0.1892	*	*
0	20-30 ↓E	0.2028	0.2028	0.2028	0.2174	0.2335	*
8	0-3 cm	0.1787	0.1787	0.1787	0.2021	0.2158	0.2409
8	3-7.5 cm	0.1787	0.1787	0.1787	0.2021	0.2158	0.2409
8	7.5 cm-E	0.1787	0.1787	0.1787	0.2021	0.2158	0.2409
8	E	0.2231	0.2231	0.2231	0.2422	0.2537	0.2754
8	E-10 ↓E	0.2231	0.2231	0.2231	0.2422	0.2537	0.2754
8	20-30 ↓E	0.2231	0.2231	0.2231	0.2422	0.2537	0.2754
23	0-3 cm	0.1787	0.1787	0.1787	0.2021	0.2158	0.2409
23	3-7.5 cm	0.1787	0.1787	0.1787	0.2021	0.2158	0.2409
23	7.5 cm-E	0.1787	0.1787	0.1787	0.2021	0.2158	0.2409
23	E	0.2231	0.2231	0.2231	0.2422	0.2537	0.2754
23	E-10 ↓E	0.2231	0.2231	0.2231	0.2422	0.2537	0.2754
23	20-30 ↓E	0.2231	0.2231	0.2231	0.2422	0.2537	0.2754
25	0-3 cm	0.1787	0.1787	0.1787	0.2021	0.2158	0.2409
25	3-7.5 cm	0.1787	0.1787	0.1787	0.2021	0.2158	0.2409
25	7.5 cm-E	0.1787	0.1787	0.1787	0.2021	0.2158	0.2409
25	E	0.2231	0.2231	0.2231	0.2422	0.2537	0.2754
25	E-10 ↓E	0.2231	0.2231	0.2231	0.2422	0.2537	0.2754
25	20-30 ↓E	0.2896	0.2896	0.2896	0.3046	0.3139	0.3316
30	0-3 cm	0.1787	0.1787	0.1787	0.2021	0.2158	0.2409
30	3-7.5 cm	0.1787	0.1787	0.1787	0.2021	0.2158	0.2409
30	7.5 cm-E	0.1787	0.1787	0.1787	0.2021	0.2158	0.2409
30	E	0.2231	0.2231	0.2231	0.2422	0.2537	0.2754
30	E-10 ↓E	0.2231	0.2231	0.2231	0.2422	0.2537	0.2754
30	20-30 ↓E	0.2231	0.2231	0.2231	0.2422	0.2537	0.2754
32	0-3 cm	0.1787	0.1787	0.1787	0.2021	0.2158	0.2409
32	3-7.5 cm	0.1787	0.1787	0.1787	0.2021	0.2158	0.2409
32	7.5 cm-E	0.1787	0.1787	0.1787	0.2021	0.2158	0.2409
32	E	0.2231	0.2231	0.2231	0.2422	0.2537	0.2754
32	E-10 ↓E	0.2231	0.2231	0.2231	0.2422	0.2537	0.2754
32	20-30 ↓E	0.2231	0.2231	0.2231	0.2422	0.2537	0.2754

Age	Depth	0-3 cm	3-7.5 cm	7.5 cm-E	E	E-10 ↓E	20-30 ↓E
8	0-3 cm	*	*	*	*	*	*
8	3-7.5 cm	0.1734	*	*	*	*	*
8	7.5 cm-E	0.1734	0.1734	*	*	*	*
8	E	0.2189	0.2189	0.2189	*	*	*
8	E-10 ↓E	0.2189	0.2189	0.2189	0.2453	*	*
8	20-30 ↓E	0.2189	0.2189	0.2189	0.2453	0.2453	*
23	0-3 cm	0.2063	0.2063	0.2063	0.2458	0.2458	0.2458
23	3-7.5 cm	0.2063	0.2063	0.2063	0.2458	0.2458	0.2458
23	7.5 cm-E	0.2063	0.2063	0.2063	0.2458	0.2458	0.2458
23	E	0.2458	0.2458	0.2458	0.2797	0.2797	0.2797
23	E-10 ↓E	0.2458	0.2458	0.2458	0.2797	0.2797	0.2797
23	20-30 ↓E	0.2458	0.2458	0.2458	0.2797	0.2797	0.2797
25	0-3 cm	0.2063	0.2063	0.2063	0.2458	0.2458	0.2458
25	3-7.5 cm	0.2063	0.2063	0.2063	0.2458	0.2458	0.2458
25	7.5 cm-E	0.2063	0.2063	0.2063	0.2458	0.2458	0.2458
25	E	0.2458	0.2458	0.2458	0.2797	0.2797	0.2797
25	E-10 ↓E	0.2458	0.2458	0.2458	0.2797	0.2797	0.2797
25	20-30 ↓E	0.3075	0.3075	0.3075	0.3352	0.3352	0.3352
30	0-3 cm	0.2063	0.2063	0.2063	0.2458	0.2458	0.2458
30	3-7.5 cm	0.2063	0.2063	0.2063	0.2458	0.2458	0.2458
30	7.5 cm-E	0.2063	0.2063	0.2063	0.2458	0.2458	0.2458
30	E	0.2458	0.2458	0.2458	0.2797	0.2797	0.2797
30	E-10 ↓E	0.2458	0.2458	0.2458	0.2797	0.2797	0.2797
30	20-30 ↓E	0.2458	0.2458	0.2458	0.2797	0.2797	0.2797
32	0-3 cm	0.2063	0.2063	0.2063	0.2458	0.2458	0.2458
32	3-7.5 cm	0.2063	0.2063	0.2063	0.2458	0.2458	0.2458
32	7.5 cm-E	0.2063	0.2063	0.2063	0.2458	0.2458	0.2458
32	E	0.2458	0.2458	0.2458	0.2797	0.2797	0.2797
32	E-10 ↓E	0.2458	0.2458	0.2458	0.2797	0.2797	0.2797
32	20-30 ↓E	0.2458	0.2458	0.2458	0.2797	0.2797	0.2797

S.E.D.s for comparison of log transformed total P concentration values at each depth of the 8 year old site with other depths at all developed sites.

Age	Depth	0-3 cm	3-7.5 cm	7.5 cm-E	E	E-10 ↓E	20-30 ↓E
23	0-3 cm	*	*	*	*	*	*
23	3-7.5 cm	0.1734	*	*	*	*	*
23	7.5 cm-E	0.1734	0.1734	*	*	*	*
23	E	0.2189	0.2189	0.2189	*	*	*
23	E-10 ↓E	0.2189	0.2189	0.2189	0.2453	*	*
23	20-30 ↓E	0.2189	0.2189	0.2189	0.2453	0.2453	*
25	0-3 cm	0.2063	0.2063	0.2063	0.2458	0.2458	0.2458
25	3-7.5 cm	0.2063	0.2063	0.2063	0.2458	0.2458	0.2458
25	7.5 cm-E	0.2063	0.2063	0.2063	0.2458	0.2458	0.2458
25	E	0.2458	0.2458	0.2458	0.2797	0.2797	0.2797
25	E-10 ↓E	0.2458	0.2458	0.2458	0.2797	0.2797	0.2797
25	20-30 ↓E	0.3075	0.3075	0.3075	0.3352	0.3352	0.3352
30	0-3 cm	0.2063	0.2063	0.2063	0.2458	0.2458	0.2458
30	3-7.5 cm	0.2063	0.2063	0.2063	0.2458	0.2458	0.2458
30	7.5 cm-E	0.2063	0.2063	0.2063	0.2458	0.2458	0.2458
30	E	0.2458	0.2458	0.2458	0.2797	0.2797	0.2797
30	E-10 ↓E	0.2458	0.2458	0.2458	0.2797	0.2797	0.2797
30	20-30 ↓E	0.2458	0.2458	0.2458	0.2797	0.2797	0.2797
32	0-3 cm	0.2063	0.2063	0.2063	0.2458	0.2458	0.2458
32	3-7.5 cm	0.2063	0.2063	0.2063	0.2458	0.2458	0.2458
32	7.5 cm-E	0.2063	0.2063	0.2063	0.2458	0.2458	0.2458
32	E	0.2458	0.2458	0.2458	0.2797	0.2797	0.2797
32	E-10 ↓E	0.2458	0.2458	0.2458	0.2797	0.2797	0.2797
32	20-30 ↓E	0.2458	0.2458	0.2458	0.2797	0.2797	0.2797

S.E.D.s for comparison of log transformed total P concentration values at each depth of the 23 year old site with other depths at all developed sites of 23 years and older.

S.E.D.s for comparison of log transformed total P concentration values at each depth of the 25 year old site with other depths at all developed sites of 25 years and older.

Age	Depth	epth 0-3 cm 3-7.5 cm		7.5 cm-E	E	E-10 ↓E	20-30 ↓E
25	0-3 cm	*	*	*	*	*	*
25	3-7.5 cm	0.1734	*	*	*	*	*
25	7.5 cm-E	0.1734	0.1734	*	*	*	*
25	E	0.2189	0.2189	0.2189	*	*	*
25	E-10 ↓E	0.2189	0.2189	0.2189	0.2453	*	*
25	20-30 ↓E	0.2864	0.2864	0.2864	0.3071	0.3071	*
30	0-3 cm	0.2063	0.2063	0.2063	0.2458	0.2458	0.2458
30	3-7.5 cm	0.2063	0.2063	0.2063	0.2458	0.2458	0.2458
30	7.5 cm-E	0.2063	0.2063	0.2063	0.2458	0.2458	0.2458
30	E	0.2458	0.2458	0.2458	0.2797	0.2797	0.2797
30	E-10 ↓E	0.2458	0.2458	0.2458	0.2797	0.2797	0.2797
30	20-30 ↓E	0.2458	0.2458	0.2458	0.2797	0.2797	0.2797
32	0-3 cm	0.2063	0.2063	0.2063	0.2458	0.2458	0.2458
32	3-7.5 cm	0.2063	0.2063	0.2063	0.2458	0.2458	0.2458
32	7.5 cm-E	0.2063	0.2063	0.2063	0.2458	0.2458	0.2458
32	E	0.2458	0.2458	0.2458	0.2797	0.2797	0.2797
32	E-10 ↓E	0.2458 0.2458		0.2458 0.2797		0.2797	0.2797
32	20-30↓E 0.2458 0.2458		0.2458	0.2458	0.2797	0.2797	0.2797

S.E.D.s for comparison of log transformed total P concentration values at each depth of the 30 year old site with other depths at all developed sites of 30 years and older.

Age	Depth	epth 0-3 cm 3-7.5		7.5 cm-E	E	E-10 ↓E	20-30 ↓E
30	0-3 cm	*	*	*	*	*	*
30	3-7.5 cm	0.1734	*	*	*	*	*
30	7.5 cm-E	0.1734	0.1734	*	*	*	*
30	E	0.2189	0.2189	0.2189	*	*	*
30	E-10 ↓E	0.2189	0.2189	0.2189	0.2453	*	*
30	20-30 ↓E	0.2189	0.2189	0.2189	0.2453	0.2453	*
32	0-3 cm	0.2063	0.2063	0.2063	0.2458	0.2458	0.2458
32	3-7.5 cm	0.2063	0.2063	0.2063	0.2458	0.2458	0.2458
32	7.5 cm-E	0.2063	0.2063	0.2063	0.2458	0.2458	0.2458
32	E	0.2458	0.2458	0.2458	0.2797	0.2797	0.2797
32	E-10 ↓E	0.2458	0.2458	0.2458	0.2797	0.2797	0.2797
32	20-30↓E 0.2458 0.2		0.2458	0.2458	0.2797	0.2797	0.2797

S.E.D.s for comparison of log transformed total P concentration values at each depth of the 32 year old site with other depths at that site.

Age	Depth	0-3 cm	3-7.5 cm	7.5 cm-E	E	E-10 ↓E	20-30 ↓E
32	0-3 cm	*	*	*	*	*	*
32	3-7.5 cm	0.1734	*	*	*	*	*
32	7.5 cm-E	0.1734	0.1734	*	*	*	*
32	E	0.2189	0.2189	0.2189	*	*	*
32	E-10 ↓E	0.2189	0.2189	0.2189	0.2453	*	*
32	20-30 ↓E	0.2189	0.2189	0.2189	0.2453	0.2453	*























(App. 3.3c)







90-20-85vclover 10-%grass sampling date 18/08/92 75 70 0 20 30 30 10 20 10 0 0 Years of Development Years of Development 3 4 - s %dead %lotus %weed 2 2. 1 1 с0 0 0-0-10 30 20 30 20 20 30 10 0 10 0 Years of Development Years of Development Years of Development

15-80-%grass %clover sampling date 3/11/92 10-70-5 30 20 10 20 30 Ó 10 0 Years of Development Years of Development 15-8-10-6 10-%weed %lotus %dead 5 5 2-0-0 0-30 30 0 30 20 20 10 10 20 10 Ó 0 Years of Development Years of Development Years of Development



Appendix 4.2

Spring 1990

a) Exchangeable Ca



b) Exchangeable Ca (concentration in oven dried soil)



c) Total Ca (concentration in oven dried soil)



Spring 1993



Appendix 4.3

Historic Olsen P levels (MAF Quicktest) for 3 Wharekohe silt loam sites on the Kaikohe Research Station (pH, in water, included at youngest site).

	Site Developed in 1982					Site Develo	ped in 1960		Site Developed in 1958			
Ols	en P	рН	Fertilis	er Aplied	Ols	en P	Fertilis	er Aplied	Olse	en P	Fertilis	er Aplied
Sampling date	Olsen P		Date	Amount & Form	Sampling date	Olsen P	Date	Amount & Form	Sampling date	Olsen P	Date	Amount & Form
1979							11/1979	21.5 (SSP)			11/1979	21.5 (SSP)
3/1980							11/1980	15.5 (SSP)			11/1980	15.5 (SSP)
6/1981	6	4.7	12/1981	73 (SSP)	6/1981	15	1981	0			1981	0
6/1982	9	5.1	9/1982	48.5 (SSP)	6/1982	7	11/1982	36 (SSP)			11/1982	36 (SSP)
6/1983			12/1983	36 (SSP)	6/1983	13	2/1984	28 (SSP)			2/1984	28 (SSP)
5/1984	11	5.7	2/1985	32 (SSP)	5/1984	20	2/1985	32 (SSP)	5/1984	15	1/1985	26 (SSP)
6/1985	14	5.8	2/1986	38 (SSP)	6/1985	15	4/1986	30 (SSP)	6/1985	15	11/1985	39 (SSP)
6/1986	20	5.5	11/1986	50 (SSP)					6/1986	15	12/1986	33 (SSP)
5/1987	12	5.8	12/1987	34 (long)					5/1987	12	1/1988	27 (long)
6/1988	10	6.0	5/1989	31 (long)			i		6/1988	10	5/1989	31 (long)
8/1989	9	6.2	11/1989	16.5 (long)					8/1989	11	11/1989	16.5 (long)
1990			3/1990	35 (long)					1990		3/1990	35 (long)
3/1991	17	6.2	5/1991	56 (RPR)					3/1991	22	5/1991	56 (RPR)
4/11992	10	5.8	5/1992	37 (RPR)					4/11992	18	5/1992	37 (RPR)
3/1993	22	5.8	5/1993	31 (RPR)					3/1993	15	5/1993	31 (RPR)
1/1994	13	5.9								20		













Appendix 7.3a Pasture Dry Matter Production for SLF Trial.

Aponga clay																
	DM 1	DM 2	DM 3	DM 4	DM 5	DM 6	DM 7	DM 8	DM 9	DM 10	DM 11	DM 12	Year 1	Year2		
Cut	27.9.91	23.10.91	22.11.91	16.2.92	3.6.92	4.8.92	5.10.92	25.11.92	5.1.93	13.4.93	9.6.93	25.7.93				
0	1375	1465	1464	2244	1040	1141	3065	3462	3556	861	1152	668	8730	12764		
20	1563	1512	1694	2448	934	1461	3414	3432	3758	915	1273	811	9611	13603		
30	1489	1643	1532	2178	925	1227	3229	3439	3738	702	1399	690	8995	13197		
40	1765	1656	1678	2369	1350	1458	3229	3530	3725	721	1388	797	10276	13390		
50	1590	1592	1628	2251	1332	1255	3121	3564	3465	884	1331	722	9648	13086		
60	1771	1696	1693	1943	1362	1192	2920	3452	3563	1039	1518	704	9656	13196		
80	1869	1828	1807	2297	1473	1537	3188	3577	3736	780	1459	816	10811	13557		
100	1354	1577	1649	2340	1039	1306	2954	3573	3824	1134	1269	739	9265	13493		
F pr.	0.604	0.142	0.405	0.633	0.254	0.29	0.686	0.919	0.63	0.067	0.016	0.645	0.357	0.795		
S.E.D.	302.7	119.3	142.8	248.6	261.1	178.6	276.6	151.3	203.9	140.7	91.4	95.2	876.2	542.5		
LSD	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	190.112	ns	ns	ns		
Wharekohe s	andy loam															
	DM 1	DM 2	DM 3	DM 4	DM 5	DM 6	DM 7	DM 8	DM 9	DM 10	Dm 11	Dm 12	DM 13	Dm 14	Year 1	Year 2
Cut	24 9 91	22,10,91	23.11.91	12.2.92	13,5.92	20.6.92	1.8.92	16,10,92	7.12.92	11.1.93	2.3.93	14.4.93	8.6.93	27.7.93		
0	1332	2046	1936	3528	1908	918	723	2786	3331	1350	716	657	1642	944	12390	11426
20	1258	2090	1998	3764	2097	783	841	2854	3086	1307	818	518	1406	967	12833	10958
30	1163	1975	2029	3924	1981	669	772	2737	3071	1032	753	637	1566	1021	12514	10817
40	1304	1832	2023	4020	2092	683	702	2613	3531	1299	919	573	1529	1009	12657	11473
50	1112	1758	2003	4204	2180	829	802	2679	3086	1419	915	579	1530	1022	12887	11230
60	1199	1916	2046	4224	1620	805	797	2678	3399	1084	935	666	1675	926	12608	11364
70	1176	1891	1895	3775	1955	758	708	2772	3379	1221	838	560	1580	1028	12158	11378
80	1025	1765	2022	4060	2135	731	808	2474	3249	1084	781	631	1568	1021	12545	10808
100	1125	1778	1831	3949	1870	685	709	2622	3123	1447	919	596	1708	1138	11948	11553
F pr.	0.746	0.023	0.616	0.075	0.649	0.156	0.58	0.671	0.217	0.182	0.209	0.925	0.681	0.795	0.813	0.868
S.E.D.	174.6	102.3	115.6	215.9	281.8	88.2	81.2	188.5	194.9	170.8	94.6	114.7	151.2	115.6	581.8	598
L.S.D.	ns	212.17	ns	ns	ns	ns	ns		ns	ns	ns	ns	ns	ns	ns	ns

ns

Harvest 2, significant linear trend for reducing DM with increasing P, trend did not persist.

Wharekohe silt	loam NFt													
	DM 1	DM 2	DM 3	DM 4	DM 5	DM 6	DM 7	DM 8	DM 9	DM 10	DM 11	DM 12	Year 1	Year 2
Cut	30/9/91	25/10/91	23/11/91	16/2/92	27/5/92	31/7/92	29/9/92	9/12/92	1/3/93	21/4/93	17/6/93	26/7/93	Year 1	Year 2
0	1450	936	1172	2100	575	860	1444	4924	631	513	1387	633	7093	9532
20	1483	1008	1232	2393	903	750	1865	5180	785	823	1899	905	7769	11457
30	1405	946	1203	2428	764	696	1776	5420	918	906	2043	895	7442	11958
40	1142	905	1273	2318	673	824	1728	4895	841	815	2048	920	7136	11246
50	1310	983	1209	2506	999	1026	1779	5308	921	1084	2120	933	8032	12146
60	1234	864	1197	2576	884	822	1550	5157	753	770	1983	861	7576	11073
70	1388	915	1073	2507	1031	862	1790	5760	780	1047	2148	981	7777	12505
80	1291	873	1172	2411	926	830	1430	5164	774	812	1992	892	7503	11066
100	1115	943	1239	2524	1161	1080	1698	5461	854	1067	2233	909	8062	12223
F pr.	0.794	0.917	0.463	0.289	0.002	0.788	0.076	0.144	0.13	0.003	< 0.001	0.061	0.589	<0.001
S.E.D.	245.8	107.5	80	177.4	124.1	227.2	155.2	292.7	95.2	123.9	153.2	93.2	541.8	536.9
L.S.D.	ns	ns	ns	ns	256.14	ns	ns	ns	ns	255.73	316.2	9	ns	1108.16

Harvest 5, significant linear trend of increasing DM with increasing P. Harvest 10, significant linear trend of increasing DM with increasing P.

Wharekohe silt loan	n Ft (MCP) (I	Means from	analysis of v	ariance adjusted	for covariate	s ie plot effect)	1

	DM 1	DM 2	DM 3	DM 4	DM 5	DM 6	DM 7	DM 8	DM 9	DM 10	Dm 11	Dm 12	DM 13	YEAR 1	YEAR 2
Cut	26/9/91	24/10/91	23/11/91	13/2/92	2/6/92	29/7/92	25/9/92	20/11/92	6/1/93	8/3/93	27/4/93	18/6/93	24/7/93		
0	2173	1498	1444	2780	624	929	1679	3868	2298	375	589	1430	855	9448	11095
20	2094	1689	1595	3001	716	1039	1951	4060	2685	500	854	1761	942	10134	12752
30	2060	1496	1528	3189	536	871	1770	4765	2621	525	778	1586	972	9681	13017
40	2282	1623	1584	3133	844	1126	1833	4485	2873	460	741	1577	928	10592	12896
50	2369	1609	1719	2874	704	1180	1975	4140	2952	500	844	1901	1107	10456	13419
60	2085	1702	1690	3152	851	1204	1877	3899	2861	500	995	1689	886	10685	12705
70	2111	1648	1652	3317	585	1002	1991	4289	2886	515	1007	1674	1018	10315	13381
80	1977	1568	1498	3153	626	896	1627	4216	2711	443	769	1698	958	9718	12421
100	2281	1560	1537	3290	593	1087	1799	4639	2695	534	1064	1589	1078	10347	13398
F pr.	0.689	0.391	0.327	0.129	0.367	0.358	0.293	0.015	0.062	0.379	0.03	0.618	0.305	0.36	0.013
S.E.D.	219.9	103.5	119.4	195.6	144.7	164.8	161.6	255.7	192.8	65.3	128.1	217.7	100.4	594.1	569.4
L.S.D.	ns	ns	ns	ns	ns	ns	ns	530.32	ns	ns	265.68	ns	ns	ns	1180.94

Harvest 11 and Year 2, significant linear trend for increasing Dm with P, basically due to 0 lower than all others. When SPR included in analysis, ie all together treatment effects were significant at Harvests 8, 13 and Year2. At Year 2, 0 significantly smaller than all other treatments except SPR60.

Wharekohe sil	t loam Ft (M	CP) (Means a	djusted for cov	variates)											
	DM 1	DM 2	DM 3	DM 4	DM 5	DM 6	DM 7	DM 8	DM 9	DM 10	Dm 11	Dm 12	DM 13	YEAR 1	YEAR 2
Cut	26/9/91	24/10/91	23/11/91	13/2/92	2/6/92	29/7/92	25/9/92	20/11/92	6/1/93	8/3/93	27/4/93	18/6/93	24/7/93		
0															
20	2094	1692	1600	2983	715	1036	1947	4038	2672	493	868	1765	939	10121	12722
40	2300	1654	1629	3080	835	1109	1827	4431	2814	443	825	1573	912	10606	12824
60	2083	1706	1695	3138	852	1203	1875	3885	2851	494	1006	1694	883	10677	12690
80	1987	1576	1508	3121	618	885	1615	4167	2679	428	802	1697	952	9695	12340
100	2259	1509	1460	3325	595	1101	1784	4638	2749	532	955	1603	1099	10249	13360
Wharekohe sil	t loam Ft (SF	PR) (Means ad	djusted for cov	variates)											
	DM 1	DM 2	DM 3	DM 4	DM 5	DM 6	DM 7	DM 8	DM 9	DM 10	Dm 11	Dm 12	DM 13	YEAR 1	YEAR 2
Cut	26/9/91	24/10/91	23/11/91	13/2/92	2/6/92	29/7/92	25/9/92	20/11/92	6/1/93	8/3/93	27/4/93	18/6/93	24/7/93		
0															
20	2138	1685	1753	3338	594	1081	1889	4241	2582	527	975	1689	1067	10589	12970
40	2418	1595	1685	3160	569	1078	1755	4590	2788	534	706	1550	945	10505	12869
60	2065	1584	1569	3085	624	931	1657	4153	2763	487	715	1371	733	9857	11880
80	2147	1651	1519	3094	504	991	1772	4372	2923	499	769	1707	1059	9905	13100
100	2051	1537	1693	3235	635	1008	1894	4301	2811	482	898	1890	980	10158	13257
F pr. FxR	0.52	0.39	0.561	0,463	0.524	0.449	0.629	0.556	0.778	0.404	0.325	0.43	0.143	0.35	0.532
S.E.D. FxR	155.2	76.3	158.4	192.6	129.8	154.5	194.2	286.3	215.7	54.6	133.2	226.7	96.2	462.1	655.6
L.S.D. FxR	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

Harvest 5, pooled MCP grew more DM than pooled SPR, F Pr was 0.027, effect did not last. Harvest 13, significant rate effect ie 60 lower than 20, 80 and 100.

i) Aponga clay

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Grass					
	Harv1	Harv 5	Harv 7	Harv 9	Harv 12
Rate P	27/09/91	3/06/92	5/10/92	5/01/93	25/07/93
0	74.1	69.88	55.3	22.7	57.2
20	77.5	72	60	20.9	55.4
30	69.3	69.76	54.3	14.4	42.4
40	70.5	72.57	60.4	18	49.2
50	64.2	73.1	60.9	18.5	55.2
60	69.1	70.28	56.3	16	41.6
80	69.4	71.83	68.2	23	51.9
100	69.8	73.96	59.7	22.1	47.7
F pr. trt	0.811	0.939	0.461	0.586	0.729
S.E.D.	7.67	3.928	6.19	5	10.6
L.S.D.	ns	ns	ns	ns	ns

Clover					
	Harv 1	Harv 5	Harv 7	Harv 9	Harv 12
Rate P	27/09/91	3/06/92	5/10/92	5/01/93	25/07/93
0	21.7	11.96	35.3	64.6	35.5
20	17.5	18.48	32.6	71.5	41.5
30	21.7	13.97	39.9	74.6	52.2
40	23.3	13.25	33.3	71.4	45.6
50	30.6	12.26	33.8	72.9	41.9
60	27.4	12.05	34.5	74.3	52.5
80	27.9	11.27	27.4	69.2	45.1
100	25.3	10.03	29.6	64.5	41.2
F pr. trt	0.661	0.428	0.64	0.493	0.692
S.E.D.	7.05	3.512	6.15	5.79	9.91
L.S.D.	ns	ns	ns	ns	ns

Lotus								
	Harv1	Harv 5	Harv 7	Harv 9	Harv 12			
Rate P	27/09/91	3/06/92	5/10/92	5/01/93	25/07/93			
0	0	0	0	0	0			
20	0	0	0	0	0			
30	0	0	0	0	0			
40	0.11	0	0	0	0			
50	0.84	0	0	0	0			
60	0	0	0.0434	0	0			
80	0	0.259	0	0	0			
100	0	0	0	0	0			
atistical analysis inanoropriate								

Statistical analysis inappropriate.
Weeds						
	Harv1	Harv 5	Harv 7	Harv 9	Harv 12	Harv 12
Rate P	27/09/91	3/06/92	5/10/92	5/01/93	25/07/93	sformation
0	2.87	7.93	7.9	8.7	7.26	14.58
20	3.48	0.94	5.6	2.8	2.71	9.18
30	7.41	7.99	3.7	7	5.15	12.77
40	4.36	3.89	5	5.8	4.9	11.54
50	3.24	3.87	3.7	4.7	2.34	8.46
60	1.83	7.54	7.4	4.9	5.84	13.54
80	1.24	3.29	2.5	1	2.59	9.07
100	3.02	5.05	9.3	9.4	10.69	18.72
F pr. trt	0.469	0.174	0.809	0.469	0.059	0.047
S.E.D.	2.671	2.809	4.63	4.08	2.596	3.069
L.S.D.	ns	ns	ns	ns	ns	6.38352

Harv 12, Angular transformation, significant quadratic trend, but a bit nonsensical.

Dead					
	Harv1	Harv 5	Harv 7	Harv 9	Harv 12
Rate P	27/09/91	3/06/92	5/10/92	5/01/93	25/07/93
0	1.4	10.23	1.51	3.97	0.092
20	1.53	8.58	1.81	4.88	0.428
30	1.59	8.29	2.15	3.89	0.292
40	1.72	10.29	1.33	4.79	0.29
50	1.11	10.78	1.56	3.83	0.511
60	1.73	10.13	1.8	4.73	0.149
80	1.49	13.35	1.85	6.83	0.32
100	1.85	10.95	1.52	3.98	0.433
F pr. trt	0.941	0.529	0.807	0.442	NA
S.E.D.	0.584	2.33	0.505	1.394	NA
L.S.D.	ns	ns	ns		NA

ii) Wharekohe sandy loam

Grass						
	Harv 1	Harv 5	Harv 8	Harv 9	Harv 10	Harv 14
Rate P	24/09/91	13/05/92	16/10/92	7/12/92	11/01/93	27/07/93
0	50.5	39.9	61.6	71.9	45.8	87.4
20	52.7	33.6	70.3	73.2	48.4	81.3
30	46.6	34.6	65.4	67.7	49	75.7
40	55.5	24.5	64.7	65.6	42	77.9
50	63.1	29.8	61	68.8	43	81.6
60	63	31.8	71.1	74.9	56.3	87.2
70	53.9	38.2	64.2	62.4	37.8	79.3
80	57.9	40.3	72.9	70.5	50.3	83.3
100	60.1	31.5	65.3	63.3	37.9	75.5
F pr. trt	0.175	0.469	0.231	0.671	0.25	0.699
S.E.D.	6.25	7.29	4.93	7.26	7.26	7.54
L.S.D.	ns	ns	ns	ns	ns	ns

Clover						
	Harv 1	Harv 5	Harv 8	Harv 9	Harv 10	Harv 14
Rate P	24/09/91	13/05/92	16/10/92	7/12/92	11/01/93	27/07/93
0	47	45.2	33.6	18.1	42.2	11.5
20	41.9	48.7	24.3	17.6	35.2	15.9
30	46.5	51.2	29.8	21	31.1	19.9
40	40.5	55.9	27.5	23.1	45.7	17.6
50	31.7	51.9	30.2	18.4	33.1	14.8
60	33.8	56.9	26	11.8	32.3	11.1
70	36.5	43.8	22.1	17.5	36.9	18.2
80	36.4	40.5	21.3	19.5	34.9	12.8
100	31.3	47.2	22.9	22.8	43	19.5
F pr. trt	0.292	0.086	0.287	0.72	0.105	0.793
S.E.D.	7.34	5.39	5.16	5.92	5.3	6.3
L.S.D.	ns	ns	ns	ns	ns	ns

Lotus						
	Harv 1	Harv 5	Harv 8	Harv 9	Harv 10	Harv 14
Rate P	24/09/91	13/05/92	16/10/92	7/12/92	11/01/93	27/07/93
0	-0.07	-0.037	-0.07	0.04	0.003	-0.041
20	0.16	0	0	0	0	0
30	0.7	0	0	0	0.055	0.226
40	0.12	0.528	0.17	1.52	0	0.437
50	0.25	0.169	0.26	0.35	0.301	0.15
60	0.78	0	0	1.28	0.123	0
70	0.48	0.101	0.27	0	0.05	0
80	0.49	0	0	0	0	0.048
100	2.46	0.088	1.98	1.15	0.34	0.281

Statistical analysis inappropriate.

Weeds						
	Harv 1	Harv 5	Harv 8	Harv 9	Harv 10	Harv 14
Rate P	24/09/91	13/05/92	16/10/92	7/12/92	11/01/93	27/07/93
0	0.62	2.12	1.42	4.4	8.4	1.11
20	3.96	3.96	2.79	4.5	12	2.81
30	4.59	2.6	1.95	5.9	15.5	4.17
40	1.88	8.51	4.61	3.8	8.2	4.01
50	1.58	6.36	6.45	8.6	19.7	3.47
60	0.93	1.53	0.59	5.8	7.5	1.74
70	7.86	6.77	10.58	14.8	20.4	2.45
80	3.37	5.86	3.31	4.9	10.4	3.82
100	4.05	10.06	7.22	9	15.4	4.78
F pr. trt	0.582	0.425	0.272	0.444	0.873	0.543
S.E.D.	3.514	4.062	3.938	4.88	10.29	1.82
L.S.D.	ns	ns	ns	ns	ns	ns

% Weeds needed to be transformed, angular transformation used but still no significant differences, so table of means above are untransformed.

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Dead						
	Harv 1	Harv 5	Harv 8	Harv 9	Harv 10	Harv 14
Rate P	24/09/91	13/05/92	16/10/92	7/12/92	11/01/93	27/07/93
0	1.87	12.8	3.49	5.58	3.59	0
20	1.28	13.73	2.64	4.77	4.42	0
30	1.59	11.58	2.9	5.46	4.38	0
40	2.05	10.58	3.01	5.96	4.06	0
50	3.45	11.74	2.08	3.82	3.8	0
60	1.44	9.74	2.31	6.14	3.77	0
70	1.24	11.09	2.85	5.31	4.93	0
80	1.8	13.31	2.48	5.24	4.44	0
100	2.1	11.13	2.56	3.68	3.39	0
F pr. trt	0.009	0.67	0.701	0.596	0.892	NA
S.E.D.	0.503	2.179	0.71	1.355	1.063	NA
L.S.D.	1.043	ns	ns	ns	ns	NA

Harv 1 significance nonsensical.

iii) Wharekohe silt loam NFt

Harv 1	Harv 5	Harv 7	Harv 9	Harv 12
30/09/91	27/05/92	29/09/92	1/03/93	26/07/93
79.2	20.09	41.6	24.4	69.9
73.2	18.78	38.4	26.5	73.4
76.5	13.58	36.7	29.5	74.2
76.7	12.25	31	24.8	73.7
67.5	14.84	40.6	29	71.8
72.6	16.38	40	27.8	73.8
76.1	15.32	41.1	32.6	74.1
70.7	17.45	46.8	29.1	69
77	14.57	52.9	36	68.2
0.817	0.346	0.014	0.71	0.915
7.1	3.251	4.87	6.35	5.39
ns	ns	10.076	ns	ns
	Harv 1 30/09/91 79.2 73.2 76.5 76.7 67.5 72.6 76.1 70.7 77 0.817 7.1 ns	Harv 1 Harv 5 30/09/91 27/05/92 79.2 20.09 73.2 18.78 76.5 13.58 76.7 12.25 67.5 14.84 72.6 16.38 76.1 15.32 70.7 17.45 77 14.57 0.817 0.346 7.1 3.251 ns ns	Harv 1Harv 5Harv 730/09/9127/05/9229/09/9279.220.0941.673.218.7838.476.513.5836.776.712.253167.514.8440.672.616.384076.115.3241.170.717.4546.87714.5752.90.8170.3460.0147.13.2514.87nsns10.076	Harv 1Harv 5Harv 7Harv 930/09/9127/05/9229/09/921/03/9379.220.0941.624.473.218.7838.426.576.513.5836.729.576.712.253124.867.514.8440.62972.616.384027.876.115.3241.132.670.717.4546.829.17714.5752.9360.8170.3460.0140.717.13.2514.876.35nsns10.076ns

Harv 7, F test Significant Lin and Quad Trend for increasing %grass with increasing P.

Clover					
	Harv 1	Harv 5	Harv 7	Harv 9	Harv 12
Rate P	30/09/91	27/05/92	29/09/92	1/03/93	26/07/93
0	11	60.76	45.7	22.4	24.5
20	15.9	54.02	48.9	23.1	24.6
30	13	66.24	47.6	17.3	23.1
40	13.5	67.19	53.4	23.2	24.2
50	23.2	65.14	50.9	26.4	24.5
60	15.6	65.6	46.9	21.2	23.3
70	14.3	62.43	45.5	21.6	23.6
80	20.2	62.83	40	17.1	25.5
100	9.2	70.26	36	22	29.9
F pr. trt	0.517	0.039	0.038	0.804	0.938
S.E.D.	6.4	4.129	4.7	5.51	4.95
L.S.D.	ns	8.5429	9.724	ns	ns

Harv 5, Significant lin. trend for increasing clover with increasing P. Harv 7, Significant lin. and quad. trend for decreasing clover with increasing P.

Lotus					
	Harv 1	Harv 5	Harv 7	Harv 9	Harv 12
Rate P	30/09/91	27/05/92	29/09/92	1/03/93	26/07/93
0	1.6	0	0.17	0.205	0
20	0.76	0.12	0.22	0	0
30	0.22	0.1	1.32	0	0
40	0.89	1.33	1.94	0	0
50	0.44	0	0	0.264	0
60	5.25	0.52	0.68	-0.02	0
70	3.75	0.81	0.92	0	0
80	0.49	0.77	1.12	0	0
100	2.24	0.14	0	0	0

Statistical analysis inappropriate.

Weeds					
	Harv 1	Harv 5	Harv 7	Harv 9	Harv 12
Rate P	30/09/91	27/05/92	29/09/92	1/03/93	26/07/93
0	4.75	13.96	12.03	36.3	5.44
20	7.21	23.82	11.97	36	1.45
30	5.62	17.75	13.97	37.2	2.52
40	5.25	16.58	13.04	34.3	1.58
50	5.67	17.77	7.81	30.6	3.37
60	4.19	15.54	11.8	34.6	2.67
70	2.58	18.77	12.09	25.3	2.14
80	5.87	16.86	11.48	35.2	5.37
100	7.02	12.42	10.28	23.3	1.58
F pr. trt	0.598	0.23	0.509	0.474	0.028
S.E.D.	2.225	3.793	2.559	7.18	1.325
L.S.D.	ns	ns	ns	ns	2.74

Harv 12, Although F significant, a look at the data reveals that 0=80 and significance is nonsensical bought about by small percentages involved and nature of weed pieces ie one big heavy piece can double % weeds.

Dead					
	Harv 1	Harv 5	Harv 7	Harv 9	Harv 12
Rate P	30/09/91	27/05/92	29/09/92	1/03/93	26/07/93
0	3.41	5.19	0.516	16.76	0.204
20	2.94	3.26	0.502	14.4	0.484
30	4.73	2.32	0.328	16.04	0.215
40	3.66	2.64	0.547	17.67	0.478
50	3.17	2.25	0.691	13.67	0.384
60	2.4	1.97	0.668	16.42	0.224
70	3.26	2.66	0.464	20.56	0.173
80	2.78	2.09	0.603	18.57	0.15
100	4.52	2.6	0.738	18.7	0.29
F pr. trt	0.199	0.052	0.729	0.454	0.669
S.E.D.	0.88	0.905	0.2245	3.052	0.2138
L.S.D.	ns	ns	ns	ns	ns

MCP Treatments Only Adjusted for covariates

Grass					
	Harv 1	Harv 5	Harv 7	Harv 9	Harv 13
Rate P	26/09/91	2/06/92	25/09/92	6/01/93	24/07/93
0	70.8	35.7	60.5	35	80.8
20	67.6	34.7	53.3	38.5	83.2
30	67.4	25.8	53.3	36.6	83.3
40	70.3	34.8	60.5	38.9	79.8
50	64.8	30.7	50.7	40.1	84.6
60	65.9	32.7	54	33.8	89
70	71.3	33.9	53	37.5	84.4
80	65.5	32.5	59.6	24.8	73.9
100	72.4	34.2	55	43.1	80.7
F pr. trt	0.906	0.602	0.746	0.421	0.231
S.E.D.	6.44	4.8	6.23	7.01	4.91
L.S.D.	ns	ns	ns	ns	ns
Clover					
	Harv 1	Harv 5	Harv 7	Harv 9	Harv 13
Rate P	26/09/91	2/06/92	25/09/92	6/01/93	24/07/93
0	17.5	46.12	26.21	23.8	15
20	22.8	49.97	33.5	33.2	13.33
30	19.9	54.33	31.43	17.3	14.36

20	22.8	49.97	33.5	33.2	13.33
30	19.9	54.33	31.43	17.3	14.36
40	18.2	52.36	29.48	27	16.69
50	24.9	53.48	34.91	25	14.12
60	21.6	48.04	33.14	31.3	9.14
70	19.4	47.32	30.64	25.6	13.78
80	21.6	46.76	26.55	15.3	23.05
100	17.9	52.32	32.94	20.8	16.1
F pr. trt	0.941	0.401	0.399	0.262	0.216
S.E.D.	6.23	4.293	4.084	7.34	4.319
L.S.D.	ns	ns	ns	ns	ns

Lotus					
	Harv 1	Harv 5	Harv 7	Harv 9	Harv 13
Rate P	26/09/91	2/06/92	25/09/92	6/01/93	24/07/93
0	0.67	0.09	0.01	-0.02	0.071
20	1.76	0.48	1.73	1.32	0.055
30	0.53	0.33	0.37	0.3	0.01
40	-0.69	-0.47	-0.44	0.17	-0.008
50	0.68	0.28	0.48	0.36	0.018
60	2.75	0.29	0.7	-0.29	-0.004
70	0.66	0.41	0.94	0.58	0.214
80	1.35	0.73	1.56	0.5	0.151
100	0.98	0.28	0.71	0.46	0.102
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Statistical analysis inappropriate.

Weeds					
	Harv 1	Harv 5	Harv 7	Harv 9	Harv 13
Rate P	26/09/91	2/06/92	25/09/92	6/01/93	24/07/93
0	8.19	16.94	12.19	39.2	3.97
20	5.01	12.8	10.49	25.9	3.17
30	8.93	18.07	13.41	44.7	2.21
40	10.02	11.77	9.46	32.2	3.28
50	7.26	14.01	12.8	33.2	1.2
60	6.8	17.14	10.89	33.8	1.67
70	5.49	16.41	14.49	34.4	1.37
80	9.59	18.14	11.66	58.1	2.88
100	5.88	11.11	10.57	33.1	2.72
F pr. trt	0.867	0.309	0.971	0.192	0.676
S.E.D.	3.712	3.539	4.238	10.91	1.563
L.S.D.	ns	ns	ns	ns	ns

Harv 1	Harv 5	Harv 7	Harv 9	Harv 13
26/09/91	2/06/92	25/09/92	6/01/93	24/07/93
2.83	1.17	1.11	1.97	0.165
2.86	2.01	1.015	1.17	0.25
3.25	1.47	1.49	1.04	0.082
2.09	1.53	1.019	1.76	0.238
2.32	1.55	1.147	1.48	0.053
2.98	1.78	1.281	1.17	0.149
3.19	1.97	0.923	1.97	0.194
1.96	1.91	0.668	1.29	0.043
2.78	2.11	0.773	2.59	0.427
0.802	0.903	0.663	0.106	0.404
0.861	0.695	0.4201	0.524	0.1633
ns	ns	ns	ns	ns
	Harv 1 26/09/91 2.83 2.86 3.25 2.09 2.32 2.98 3.19 1.96 2.78 0.802 0.861 ns	Harv 1 Harv 5 26/09/91 2/06/92 2.83 1.17 2.86 2.01 3.25 1.47 2.09 1.53 2.32 1.55 2.98 1.78 3.19 1.97 1.96 1.91 2.78 2.11 0.802 0.903 0.861 0.695 ns ns	Harv 1Harv 5Harv 726/09/912/06/9225/09/922.831.171.112.862.011.0153.251.471.492.091.531.0192.321.551.1472.981.781.2813.191.970.9231.961.910.6682.782.110.7730.8020.9030.6630.8610.6950.4201nsnsns	Harv 1Harv 5Harv 7Harv 926/09/912/06/9225/09/926/01/932.831.171.111.972.862.011.0151.173.251.471.491.042.091.531.0191.762.321.551.1471.482.981.781.2811.173.191.970.9231.971.961.910.6681.292.782.110.7732.590.8020.9030.6630.1060.8610.6950.42010.524nsnsnsnsns

v) Wharekohe silt loam Ft, MCP vs SPR

Analysis of variance adjusted for covariates

Grass										
	Harv 1		Harv 5		Harv 7		Harv 9		Harv 13	
Rate P	26/09/91		2/06/92		25/09/92		6/01/93		24/07/93	
	MCP	SPR	MCP	SPR	MCP	SPR	MCP	SPR	MCP	SPR
20	67	68.8	34.91	36.79	53.3	60.2	38.7	37.7	83.3	87.1
40	69	62.1	36.06	32.2	61	48.7	39.9	28.3	80	78.8
60	65.4	68.3	32.91	29.84	54.1	54	34	32.7	89.2	82.8
80	64.5	66.5	32.79	26.28	59.5	48.9	25.2	33	74.1	70.8
100	72.9	69.6	32.18	33.87	53.7	58.6	41.7	38.1	80.9	83.3
F pr. RxF	0.607		0.433		0.083		0.384		0.595	
SED RxF	5.21		3.471		5.3		6.87		4.95	
L.S.D.	ns		ns		ns		ns		ns	

RxF is Rate X Fertiliser Type

Clover										
	Harv 1		Harv 5		Harv 7		Harv 9		Harv 13	
Rate P	26/09/91		2/06/92		25/09/92		6/01/93		24/07/93	
	MCP	SPR	MCP	SPR	MCP	SPR	MCP	SPR	MCP	SPR
20	23.3	20.1	49.83	50.09	33.56	27.31	33.3	24.5	13.2	10.67
40	20.4	21.8	52.07	43.2	29.82	31.36	26.4	23.2	16.59	17.57
60	22	23.6	47.96	49.42	33.2	27.8	31.5	26.3	9.02	13.36
80	22.7	22.9	46.44	52.64	26.67	31.37	15.2	27.2	22.87	27.08
100	15.7	21.4	52.15	50.68	32.46	28.03	22.1	25.5	15.81	15.71
F pr. RxF	0.764		0.115		0.383		0.238		0.77	
SED RxF	4.92		3.929		4.404		6.91		4.353	
L.S.D.	ns		ns		ns		ns		ns	

RxF is Rate X Fertiliser Type

Harv 13 rate was significant ie F pr 0.045 and <0.001 for quadratic component but this dif not picked up in MCP analysis.

Harv 1		Harv 5		Harv 7		Harv 9		Harv 13	
26/09/91		2/06/92		25/09/92		6/01/93		24/07/93	
MCP	SPR	MCP	SPR	MCP	SPR	MCP	SPR	MCP	SPR
1.74	1.76	0.49	0.27	1.7	1.77	1.32	0.86	0.055	-0.018
-0.67	0.18	-0.45	0	-0.46	0.08	0.32	-0.09	0.014	0.011
2.73	0.52	0.3	0.38	0.68	0.25	-0.14	0.17	-0.004	0.005
1.33	0.76	0.74	0.49	1.49	0.56	0.52	1.02	0.156	0.018
0.85	0.71	0.24	0.78	0.57	0.65	0.14	0.38	0.058	0.062
NA		NA		NA		NA		NA	
NA		NA		NA		NA		NA	
NA		NA		NA		NA		NA	
	Harv 1 26/09/91 MCP 1.74 -0.67 2.73 1.33 0.85 NA NA NA	Harv 1 26/09/91 MCP SPR 1.74 1.76 -0.67 0.18 2.73 0.52 1.33 0.76 0.85 0.71 NA NA NA	Harv 1Harv 526/09/912/06/92MCPSPR1.741.760.670.18-0.670.182.730.520.31.330.760.740.850.710.24NANANANANA	Harv 1 Harv 5 26/09/91 2/06/92 MCP SPR MCP SPR 1.74 1.76 0.49 0.27 -0.67 0.18 -0.45 0 2.73 0.52 0.3 0.38 1.33 0.76 0.74 0.49 0.85 0.71 0.24 0.78 NA NA NA NA NA NA	Harv 1Harv 5Harv 726/09/912/06/9225/09/92MCPSPRMCP1.741.760.490.271.741.760.490.27-0.670.18-0.4502.730.520.30.380.850.710.240.780.850.710.240.78NANANANANANA	Harv 1Harv 5Harv 726/09/912/06/9225/09/92MCPSPRMCPSPR1.741.760.490.271.7-0.670.18-0.450-0.460.082.730.520.30.380.680.251.330.760.740.491.490.560.850.710.240.780.570.65NANANANANANANANA	Harv 1Harv 5Harv 7Harv 926/09/912/06/9225/09/926/01/93MCPSPRMCPSPRMCP1.741.760.490.271.71.771.741.760.490.271.71.77-0.670.18-0.450-0.460.080.322.730.520.30.380.680.25-0.141.330.760.740.491.490.560.520.850.710.240.780.570.650.14NANANANANANANANANANA	Harv 1 Harv 5 Harv 7 Harv 9 26/09/91 2/06/92 25/09/92 6/01/93 MCP SPR MCP SPR MCP SPR MCP SPR 1.74 1.76 0.49 0.27 1.7 1.77 1.32 0.86 -0.67 0.18 -0.45 0 -0.46 0.08 0.32 -0.09 2.73 0.52 0.3 0.38 0.68 0.25 -0.14 0.17 1.33 0.76 0.74 0.49 1.49 0.56 0.52 1.02 0.85 0.71 0.24 0.78 0.57 0.65 0.14 0.38 NA NA NA NA NA NA NA NA NA NA NA NA NA	Harv 1Harv 5Harv 7Harv 9Harv 1326/09/912/06/9225/09/926/01/9324/07/93MCPSPRMCPSPRMCPSPRMCP1.741.760.490.271.71.771.320.860.055-0.670.18-0.450-0.460.080.32-0.090.0142.730.520.30.380.680.25-0.140.17-0.0041.330.760.740.491.490.560.521.020.1560.850.710.240.780.570.650.140.380.058NANANANANANANANANANANANANANA

RxF is Rate X Fertiliser Type

Weed										
	Harv 1		Harv 5		Harv 7		Harv 9		Harv 13	
Rate P	26/09/91		2/06/92		25/09/92		6/01/93		24/07/93	
	MCP	SPR	MCP	SPR	MCP	SPR	MCP	SPR	MCP	SPR
20	5.04	5.83	12.76	11.96	10.42	9.82	25.5	35.2	3.14	1.8
40	8.96	14.09	10.8	22.67	8.49	19.34	31.3	46.7	3.14	3.44
60	6.84	5.54	17.06	18.57	10.76	17.19	33.4	39	1.65	3.62
80	9.41	7.2	18.07	17.88	11.6	17.22	57.7	37.6	2.8	1.95
100	8.04	5.58	13.16	13.72	12.63	11.67	33.8	34.8	2.85	0.78
Fpr. RxF	0.657		0.219		0.391		0.143		0.411	
SED RxF	4.063		4.13		4.49		10.23		1.574	
L.S.D.	ns		ns		ns		ns		ns	

RxF is Rate X Fertiliser Type

For harvest 7, F value for Fert type was significant ie SPR significant higher weed content than MCP overall. ie F pr for fert was 0.046 for SPR higher than MCP.

Dead										
	Harv 1		Harv 5		Harv 7		Harv 9		Harv 13	
Rate P	26/09/91		2/06/92		25/09/92		6/01/93		24/07/93	
	MCP	SPR	MCP	SPR	MCP	SPR	MCP	SPR	MCP	SPR
20	2.91	3.5	2.02	0.9	1.03	0.88	1.23	1.83	0.261	0.411
40	2.32	1.87	1.51	1.92	1.12	0.51	2.06	1.93	0.259	0.144
60	3.03	2.02	1.78	1.79	1.29	0.75	1.21	1.88	0.158	0.232
80	2.06	2.62	1.96	2.71	0.71	1.97	1.44	1.28	0.06	0.18
100	2.51	2.66	2.27	0.95	0.64	1.04	2.29	1.27	0.424	0.116
F pr. RxF	0.709		0.454		0.046		0.205		0.367	
SED RxF	0.958		0.883		0.479		0.566		0.1894	
L.S.D.	ns		ns		0.98674		ns			

RxF is Rate X Fertiliser Type

Harv 7 significant interaction probably not a real effect.

Appendix 7.3 Monthly rainfall (mm) at the Kaikohe Research Station for the two year trial period (3 months prior to trial start in brackets).

Month	1991	1992	1993
January	-	80	24
February	-	45	61
March	-	53	25
April	-	54	292
May	(26)	161	124
June	(141)	149	126
July	(179)	295	26
August	183	251	-
September	224	198	
October	93	128	
November	55	110	-
December	69	116	-

Appendix 8.1

Derivation of Equation 2

d P(t)

Rate of P Accumulation = K - a. P(t)

....

or
$$\frac{d P(t)}{d(t)} = K - a. P(t)$$
(1)

SO

so
$$\frac{1}{K-a.P(t)} = d(t)$$

then $-\frac{1}{a} ln(K-a.P(t)) = t + c$ where c is an arbitrary constant
and $ln(K-a.P(t)) = -at - ac$
and $K-a.P(t) = exp^{-at-ac}$
and $-a.P(t) = -K + exp^{-at-ac}$
and $P(t) = \frac{K}{a} - \frac{exp^{-at-ac}}{a}$

which is in the form $P(t) = F - Ge^{-at}$

where $F = \frac{K}{a}$, $G = \frac{e^{-ac}}{a}$

At time 0, P(t) = F-G and if this is 0 (which it is), G=F

 $P(t) = G - Ge^{-at}$ and so

Therefore $P(t) = G(1 - e^{-a.t})$

Where:

- P(t)is the amount of P which has accumulated in the soil following pasture development for a given pasture age (kg/ha).
- 1 is the pasture age (years).
- K is a constant corresponding to the rate of P accumulation at age 0.
- is the rate constant. a
- G is the maximum amount of P which can accumulate in the soil following pasture development (kg/ha).

(2)