PHOSPHATE CYCLING IN GRAZED HILL-COUNTRY PASTURE

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ABSTRACT

A detailed study of the "above-" and "below-ground" components of the phosphorus (P) cycle was carried out in the North Island hill country of New Zealand. The effect of P fertiliser rate and degree of land-slope on pasture P uptake, faecal P return and changes in soil P fractions was examined over a three year period.

Plant P uptake was found to decrease with increasing slope and increase with increasing rate of P fertiliser. The changes in plant P uptake were a function of changes in both dry matter yield and pasture P concentration. Pasture on campsites which initially had a high Olsen P status (>30) showed an unexpected apparent P response in both dry matter yield and plant P uptake. This response results from an artefact of the trial design whereby P fertiliser was applied to whole paddocks. The resulting improved nitrogen status of slopes at high rates of P fertiliser created abnormally high soil nitrogen levels on campsites, leading to very high levels of production. These findings are of significance in relation to soil fertility field trials conducted on individual slopes in hill country. Over the three year period of the trial seasonal plant P uptake followed the order: spring ≥ summer > autumn > winter, irrespective of slope category, fertiliser rate or grazing regime.

The distribution of faecal material was found to be markedly affected by slope and approximately 60% of the material deposited in each paddock was returned to campsites. In the remainder of the paddock, faecal P return decreased by at least 50% with each 10° increase in slope.

Paddock faecal P concentration (FP%) was predicted from the pre-grazed pasture P concentration (PP%) (calculated on a paddock basis) using the relationship:

$$FP\% = 3.19\ PP\% - 0.09\ (r = 0.94\ {**}).$$

Net P balance calculations for various slope group categories showed that deficits between plant P uptake and faecal P return increased with increasing slope but were little affected by increasing P fertiliser rate and consequent increase in stocking rate. This finding verifies the use of a single animal loss factor for a given topography, irrespective of sheep stocking rate, in the Ministry of Agriculture's (MAF's) Computerised Fertiliser Advisory Scheme (CFAS) for P.

Measurements of faecal distribution in this trial suggested the use of a lower animal loss factor (0.5 kg su^{-1} of P) for "Easy" hill country than that used currently (0.7 kg su^{-1} of P) in the CFAS model.

Independent studies on the rate of P cycling from faeces were conducted. The study investigating breakdown of faecal material revealed that physical disintegration of faecal material is likely to occur before chemical decomposition. In winter conditions faecal material disintegrated within a month; in summer conditions disintegration took approximately three months. In both seasons material on campsites disintegrated more rapidly than that on steeper slopes.

A further study using radioisotopes in the field found that the short-term plant availability of inorganic faecal P was approximately half that of monocalcium phosphate fertiliser over a two month period in the spring.

In a study on the "below-ground" components of the P cycle total soil P was found to increase with increasing rate of P fertiliser. The magnitude of these increases decreased with increasing slope and depth.

Increases in organic P were found to be higher on campsites than steeper slopes. On campsites, the extent of increase in organic P decreased with increasing rate of P fertiliser.

Inorganic P increased with increasing rate of P fertiliser on all slopes; the magnitude of the increase decreased with increasing slope. At low rates of P fertiliser a decrease in inorganic P was measured on steep-slopes over time indicating that P inputs were not balancing P outputs.

A change in the non-occluded P fraction accounted for the greatest proportion of the change in inorganic P on most slopes. The fact that calcium-bound P accumulated on all slopes, and that large increases were evident at high rates of P fertiliser suggested that this fraction was not playing an active part in the P cycle but was accumulating as an insoluble residue from superphosphate.

The plant availability of soil P fractions was investigated in a glasshouse study. Total plant P uptake was found to be highly correlated with initial levels of total P ($r = 0.92$),non-occluded P ($r = 0.82$), inorganic P ($r = 0.91$), Olsen P ($r = 0.93$) and water-extractable P ($r = 0.97$). Levels of organic P, occluded P and calcium-bound P were found to be essentially unchanged by plant growth over the eleven month trial period.

Changes in the size of the cycling soil P pool were examined by combining results from the field trial with those from the glasshouse study. At low rates of P fertiliser (10 kg ha^{-1}), increases in occluded P and calcium-bound P (i.e., unavailable inorganic P) in the 0-15 cm depth were occurring at the expense of available P. At a high rate of P fertiliser (100 kg ha^{-1}) approximately two thirds of the P applied remained in the available form.

On an annual basis, Olsen P increased with an increasing rate of P fertiliser and decreased with increasing soil depth and slope. Over the period of the trial Olsen P decreased significantly at the lowest rate of P fertiliser (10 kg ha^{-1}) and increased significantly at the highest rate (100 kg ha^{-1}) on the two slope groups studied. This indicated that these areas were not at "equilibrium" as defined by a stable Olsen P. At moderate rates of P fertiliser (20 and 30 kg ha^{-1})

it was not possible to determine whether or not equilibrium conditions existed as the annual variability in Olsen P was too high.

An attempt was made to determine soil P losses (as defined by the CFAS model) at the trial site. Despite intensive and careful soil sampling Olsen P could not be used to determine "equilibrium" conditions which are a pre-requisite for measurement of soil P loss. This finding prevented validation of soil loss factors on this hill-country site.

Data generated from the large field trial for "above-" and "below-ground" components of the P cycle enabled recommendations to be made on the location of suitable soil sampling sites and also on the location of priority areas for application of P fertiliser in grazed hill country.

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CHAPTER 1

INTRODUCTION

Phosphorus (P) is a constituent of all living organisms. It is believed to be the most important element ecologically (Hutchinson, 1970) because:

(a) it is concentrated by living organisms to levels considerably above that of P sources

(b) it functions as an agent of energy transfer

(c) a deficiency of available P is more likely to limit reproduction, and hence productivity, than any other material except water.

Phosphorus is not found in its elemental form in nature, but occurs principally as orthophosphate (PO_4^{3-}). Transformations during pedogenesis convert apatite P (general formula $Ca_{10}(PO_4)_6F_2$) to organic P (P_O) and secondary forms of inorganic P (P_I) (Syers and Walker, 1969a and b; Syers et al., 1969). The primary P (apatite) tends to be found in the sand fraction of the soil whereas the secondary forms accumulate in the finer textured fractions of the soil (Williams and Saunders, 1956; Halstead, 1967; Syers et al., 1969).

In intensively-grazed pastoral systems, such as those found in New Zealand, the greatest proportion of total P in the P cycle at any one time is contained in the soil. It is, however, the "above-ground" components of the P cycle that appear to have the greatest effect on the efficiency of the cycle (Karlovsky, 1975) and offer the greatest scope for manipulation (Gillingham, 1978).

Recent rapidly escalating costs of on-ground P fertiliser in New Zealand have resulted in a change of emphasis by farmers from "maximum production" to "economically efficient production". Manipulation of the "above-ground" components of the P cycle could allow more efficient production to be achieved.

In the past, New Zealand farmers had access to cheap P fertiliser. Prior to 1963 much of New Zealand was in a development phase and increasing rates of P fertiliser addition allowed an increase in stocking rate. The amount of P added per ewe equivalent varied little during this time (e.g., 1.14 kg P in 1950 and 1.19 kg P in 1963). However, between 1963 and 1966 the consumption of P fertilisers increased 50% (about half a million tonnes of superphosphate) while stock numbers increased by only 11% (approximately seven million ewe equivalents). A further half a million tonnes increase in superphosphate usage between 1971 and 1974 was not associated with any increase in stocking rate.

The amount of P required per ewe equivalent has been calculated as being 1.32 - 1.33 kg per year (Karlovsky, 1975). Thus it is clear that during the 1960's and early 1970's P fertiliser considerably in excess of requirements was being applied to New Zealand pastures. More recently a dramatic decline in the use of P fertilisers means that rather less than this calculated requirement is being applied.

The level of P fertiliser addition required to maintain an efficient level of production (i.e., appropriate to the soil group and type of farm under consideration) can be determined by relating P fertiliser inputs to P output in products, plus other P losses. The latter category includes P effectively lost from the cycling pool by immobilisation or in runoff. To date there have been few studies in New Zealand on the effect of increasing stocking rate or pasture utilisation on P losses in animal products. Similarly, there has been little work carried out on the effect of increasing rate of P fertiliser addition on losses of P in the soil. Without this knowledge it is difficult to determine not only the required level of P fertiliser addition but also efficiency of production. Thus it is clear that an increased understanding of the P cycle must be gained.

To understand and quantify the P cycle for grazed pasture it is necessary to design a conceptual model to represent the main compartments and pathways. To do this more fully requires a knowledge of P chemistry and of the nature and sizes of the compartments, the pathways between them, the quantity and rate of transfer of P along these pathways, the reference time period, and definition of the area and boundaries of the system under consideration.

Though the total amounts of the different forms of P present in the various compartments of a P cycle can be determined relatively easily, the definition of transfer rates between compartments is rather more difficult. In systems in a state of flux it can be difficult to characterise P turnover as the net effects can obscure individual reaction rates. For this reason most of the few studies made on whole systems have been on systems at equilibrium where compartment levels are stable and rates of P movement can, therefore, be determined more readily. Furthermore, the systems chosen have generally had few P compartments and have thus been relatively simple, e.g., native grassland ecosystems (Halm et al., 1972; Cole et al., 1977).

Alternative approaches to the problem of obtaining data for modelling of the P cycle in more complex ecosystems, i.e., those involving the grazing animal, are to:

(a) construct a model using data available in the literature from investigations carried out on individual parts of the cycle (e.g., Blair et al., 1977).

(b) use a simplistic approach whereby product input can be related to product output (e.g., Cornforth and Sinclair, 1982a).

In the former case problems may arise in generalising if different parts of the cycle are studied in different countries where chemical and physical composition of "starting materials" and climatic conditions are likely to vary. In the latter case problems may arise if the cycle is oversimplified. Although simplification may make quantification easier, the results may be rendered site specific.

In New Zealand, the Computerised Fertiliser Advisory Scheme (CFAS) administered by the Ministry of Agriculture and Fisheries (MAF) is being used to advise farmers on the amount of P fertiliser that should be applied in the short term or for maintenance. The model is necessarily of the relatively simple type, relating product input and output, because insufficient studies have been carried out on components of the P cycle to enable a more detailed model to be constructed. This is particularly the case in hill country where the greatest need for economies of fertiliser are required.

An improved understanding of the P cycle offers, potentially, the most useful method for achieving economically efficient production by enabling knowledgeable manipulation of components and facilitating assessment of P fertiliser requirements. This approach involves evaluating "above-" and "below-ground" P losses in a grazed system.

The general objectives of the present study were to:

1. Monitor the effect of slope and rate of P fertiliser addition on changes in soil P pools with a view to:

    (a) defining changes in the magnitude of soil P fractions.

    (b) identifying those soil P pools which reflect changes in the "above-ground" components of the P cycle.

2. Monitor the effect of slope and rate of P fertiliser addition (i.e., increasing stocking rate) on the "above-ground" components of the P cycle with a view to establishing the relationship between plant P uptake and faecal P return.

3. Evaluate transfer rates between P inputs (i.e., faecal P and fertiliser P) and plant P via the soil.

4. Provide data with which to validate the CFAS model.

It was thus intended to provide an improved understanding of the dynamics of P cycling as influenced by fertiliser P input, grazing management and topography.

CHAPTER 2

REVIEW OF LITERATURE

2.1 INTRODUCTION

This review covers the major aspects of the P cycle with particular reference to fertilised hill-country pasture grazed by sheep in the North Island of New Zealand. The format of the review will follow the components of the P cycle as shown in Fig 2.1. Emphasis will be given to the larger P pools within the cycle and the rates of transfer between them. Finally, attempts to model part or all of the P cycle will be discussed.

2.2 SOIL PHOSPHORUS

2.2.1 Forms and reactions of soil phosphorus

Soil P may be classified conveniently into the two broad categories of organic P(P_O) and inorganic P(P_I).

2.2.1.1 Organic phosphorus

In most agricultural soils, P_O comprises from 30-80% of the total P present (Anderson, 1980). In some of these soils, particularly in tropical regions where high temperatures encourage rapid mineralisation (the release of P_I into the soil solution after

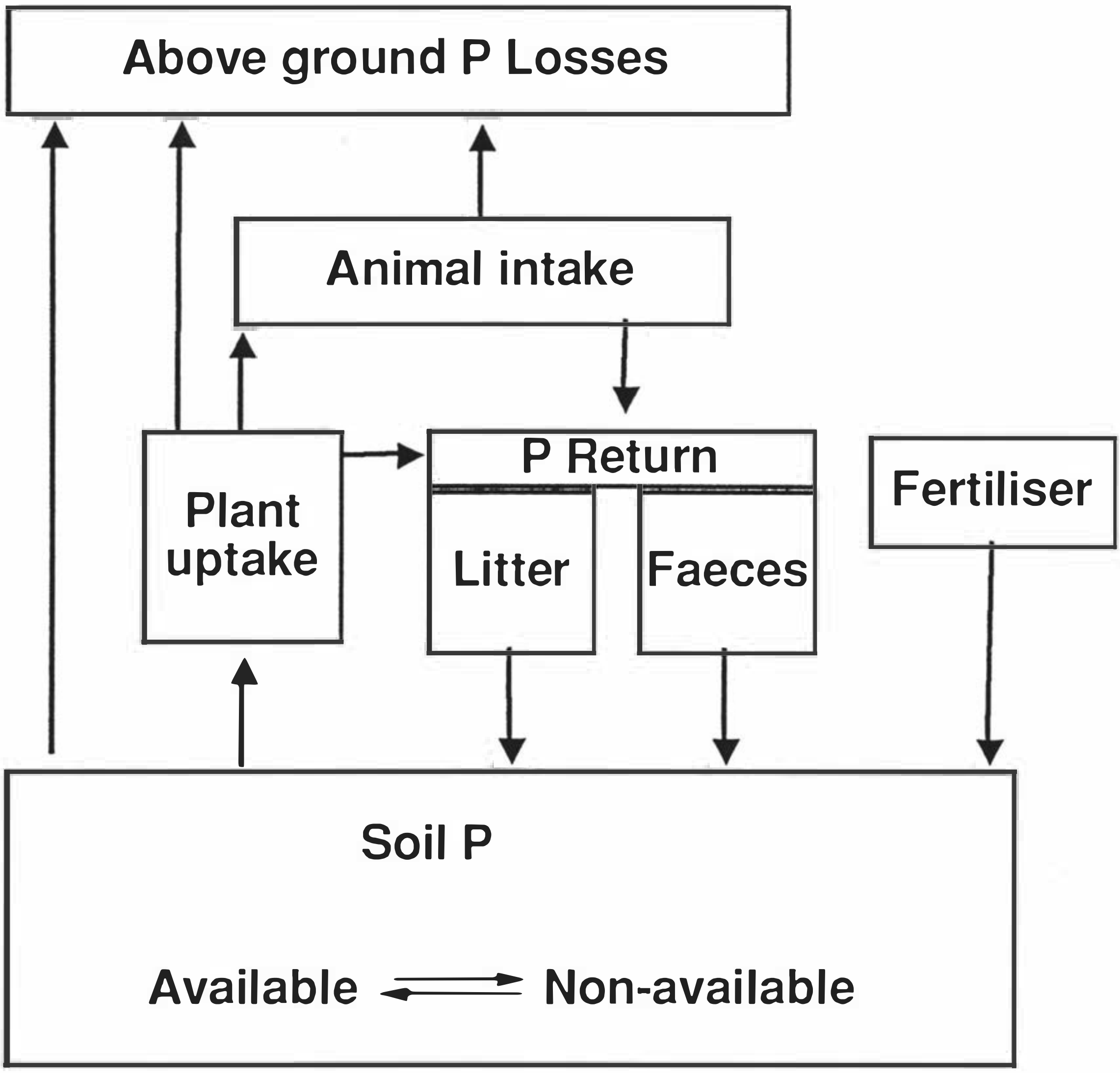

Figure 2.1 "Above-" and "below-ground" components of the P cycle in grazed, fertilised pasture.

microbial conversion of P_O), P_O can contribute considerably to the P nutrition of plants (Halm et al., 1972; Tate, 1984). This is unlikely to be the case in hill country where P_O levels are low (Gillingham, 1978) and the climate is temperate.

Organic P can also be present in the soil solution (Wild and Oke, 1966) and has been found to form over 80% of solution P in coarse-textured soils (Pierre and Parker, 1927). The plant availability of many of the P_O compounds commonly found in soil solutions has been demonstrated under aseptic conditions by several workers (for a review, see Dalal, 1977). As yet, however, there is no unequivocal evidence to prove that P_O is available to plants under field conditions. Consequently, P_O is usually considered to be unavailable for plant P uptake (Cosgrove, 1977).

The rate of increase in P_O is frequently limited by the rate of supply of available P_I. This is influenced by fertiliser application, animal returns and weathering of the parent material (Walker and Adams, 1958; McLachlan and Norman, 1962). In soils of low organic matter status and, perhaps more importantly, low carbon to nitrogen ratios, such as those generally found on New Zealand hill country, large quantities of applied fertiliser can be immobilised by the microbial population of the soil and thus rendered unavailable for plant uptake (Walker et al., 1959; Jackman, 1964; Rixon, 1966; Shelton and Coleman, 1968; Quin and Rickard, 1983). The rate of conversion to P_O declines as organic matter builds up in the soil until an equilibrium is reached between rates of mineralisation and immobilisation (the removal of P_I from the soil solution by microbial conversion) (During, 1972). The processes of mineralisation and immobilisation occur concurrently in the soil. The balance between the two processes is largely governed by the factors which control the population dynamics and activities of soil microorganisms, such as temperature, moisture, pH, fertiliser application, cultivation and the presence of plants. These factors have been reviewed by Dalal (1977). In summary, Dalal (1977) reported that increasing temperatures result in increased mineralisation and hence less net immobilisation. Suboptimal temperatures also decrease the rate of immobilisation due to reduced biological activity; suboptimal moisture has a similar effect. Increase in soil acidity can restrict P_O accumulation. Addition of fertiliser to native soil stimulates immobilisation whereas cultivation tends to result in net mineralisation. The type of vegetation supported also has an effect on P accumulation. For instance, it has been observed (Rixon, 1966) that P_O is significantly lower under Wimmera ryegrass than under clover or perennial ryegrass.

2.2.1.2 **Inorganic phosphorus**

The major sources of primary P in soils are the minerals of the apatite group $Ca_{10}(PO_4)_6Z_2$ where Z=F, OH, Cl, or 1/2 CO_3), particularly fluoropatite. The plant availability of these compounds is generally low and P release is dependent upon the rate of weathering. Thus under natural conditions soil apatite levels tend to decrease with age (Syers and Walker, 1969a and b, Smeck and Runge, 1971; Smeck, 1973; Walker and Syers, 1976; Tiessen et al., 1984) and increase with depth (Walker and Syers, 1976). As the rate of weathering of primary minerals is slow (Walker et al., 1969) and is generally considered to be inadequate to provide sufficient P for rapid plant growth, secondary forms of P_I (i.e., sorbed and precipitated P) become the most important regulators of the P in soil solution in most soils.

Aluminium, iron and calcium phosphate compounds are the main types of precipitated P found in soils (for a review see Sample et al., 1980). Evidence for the existence of these compounds in soils is often presented based on results of selective fractionation schemes, such as that of Chang and Jackson (1957). Such schemes, however, are not believed to differentiate adequately between precipitated and sorbed forms of P_I (Williams et al., 1967).

It has been suggested that P compounds are precipitated in soil as reaction products when water soluble fertiliser P compounds are added to the soil. However, very few studies have been carried out in which reaction productions of fertiliser P have been isolated from soil and identified successfully. Most compounds deemed likely as fertiliser reaction products have been isolated from simulations of the chemical environment surrounding a fertiliser particle.

As the fertiliser reaction products dissolve slowly with time, P will be released and so become available for plant uptake (Taylor et al., 1963). However, the rate of dissolution depends largely on the solubilities of the compounds, and given the complexity of the chemical composition of the soil solution, these solubilities are not easy to predict. There is also evidence in the literature to suggest that the reaction products are metastable and, in time, will change into more stable and less soluble P compounds (for a review, see Sample et al., 1980).

It is now believed that, except in recently fertilised soils, it is the balance between sorption and desorption reactions that governs the concentration of P in the soil solution, rather than the balance between precipitation and dissolution reactions (Syers and Iskander, 1981).

Adsorption of P refers to the process by which phosphate ions are removed from the soil solution and retained at the surfaces of soil components. When this process is followed by a more or less uniform penetration of the adsorbed P into the solid phase, the reaction is called absorption. As it is difficult to distinguish these two reactions (Glasstone, 1960; Larsen, 1967) the term "sorption", embracing both reactions, is often preferred.

Phosphate sorption by soils has been the subject of extensive reviews (e.g., Larsen, 1967; Ryden et al., 1973; Parfitt, 1978; Sample et al., 1980). It is generally agreed that short-range order and crystalline hydrous oxides of iron and aluminium and short-range order aluminosilicates are largely responsible for the phenomenon of P sorption (Saunders, 1965; Syers et al., 1971). These can occur as discrete compounds in soils or as coatings, particularly on clay minerals. They can also exist as short-range order aluminium hydroxy compounds between the layers of expandable aluminium silicates (Parfitt, 1978).

The mechanisms of P retention in soils by aluminium and iron compounds have not been resolved fully, but it is agreed that a fast reaction is followed by a slow one. Two contrasting explanations are currently in use for the initial reaction. Ryden et al. (1977) proposed that P is sorbed at three energetically different types or regions of sites. They suggested that at low levels of P concentration chemisorption, involving the replacement of OH_2 and OH groups on the surface (regions I and II), occurred by ligand exchange and possibly by the formation of binuclear or bridging compounds (Parfitt, 1977).

At high P concentrations more-physical sorption of P, involving a weaker bonding to the surface (region III), was suggested. In contrast, Bowden et al. (1977, 1980) have proposed that changes in the energy of P sorption can be explained by a progressive increase in surface negativity as sorption proceeds.

The slow sorption reaction has been explained variously as a precipitation reaction (Barrow, 1974), a shift from a monodentate to a bidentate form of sorbed P (Mattingly, 1975), absorption of surface sorbed P into soil components (Holford and Mattingly, 1976), and a shift from more-physically sorbed to chemisorbed P (Ryden et al., 1977). Recently, Barrow (1983) proposed that the initial rapid P sorption reaction induces a diffusion gradient towards the interior of the particle and begins a solid state diffusion process. Penetration of P into the particle will produce vacant sites on the surface for further sorption.

The process of desorption of P has been less well researched. Desorption appears to occur more readily at a higher saturation due in part to the decrease in energy of P sorption with increasing surface coverage (Muljadi, et al., 1966; Hingston et al., 1974; Ryden et al., 1977). The ease of desorption also decreases as the period of prior reaction increases. This may be due to increased penetration of P into the sorbing medium (Barrow, 1983).

Properties affecting the balance between desorption and sorption include pH and the presence of other ions in the soil. These have been summarised in review papers by Parfitt (1978) and Syers and Iskander (1981).

The processes of immobilisation-mineralisation, precipitation-dissolution and sorption-desorption discussed above remove P_I from and add P_I to the soil solution. Thus solution P_I, which is the immediate source of P for plants growing in a soil, is subject to rapid and continual changes in concentration.

The overall balance between P_I in the solid and solution phases of the soil is heavily biased towards the solid phase and soil P can therefore be classified as sparingly soluble (Larsen, 1967). The concentration of P in the soil solution is of the order of 1 to 0.1 μg g^{-1} soil and varies with the properties of both the solid and liquid phases (Larsen, 1967).

2.2.2 Availability of Phosphorus

The availability of P in the soil is determined not only by factors that affect the sorption of P by the soil but also by the various factors that affect absorption of P by the plant. These include the type of plant under consideration as well as the specific conditions under which the plant is grown.

In this section the chemical availability of the P fractions described in section 2.2.1.2 will be considered, followed by a review of the factors affecting the physical availability of the P in terms of plant uptake.

2.2.2.1 Chemical availability of phosphorus

A considerable amount of research has been carried out in an attempt to discover which fraction or fractions of P in the soil are important in supplying P to plants. Unfortunately, much of the work has been carried out under very different conditions in terms of fertiliser P regimes and soil conditions, and so direct comparison of results is not possible. In this section general trends in results will be considered, where appropriate, and the review will follow the order: organic, inorganic and total P; fractions of inorganic P; soil available P (as extracted by recognised soil-testing procedures).

Under a cropping regime, P_O decreases (Haas et al., 1961; Hedley et al., 1982; Tiessen et al., 1982; Sharpley and Smith, 1983). The rate of decrease in P_O increases with increasing numbers of years of cultivation (Tiessen et al., 1982) and is not prevented by the addition of animal manure at realistic rates (Haas et al., 1961). In contrast, in most studies, P_I was found to be unchanged by cropping (Haas et al., 1961; Hedley et al., 1982; Tiessen et al., 1982) unless animal manure was added to the soil, in which case an increase in P_I was measured (Haas et al., 1961). As P_O is not considered to be plant available until after mineralisation has occurred (Cosgrove, 1977), these results suggest that the effect of cropping, with associated processes of cultivation and hence increased soil aeration and surface area of organic residues, is to increase net mineralisation.

In these studies P_I did not decrease as P_I levels were maintained by P_O mineralisation and inputs of P fertiliser. It is conceivable that P_I would decrease under a cropping regime in soils of low P_O status where fertiliser P additions were not made.

The effect of a cropping regime on soil total P levels depends upon the amount of P fertiliser added, the amount of P removed by the plant and the balance between changes in the amounts of P_I and P_O in the soil. It has been reported that in general, total P decreases under cropping due to a decrease in P_O (Haas et al., 1961; Hedley et al., 1982; Tiessen et al., 1982). However, results from a more detailed study (Sharpley and Smith, 1983) showed that although P_O always decreased under a cropping regime, P_I sometimes increased more, resulting in an increase in total P. Changes in bulk density of the soil due to cultivation and the effect this had on apparent changes in soil P concentrations were considered in the studies by Hedley et al.

(1982) and Tiessen et al. (1982). It is not clear from their reports whether Haas et al., (1961) and Sharpley and Smith (1983) did allow for the effect of increased bulk density due to cultivation in their calculations. Incorporation of the effect of increased bulk density (if previously omitted) would reduce the difference in P concentration between cultivated and non-cultivated soil.

Under grazing, P_O is known to increase (Jackman, 1955; Rixon, 1966) and this increase does not appear to be influenced by stocking rate (Simpson et al., 1974). Whereas increasing rate of P fertiliser addition results in an increase in P_I (Simpson et al., 1974; Quin and Rickard, 1983), both increases (Walker and Adams, 1958) and decreases (Simpson et al., 1974) in P_O have been associated with increasing rate of fertiliser. The balance between immobilisation and mineralisation (governing whether P_O increases or decreases) is in part dependent upon such factors as soil temperature and pH. Recent work in Australia (Williams, 1980), has indicated a relationship between decrease in soil pH and increase in both soil organic matter and total soil P over a fifty year period. Furthermore, in a long term grazing trial, Quin and Rickard (1983) measured an increase in P_I which occurred at the expense of an increase in P_O only after liming had occurred.

From the discussion in this and preceding sections it is apparent that P_I, rather than P_O, is considered to be directly plant available. However, P_I is a term embracing many different P compounds. Attempts have been made in the past to determine which of the P_I compounds within the larger P_I pool actually supply plants with P.

Chemical schemes for separating P_I into different fractions were based on the assumption that P_I exists in soils as discrete P compounds. Initially, soils were extracted with solutions varying in pH from 2 to 10. Comparison of the solubility curves of known minerals with those from soils gave an indication of the major P compounds present (Stelly and Pierre, 1942; Bishop and Barber, 1958). From here a scheme for fractionating soil P_I discretely into four principal forms was developed (Chang and Jackson, 1957).

These four forms were calcium-P, aluminium-P, iron-P and reductant soluble-P extractable after removal of the first three forms (Chang and Jackson, 1957). Calcium-P is present mainly in the form of apatite, but monocalcium, dicalcium and octacalcium-P also exist in small amounts or as transitional forms. Calcium-, aluminium- and iron-P also include adsorbed and surface-precipitated P associated with their respective types of soil particles. Reductant soluble- P is thought to exist as chemisorbed P dispersed at random in the matrix making up iron-manganese concretions in the soil and the iron coatings of the clay separates (Bauwin and Tyner, 1957). The availability of these soil P compounds to plants depends to a certain extent on the surface area of the P compound under consideration (Kittrick and Jackson, 1956; Olsen and Watanabe, 1957).

Since its introduction, the scheme has been refined as a result of the research of Fife (1959a and b), Saunders (1959), Khin and Leeper (1960), Smith (1965) and Williams et al., (1967), all of whom attempted to separate the P compounds more precisely. It is now generally believed that the absolute separation of aluminium-P and iron-P in a soil system is not possible (Fife, 1962, 1963; Williams et al., 1967) and the two fractions together are termed "non-occluded" or "surface-P".

As the basic premise behind fractionation schemes (i.e., that inorganic P exists in soils as discrete P compounds) is open to question, care is necessary in interpretation of results. Accepting this limitation as a *caveat* against overinterpretation of results, fractionation schemes have been used to provide useful information not only on soil pedogenesis (as discussed in section 2.2.1.2) but also on the effect of plant growth and agronomic practices on the size of the identified fractions.

Most of the studies have involved fractionating soil P_I before growing a test crop on that soil. Correlations between plant P uptake (used as a measure of plant-available P) and the amounts of P found in the various fractions in the original soil are used to indicate which P fractions are best related to plant P uptake. In a few studies a soil P fractionation has also been carried out after final harvesting of the test crop, enabling correlations of plant P uptake and change in the amount of P in a particular fraction to be made.

Total P_O is not used in correlations with plant-P uptake because it is considered to be unavailable to plants until after mineralisation has occurred (Cosgrove, 1977), as discussed earlier. It is probably for this reason that schemes for fractionating P_O are still being developed (e.g., Bowman and Cole, 1978).

Using fractionation schemes based on that derived by Chang and Jackson (1957) it has been found that the form of P whose depletion in the soil is best correlated with plant P uptake varies according to soil properties.

In the generally slightly acid soils of New Zealand, adsorbed and surface-precipitated iron and aluminium compounds (as discussed in section 2.2.1.2) are sources of plant-available P (Grigg, 1968). A decrease in pH is associated with an increase in the supplying power of "aluminium-P" (as defined by Chang and Jackson, 1957) and at low pH's calcium-P may make a contribution (du Plessis and Burger, 1966), particularly if it is supplied in the form of rock phosphate (Martens et al., 1969). As pH increases within the acid range, "iron-P" makes an increasing contribution to plant-available P (Novais and Kamprath, 1978). However, "iron-P" is considerably less soluble than "aluminium-P" (Lindsay and Moreno, 1960); it has been noticed that in soils where the effective contribution to plant P uptake from "aluminium-P" and "iron-P" is equal, the latter is present in the soil at three times the concentration of the former (Novais and Kamprath, 1978).

A limited amount of work has been carried out on the effect of agricultural practices such as cultivation, fertiliser application and grazing on the occurrence of the various fractions discussed above.

Cultivation is thought to reduce supplies of "readily-available" aluminium and iron-P in the soil as it generally results in increased mineralisation and enhanced plant P uptake (Hedley et al., 1982;

Tiessen et al., 1983). The effect of cultivation on calcium-P levels in the soil is less well established, however. Both increases (Tiessen et al., 1983) and decreases (Hedley et al., 1982) have been measured in levels of residual-P (resistant calcium-P) in cultivated soils compared with levels in the same soil under virgin conditions. However, as the extraction techniques used were slightly different in each study there is little or no basis for direct comparison. Calcium-P has been found to increase under high rates of fertiliser addition in New Zealand (Rickard and Quin, 1981) either as an insoluble residue from fertiliser or as a stable reaction product.

"Aluminium-P" and "iron-P" have been found to decrease under the effects of cultivation (Tiessen et al., 1983) but to increase when large applications of fertiliser P are made to a high P-fixing soil (Shelton and Coleman, 1968). In the latter study it was noted that there was an increase in "iron-P" at the expense of "aluminium-P" during the eight years following fertiliser application. Thus it can be seen that the effect of agricultural practices on soil P fractions will depend not only on the balance of cultivation and fertiliser P addition, but also on soil type as it affects P-sorption.

More investigations have been carried out on the effect of development practices on plant-available P as measured by recognised soil testing procedures (e.g., Truog, 1930; Bray, 1945; Olsen et al., 1954). In contrast to fractionation schemes, the conventional soil testing methods for the determination of available P are believed to extract a portion of all chemical forms having either a high solubility in the extractant or a high specific area (Chang and Jackson, 1957). In general, alkaline solutions (e.g., Olsen) and NH_4F (e.g., Bray) extract aluminium-P preferentially, whereas acid solutions (e.g., Truog) extract calcium-P preferentially (Kamprath and Watson, 1980). Thus the soil type and the major form of P present in the soil are important considerations when choosing an extractant.

In New Zealand, the bicarbonate-extraction (Olsen et al., 1954) has been the standard technique for evaluating the soil P status since 1976 (During et al., 1981). Prior to this the Truog test, which extracts mainly calcium-P, was used. It was found, however, that on recent alluvial soils (which contain large amounts of apatite, a mineral which releases P only very slowly) the test gave erroneously high values of plant-available P. In contrast to the Truog test the Olsen test does not suffer from this limitation.

The effect of agricultural practices on the different "available-P pools" measured by soil testing procedures is somewhat unclear as the trials which have been carried out to measure these effects are generally not directly comparable with each other and yield conflicting results.

Olsen P has been found to increase under cropping, both with and without the addition of animal manure, although the former treatment resulted in a larger increase than the latter (Haas et al., 1961). The addition of fertiliser P has resulted in an increase with time in Bray-extractable P during cultivation (Sharpley and Smith, 1983) and an increase in Truog P (Quin and Rickard, 1983) and acetic-acid soluble P (Rixon, 1966) under pasture.

In summary, the effect of cultivation is generally to reduce primary calcium-P and P_O whereas under permanent pasture, the normal regime for hill country, P_O increases with development. The effect on soil solution P is dependent upon soil properties and management practices, but under both cultivation and pasture it tends to increase with increasing rate of fertiliser P application. On high P-fixing soils there is evidence to suggest that a considerable amount of added P will form "aluminium-P" and "iron-P" complexes and that, with time, "iron-P" will form at the expense of "aluminium-P", thus rendering the P less available for plant uptake (Lindsay and Moreno, 1960; Shelton and Coleman, 1968; Novais and Kamprath, 1978; Tiessen et al., 1983)

2.2.2.2 **Availability of P for plant uptake**

The second factor influencing the plant-availability of P is the plant itself and its ability to take up P from the soil.

As the concentration of P in soil solution is usually very low (section 2.2.1.2) only small amounts of P will be found at the root surface initially. After this small amount is absorbed it is replenished by P moving to the root by mass flow and diffusion or by the root moving into a new area, i.e., root interception (Lewis and Quirk, 1967).

The amount of P moving to the plant by mass flow depends upon the concentration of P in solution and the amount of water being transpired by the plant. Mass flow is considered to be the most important process of P transfer to roots in soils that have been fertilised recently (Omanwar and Robertson, 1970). However, under most conditions neither transpiration rates nor soil solution P concentration are large enough to supply sufficient P to the plant by this means (Bole, 1973). Thus diffusion of P is considered to be the dominant mechanism governing the supply of P to the roots (Nye, 1977; Barber, 1980).

The most important factors affecting diffusion of P are thought to be the soil water content, buffering capacity and the tortuosity factor. Thus in hill-country soils the rate of P uptake by plants is likely to be markedly affected by slope, not only because steeper slopes tend to have less total P (Gillingham et al., 1980) and P in solution, but also because water content is likely to be lower on slopes than on the flat.

At low levels of available P, plant P uptake will be limited by the rate of transport of P to the roots. In this case, water content of the soil and other soil properties affecting tortuosity will be important. When P concentration in the soil solution is higher, however, the rate of P uptake will be more limited by plant factors (White, 1973).

2.3 PLANT PHOSPHORUS

The amount of P taken up from soil by pasture is generally thought of as the product of pasture dry matter yield (DMY) and pasture P concentration. Though the amount of P in roots can equal that in above-ground material, very little work has been done on this aspect of the P cycle. It is generally assumed that root P will be returned to the soil *in situ* and as it does not constitute a loss of P to the system, can be ignored as a loss pathway. Total P uptake is influenced predominantly by DMY and in a hill-country grazing system spring and summer pasture growth generally account for about 75% of annual P uptake (Gillingham et al., 1980).

2.3.1 **Dry Matter Yield**

Climatic features (moisture, temperature and light) influence DMY and this means that pasture production can vary markedly with season. In general, in the North Island of New Zealand, spring pasture production exceeds that of summer which in turn exceeds that of autumn. The decrease in production, particularly in the latter season, is usually due to a marked decrease in soil moisture caused by drought conditions (Anslow and Green, 1967; Saunders and Metson, 1971; Gillingham and During, 1973; Lambert and Roberts, 1978; Gillingham, 1980a; Radcliffe, 1982; Chapman et al., 1983; Lambert et al., 1983; During et al., 1984a and b). In a wet season, however, summer production can exceed spring production (Radcliffe, 1982; Lambert et al., 1983). Winter is the season of least grass growth in the North Island of New Zealand. This is a reflection of low soil temperature. Although the mean soil temperature is slightly above the assessed threshold level for plant growth (McCloud et al., 1964), at least some of the season is spent with temperatures below the minimum. This results in reduced pasture growth during winter and early spring (Anslow and Green, 1967; Gillingham and Bell, 1977; Radcliffe, 1982).

In hill country it is possible that sloping land may receive less direct radiation than flat campsites (depending upon aspect) and so have lower soil temperatures than the campsites. It has been calculated that in New Zealand no direct radiation falls on 30° south-facing slopes at 37° 48′ S during June and most of May and July (P.F. Noble, reported in Gillingham and Bell, 1977).

The degree of slope of the land under consideration has a large effect on the quantity of DM produced annually. It has been estimated that annual DMY decreases by 100 kg ha^{-1} for each degree increase in slope (Gillingham and During, 1973). More recent estimates (made on land slightly less steep in nature) indicate that the drop in annual production per degree increase in slope is over 220 kg ha^{-1} (Lambert et al., 1983). Much of this decrease in production is attributed to nutrient transfer (Gillingham and During, 1973; Gillingham et al., 1980; Radcliffe, 1982; Lambert et al., 1983). Nutrient transfer refers to the preferential enrichment of campsites at the expense of steeper slopes in plant nutrients transported there in faeces and urine. A further effect, partially due to the return of faeces and partially due to litter formation, is that organic matter is present in larger quantities on campsites than on steeper slopes (Gillingham, 1978). Organic matter is an important component in soil water retention and in dry seasons this may allow pasture to continue to grow on campsites when growth has stopped on steeper slopes. However, pasture species found on campsites (e.g., ryegrass and clover) tend to be more sensitive to moisture stress than those found on steeper slopes (e.g., browntop and paspalum) (Gillingham and During, 1973;

Gillingham, 1980a). Seasonal production on each slope, as a percentage of annual production on that slope, is usually little affected by degree of slope (Gillingham and During, 1973; Gillingham, 1980a; Lambert et al., 1983). In a very long dry summer, however, percentage production from campsites (as a percentage of the annual total) is likely to be more reduced than production from other slopes due to the sensitivity of the pasture species present (Lambert et al., 1983).

2.3.2 Plant P concentration

Pasture P concentration (µg g^{-1} DM) also follows an annual pattern. On flat land maximum P levels are found in late autumn to late winter (May or June to August or September) and minimum levels are found in summer (December to January or February) (Butler and Metson, 1967; McNaught et al., 1968; Saunders and Metson, 1971). The low concentration of P in plants during summer months is attributed to lack of soil moisture (Saunders and Metson, 1971; Mouat and Nes, 1986). The effect of low soil moisture on P mobility in the soil has been discussed in section 2.2.2.2.

Although the pattern described above is seen on campsites in hill country, trends are slightly different on sloping land in that P concentrations are lowest in autumn and highest in spring (Gillingham and During 1973; Gillingham et al., 1980). The "delay" of a season may be due to lack of moisture, or to physiological differences in growth between the species on different areas. As very little work has been done on the effect of slope on seasonal changes in pasture P concentration in hill country it is not possible to be more specific.

2.4 ANIMAL P INTAKE

In New Zealand the nutrient intake of a grazing animal is derived almost entirely from pasture. In some cases, however, soil ingestion can provide significant amounts of nutrients. Sheep have been found to eat 75 kg or more of soil annually (Healy, 1969). This soil ingestion is incidental to pasture consumption and tends to increase in winter, due to slow pasture growth, increased appetite and wet conditions. Increased pasture utilisation and pugging associated with increased stocking rate, also result in increased soil ingestion (Healy, 1969). Assuming a total P content in the soil of 800 $\mu g \ g^{-1}$ the ingestion of 75 kg of soil would mean an annual intake of 60 g P via the soil. This represents approximately 4% of the total P ingested via herbage per stock unit (assuming an annual intake of 550 kg DM per stock unit and a pasture P content of 0.30%). It should be stressed, however, that soil ingestion varies not only with season and grazing management, but also varies widely between individual animals (Wilson pers. comm.).

The bulk of animal P intake occurs via herbage and so is governed by the pasture available, its P concentration, and the level of pasture utilisation. Young pasture plants contain higher nutrient concentration levels than those plants in a senescent or flowering condition. As they contain a richer source of crude protein than older plants and are more palatable and digestible, young plants tend to be grazed selectively (Blaser et al., 1960), particularly by sheep (Meyer et al., 1957). However, management of grazing patterns to minimise selective grazing and obtain a high degree of utilisation from all pasture components is likely to result in reduced animal performance (Blaser et al., 1960). The role of grazing management, therefore, is to find a compromise which enables the best production per animal and per unit area of land.

In New Zealand set stocking (where animals are relatively lightly stocked over most of a farm and are moved only infrequently for special purposes) and rotational grazing (where stock are concentrated into one or two mobs and moved from paddock to paddock, spending a number of days in each) are the two grazing systems in use. In practice most farmers use a combination of these systems according to the type of sheep and time of year.

The relative merits of these two systems have been the topic of much discussion. Although the rotational grazing system is thought to make more feed available (Lambourne, 1956; Lambert et al., 1983), a decrease in animal performance can result due to a decline in feed quality (Lambourne, 1956; Clarke et al., 1982), unless stocking rate and pasture utilisation are high.

The annual P intake of a stock unit can be calculated from DM intake (a standard stock unit is assumed to have an annual intake of 550 kg DM (Cornforth and Sinclair, 1982b) and pasture P concentration of that DM. Assuming a pasture P concentration of 0.30%, this means a P intake of 1650 g per year. Approximately 163 g will be retained in the body of the stock unit (Gillingham, 1978), representing 10% of that actually ingested.

2.5 PHOSPHORUS RETURN TO THE SOIL

In a grazed pasture, nutrients taken up by the plant can be returned to the soil in either of two ways:-

(a) in animal excreta, which may lead to nutrient transfer.

(b) as a constituent of ungrazed plant material that has either been rejected by grazing animals or has been inaccessible to them, and which will subsequently collapse or be trampled to the soil surface *in situ* as plant litter.

2.5.1 Phosphorus return via faeces

The excretion of P by animals occurs almost entirely via faeces (Sears and Newbold, 1942; Barrow and Lambourne, 1962). Thus the return of P to the soil via the animal is dependent upon the factors influencing distribution and decomposition of faeces in the field.

2.5.1.1 Distribution of faecal matter

Sheep campsites are usually small in area and, in relatively flat paddocks, tend to be located on an elevated portion or close to shelter. About 5% of a flat paddock is "selected" by a flock for campsites (May et al., 1968) and over 30% of the total faecal material dropped within a paddock is likely to be found in this small area and its immediate surroundings (Hilder and Mottershead, 1963). In hill country, campsites occupy almost all of the 0-10^{o} slopes within the paddock and up to 90% of the total faeces dropped within the paddock has been recorded there in some instances (Gillingham, 1980a).

Very few attempts have been made to quantify losses due to animal transfer. Based on results from a trial carried out on hill country in the North Island of New Zealand (Gillingham, 1980a), losses of P due to animal transfer and loss in animal products have been estimated at 0.7, 0.9 and 1.1 kg of P per stock unit for flat land, "easy" hill country and "steep" hill country, respectively, (Cornforth and Sinclair, 1982b). A description of the derivation of losses of P due to animals is contained in Appendix III.

These estimates have been revised for intensive, rotationally-grazed systems at 0.5, 0.7, and 0.9 for flat land, "easy" hill country and "steep" hill country, respectively, (Cornforth and Sinclair, 1984). Here it is assumed that nutrient transfer is reduced by intensive, rotational grazing management due to more even distribution of faeces as a result of reduced stock camping behaviour.

2.5.1.2 **Faecal phosphorus concentration**

Total P in faeces comprises both inorganic and organic P, which may be derived directly from the feed consumed or from endogenous P excreted by the animal.

Endogenous P is added to ingested feed predominantly in the saliva. It tends to increase as P concentration in the diet increases, but is a significant addition to faecal P even at low levels of P intake (Tomas et al., 1967). This can lead to negative net P balances in sheep grazing pasture of low P concentration (Bromfield and Jones, 1970).

The total P concentration of faeces is closely related to total P intake and hence the pasture P concentration (Barrow and Lambourne, 1962; Bromfield and Jones, 1970; Floate and Torrance, 1970). The concentration of P_O in faeces is not significantly affected by the P content of ingested herbage, as net mineralisation of plant P_O can occur when pasture is of high digestibility (Bromfield and Jones, 1970). This means that the proportion of P_I in faeces increases as total P in herbage increases (Bromfield, 1961; Barrow and Lambourne, 1962).

2.5.1.3 **Availability of phosphorus in faeces**

The plant availability of P in faecal matter is the subject of some controversy, and numerous trials under field, glasshouse and laboratory conditions have been carried out in an attempt to resolve the question. Faecal P availability depends upon both physical and chemical decomposition of the faecal matter.

Limited observations have been made on physical faecal decomposition in the field. In temperate regions faecal material decomposes more rapidly in areas where there is little shelter (resulting in exposure of faeces to the climatic elements) and where soil macrofauna are active than where the converse applies (White, 1960). Samples deposited in summer appear to be more resistant to breakdown than those deposited in winter. This is a reflection of climatic conditions (White, 1960), as the drier, more lignified grass of summer results in dry faeces which are deposited at a time of minimum fauna activity and low rainfall. The combination of these factors results in slow faecal decomposition.

In drier regions, e.g., those found in some areas of Australia, faecal decomposition occurs only very slowly (Bromfield and Jones, 1970; Rixon and Zorin, 1978). Furthermore, in Australia the addition of moisture to samples, either by rainfall or irrigation, does not result in a substantial increase in the rate of disappearance of faecal material (Rixon and Zorin, 1978). Although this contrasts markedly with results from the Northern Hemisphere (White, 1960), it should be noted that whereas the British trials involved faeces dropped *in situ*, the Australian studies involved large amounts of pre-dried faeces placed in chosen locations. In the same way that faeces produced in summer are more resistant to breakdown than faeces produced in winter so dried faeces are more resistant to breakdown than fresh faeces.

Investigations into the availability of faecal P due to chemical rather than physical decomposition, and the form of P becoming available, have been carried out in some detail in pot trials and laboratory leaching and incubation experiments. Although studies made under controlled conditions allow measurement of (a) the effect of changes in individual components of the environment (e.g., moisture or temperature) and (b) small changes in faecal composition, it is unlikely that the conditions imposed in a laboratory or greenhouse will reflect those found in the field. For this reason results from laboratory studies or pot trials should be interpreted with caution before being applied to the field.

Organic P in faeces is thought to contribute little to plant nutrition in the short term (McAuliffe et al., 1949; Kaila, 1950; Bromfield, 1961) as it is insoluble in water (Bromfield, 1961; Floate, 1970a; Gillingham, 1978).

After microbial mineralisation, however, the P_O can contribute to plant nutrition. This is the likely explanation for the apparent increase in effectiveness of faecal P after two to three months under artificial conditions (McAuliffe and Bradfield, 1955; Hanley and Murphy, 1976; Goss and Stewart, 1979). These artificial conditions include providing a warm, moist environment, and mixing dried faeces with the soil. Intensive root exploration of the faecal material is thus facilitated.

Floate (1970b) found that mineralisation of faecal P_O was induced by incubating faeces at $30^{O}C$ with an aqueous soil extract for three months. Lowering the incubation temperature to 10^{O} C reduced mineralisation from 10% of the original total P to 2.5%. At 5^{O} C net immobilisation (1-2% of original total P in three months) occurred. In contrast, the moisture content at which incubation occurred had little effect on mineralisation (Floate, 1970c).

Inorganic P in faeces is as, or nearly as, effective as that in superphosphate in the long term (three to four months) and appears to become more effective with time (Gunary, 1968; Batten, 1976). As already explained, this may be a reflection of mineralisation of P_O, or it may be a result of increasing root/faecal P contact. As faecal material is deposited on the soil surface in the field, the usefulness of faecal P to plants depends on the chance of contact between plant roots and faecal P. The speed with which this is likely to occur therefore assumes major importance (Gunary, 1968).

Faecal P_I is partially soluble in water. The amount of P_I released when faecal material is leached sequentially depends on the type of faecal material being investigated and has ranged from 29% of the total P_I (Bromfield, 1961) to 99% (Floate, 1970a). Thus at least part of the P_I present will be available for direct leaching into the soil during rainfall. The total amount of P_I leached appears to depend on the number of leachings and not the intervening time between them (Bromfield and Jones, 1970). These authors also noted that more P_I can be leached from crushed than intact pellets. In contrast, Batten (1976) found no effect of surface area of faeces in a glasshouse trial when the faeces were incorporated with the soil. As the faeces were dried prior to application, and as the trial was a pot experiment (i.e., the effects of soil macrofauna and heavy rain were excluded) this is, perhaps, not surprising.

Grazing trials investigating the effects of both physical and chemical faecal decomposition by the simple expedient of measuring DMY, P uptake and soil P have been carried out in the past. Under intensive grazing conditions, withholding of faeces generally results in lower DMY's and nutrient uptake, and leads to a decline in the level of soil nutrients (Sears and Newbold, 1942; Sears et al., 1948; Wolton, 1955; Wheeler, 1958b). If, however, some factor other than P is limiting production, e.g., moisture (Sears and Thurston, 1953) or nitrogen (Wheeler, 1958a), then withholding excreta will not affect yield in the short term. As P is returned to the soil in the form of unevenly-distributed, discrete faecal deposits it has been concluded that faecal P will increase soil P in a majority of the grazing area only under a heavy stocking regime (associated with intensive faecal return) and after sufficient time to allow decomposition of the faecal material (Wolton, 1955; Herriot and Wells, 1963).

Very little work has been carried out in New Zealand hill country on the rate of P release from faeces, but it would seem likely that the additions of faecal P to campsites are large enough to make an appreciable difference to the P status of the area. Some water-soluble P will probably be available for leaching into the soil immediately (contingent upon rainfall); the remaining P_I will be more resistant. Under warm conditions, before faecal material dries out completely, net mineralisation of P_O and rapid physical breakdown of the material (due to rainfall and macrofauna activity) are expected to occur. Under dry conditions, e.g., summer and early autumn, breakdown and mineralisation may take an extremely long time. As slopes tend to be drier and have less macrofauna activity than campsites (Sharpley and Syers, 1977), the relatively small amount of faecal material that is dropped upon them will take longer to break down than that deposited on campsites. There is also the possibility that dry faecal material may be blown or washed off slopes and come to rest on flatter, campsite areas. Thus the "above-" and "below-ground" P pools will not only be smaller on steeper slopes than on campsites, but the rates of transference of P between pools will be slower.

2.5.2 Phosphorus return via pasture litter

This subject has been reviewed extensively by Gillingham (1978) and consequently only the major points will be discussed here.

Litter constitutes that portion of dead material in pasture rejected by stock because of fouling (trampling, uprooting or spoiling with faeces and/or urine), inaccessibility or unpalatability. The amount of litter forming is inversely related to grazing pressure (Lambourne, 1956; Clark et al., 1982).

Litter tends to have a lower P content than pre-grazed pasture, as the pasture removed preferentially by sheep has a high protein (and hence P) content (Blaser et al., 1960). Plant leaf and stem material form the major part of litter, but roots of plants uprooted and subsequently rejected by grazing animals can contribute a significant proportion.

The effect of slope on litter formation is not as marked as it is on faecal deposition and although the quantity of litter on campsites exceeds that on steeper slopes in all seasons but winter, no significant difference has been recorded between litter formation on steeper slopes varying in steepness from 25^{o} to 45^{o} (Gillingham, 1980a).

The release of P from litter depends, in the short term, on the proportion of P that is water soluble and able to be removed readily by rainfall. This proportion is likely to increase markedly if the litter is subjected to frost (Harley et al., 1951). In the longer term, major release of P is related to microbial activity and the breaking down of plant cells. The extent of P release by direct leaching is (apart from physical release due to frost damage) inversely related to conditions favouring microbial attack, i.e., if environmental conditions favour microbial attack, P will be immobilised before it can be leached into the soil and will not be released until the microbial population dies (Jones and Bromfield, 1969; Bromfield and Jones, 1972; Halm et al., 1972).

The net effect of mineralisation and immobilisation, both of which processes occur during litter decomposition, depends upon the initial nutrient content of the material. This is probably due to an effect on the rate of build-up of the microbial population (Birch, 1961). Young plant material promotes a microbial explosion, leading to rapid substrate exhaustion and subsequent release of P_I from dead micro-organisms by enzymatic phosphorylation. In older plant material, microbial build-up is slower and the more prolonged supply of less readily-available substrate maintains a fairly uniform cycle of growth and decay. Microbial P_O mineralised under these circumstances can be used again (Birch, 1961).

Seasonal variability in the decomposition rate of litter is directly related to changes in temperature and moisture content, which probably have their effect on the microbial and earthworm populations. Floate

(1970b and c) showed that release of P from litter by mineralisation was reduced by decreasing temperature from 30°C to 5°C, and that a water content between 50 and 100% moisture-holding capacity was the optimum for decomposition. The activity of earthworms is markedly reduced during conditions of lower soil moisture and high soil temperatures (e.g., summer and early autumn) as these conditions cause them to enter an inactive diapause phase (Gerard, 1967). When active, and if present in sufficient numbers, earthworms can play an important role in accelerating the rate of P cycling. It has been found that water-extractable P concentrations in worm casts are generally higher than in the underlying soil (Sharpley and Syers, 1976). It follows that worm casts have a higher level of short-term plant-available P than surrounding soil (Mansell et al., 1981).

A further factor to consider in the seasonal variation of P release from litter is that in summer and early autumn, when conditions do not favour decomposition, the material comprising litter is likely to be old "hayed-off" pasture. As commented earlier, release of P from this type of material via micro-organisms is slow. However, if rain occurs some P will be released from this type of litter by direct leaching (Jones and Bromfield, 1969). Assuming that heavy rain is unlikely to occur during the droughty conditions often experienced in summer and early autumn on hill country it can be seen that the cycling of P through litter will be extremely slow at this time. This will be the case particularly on steeper slopes where low soil moisture, as discussed above, means pasture matures and enters into the less palatable reproductive phase early in the season.

2.5.3 Phosphorus from fertiliser

The evaluation of P as a fertiliser nutrient in New Zealand has been more extensive than that of any other plant nutrient. During (1984) has reviewed the bulk of New Zealand field trial work conducted primarily by the Department of Agriculture and subsequently by the Ministry of Agriculture and Fisheries. Because of this, only major points will be considered here and this section will concentrate on reviewing the residual effects of P from fertiliser.

The measurement of pasture dry matter production at increasing levels of P fertiliser addition produces a characteristic sigmoid response curve when plant-available P levels are low initially. In the first part of the response curve increasing rates of P fertiliser addition result in a slow increase in plant uptake of P as the soil will absorb most of the P. In the second part of the response curve increasing fertiliser P addition results in a rapid increase in plant uptake of P. This is due to the fact that as P sorption sites in the soil are saturated progressively with increasing rate of fertiliser, a larger proportion of the added fertiliser P remains in solution where it is available for plant uptake.

This process continues as further P is added, but at higher levels of P addition the ability of faster growing plants to take up available P becomes limited by other factors, such as the availability of moisture or other nutrients. Consequently, the marginal increase in dry matter growth per unit addition of P gradually declines.

The amount of annually-applied P required to maintain a certain level of pasture growth will, over a long period, represent the sum of both "above-ground" and "below-ground" losses. At a high level of pasture production and utilisation, these losses are predominantly "above-ground" and can, therefore, be minimised by prudent management (Karlovsky, 1975). This concept will be discussed further in section 2.8.

The residual availability of P from fertiliser P additions is generally evaluated by comparing the response to P in its second, third or fourth year after application with that to P in its first year. All responses are related to production (i.e., DMY, P concentration or whatever other factor is being measured in the trial) from control plots (Saunders et al., 1963). Residual P causing a response may be due to P still being released from the fertiliser itself (i.e., from dicalcium phosphate or unreacted apatite) or to P which has reacted with the soil after release from the fertiliser, but which is still in an available form. Thus the residual availability of P in superphosphate is thought to depend on the P-sorption capacity of the soil and the amount of P fertiliser that has been added in the past. The residual effect of P fertiliser appears to be decreased on soils with high P-sorption capacity (Karlovsky, 1959, 1973; O'Connor et al., 1985; Williams and Morton, 1985) and the effect of cessation of fertiliser P addition is more immediate on soils with low P status than on those with high P status (O'Connor et al., 1985).

As yet the importance of P_O and its contribution, if any, to the "residual availability" of superphosphate, has not been investigated. However, it is known that P_O increases under pasture and fertiliser P additions. It is not unreasonable to expect that if fertiliser P additions are halted, net mineralisation may occur, resulting in depletion of P_O. If this is so, increase in P_O should not be regarded as a loss of P, but rather as a P reserve. Considerable research is necessary to investigate the changes in P_O following cessation of fertiliser P addition before further interpretation of likely effects can be made.

After a period of years without maintenance fertiliser P addition there is evidence to suggest that high rates of fertiliser P are required if original production levels are to be achieved (Lynch and Davies, 1964; O'Connor et al., 1985). Furthermore, during the period of no fertiliser addition, pasture composition is likely to change, as a decrease in the amount of available soil P is detrimental to the presence of high-producing species, such as ryegrass and clover (Lynch and Davies, 1964; O'Connor et al., 1985; Williams and Morton, 1985). Thus it may take some time before the original level of production is restored. This evidence would suggest that the rate of any mineralisation of P_O "reserves" that does occur is insufficient to supply plant needs.

Residual P appears to be more effective in spring and summer than in autumn (Saunders et al., 1963). This is probably related to factors connected with soil microbial activity and plant root activity. In spring net mineralisation of P_O is likely to be occurring due to warm soil temperatures and adequate soil moisture, whereas in autumn net immobilisation is probable. Furthermore, in autumn root numbers and weight are at a minimum (probably as a result of low soil moistures during late summer and early autumn) and so are not able to explore and exploit as large a soil volume as can plants in spring (Jacques, 1956). The higher area of surface contact between root and soil solution in spring than autumn means that plants can be supplied with sufficient P for good growth.

It is this evidence that has contributed in part to the widespread practice of adding fertiliser P to hill-country pastures in the autumn.

2.6 PHOSPHORUS LOSSES IN ANIMAL PRODUCTS

The animals sold from hill-country sheep farms are usually store wether lambs, surplus 2-tooth ewes and cull mature ewes. The annual P losses in animal products from this type of farm may be calculated as follows (Gillingham, 1978):

> A 27 kg carcass weight Romney ewe contains about 9.3% bone, 48.4% muscle and 39.8% fat (McMeekan, 1959). This represents about 210 g P in bone and 40 g P in other tissues. Assuming an annual wool production from ewes and wethers of 4.5 kg, then P loss in wool amounts to a further 9 g P per animal. With a stocking rate of 15 stock units ha^{-1} and with a culling rate of 20%, then the annual loss of P ha^{-1} is 777 g. If lambing is 80% from ewes of the above body weight (Hight and Wright, 1972), wether lambs are sold as stores at 34 kg live weight and surplus ewe lambs are sold as 2-tooths at 45 kg

live-weight, then this represents a further loss of P in animal products of about 1640 g ha^{-1} giving a total annual P loss of 2415 g ha^{-1} or 161 g P stock $unit^{-1}$.

If it is assumed that 550 kg of pasture containing 0.35% is necessary to support one stock unit, and that pasture utilisation is 80%, then the annual P loss in animal products represents about 6.7% of pasture P uptake.

2.7 PHOSPHORUS LOSS IN SURFACE RUNOFF

Losses of P in surface runoff from pasture area are associated predominantly with sediments, i.e., particulate forms which include both "native" P and "fertiliser" P (Burwell et al., 1975). Thus P loss from pasture depends on the factors affecting the volume of surface runoff water and the P status of the surface soil.

The contribution of fertiliser P to surface runoff increases as slope increases (Sharpley, 1977), but is little affected by grazing regime (continuous or rotational) or fertiliser rate (Lambert et al., 1985). Though higher concentrations of P have been recorded in the runoff water from high fertiliser treatments than from low fertiliser treatments, the volume of runoff water from the former was approximately 25% less than from the latter treatments.Thus the total amount of P lost (approximately 0.7 kg ha^{-1} y^{-1} of P) was similar for all paddocks (Lambert et al., 1985).

During winter, surface casting by earthworms (which occurs particularly on campsites) may contribute an important source of particulate P to surface runoff. Similarly, overgrazing leading to exposure of soil will increase losses.Over the period of a year, however, losses of P in runoff are generally considered to be insignificant from an agronomic point of view unless significant soil erosion is occurring (Rennes, 1978).

2.8 MODELLING OF PHOSPHORUS CYCLING

As discussed in the Introduction, nutrients essential for the growth of plants and animals are passed from soil to plant to animal and back to soil again. This sequence of transfers through a series of compartments is a simple representation of what is, in most practical situations, a highly complex system of compartments and transfers. The major compartments and transfers of P in grazed hill country have been discussed in the preceding sections.

Due to the difficulty of measuring transfer rates between P compartments, most of the studies carried out have been on systems at equilibrium, where the amounts of P in the various compartments are considered stable and the rates of P transfer can therefore be determined more readily.

Phosphorus cycling studies at the Matador Site (Latitude 50° 42′ N, Longitude 107° 43′ W) in Saskatchewan by Stewart and co-workers have provided the most complete data available for evaluating large P pools and pathways in semi-arid grasslands (Halm et al., 1972). These studies included evaluation of soil P_I and P_O, rooting activity of grasses as a function of soil depth, and estimates of microbial turnover rates. In the native grassland ecosystem studied plant P uptake was found to balance litter P return. Addition of nitrogen and water resulted in an increase in the rate of cycling associated with increased mineralisation of P_O and a consequent increase in the availability of soil P. The studies indicated an important limiting role of P_O turnover in P cycling and concluded that labile P_O plays a more important role in the availability of P in grasslands than has generally been recognised.

A simulation model was developed from data collected during the "Matador Project". Results from the model indicated that in a native grassland ecosystem: (1) the P cycle is more sensitive to soil parameters than to plant parameters, (2) microbial P uptake is four to five times greater than plant P uptake, (3) P concentration in live plant tops is highly responsive to the pattern of seasonal rainfall. Parts of the cycle identified by the model as requiring further study included areas of activity and morphology of roots and the effect of soil depth on the rate of mineralisation of P_O (Cole et al., 1977).

In intensive agricultural systems, the addition of P fertiliser and the presence of large numbers of grazing animal per unit area causes the cycle to become more complex. There have been very few studies that have taken a holistic approach to P cycling, i.e., that have considered both the "above-" and "below-ground" components of the P cycle, because such studies are extremely time-consuming and labour intensive.

A preliminary study on P cycling in New Zealand hill country (Gillingham et al., 1984b) was carried out in order to identify factors which could be manipulated to improve the effectiveness of nutrients in stimulating pasture growth, and to reduce losses. Pools of P measured were: Soil P (P_O, P_I and available P), pasture P, litter P, and faecal P. Losses of P in runoff, erosion, and animal products were calculated from the literature. Although soil P accounted for more than 90% of the P in the system, "above-ground" components were considered to have more potential for manipulation. It was concluded that more efficient use of P could result from the development of fertiliser policies which recognise inefficiencies in the P cycle caused by seasonal and year to year variability in climate.

A second approach to the problem of quantifying the P cycle has been adopted by several workers (e.g., Wilkinson and Lowrey, 1973; Halstead and McKercher, 1975; Till, 1981). By gathering information on specific areas of the P cycle from the literature a complete picture of the cycle can be built up. This approach was used to develop a dynamic model of P utilisation as a tool for identifying the sensitive areas of the P cycle (Blair et al., 1977). The model was constructed using data from a variety of investigations that had been carried out on individual parts of the P cycle. The comment was made that although much of the data came from different countries, the results were similar in the well-documented areas (e.g., responsiveness to P as indicated by the bicarbonate test). Unfortunately, some areas of the P cycle (e.g., availability of P from litter and faeces) have not been studied intensively, therefore no comparisons between countries could be made. As climatic variations are likely to affect the availability of P in these P sources, application of the model is restricted to specific climatic zones.

In the above model, plant response to P addition was identified as being the area where P fertiliser utilisation could be most improved. A small change in plant response in the model (i.e., a higher growth rate of pasture at lower levels of available soil P) resulted in a large increase in annual DM production. From this it was suggested that attempts should be made to develop plants capable of producing animal forage of "acceptable" quality under low P conditions.

The native grassland model (Cole et al., 1977) and the grazed pasture model (Blair et al., 1977) differ in that the former was more sensitive to soil parameters than plant parameters, whereas the latter was more sensitive to plant than soil parameters. Blair et al. (1977) concluded that more work is needed to investigate immobilisation and organic matter turnover rates in grazed pasture systems. Investigations into the effects of stocking rate and class of animal on the redistribution and subsequent recycling of nutrients were also deemed necessary.

Comparison of conclusions drawn from the native grassland model (Cole et al., 1977) and the grazed pasture model (Blair et al., 1977) shows that P_O turnover is considered to be an important factor in both, and one that requires further research. However, whereas the native grassland model (Cole et al., 1977) is considered to be more sensitive to "below-ground" than "above-ground" factors, the position is reversed for the grazed pasture model. This is a direct reflection of the fact that the grazed pasture model was constructed for a farming situation where animal output is an important factor. However, some of the difference in sensitivities to the various components of the models is likely to be due to (a) the amount and type of data from which they were constructed, (b) the fact that soil P status and plant P requirements in the two systems were different, (c) a combination of both (a) and (b).

Recently, modelling has been used not only to describe P cycling and to identify areas where research is necessary, but also for calculating P inputs required to keep a system in equilibrium under grazing, i.e., for calculating maintenance P requirements (Bowden and Bennett, 1975; Helyar and Godden, 1977; Cornforth and Sinclair, 1982a).

Most of the models have been developed using the Mitscherlich equation as a basis. The Mitscherlich curve is generally presented as

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

where Y = relative yield (%)

100 = maximum yield

B = 100 - production without fertiliser

C = response factor

X = fertiliser addition

This equation has the double advantage that it is relatively easy to manipulate mathematically and the parameters involved have conceptual significance in themselves.

In order to characterise a Mitscherlich curve it is necessary to identify three points upon it. Workers have varied in their decisions as to which three points to choose, e.g., 70, 85 and 96% of a maximum obtainable yield (Middleton, 1977); maximum yield, yield without fertiliser, and a "mid-point" (Bowden and Bennett, 1975); and maximum yield, yield without fertiliser (assumed to be zero) and yield at 90% of maximum (Cornforth and Sinclair, 1982a).

The data needed to calculate the chosen points on the curve are taken from long-term field trial data. The long term field trials required to obtain the necessary constants involve a large number of resources and the data upon which the various models are built are site specific. When the data base is large, however, as is the case for the "Decide" model (Bowden and Bennett, 1975) and CFAS model (Computerised Fertiliser Advisory Scheme; Cornforth and Sinclair, 1982b), the model can be used for a large number of sites.

Although both of the above models are based on the Mitscherlich equation, they differ in several ways, both in the way in which they can be used and in their inherent weaknesses.

The CFAS model, developed in New Zealand, is based on a balance sheet approach originally suggested by Karlovsky (1966). Karlovsky proposed that the maintenance P requirement would depend on:

(a) inorganic and organic "fixation" of P by soils and the downward movement of P in soils

(b) the removal of P in animal products and excretion of faeces outside the grazing area

(c) the level of pasture DM production.

On the basis of field trials and laboratory studies it was suggested that the major soil groups of New Zealand could be categorised according to their extent of P "fixation" into high, medium, low and very low "P-fixing" soils. Within each soil category, mowing trials were established to determine relationships between:

(a) P output and total pasture DM production

(b) P input and P output.

The P output:pasture DM relationship describes the amount of P removed from the soil in pasture, corresponding to different levels of pasture DM production, i.e., the relationship describes the way in which percentage P in pasture changes with pasture DM produced.

The P input:P output relationship describes the amount of P input required to maintain different levels of P output from the system. This relationship also exhibits diminishing returns in that increasing quantities of P inputs are required for successive increments of P output. As these relationships are determined from mowing trials (with full return of clippings), the difference between P input and P output represents an estimate of soil P loss, which must be replaced by fertiliser, i.e.:-

Under zero grazing P input (for maintenance)-P output = soil P loss

To calculate the losses of P from the system under grazing Karlovsky assumed the the level of pasture utilisation at any pasture production level was 80% of the grass grown in a year, that removal of P in animal products amounted to 4 kg ha^{-1} at a production level of 50 kg ha^{-1} P uptake, and that losses of faecal P outside the grazing area amounted to 10%. Although not limited geographically within New Zealand, the Karlovsky model is static in that it can apply strictly only to grazing systems where the assumptions apply, i.e., where PU = 80%, animal product losses amount to 4 kg ha^{-1} and 10% faecal P is lost outside the grazing area. Thus no flexibility for changing stocking rate exists. Furthermore, though it is possible that losses of faecal P outside a single paddock may not exceed 10%, within a hill-country paddock there will be pronounced transfer of faecal P from steep-slopes to campsites (Gillingham et al., 1980); for a steep-slope losses will be greater than 10%. Thus, maintenance P fertiliser requirements are likely to vary according to the slope under consideration.

The CFAS model was developed from that of Karlovsky. It requires that the farming situation under consideration be characterised in terms of the following basic parameters:

(a) Ymax which is the maximum average annual pasture DMY for the area under consideration. Ymax refers to a grass/legume pasture of "appropriate" botanical composition for its situation where plant nutrients (except nitrogen) are non-limiting.

Alternatively, carrying capacity (CC) can be used, where CC is the number of standard stock units (SU) that could be carried in a particular situation where:-

(i) each SU requires 550 kg DM annually.
(ii) actual DMY is 95% of Ymax
(iii) pasture utilisation (PU) is 90%.

(b) Pasture P (%) at 90% relative yield (RY) varies with maximum average annual pasture DMY for any given situation.

(c) Soil loss factor (SLF) which is the P lost in the soil, expressed as a fraction of the P uptake in pasture when it is maintained at 90% RY.

(d) Animal loss factor (ALF), which is the amount of P (kg) lost via animal products and faecal transfer to non-grazing areas for each 550 kg of pasture DM consumed by livestock grazing pasture with a P content of 0.35% and maintained at a pasture DM yield of 90% relative to Ymax. The ALF for a given farming situation varies according to the livestock production system and increases with land slope due to increased "tracking" and "camping".

(e) Stocking rate (SR) which is expressed in terms of the SSU (like CC) and is the SR for the area under consideration.

(f) Pasture utilisation (PU) which is the pasture eaten annually expressed as a percentage of total annual DM production.

Once the factors (a) to (f) have been chosen (as appropriate to the farming situation) maintenance P fertiliser requirements can be calculated as follows:

$$\text{Maintenance P (kg ha}^{-1}\text{)} = \log^{10}\left(\frac{100}{\left(100-\frac{(8550\text{x}SR)}{(CC\text{x}PU)}\right)}\right)\text{x}CC\text{x}(0.005\text{x}CC+0.275)\ \text{x}\ (PU\text{x}ALF\text{x}0.0301-SLF\text{x}5.79)$$

The model then allows modifications to the calculated maintenance P requirement to be made according to the current P status of the soil, as measured by the Olsen test.

From this it can be seen that although the Karlovsky and CFAS model operate from the same basic premise (i.e., that P output is related both to P input and total pasture DMY) the CFAS model, with its more complex structure, can apply to far more farming situations than can the Karlovsky model.

The CFAS model is receiving widespread use in New Zealand because it has been adopted by Ministry of Agriculture and Fisheries Advisory Officers. There are, however, inherent weaknesses within the model structure and problems associated with its application. Furthermore, all appropriate field trial data currently available in New Zealand have been used in the construction of the model, which means that no data are available for its validation.

The five major problems associated with the structure of the model are as follows:

(1) Soil P loss is calculated as the difference between P input (for maintenance) and P output. This means that an error in measuring the P input or P output of a particular system will lead to an error in the estimate of soil P loss; although P input is relatively easy to measure, P output is not.

Output of P is the amount of P removed in animal products or transferred in faeces. It depends not only on numbers and type of stock being grazed in a system, but also, as indicated earlier, on the topography of that system. Quantifying P transfer from steeper slopes to campsites involves measuring DM distribution of faeces and P concentration of that faeces. Consequently, very little work has been done in this area and hence "P output" figures included within the CFAS model can be regarded as preliminary estimates.

(2) The CFAS model incorporates ALF's based on work on faecal transfer in hill country (Gillingham, 1980a, 1980b; Gillingham et al., 1980). The animal losses were calculated from data from only one large scale grazing trial. It is not known if any effects of trial design, paddock size or grazing management were incorporated inadvertently.

Modifications to the CFAS model (Cornforth and Sinclair, 1984) have included the addition of reduced animal losses for intensively rotationally-grazed pasture. However, there is no experimental basis for the modification as the trial from which the original animal losses were calculated was already under an intensive rotational grazing regime.

(3) As explained earlier, the CFAS model generates a response curve relating losses of P to production levels. Assuming no production with zero fertiliser, and taking maximum production field trial data, the other point required to generate the curve was chosen as 90% of maximum production. A large quantity of field trial data was used to estimate the quantities of P lost in the soil, and also due to the animal, at this point. The combination of these two losses gives total P loss. For the remainder of the curve the model estimates total loss but makes no claims as to how this is apportioned between animal loss and soil loss.

In practice, a farmer using the CFAS model will choose the SLF for the appropriate soil group and ALF for the appropriate farming system regardless of what level of production he is maintaining. This means that if he is operating at below 90% RY SLF's and ALF's are likely to be overestimated and "surplus" P will be applied. Conversely, if he is operating at above 90% RY, "insufficient" P will be applied for maintenance.

(4) The model generates a response curve for an area - either a part of or a whole farm - in which all parameters are supposed to be constant. In hill country, however, paddocks consist of an amalgam of land in different slope categories. Different slopes may contain different soils which will have different production potentials and different responses to added P. Thus the maintenance P requirements of these different areas are likely to be different.

(5) Whatever rate of maintenance fertiliser P is chosen, all of the P within it is assumed to become available within the year of application, i.e., no residual value of fertiliser is incorporated within the model. As over 85% of P within superphosphate fertiliser is water-soluble (During, 1972) and is therefore likely to be available for plant uptake within the year of application, the residual value of this form of fertiliser is likely to be small, assuming, of course, that maintenance rates are being applied. If, however, a change in economy and/or policy causes a different and lower maintenance rate to be chosen, then a true maintenance situation will not operate for a few years until equilibrium is attained once more. During the years of transition the residual value of

> previous applications of fertiliser P may be of importance. There are trials in progress from which preliminary data have become available (O'Connor et al., 1985), the results of which will allow a modification of the CFAS model incorporating residual fertiliser value (St-Pierre and Scobie, 1985).

Accepting these inherent weaknesses within the model, there can be difficulties in applying it. The model states that maintenance P requirements are a function of soil loss, animal loss, stocking rate, carrying capacity, and pasture utilisation. Although it is relatively easy to select the correct ALF and SLF, estimating SR, CC and PU can be difficult (Parker, 1982).

A further problem associated with the CFAS model as a whole, and its application, is that it considers only maintenance requirement curves. In contrast to the Australian "Decide" model (modified by Godden and Helyar, 1980) no attempt is made to specify the input/output relationships involved when a production system is moving from one steady-state maintenance situation to another. As a result, the CFAS model is limited in the extent to which it can be used in evaluating management strategies which alter stocking rate.

The basic form of the Australian "Decide" model (Bowden and Bennett, 1975) is very similar to that of the CFAS model. Application of the "Decide" model requires estimation of the parameters within the Mitscherlich equation and calculation of the optimum fertiliser input, assuming there is no soil P currently available to plants.

Subsequently, however, estimations of the current value of the previous year's fertiliser addition and the contribution of "native" soil P to current yield are deducted from the amount first calculated. This is in contrast to the CFAS model which incorporates a "modifying factor" according to the Olsen soil P test, used only for the final maintenance P calculation.

Two areas of weakness have been identified (Godden and Helyar, 1980) in the original "Decide" model:

(1) Residual fertiliser P is considered to contribute to P availability in the following year only

(2) the model assumes a steady-state balance between yield and applied fertiliser by considering past and present fertiliser decisions. It does not, however, assist with the question as to whether or not the current steady-state balance is appropriate.

Modifications to the Decide Model (Godden and Helyar, 1980) have overcome these weaknesses. The modifications not only allow residual fertiliser to be included for several years, but also attempt to take account of the three processes which occur when fertiliser P is added to a soil-plant system, i.e., those of increased production, increased removal of nutrients by animals, and organic and inorganic conversions of available P to unavailable forms. The relationship between losses of P and production have been quantified, depending on the state of the system, relative to three phases:

(1) development phase, where the soil pool is being increased due to fertiliser P addition exceeding losses of P from the system

(2) steady-state maintenance, where no change in the pool of P occurs over time; that is, losses from the system are balanced by further P application

(3) "run-down" phase, where the soil P pool is depleted because losses from the system are greater than P fertiliser additions.

Thus, by relating true maintenance fertiliser rates to corresponding yields it is possible to define maintenance requirement curves (Godden and Helyar, 1980). Maintenance requirement curves allow the economically optimum choice to be made between building up or depleting soil P via fertiliser P programmes.

The Decide model, plus modifications, thus has far more flexibility than the CFAS model in that it can be used for developing as well as developed farming situations, and it can, therefore, be used to determine strategy of fertiliser addition.

2.9 SUMMARY

The P cycle in grazed hill-country pasture involves the uptake of P from soil by plants, the intake of plant P by animals, and the return of P to the soil directly from the plant as litter or indirectly via animal faeces. In reality, the system is more complex than this because these general soil, plant or animal compartments contain sub-compartments which undergo complex interactions.

As the measurement of transfer rates between some compartments is difficult, studies have tended to focus either on particular aspects of the P cycle or on whole systems at or near equilibrium.

Attempts to model the P cycle in grazed pasture with a view to predicting P fertiliser requirements for maintenance situations have been made recently. The model currently in use in New Zealand was developed by combining data relating DMY with P fertiliser input from a large number of field trials.

The model states that maintenance P fertiliser input is equal to the sum of animal and soil losses, and supplies a range of animal and soil loss factors from which the appropriate figure for particular farming systems (designated by stock type, grazing management and topography) and soil groups can be chosen.

Many studies have been carried out in an attempt to relate DMY and uptake of plant P to soil P. In most studies the soil P has been measured by traditional soil testing procedures which extract illdefined pools of soil P considered to be plant available in the short term. In some studies, however, the soil P pool was fractionated so that information on the chemical form of P being used by the plant was obtained. From these studies it would appear that P_I, more particularly non-occluded P, is likely to supply P to pasture in the generally slightly acid soil conditions found in New Zealand hill country. Under pasture, development of soil P_O content will increase to a steady-state value and, with continued additions of locally produced superphosphate (which has in the past been found to contain unreacted phosphate rock), calcium-bound P will also increase. It is not known what effect degree of land slope will have on soil P fractions. As hill country comprises land in different slope categories knowledge of the effect of slope on changes in the size of soil P fractions would increase understanding of the P cycle in hill country. This may be of importance when considering the magnitude of soil P losses as defined within the CFAS model (section 2.8) with a view to calculating maintenance P requirements for a particular site. Thus more detailed studies on the "below-ground" components of the P cycle in New Zealand are required in order to validate the model currently used to predict maintenance fertiliser P requirements.

"Above-ground" components of the P cycle have been studied in more detail than "below-ground" components.

Losses of P from the system occur via surface runoff and in the grazing animal. Loss of P in surface runoff is larger from slopes than from flat areas, due not only to ground angle but also to the fact that sward density is not as high on steep-slope as on campsites.

However, the amount of P lost from the system due to runoff is generally insignificant in agronomic terms. Loss of P via the grazing animal, due to retention of P within the body, amounts to about 10% of ingested P for a "typical" hill-country stock regime, i.e., most of the sheep are ewes, and lambs are raised for less than six months of the year. Losses of P via runoff and via the grazing animal contribute towards the soil loss factors and animal loss factors used within the CFAS model.

Plant uptake of P is known to vary not only with season and fertiliser rate, but also with degree of slope. Maximum rates of P uptake for a given fertiliser rate are likely to occur on campsites in late spring, whereas minimum rates occur in winter on steep slopes. Plant uptake of P increases with increasing rate of fertiliser P addition. This may lead to increased animal transfer of P at high rates of P fertiliser addition.

Sheep have a major effect on the P cycle in hill country because of their tendency to camp on flat areas. This can result in marked transfer of P in faeces to campsites at the expense of steeper areas. This P transfer, together with P loss in animal products, is used to calculate the animal loss factors used within the CFAS model.

The ratio of faecal P return to plant P uptake decreases as land slope increases. The effect, if any, of rate of fertiliser P addition and topography (i.e., the balance between easy and steep slopes within a paddock) on this ratio is not known. Since maintenance P requirements are calculated not only to replace soil losses, but also animal losses, a change in the ratio of faecal P return to plant P uptake could affect maintenance P requirements. This requires further investigation to enable validation and, possibly, refinement of the CFAS model.

The plant availability of P in faecal material should be considered in the ratio between faecal P return and plant P uptake. In the CFAS model it is assumed that faecal P will ultimately be as available as fertiliser P. The time required for faecal P to become available, or equal to fertiliser P is, however, the subject of some debate. Laboratory leaching experiments indicate that some P_I is capable of being leached into the soil immediately after deposition. Thus the plant availability of a portion of faecal P_I will depend on rainfall and the likelihood of root contact. The remaining P_I will be more resistant. In warm conditions, before the faecal material dries out, net mineralisation of P_O and rapid physical breakdown of the material can occur. In dry conditions, breakdown and mineralisation are likely to occur only slowly. In New Zealand hill country, how rapidly or slowly these processes occur, and if there is any effect of land slope on rates of decomposition, is not known. Furthermore, although work has been carried out on the availability of faecal P using pot trials and laboratory experiments, there have been no studies carried out on the turnover time for faecal P to become plant P in the field. This information could be of importance when determining P requirements of a system.

The animal loss factors for hill country used within the CFAS model were calculated originally from only one grazing trial, which involved rotationally-grazed sheep on steep hill country. As the effect of changes in grazing management and in topography were predicted from this single trial, rather than measured in separate trials, the CFAS ALF's may be influenced by trial design. This requires investigation, not only because the ALF's themselves require wider validation, but also because soil loss in the model was calculated originally as being the difference between P fertiliser input and animal loss. This means that any over- or under-estimation in animal loss will cause an automatic under- or over-estimation in soil loss, and therefore influence maintenance P requirements.

Assuming a stocking rate of 15, carrying capacity of 18, pasture utilisation of 80% and an SLF of 0.25, the effect of increasing the ALF from 0.50 to 0.70, 0.90 and 1.10 is to increase maintenance P requirements from 17 kg ha^{-1} to 20, 23 and 26 kg ha^{-1}, respectively. Similarly, holding the ALF constant at 0.7, increasing the SLF from 0.10 to 0.25 and 0.40 will increase maintenance P requirements from 14 to 20 and 25 kg ha^{-1}, respectively. Thus the effect of using the "wrong" ALF or SLF within the maintenance P calculation would be to increase or decrease recommended fertiliser P additions by 15 or 30% respectively. Given that the basis for deciding the animal and soil losses within the model has not been validated it is clear that research needs to be carried out as an incorrect assessment of animal and soil losses could have serious economic consequences.

CHAPTER 3

"BELOW-GROUND" COMPONENTS OF THE P CYCLE AS AFFECTED BY P FERTILISER ADDITION AND SLOPE

3.1 INTRODUCTION

The effect on soil P fractions of adding P fertiliser to pasture has been investigated by many workers. It has been found that organic P (P_O) levels increase under pasture until a balance between immobilisation and mineralisation is achieved. This equilibrium is not greatly affected by fertiliser rate, but is pH dependent (Dalal, 1977; Rickard and Quin, 1981; Quin and Rickard, 1983). In contrast, inorganic P (P_I) does increase with increasing rate of fertiliser P addition (Simpson et al., 1974; Quin and Rickard, 1983). Most of this increase in P_I occurs within the aluminium- and iron-bound P fractions but there is evidence to suggest that addition of high rates of fertiliser P will result in an increase in calcium-bound P (Rickard and Quin, 1981). However, in the latter study it was not clear whether the calcium-bound P accumulated as a stable reaction product or was due to unreacted rock phosphate in the fertiliser.

Transfer of P, which is known to occur from the major proportion of the grazing area onto comparatively small campsite areas, was not taken into account in any of the above studies. Limited work has been carried out to measure the effect of transfer on the immediately plant-available P pool but it is well accepted that with time, campsites will become preferentially enriched in P (available and total) at the expense of other areas in the paddock (Hilder, 1964; Saunders and Auld, 1969). In hill country, this means that flat areas are enriched at the expense of steeper slopes (Gillingham and During, 1973; Lambert and Roberts, 1978; Gillingham et al., 1980).

Work on the "above-ground" P transfer losses in New Zealand has yielded quantitative information in terms of pasture P concentration, degree of pasture utilisation, and the camping behaviour of stock with its consequent effect on return of faeces (Gillingham and During, 1973; Gillingham et al., 1980). However research into the magnitude of "below-ground" components of the P cycle has been limited. As the relative contributions of plant litter P, faecal P and fertiliser P vary markedly, depending upon what area in a paddock is being considered, the size of the "below-ground" P pools, and the relative rates of transfer between them, might also be expected to vary.

This has direct implications to the amount of fertiliser P that will be required to balance P losses on different slopes. With increasing emphasis being placed on efficiency of fertiliser use, variation in P demand according to slope assumes importance.

The investigation reported in this chapter was conducted to provide quantitative information on the forms of P accumulating, or being depleted, in various "below-ground" P pools. It was hoped that doing so would provide the necessary chemical data to define soil P status adequately, including any modifications induced by slope-related factors.

3.2 MATERIALS AND METHODS

3.2.1 Trial site

The trial area was at Whatawhata Hill Country Research Station, latitude 37° 48′S, altitude 220 m a.s.l., 22 km west of Hamilton in the North Island of New Zealand. The major trial site consisted of twenty hill-country paddocks with a northerly aspect.

The soil was predominantly a Kaawa hill soil (Bruce, 1976), a northern yellow-brown earth (Typic haplohumult) derived from argillaceous greywacke. Some volcanic ash was present on ridge crests which were consequently more free draining and had a higher P-sorption capacity than the soil on the slopes. Areas with a P-sorption capacity exceeding 80% were identified as a Dunmore yellow brown loam (Entic dystrandept); areas with a P-sorption capacity between 60 and 80% were identified as a Naike hill soil (Typic haplohumult) (Gary Orbell pers. comm.).

The pasture had been topdressed annually with approximately 400 kg ha^{-1} of single superphosphate which had, at times, included the nutrients molybdenum and potassium.

The trial began in April 1980, and was concluded in February 1984. Of the twenty paddocks, ten were set stocked by wether hoggets, the numbers of animals being adjusted to maintain the standing dry matter (DM) at approximately 1000 kg ha^{-1}. The remaining ten paddocks were grazed rotationally by ewes, the grazing period and growing period being one to three days and four to six weeks , respectively, according to grass growth. Grazing on the paddocks was terminated once the pasture cover had been reduced to 1000 kg ha^{-1} of DM.

The ten paddocks within each grazing treatment were topdressed at five different rates of P addition : 10, 20, 30, 50 or 100 kg ha^{-1}. Thus there were four replicate paddocks for each fertiliser rate and four experimental blocks for the trial, each block consisting of five paddocks each receiving a different fertiliser rate.

3.2.2. **Topographic survey**

A topographic survey (Appendix 1) provided a measure of the relationship between surface slope and area within each paddock. Surface slope (i.e., as the angle of departure from the horizontal) was measured along ten transects, located evenly across each paddock. On all transects, slope was recorded at one metre intervals to the nearest five degrees to give a total of four hundred points per paddock.

3.2.3. **Soil sampling sites**

Within each paddock, five areas within each of two categories of topographic slope (easy (11-20^{o}) and steep (31-40^{o})) were identified and marked with pegs. For the final soil sampling in 1984, samples were also taken from campsites (0-10^{o}).

In one of the rotationally-grazed blocks of the trial, five areas within each of five categories of topographic slope were identified and marked with pegs, thus enabling a more detailed study on the "below-ground" compartments of the P cycle to be carried out within the more extensive framework of the trial. All measurements on the soil were made on samples collected from within the areas denoted by the pegs.

The soil was sampled prior to fertiliser application each summer. Four cores (2 cm diameter) were taken to a depth of 15 cm from each of the areas described previously. The cores were sectioned into 0-3, 3-7 and 7-15 cm depths in order to investigate the effect of depth on changes in soil P fractions. Samples were then air-dried, passed through a 2 mm sieve, bulked according to depth, and stored for analysis. Prior to soil P fractionation and analyses of total P, subsamples of soil from each of the five replicate areas within each slope were bulked.

3.2.4 **Soil analysis**

3.2.4.1 **pH**

Soil pH was measured with a combination electrode pH meter after stirring 10 g of soil in 25 ml of distilled water and leaving to stand overnight before reading.

3.2.4.2 **Phosphorus-sorption capacity**

Five g of air-dried soil (<2 mm) were shaken for 16 h in 25 ml of 0.2 sodium acetate solution containing 1000 µg ml^{-1} of P as KH_2 PO_4 and adjusted to pH 4.65 with glacial acetic acid. P-sorption capacity was calculated from the amount of P removed from solution by the soil, expressed as a percentage of the amount added originally (Saunders, 1965).

3.2.4.3 **Olsen-extractable P**

Five g of air-dried soil (<2 mm) were shaken with 100 ml of 0.5 M $NaHCO_3$ (pH 8.5) on an end-over-end shaker at 28 rpm at 20°C for 30 min (Olsen et al., 1954). The suspension was then centrifuged at 10,000 rpm for 2 min before filtering. Inorganic P was determined colorimetrically in an aliquot of the extract using the method of Murphy and Riley (1962), absorbance being measured at 712 nm using a Pye Unicam SP 1800B spectrophotometer.

3.2.4.4 **Water-extractable P**

The single-water extraction method of Sorn-srivichai (1985) involves shaking 2 g of air-dried soil (<2 mm) with 240 ml of distilled water at 20°C for 1 h. Inorganic P was determined in a filtered aliquot of the sample as in section 3.2.4.3.

3.2.4.5 **Total, inorganic and organic P**

Two g samples of air-dried soil (<2 mm) were ignited at 550° C for 1 h, then extracted with 100 ml of 0.1 M H_2SO_4 for 16 h on an end-over-end shaker (Walker and Adams, 1958). Inorganic P was extracted in the same way with 0.1 M H_2SO_4 from a comparable sample of unignited soil and determined colorimetrically as described in section 3.2.4.3. Organic P was calculated by difference.

3.2.4.6 **Inorganic P fractionation**

Soil inorganic P was further separated into four fractions (easily soluble P, non-occluded P, occluded P and calcium-bound P) using a modification of the method of Chang and Jackson (1957). Easily soluble P, which is thought to be soil solution P with some very loosely-bound P, was extracted by shaking the soil in 1 M NH_4Cl for 30 min. Aluminium- and iron-bound non-occluded P was extracted after 16 h shaking in a solution containing 0.1 M NaOH and 1 M NaCl (the latter was included to facilitate centrifugation (Walker et al., 1967)). Reductant-soluble iron phosphate (occluded P) was dissolved using a citrate dithionite extraction. This involved adding 1 g solid $Na_2S_2O_4$ to the soil sample suspended in 0.3 M tribasic sodium citrate ($Na_3C_6H_5O_7.2H_2O$). A water bath was used to keep the temperature of the samples between 80 and 90° C and, after the sodium dithionite was added, the samples were stirred for 15 min. Samples were washed twice with saturated NaCl (washings being added to the sodium dithionite extract) before extraction of calcium-bound P by shaking the samples in 0.5 M HCL for 1 h. The soil used was ground to pass 150 µm sieve before analysis. All extractions were carried out at a solution:soil ratio of 40:1 in 50 ml polypropylene tubes, and samples were centrifuged and filtered (<0.45 µm) between each step. Inorganic P was measured as described earlier. Colour was developed in the citrate dithionite extracts after three days had elapsed. This allowed complete oxidation of any unreacted dithionite to occur, and prevented interference with colour development, (Williams et al., 1967) in the Murphy and Riley method.

The fractionation scheme is outlined in Fig. 3.1.

3.2.5 Statistical analysis

Results were subjected to a statistical analysis of variance where possible. However, the large number of samples collected each year necessitated bulking for some chemical analyses (i.e., analysis of total, organic, and inorganic P plus inorganic P fractions). For these analyses statistical analyses were possible in the final year of the trial when soil samples from campsites, easy- and steep-slopes were collected from all paddocks within the trial.

3.3 RESULTS AND DISCUSSIONS

As trends in results in all experimental blocks were similar, detailed annual results are presented only for the rotationally-grazed block in which intensive soil sampling was carried out for all years of the trial. No significant differences in any chemical parameter measured

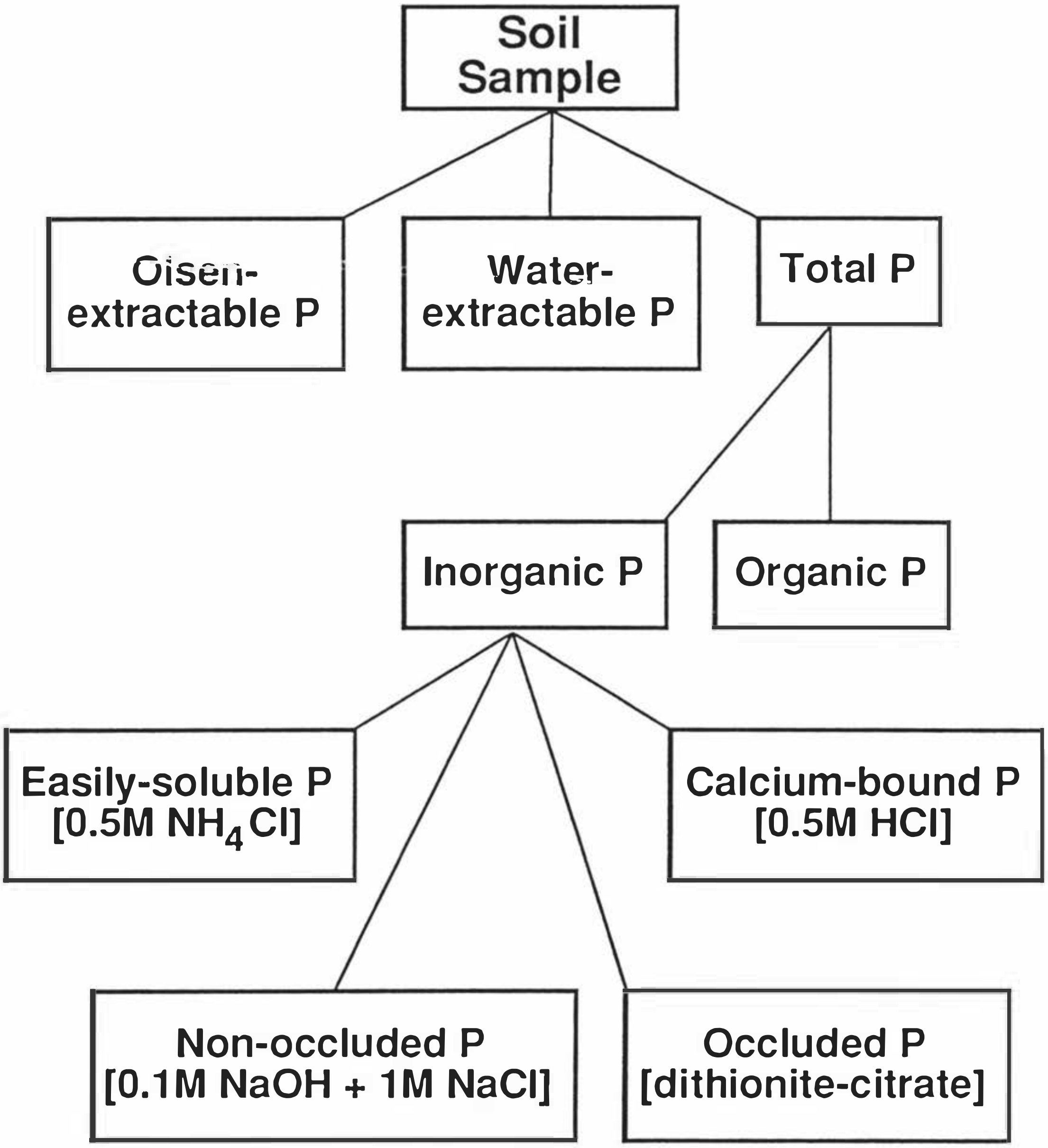

Figure 3.1 Schematic representation of chemical fractionation of soil P.

were found between 11-20^{o} and 21-30^{o} slopes or 31-40^{o} and 41^{o}+ slopes, so, for reasons of simplicity, results are given for campsites, and easy- and steep-slopes only.

Analysis of total P and fractionation of P_I were carried out in 1984. Unfortunately, by this time some of the samples collected in 1981 had been destroyed, due to a misunderstanding between Ruakura Soil and Plant Research Station, Whatawhata Hill Country Research Station and Massey University.

Final year results, which included more intensive sampling on all paddocks, are discussed for the entire trial.

3.3.1 pH

Soil pH in the surface 3 cm varied from 5.7 to 5.9 on the flat campsites to 5.3 to 5.4 on the steep-slopes (Table 3.1). The effect of slope on pH was significant, and decreased with depth (0-3 cm $P<0.01$; 3-7 cm $P< 0.05$).

Variability in pH between years was apparent. In 1982 pH was approximately 0.4 units lower on all sites than in 1981 and in 1983 it was about 0.2 units lower than in 1981. Samples collected in 1982 were re-analysed at a later date as a check against laboratory error. No differences between readings at the two different times were found.

Table 3.1 Effect of slope, depth and rate of P fertiliser addition (kg ha^{-1}) on pH in the first year of the trial. Data presented are from the five intensively sampled paddocks.

		Rate of P fertiliser addition (kg ha^{-1})				
		10	20	30	50	100
Slope	Depth (cm)					
0-10°	0-3	5.7	5.9	5.8	5.8	5.8
	3-7	5.4	5.5	5.5	5.4	5.4
11-20°	0-3	5.7	5.8	5.7	5.7	5.7
	3-7	5.4	5.6	5.6	5.5	5.6
31-40°	0-3	5.3	5.4	5.4	5.4	5.4
	3-7	5.2	5.4	5.4	5.3	5.3

3.3.2 Phosphorus-sorption capacity

For simplicity, P-sorption capacities are presented only for the five paddocks included in the more detailed study described earlier (Table 3.2). P-sorption capacities tended to (1) be highest on easy-slopes and lowest on steep-slopes (2) increase with depth. Between paddock variation was least on steep-slopes and greatest on campsites. There was little or no change in P-sorption capacity during the trial.

Most soil P-sorption capacities fell into the medium range (Saunders, 1965). High P retentions indicated the presence of volcanic ash on the campsites and easy-slopes in the 20 kg ha^{-1} and the easy-slope in the 50 and 100 kg ha^{-1} P paddocks; this influenced interpretation of later results from these slopes.

3.3.3 Initial P status

Before fertiliser P treatments were added in the first year (1980) the initial P status of the soil was measured using the Olsen test. Although P levels for most of the paddocks were approximately the same (20 µg g^{-1} soil) for campsites a few paddocks had distinctly higher amounts of Olsen-extractable P (38 µg g^{-1} soil) (Table 3.3). To avoid confounding results at realistic P fertiliser rates, the highest rates of fertiliser treatment were assigned to the paddocks which already had a high P status. This influenced subsequent interpretation of some results.

Table 3.2 Effect of slope and rate of P fertiliser addition ($kg\ ha^{-1}$) on P-sorption capacities (%) in the first year of the trial. Data presented are from the five intensively sampled paddocks (0-7 cm).

		Rate of P fertiliser addition ($kg\ ha^{-1}$)				
		10	20	30	50	100
Slope	Depth (cm)					
11-20°	0-7	52	90	NA	75	77
31-40°	0-7	57	56	NA	69	49

NA = data not available

Table 3.3 Effect of slope, depth and rate of P fertiliser addition (kg ha^{-1}) on initial Olsen P values. Data presented are from the five intensively sampled paddocks.

		Rate of P fertiliser addition (kg ha^{-1})				
		10	20	30	50	100
Slope	Depth (cm)					
0-10^{o}	0-3	20	20	NA	21	38
	3-7	15	14	NA	16	33
11-20^{o}	0-3	18	17	NA	17	28
	3-7	9	8	NA	8	18
31-40^{o}	0-3	16	15	NA	13	19
	3-7	9	8	NA	7	11

NA = data not available

3.3.4 **Olsen-extractable P**

Olsen P values increased on campsites at all but the lowest rate of fertiliser P addition, and on all slopes at high rates of fertiliser P addition during the trial (Fig. 3.2). On campsites at high (50 and 100 kg ha^{-1}) rates of P fertiliser addition most of the increase occurred after the first application of fertiliser, whereas on steeper slopes the increase occurred gradually over time. The effect of fertiliser on Olsen P became significant ($P<0.01$) in the 0-3 cm depth after two years of differential fertiliser application. After three years of differential fertiliser application the effect of fertiliser was also significant at depth (3-7 and 7-15 cm; $P<0.05$) (Fig. 3.3). As routine soil testing is normally carried out on soil taken from 0-7.5 cm depth, it is clear that any effect on soil P of changing P fertiliser additions will probably not become apparent until at least two years have elapsed.

At low to medium rates of fertiliser P addition (10, 20 and 30 kg ha^{-1}) there was little change in Olsen P on campsites, except in the 20 kg ha^{-1} P paddock in 1984. Re-analysis of soil samples indicated that the large increase in this paddock was real and not due to laboratory error. It is possible that the large increase is a combination of two factors. In this paddock, campsites occupy only a small area (9%) which means that return of faeces to this area is intense, leading to preferential enrichment of the soil beneath. A second factor is that in 1984 soil samples were ground and sieved mechanically, whereas samples had been sieved by hand in all previous years. Hand sieving enables removal of faecal material and

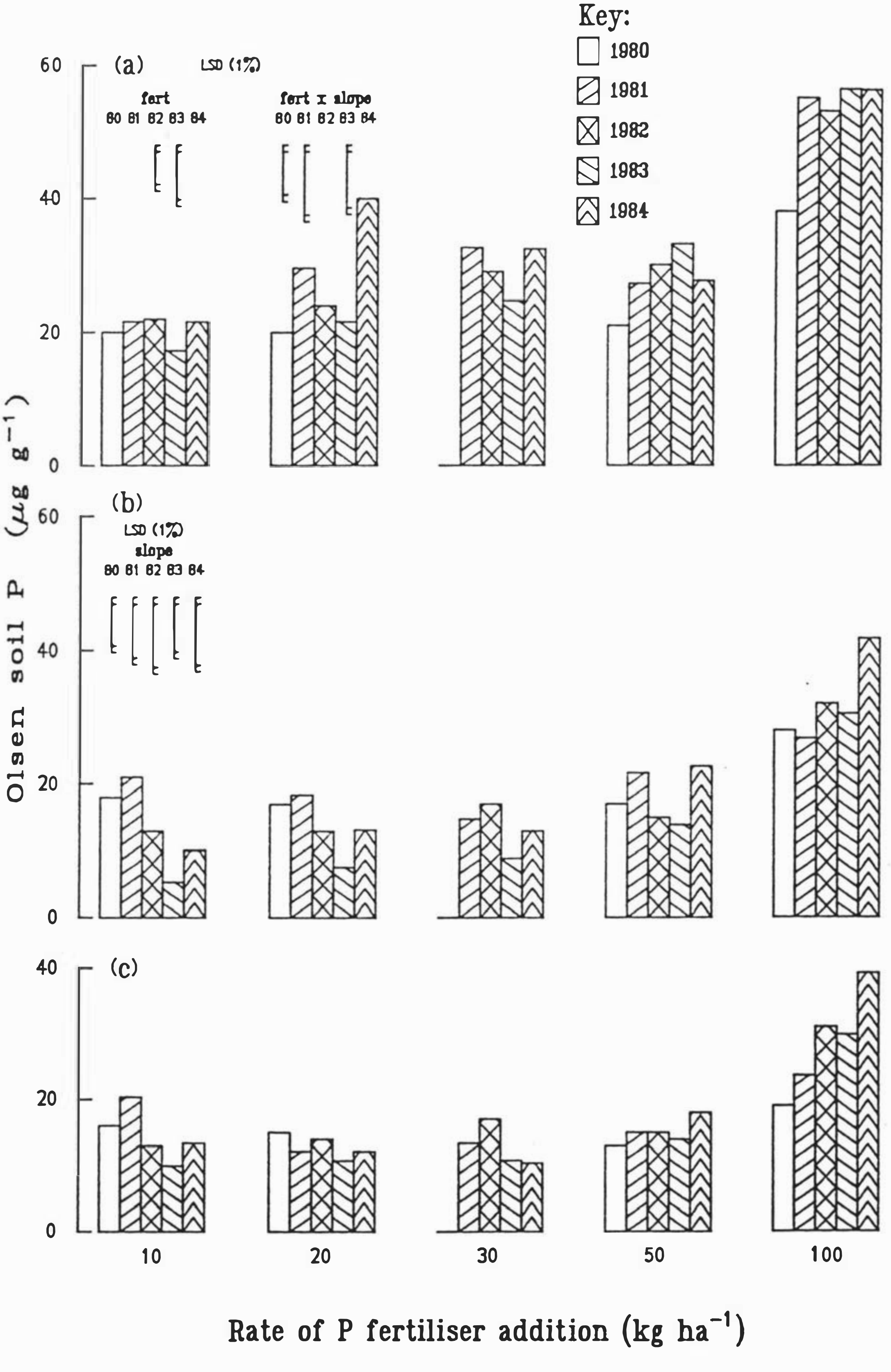

Figure 3.2 Change in Olsen-extractable P in 0-3 cm depth over a four year period on campsites (a) easy-slopes (b) and steep-slopes (c) following the application of differential rates of fertiliser.

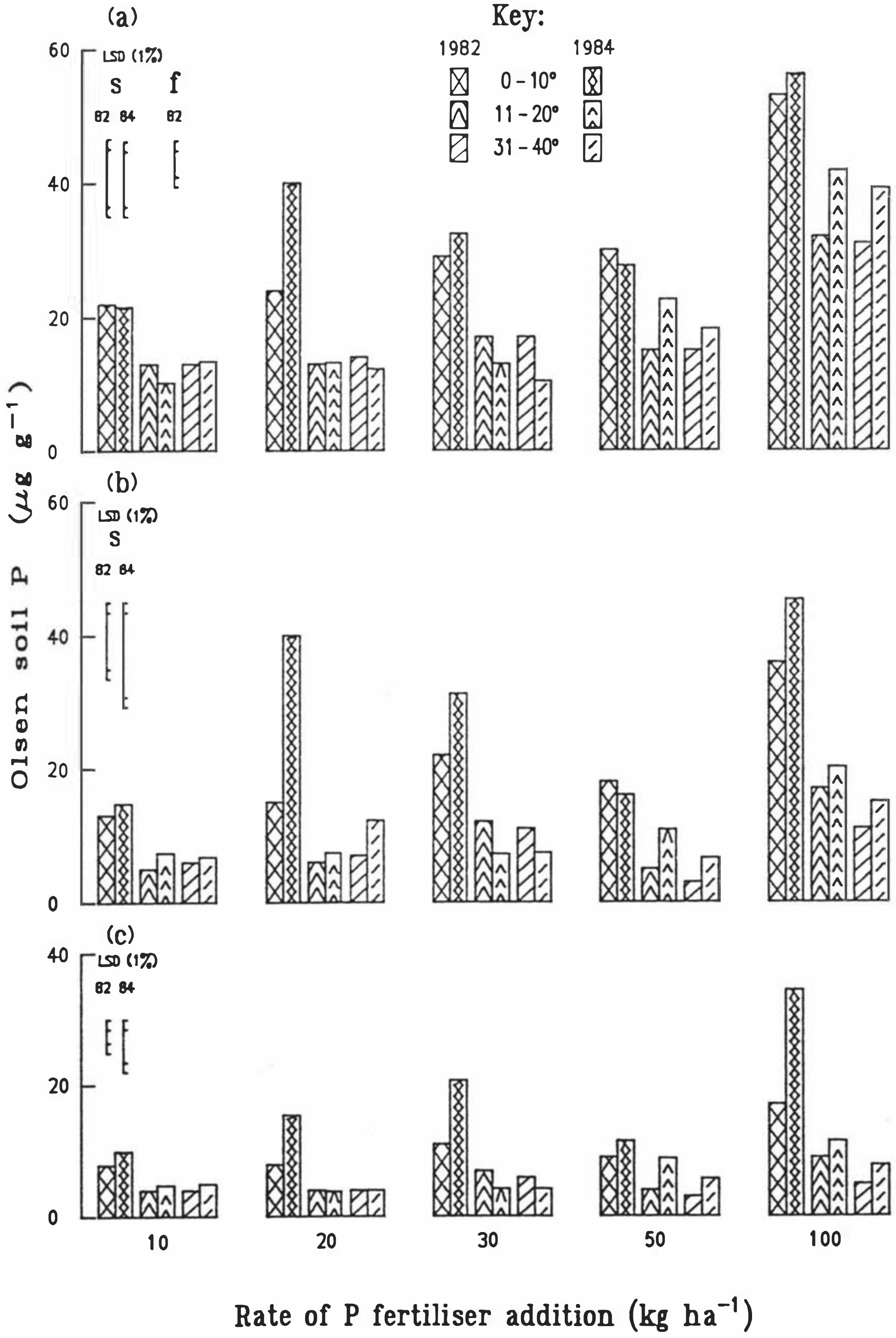

Figure 3.3 Change in Olsen-extractable P on campsites over a two year period at the 0-3 (a) 3-7 (b) and 7-15 (c) cm sampling depths following the application of differential rates of fertiliser.

undissolved fertiliser particles during the process; machine grinding does not. It is possible therefore that some faecal material was included in the sample from the 20 kg ha^{-1} P paddock. However, although this could explain the increase in the surface soil (0-3 cm) it does not explain the increase in P in the 3-7 and 7-15 cm depths.

On easy- and steep-slopes at low (10 kg ha^{-1}) and medium (20 and 30 kg ha^{-1}) rates of fertiliser P a decrease in Olsen P was noticed over the period of the trial. This suggests that, in the cycling P pool, P losses were exceeding P gains resulting in depletion of the soil P pools.

The effect of slope on Olsen P was significant ($P<0.01$) in all years of the trial at all depths, including the year before differential rates of fertiliser were applied, which indicates that there are inherent differences in Olsen P values between slopes. These inherent differences reflect, in part, the fact that the paddocks had been grazed by sheep for many years before the trial commenced. Campsites had the highest levels of Olsen-extractable P within each fertiliser P rate and contained significantly more P than easy-slopes which, in turn, had slightly higher Olsen P values than steep-slopes.

During the period of the trial it was noticeable that Olsen P increased more on steep-slopes than on easy-slopes at high rates of fertiliser P addition. At low rates of fertiliser P addition, Olsen P decreased less on steep-slopes than on easy-slopes. Those changes are in part a reflection of the balance between plant P uptake and faecal P return which will be discussed in full in chapter 5.

During 1982 and 1983 there was a slight decrease in Olsen P values on all slopes and at all depths in the 10, 20 and 30 kg ha^{-1} P rate paddocks. The decrease was most noticeable on intermediate slopes and at 0-3 cm depths, particularly in 1983. This trend was not observed in other soil P fractions and could not be explained by laboratory error or by unusual weather conditions.

The levels of Olsen P discussed previously in this section have been expressed as $\mu g\ g^{-1}$ soil and therefore, the comparison between slopes and rates are confounded by topography and soil bulk density. That is, because of the camping behaviour of sheep, the increase in some P fractions may depend on the area occupied by the slope under consideration in a particular paddock and the bulk density of the soil from that slope. Bulk densities were measured by MAF research staff on representative soil from two sites (0-3, 3-7 cm and 7-15 cm depths) in the trial (Table 3.4). Since the soils differed in their respective volcanic ash content, P-sorption capacities measured at these sites were used to derive a simple relationship between P-sorption capacity and bulk density at two depths. This relationship was then used to predict bulk densities on other areas within the trial using data from Table 3.2. As bulk densities were not measured directly, only general trends in results will be discussed. To obtain more information on the increase in Olsen P in each paddock with time, the change between 1982 and 1984 in Olsen P values for each slope within each paddock was calculated, corrected for bulk density and area and summed to give an overall change in P (kg ha^{-1}) for that Paddock. The method involves subtraction of large numbers to reveal

Table 3.4 Bulk density at three soil depths for two main soil components within the trial. Data presented are the average of results from North and South aspects.

	Depth (cm)		
Soil Type	0-3	3-7	7-15
Yellow-brown loam	0.56	0.58	0.79
Yellow-brown earth	0.64	0.90	0.97

comparatively small differences and is, therefore, prone to variability. Furthermore, the differences being identified have occurred during a two-year period which is a comparatively short time in terms not only of pasture development, but also of the sensitivity of the Olsen P test.

Despite this inherent variability, trends in the data were obvious (Fig. 3.4). At low rates of fertiliser P addition a decrease in Olsen P was apparent, whereas at high rates there was an increase. It is interesting to note that on a per paddock basis the increase in Olsen P at the highest rate of P addition was only 0.8 kg ha^{-1} each year, which is less than 1% of that fertiliser P added.

3.3.5 **Water-extractable P**

Between 1981 and 1984, water-extractable P increased on campsites at all rates of fertiliser addition and on easy- and steep-slopes at the highest rate of fertiliser (Fig. 3.5). There was a decrease in P on the easy-slopes in the 10 and 20 kg ha^{-1} paddocks and on the steep-slope in the 10 kg ha^{-1} paddocks. These results tend to suggest that at low rates of P fertiliser, insufficient P was being applied to meet P losses and so water-extractable P was being depleted. The pattern was similar at depth (Fig. 3.6) but the effect was less marked.

The effects of fertiliser rate and slope on water extractable P were significant ($P<0.01$) in each year of the trial. In general, P levels at high rates of fertiliser exceeded those at low rates and, within a

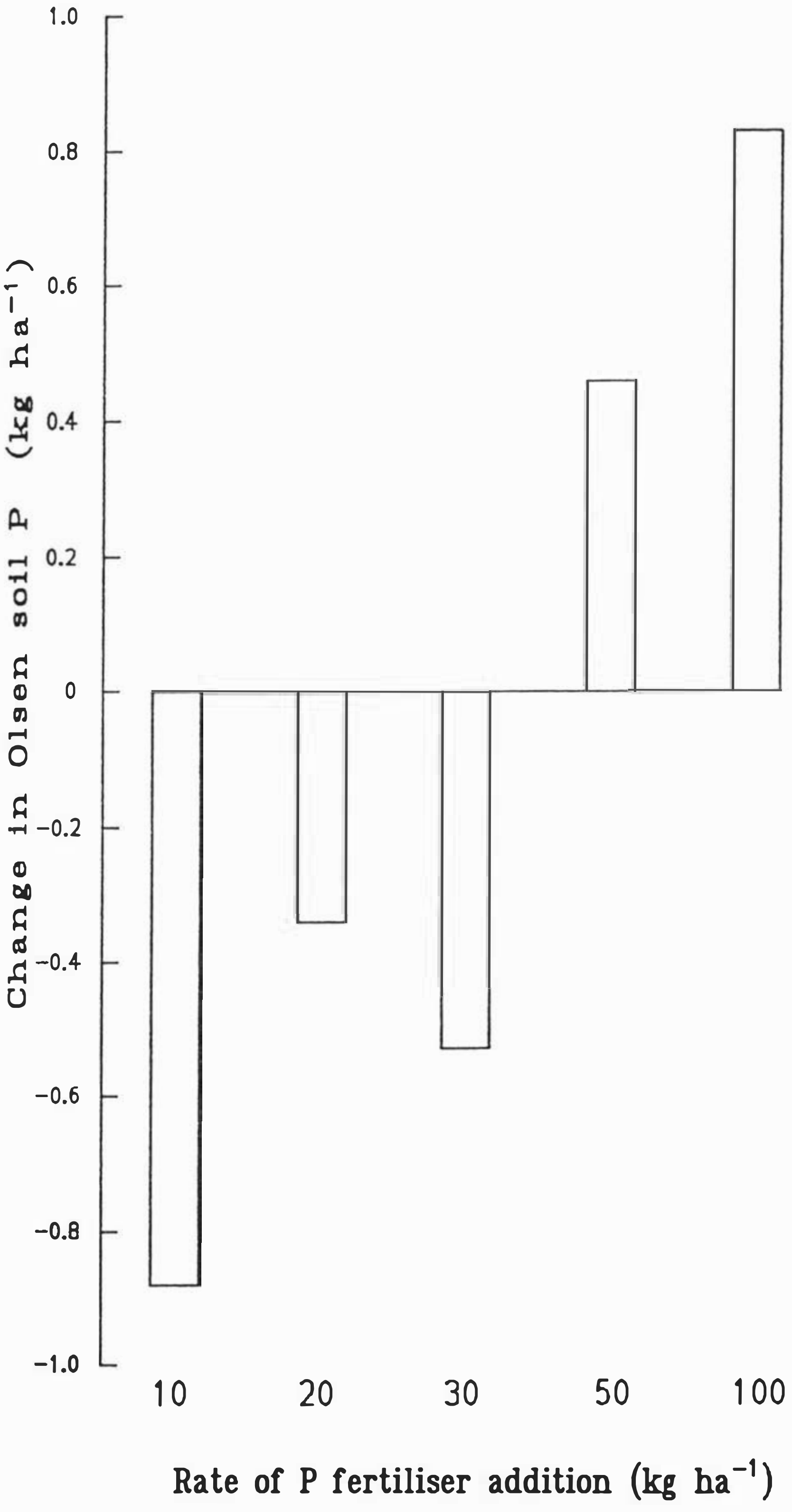

Figure 3.4 Relationship between change in Olsen-extractable P (kg ha^{-1} P; 0-3 cm depth) and fertiliser rate over a two year period.

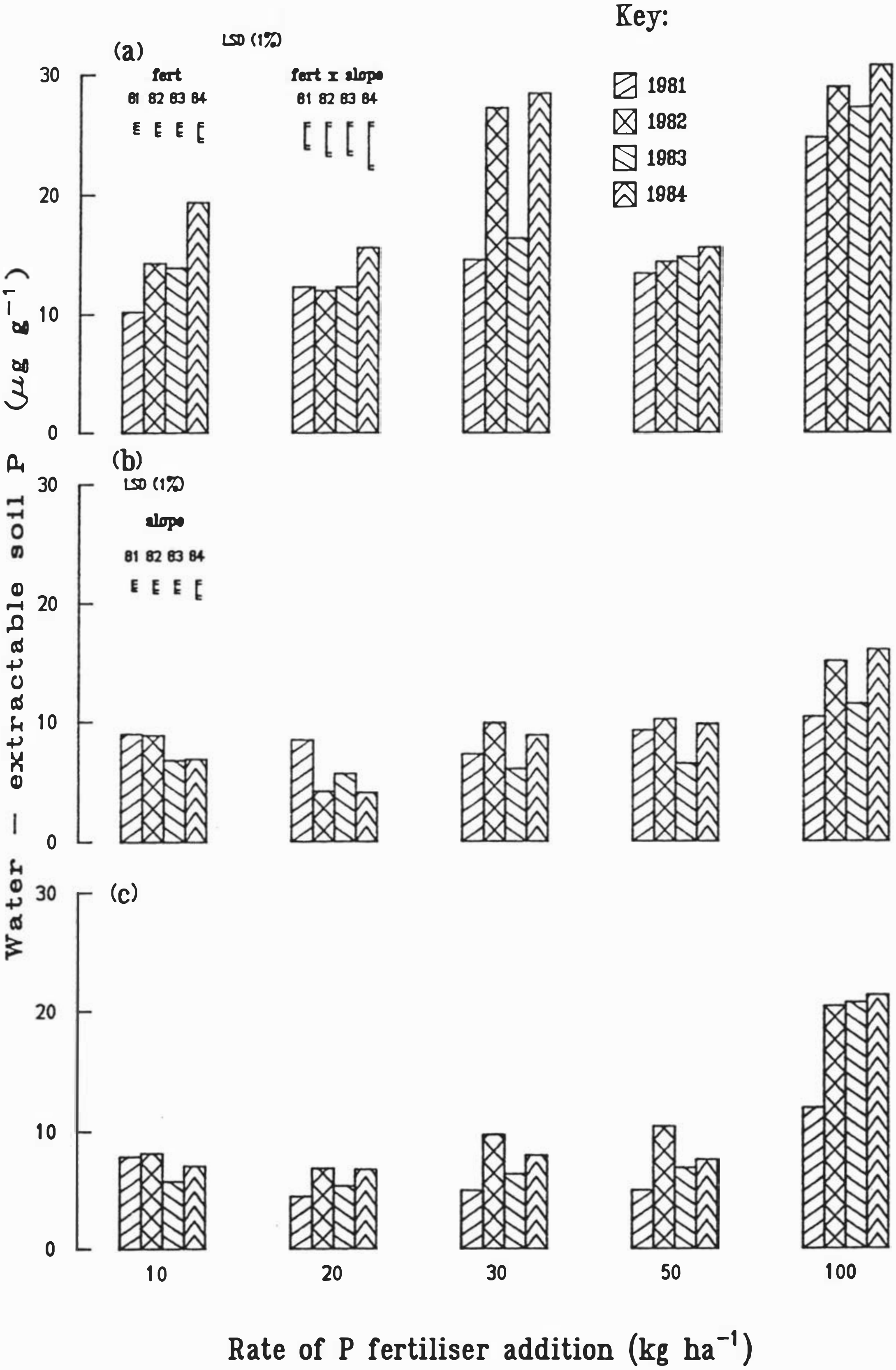

Figure 3.5 Change in water-extractable P in 0-3 cm depth over a four year period on campsites (a) easy-slopes (b) and steep-slopes (c) following the application of differential rates of fertiliser.

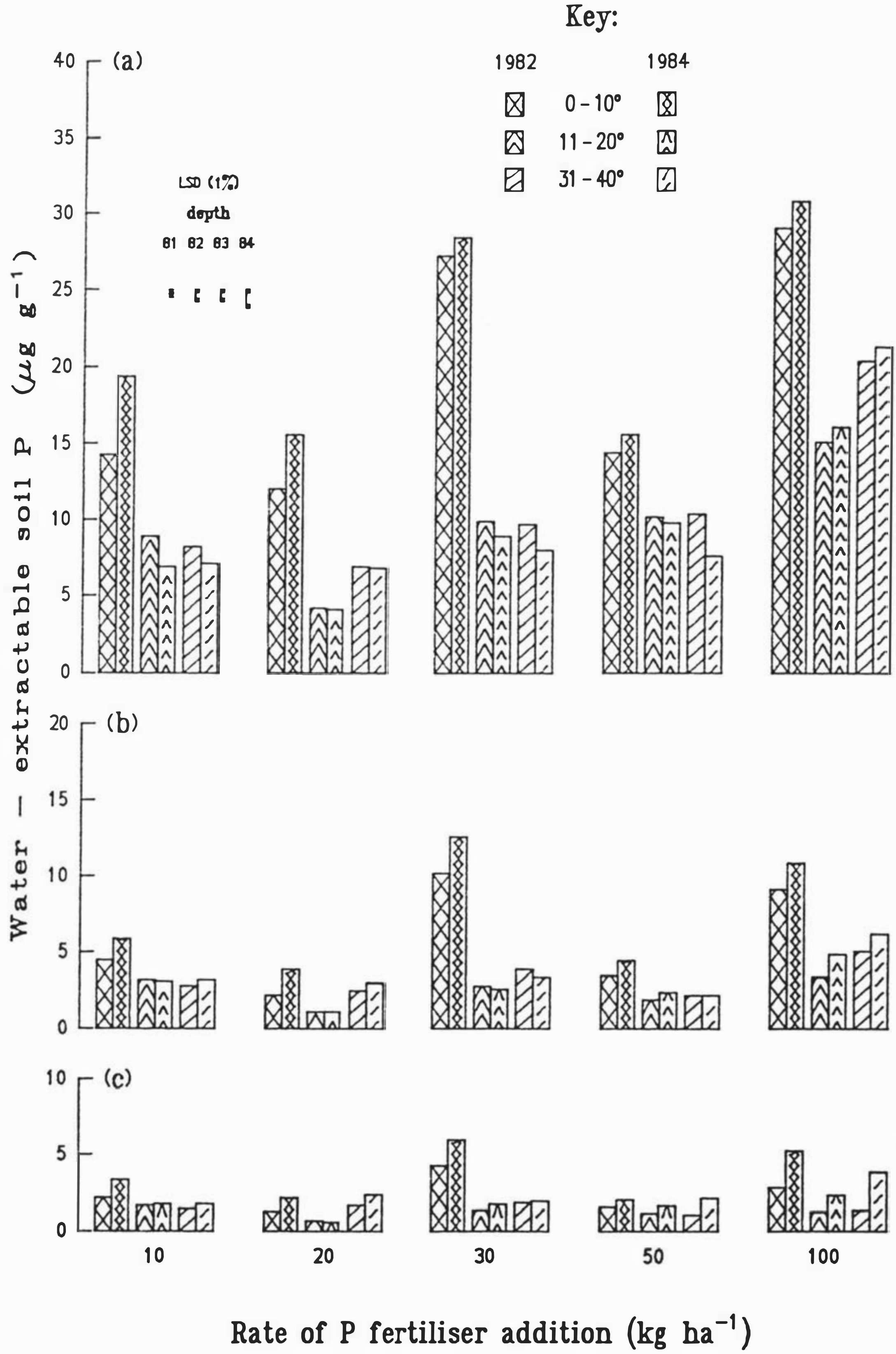

Figure 3.6 Change in water-extractable P on campsites over a two year period at the 0-3 (a) 3-7 (b) and 7-15 (c) cm sampling depths following the application of differential rates of fertiliser.

fertiliser rate, campsite P levels exceeded those of easy-slopes which in turn were higher than steep-slope P levels.

The increase on campsites was a result of P transfer, as discussed in section 3.3.4. The fact that the increase on steep-slopes exceeded that on easy-slopes, particularly at high rates of fertiliser P, was probably a function of lower soil moistures on steep- than easy-slopes (Gillingham and Bircham, 1985), low P-demanding species growing on these steep-slopes, and poor utilisation of the pasture by animals (Gillingham and During, 1973). With little uptake from the soil, soluble P in applied fertiliser would be expected to accumulate, particularly at high levels of application.

Exceptions to these general trends occurred on the campsites in the 10 and 30 kg ha^{-1} paddocks. Re-analysis indicated that these exceptions were real, but it is thought that the large increases apparent in 1984 may have been part of the general variability seen in this year as discussed in the previous section.

In the 10 kg ha^{-1} paddock, the large increase seen in 1982 is likely to have been a result of P transfer to an area not previously used as a campsite. Subdivision fencing of the trial area in 1980 of previously large paddocks meant that some of the new small paddocks, including the 10 kg ha^{-1} P paddock, did not contain established campsites. The return of large amounts of faeces to the newly designated campsites would have meant a readjustment of the equilibrium between mineralisation and immobilisation, and an increase in water-extractable P.

High levels of water-extractable P were measured on the campsite in the 50 kg ha^{-1} rate paddock in 1982 and 1984. These high levels were also obtained at depth, but were not present on easy- or steep-slopes. At the 0-3 cm depth, the level of water-extractable P was almost equal to that of Olsen-extractable P.

Olsen-extractable P includes water-extractable P and, although both provide an estimate of plant-available P, that removed by water extraction is likely to be more readily available than P removed by the Olsen extraction. The fact that in 1982 and 1984 the water-extractable P accounted for nearly all the Olsen P indicates that in those years most of the "plant-available" P in the soil was in the readily-available form.

In 1982 this may have been due to a dry January (Appendix II). The soil in the 30 kg ha^{-1} P rate paddock has a stronger yellow-brown earth component and less ash influence than the other paddocks, as mentioned in section 3.3.2. This means that the area has a lower available moisture level and is therefore more drought prone than sites with a larger volcanic ash influence (Gillingham et al., 1984a). A dry January would mean a restriction of plant growth and of P uptake, and a consequent increase in soil solution P. A similar increase in P levels during dry conditions has been measured by Sornsrivichai (1985). The phenomenon has been explained by Larsen (1967) and Wilson (1968) who considered that the readily-available sources of P were depleted during periods of rapid growth and then restored from slowly-available sources during subsequent periods of slow growth.

The high water-extractable P level in 1984 is part of the variability shown in the data for that entire year. As discussed in the preceding section the fluctuation may be linked to the different preparation technique used.

At the highest rate of fertiliser P it is interesting to note that water-extractable P levels on the steep-slopes exceed those on easy-slopes in all years of the trial. This indicates that more water-extractable P was being added to the steep-slope soil in fertiliser than could be used by pasture due to other limitations to plant growth, such as low moisture and nitrogen status. This occurred despite the fact that addition of faecal P is minimal on steep-slopes and that litter return (%) was considered to be similar on all slopes (Gillingham, 1980a).

3.3.6 Total, inorganic and organic P

With one exception, total P increased at all fertiliser rates on all slopes during the four years of the trial (Fig. 3.7). The exception was at the lowest rate of fertiliser P on the steep-slope, where there was little change.

As explained in section 3.2.5 no statistical evaluation of this data was possible because the large number of samples made it necessary to bulk them prior to analysis. However, after two years of differential fertiliser P application it was clear (Fig. 3.7) that increasing rate

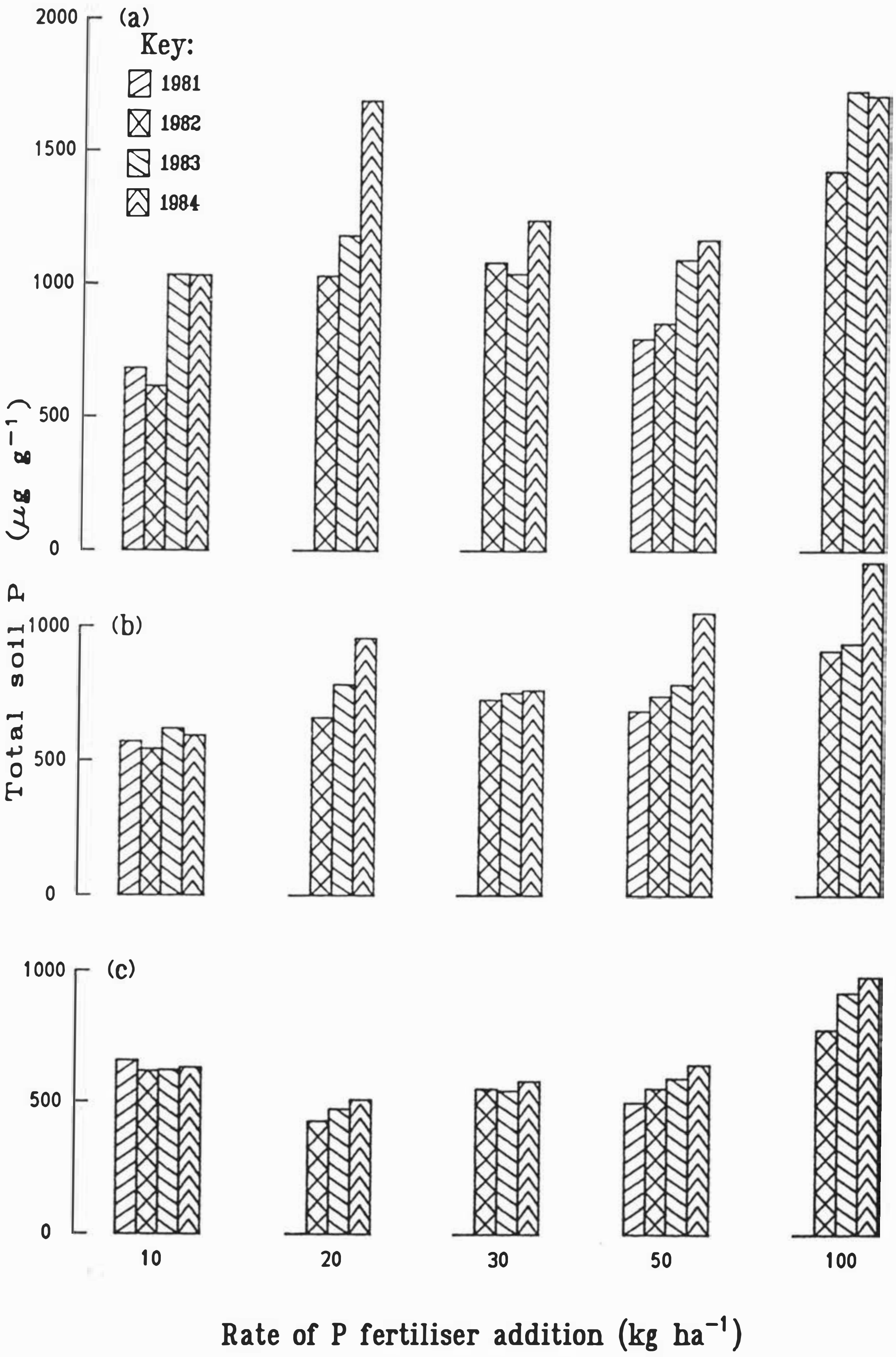

Figure 3.7 Change in total P in 0-3 cm depth over a four year period on campsites (a) easy-slopes (b) and steep-slopes (c) following the application of differential rates of fertiliser.

of fertiliser P addition was associated with an increase in total P. This trend was interrupted in 1984 (after four years of differential P fertiliser addition) due to a very large increase in total P in the 20 kg ha^{-1} P paddock. This increase may have been an artefact connected with machine grinding, as discussed in section 3.3.4.

Easy- and steep-slopes showed similar trends in total P as those shown in campsites. However, although the actual increases were similar, the yearly fluctuations were not as marked. Total P on campsites exceeded that on steeper slopes and, in all but the 10 kg ha^{-1} P paddock, easy-slope soils contained more than steep-slope soils. The comparatively high P status of the steep-slope in the 10 kg ha^{-1} P paddock was inherited at the beginning of the trial.

Inorganic P followed the same pattern as that of total P and was, in fact, responsible for most of the increase in total P with increasing rate of fertiliser P addition. Thus the increase in P_I was greater at high rates of fertiliser P than low (Fig. 3.8). Similar increases in P_I rather than P_O with increasing rate of fertiliser have been noted by other workers (e.g., Simpson et al., 1974; Quin and Rickard, 1983).

Organic P showed a small increase with time (Fig. 3.9) but was not greatly affected by rate of fertiliser addition. The effect of slope was apparent in that, for a given P fertiliser rate, P levels were higher on campsites than on easy-slopes, which in turn, were higher than on steep-slopes. Also, fluctuations between years and fertiliser rates were more noticeable on campsites than on other slopes, which

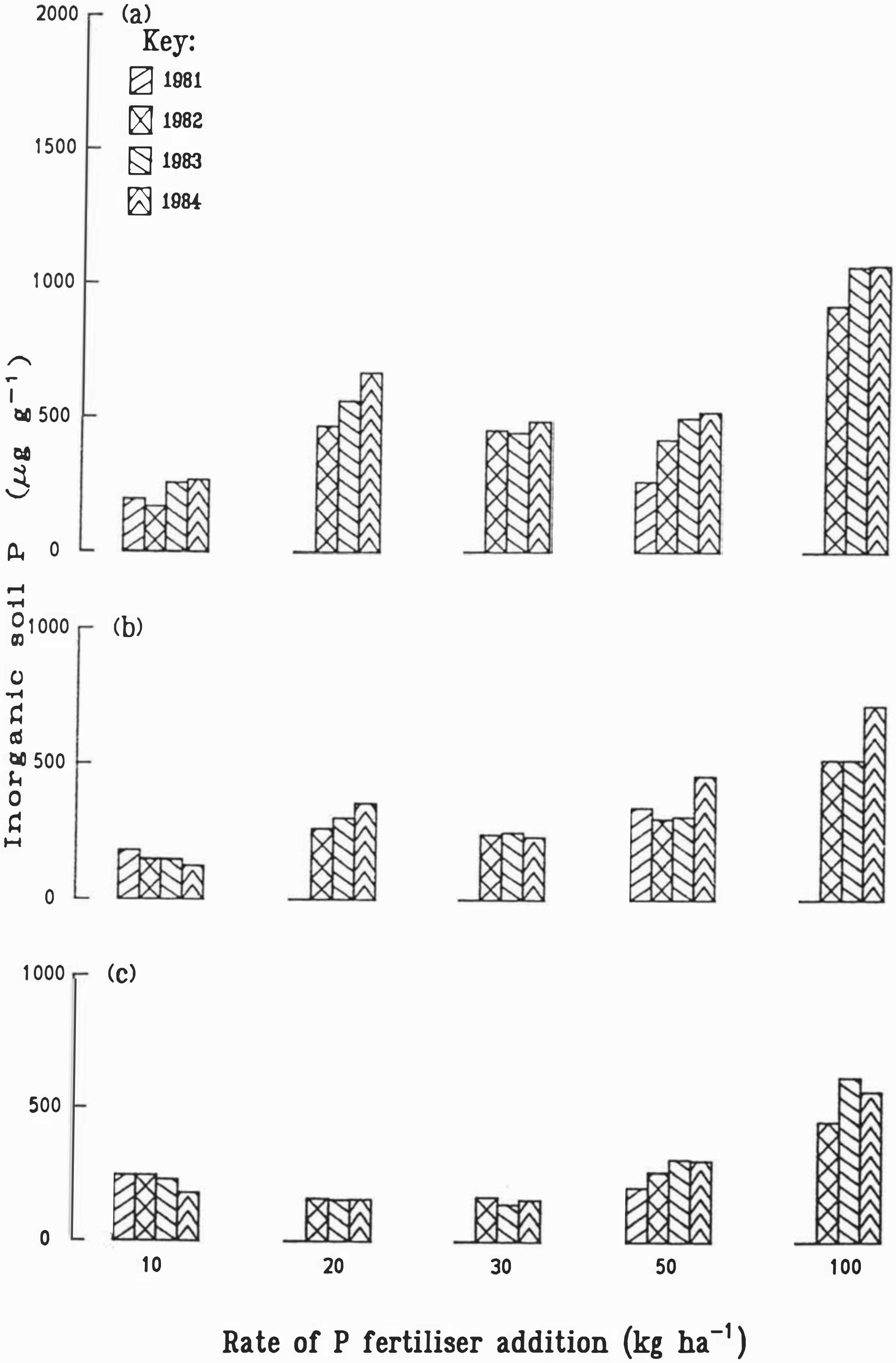

Figure 3.8 Change in inorganic P in 0-3 cm depth over a four year period on campsites (a) easy-slopes (b) and steep-slopes (c) following the application of differential rates of fertiliser.

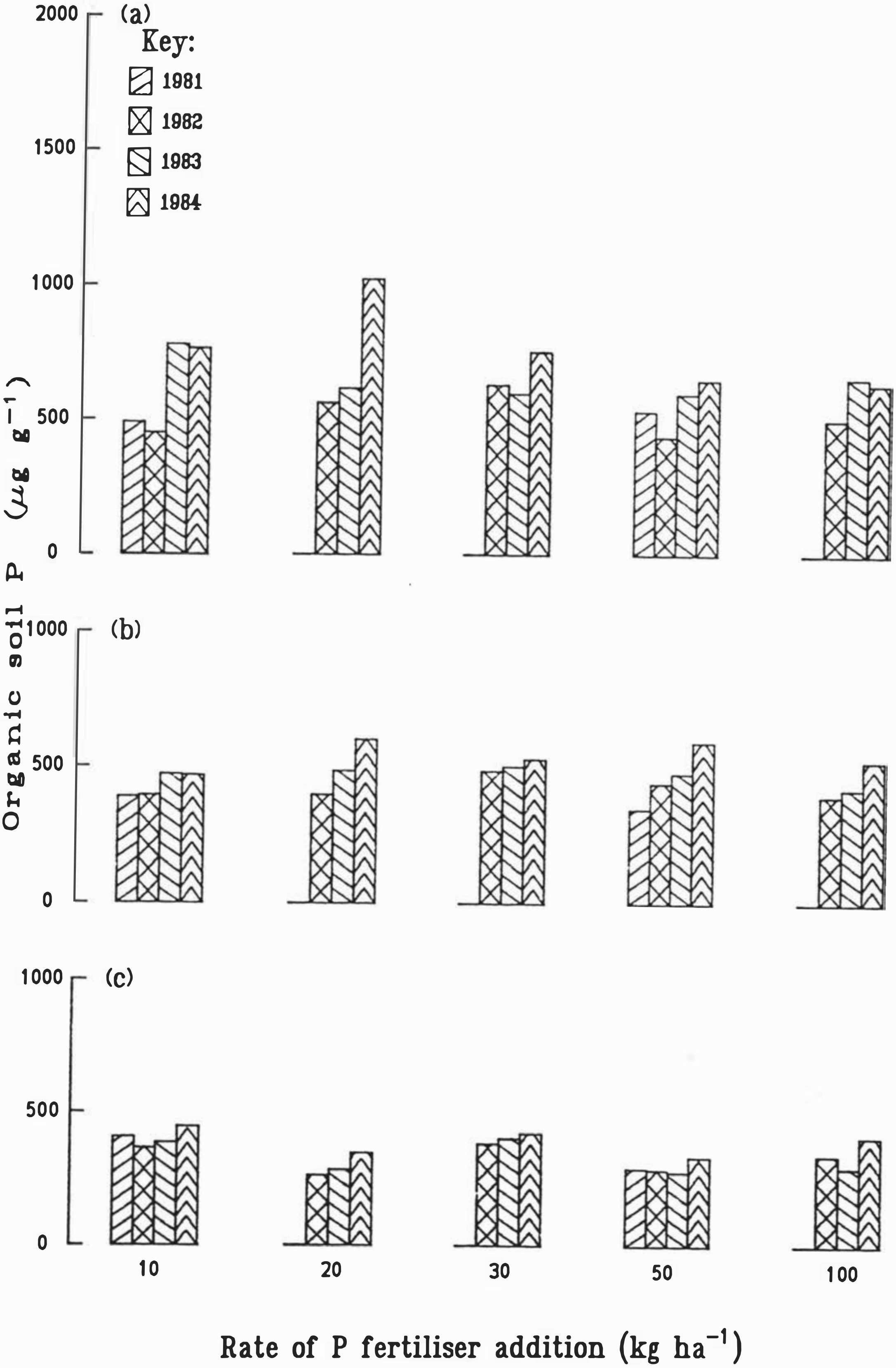

Figure 3.9 Change in organic P in 0-3 cm depth over a four year period on campsites (a) easy-slopes (b) and steep-slopes (c) following the application of differential rates of fertiliser.

was probably related to faecal P return. As stated earlier, on easy- and steep-slopes there was no effect of P fertiliser, but on campsites, the amount of P_O appeared to be inversely related to P fertiliser rate during the later years of the trial. This may have been due to enhanced mineralisation brought about by the greater influx of nutrients to the camp areas. The large increase in campsite P levels on the 20 kg ha^{-1} P paddock is probably a reflection of the very small area of campsites in the paddock, as explained in section 3.3.4.

Calculation of the effect of adding 100 kg ha^{-1} of P to the 0-3 cm depth (i.e., adjusted for bulk density) in the appropriate paddock indicates that an increase in P of 562 µg g^{-1} soil might be expected. Over a four year period that would be an increase in P of 2248 µg g^{-1} soil. Similarly the addition of 10 kg ha^{-1} P in the relevant paddock would be expected to cause an increase in P of 51.3 µg g^{-1} soil, which would amount to 205 µg g^{-1} soil over a four year period. All these increases are sufficiently large to be measured.

When average annual changes in total, P_I and P_O were calculated in terms of kg ha^{-1} of P in each paddock (i.e., corrected for topography and bulk density as described in section 3.3.4) for the period of the trial it could be seen clearly (Fig. 3.10) that on a per paddock basis all three soil P pools increased with increasing fertiliser rate. The effect on P_O was slight, but there appeared to be a direct relationship between increase in fertiliser P addition and increase in P_I. The overall effect on total P was a positive relationship between increasing fertiliser rate and increase in total P.

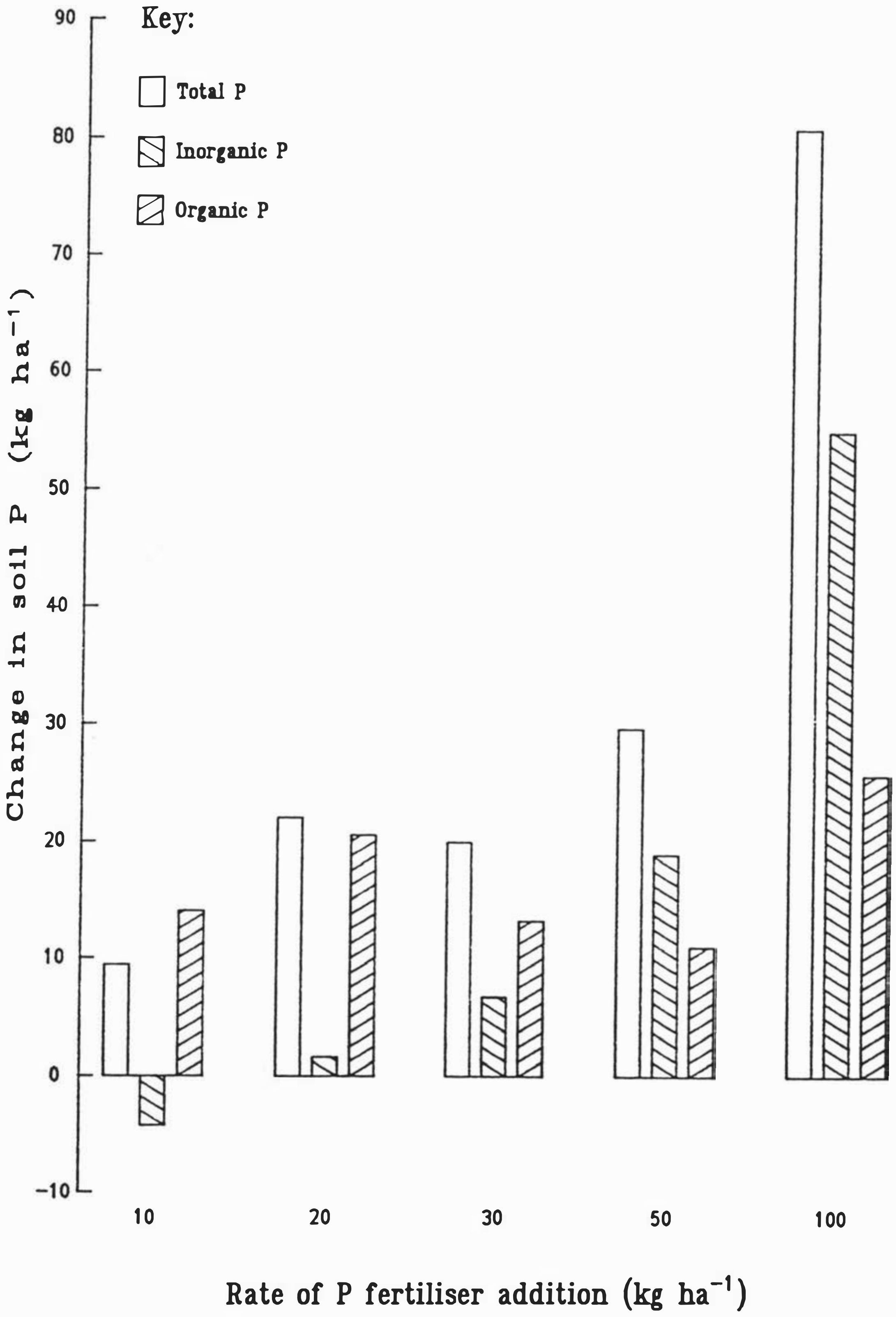

Figure 3.10 Relationship between average annual change in various fractions of soil P (kg ha^{-1} P; 0-15 cm depth) and fertiliser rate.

A comparison of the measured change in total P and calculated change showed that only a third of the expected increase in P occurred in the 10 kg ha^{-1} paddock and only a sixth of the expected increase occurred in the 100 kg ha^{-1} P paddock.

3.3.7 **Inorganic P fractionation**

3.3.7.1 **Easily-soluble P**

Easily-soluble P did not exceed 4 µg g^{-1} soil even after four years of exceedingly high rates of fertiliser P application. Although there was a slight increase in easily-soluble P with increasing fertiliser P rate and a decrease with increasing slope and depth, changes were extremely small.

3.3.7.2 **Non-occluded P**

Non-occluded P formed the greatest proportion of P_I in the soils. In each paddock, levels of this form of P were highest on campsites and lowest on steep-slopes (Fig. 3.11). Exceptions to this general trend occurred in the 10 kg ha^{-1} P fertiliser addition paddock where levels of non-occluded P on steep-slopes exceeded those on easy-slopes in 1984 and both campsites and easy-slopes in 1982.

Non-occluded P increased more at high rates of fertiliser P than at low rates, and was highest at the highest rate of fertiliser P addition on all slopes. Non-occluded P was lowest at the lowest

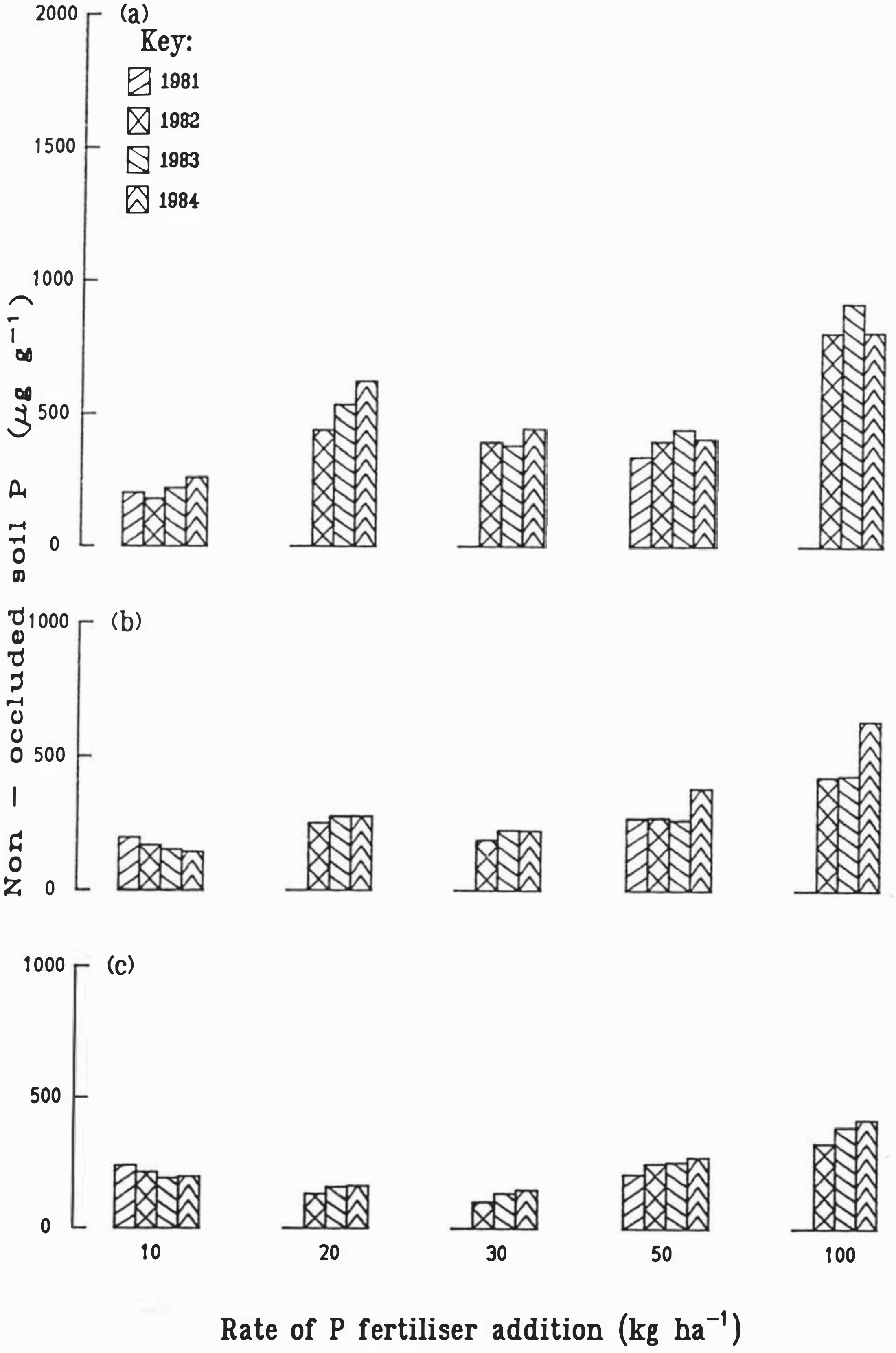

Figure 3.11 Change in non-occluded P in 0-3 cm depth over a four year period on campsites (a) easy-slopes (b) and steep-slopes (c) following the application of differential rates of fertiliser.

fertiliser P rate on campsites and easy-slopes; the comparatively high level of non-occluded P on the steep-slopes in the 10 kg ha^{-1} P paddock was inherited at the beginning of the trial, as has been discussed in section 3.3.6.

Examination of the change in non-occluded P (μg g^{-1} soil) between 1982 and 1984 on each slope at each fertiliser rate (Fig. 3.12) revealed that campsite non-occluded P accumulated at low levels of fertiliser P addition. This was probably a result of P transfer in faeces. The large increase in campsite non-occluded P in the 20 kg ha^{-1} P paddock reflects intense faecal P return as discussed throughout this chapter.

Although non-occluded P did not increase on campsites at high rates of fertiliser, it did increase on easy-slopes. This difference is believed to be a consequence of (a) production potential being approached on campsites and a near steady-state being reached (i.e., at high levels of fertiliser P addition, high dry matter yield results in a high stocking rate and high returns of nitrogen in urine. On campsites this means that fertiliser P can be utilised more efficiently than on areas where nitrogen is more limiting) and (b) enhanced production on easy-slopes leading to increased grazing utilisation and faecal return on these areas.

Calculation of the average annual change in non-occluded P on a per paddock basis (0-15 cm) (Fig. 3.13) showed that this fraction decreased slightly at low (10 kg ha^{-1}) to medium (20 and 30 kg ha^{-1}) rates of P fertiliser, but increased markedly at the highest rate of P fertiliser addition. As the adsorbed and surface-precipitated P

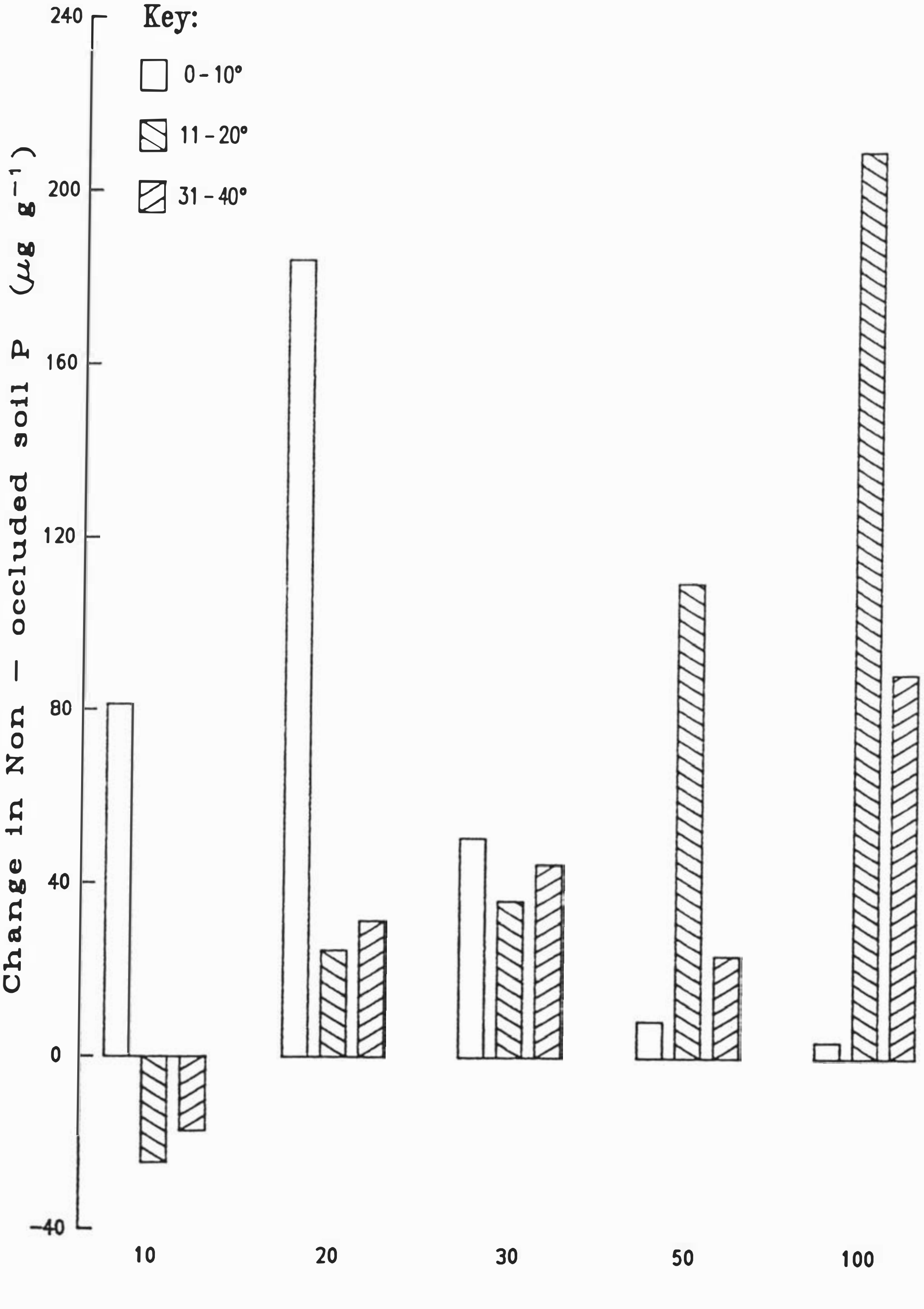

Figure 3.12 Relationship between change in non-occluded P (μg g^{-1} soil) and fertiliser rate over a two year period. Results are presented for 0-3 cm depth on three slope categories.

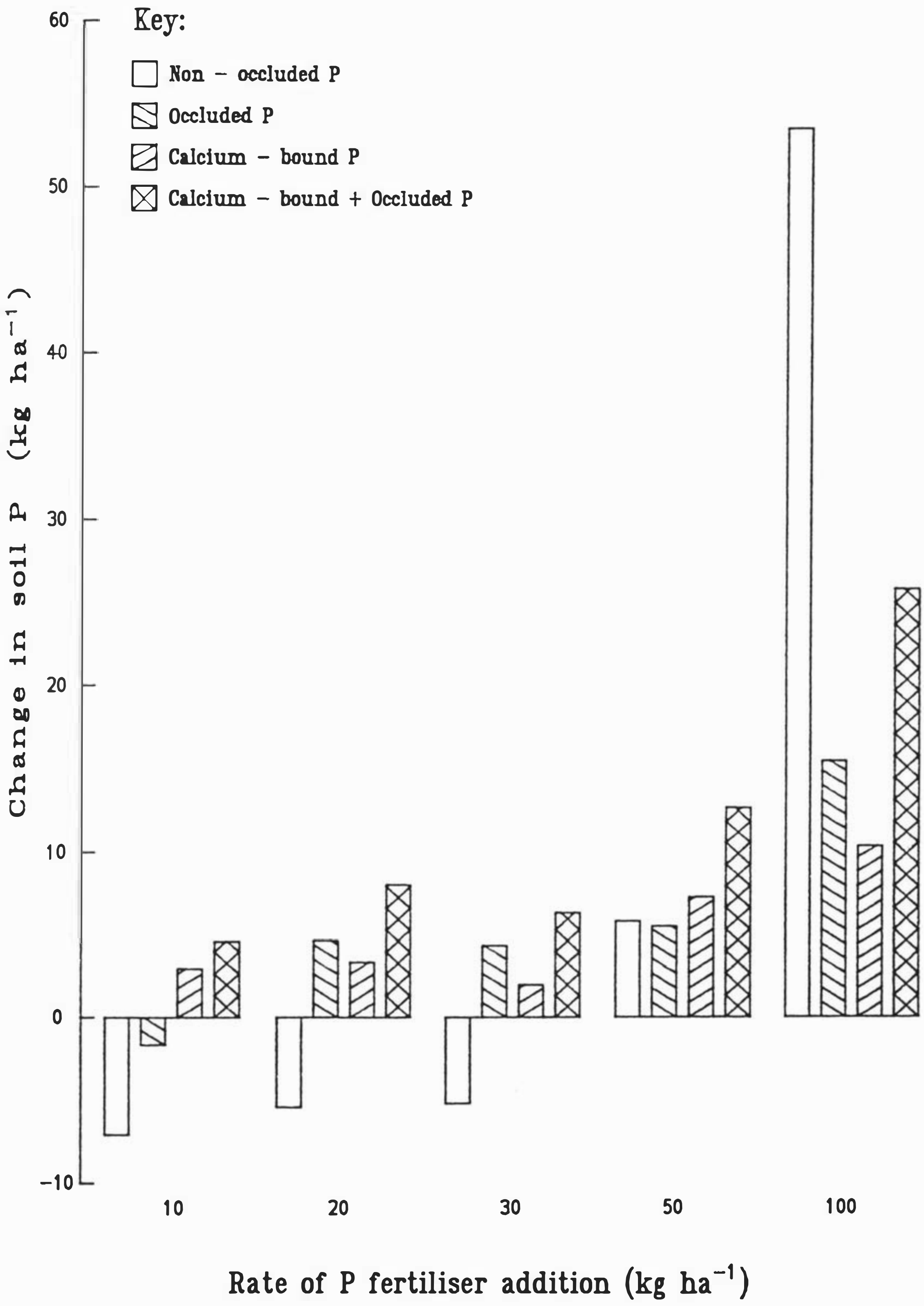

Figure 3.13 Relationship between average annual change in inorganic P fractions (kg ha^{-1} P; 0-15 cm depth) and fertiliser rate over a two year period.

compounds associated with iron and aluminium (making up the non-occluded P fraction) are considered to be sources of plant-available P in the weakly weathered soils of New Zealand (Grigg, 1968), the changes seen (Fig. 3.13) indicate an overall decrease in plant-available P at low and medium levels of P fertiliser addition, and an increase in plant-available P at high levels.

3.3.7.3 **Occluded P**

As with other P fractions, occluded P was highest on campsites (Fig. 3.14). In this fraction there was, however, very little change with either time or fertiliser rate. Occluded P comprises P occluded in iron oxides in a form believed to be similar to that of P in soil concretions (Bauwin and Tyner, 1957). Whereas soil concretions tend to be discrete particles, occluded-P compounds occur in the colloidal fraction, either in micro-concretions or in surface coatings on weathered silicates. Thus the amount of occluded P would not be expected to change very much on a yearly basis, unless there was inadvertent grinding of soil concretions, leading to increased extractability of P contained within.

On a per paddock basis (Fig. 3.13) the average annual change (0-15 cm depth) in occluded P, which tended to increase with increasing rate of P fertiliser and which was particularly apparent at the highest rate of P fertiliser addition, was probably an artefact of the analysis technique. In the fractionation scheme used (section 3.2.4.6) the step removing occluded P was not buffered. This means that there was

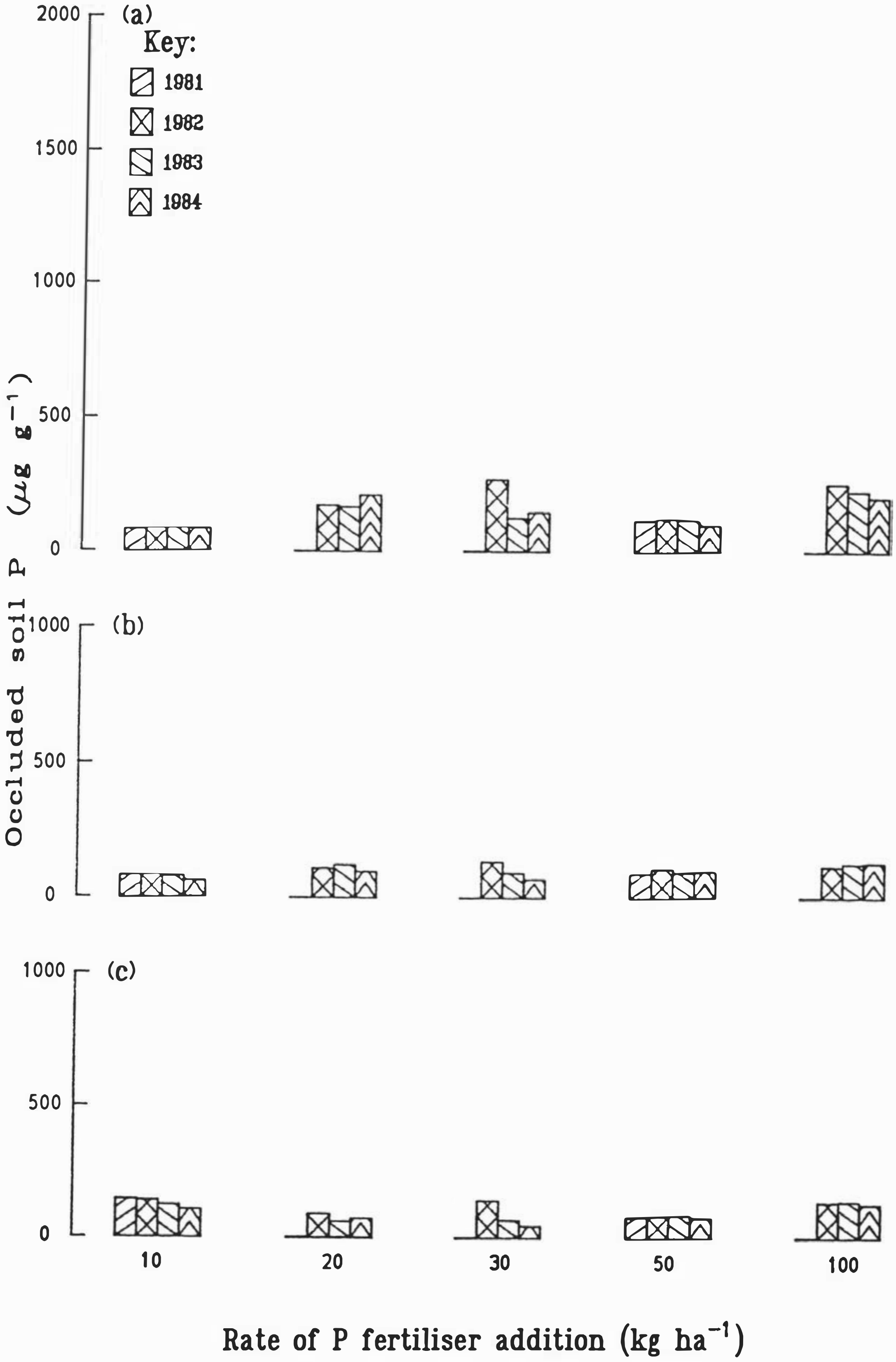

Figure 3.14 Change in occluded P in 0-3 cm depth over a four year period on campsites (a) easy-slopes (b) steep-slopes (c) following the application of differential rates of fertiliser.

the possibility of dissolution of some calcium-bound P in the unbuffered citrate-dithionite reagent (Mehra and Jackson, 1960) during extraction.

3.3.7.4 **Calcium-bound P**

The results were highly variable. Calcium-bound P tended to be highest on campsites and lowest on steep-slopes (Fig. 3.15). After two years of differential fertiliser P application a marked increase in this fraction was apparent at high rates of P fertiliser addition on all slopes (Fig. 3.16). Only on steep-slopes was there a consistent pattern of increasing calcium-bound P with increasing rate of fertiliser P addition. Variability was not removed by considering the change in occluded P and calcium bound P together (Fig. 3.17). In fact, because of the very large decrease in occluded P in the 30 kg ha^{-1} P paddock variability appeared to be increased.

Reanalysis of 1982 samples did not change the results and it was clear that occluded P levels in the 30 kg ha^{-1} P paddock were considerably higher than for other paddocks in the same year or for the 30 kg ha^{-1} P paddock in subsequent years.

This means that the potential for variability in results is intensified as calculation of the difference between two levels involves two sets of analyses (in this case those in 1982 and 1984). Thus the significance of any error in the first or second measurement will be increased simply because the "difference" being examined tends

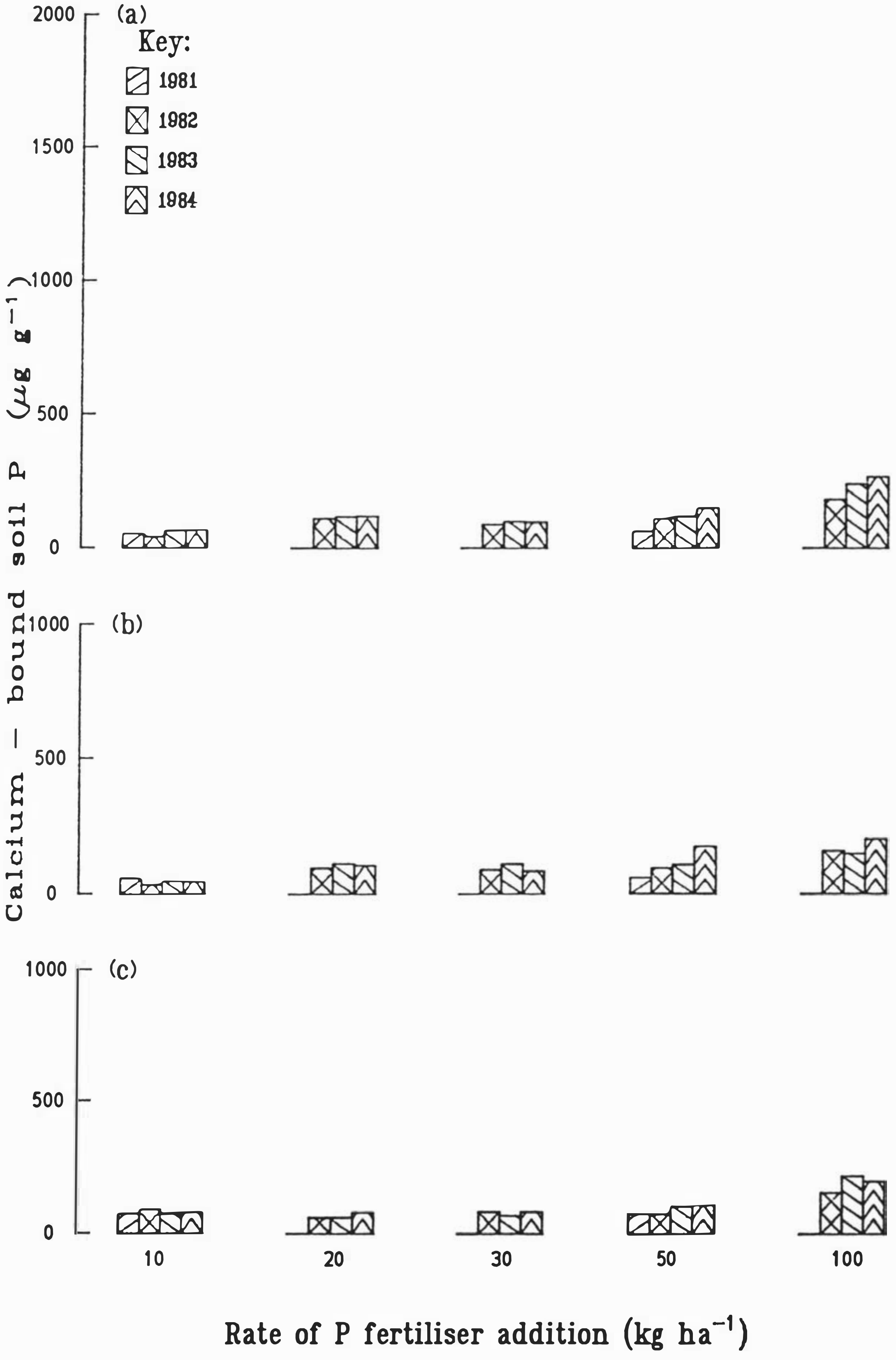

Figure 3.15 Change in calcium-bound P in 0-3 cm depth over a four year period on campsites (a) easy-slopes (b) and steep-slopes (c) following the application of differential rates of fertiliser.

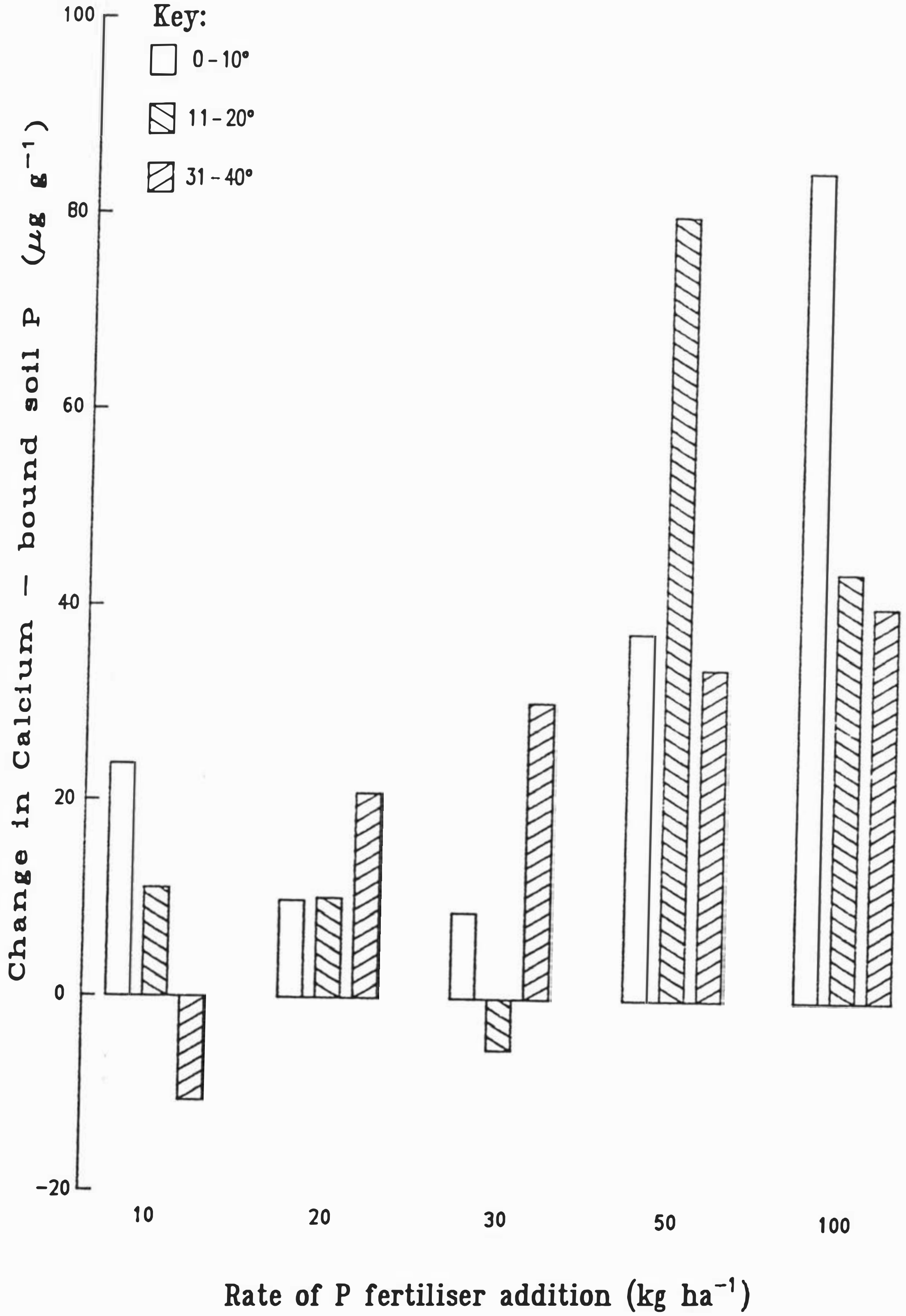

Figure 3.16 Relationship between change in calcium-bound P (μg g^{-1} soil) and fertiliser rate over a two year period. Results are presented for 0-3 cm depth on three slope categories.

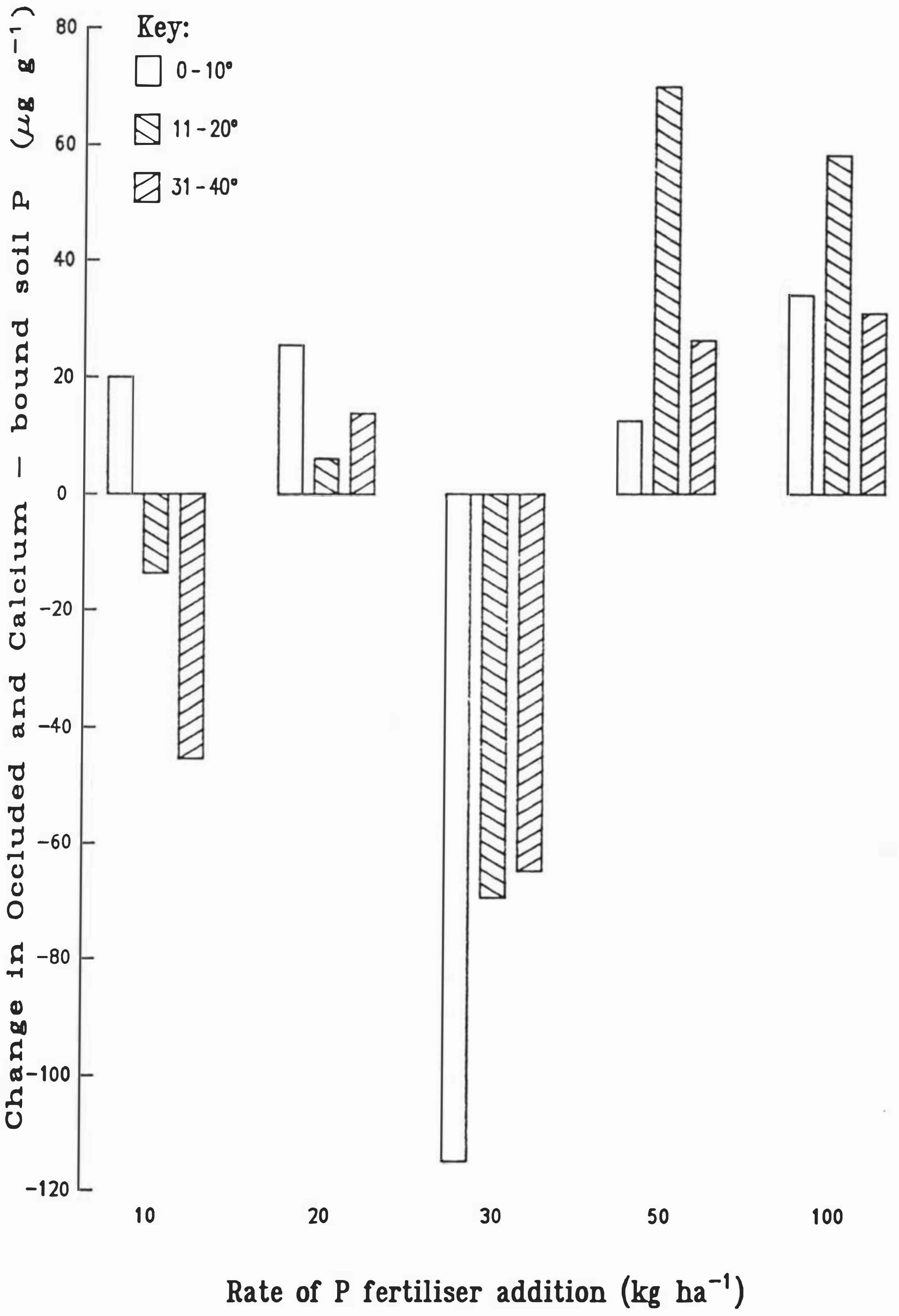

Figure 3.17 Relationship between change in occluded and calcium-bound P (µg g^{-1} soil) and fertiliser rate over a two year period. Results are presented for 0-3 cm depth on three slope categories.

to be of a smaller amount than either of the two measurements from which the difference is calculated.

Notwithstanding this problem, it can be seen (Fig. 3.17) that whereas P increased on campsites at low levels of P, there was an increase on easy-slopes at high levels of P. This reflects changes that occurred in the non-occluded P fraction, discussed in section 3.3.7.2.

The general trend for calcium-bound P (with or without the addition of occluded P) to increase on all slopes at high rates of fertiliser tends to suggest that this fraction is not playing a large role in cycling and so is accumulating at high rates of P addition. A similar accumulation of calcium-bound P at high rates of P addition was measured in a flat-land trial (Rickard and Quin, 1981). However, as P transfer via faecal material was not a factor measured within their trial, Rickard and Quin (1981) were unable to determine whether the calcium-bound P was accumulating before or after entering the P cycle.

The average annual change in calcium-bound P on a per paddock basis (0-15 cm) increased with increasing fertiliser rate (Fig. 3.13). The levels of calcium-bound P presented are minimum estimates due to the possibility of dissolution of calcium-bound P in the citrate-dithionite extraction.

If the calcium-bound P and occluded P fractions are added (assuming that both fractions are unavailable to plants in the medium to long term) then it can be seen (Fig. 3.13) that at the highest rate of fertiliser twice as much P became available (i.e., was measured in the non-occluded P pool) than became unavailable (i.e., was measured in the calcium-bound and occluded P fractions). In the 50 kg ha^{-1} P paddock half as much became available as unavailable. At lower rates of fertiliser the decrease in available P was slightly less than the increase in unavailable P.

However, at moderate rates of fertiliser P addition (up to at least 30 kg ha^{-1}) the applied P does not appear to be causing an increase in the plant-available P pool when the soil profile to root depth (0-15 cm) is considered. This indicates that P losses from the paddock as a whole are exceeding gains in available P in the 0-15 cm depth.

3.3.8 Final P status

Using data from all twenty paddocks collected in the final year of the trial, a statistical analysis was carried out for all P fractions. After four years of differential fertiliser P addition, increases in P_I were significantly related to an increase in fertiliser P rate ($P<0.01$; Fig. 3.18). In contrast, P_O did not increase with increasing rate of fertiliser P (Fig. 3.19). For a given rate of fertiliser P, P_I and P_O on campsites was significantly higher than on steeper slopes ($P<0.01$).

Fractionation of P_I showed that most of the increase in P_I with fertiliser P was due to the non-occluded P fraction (Fig. 3.20) and calcium-bound P fraction (Fig. 3.21), with only a small contribution

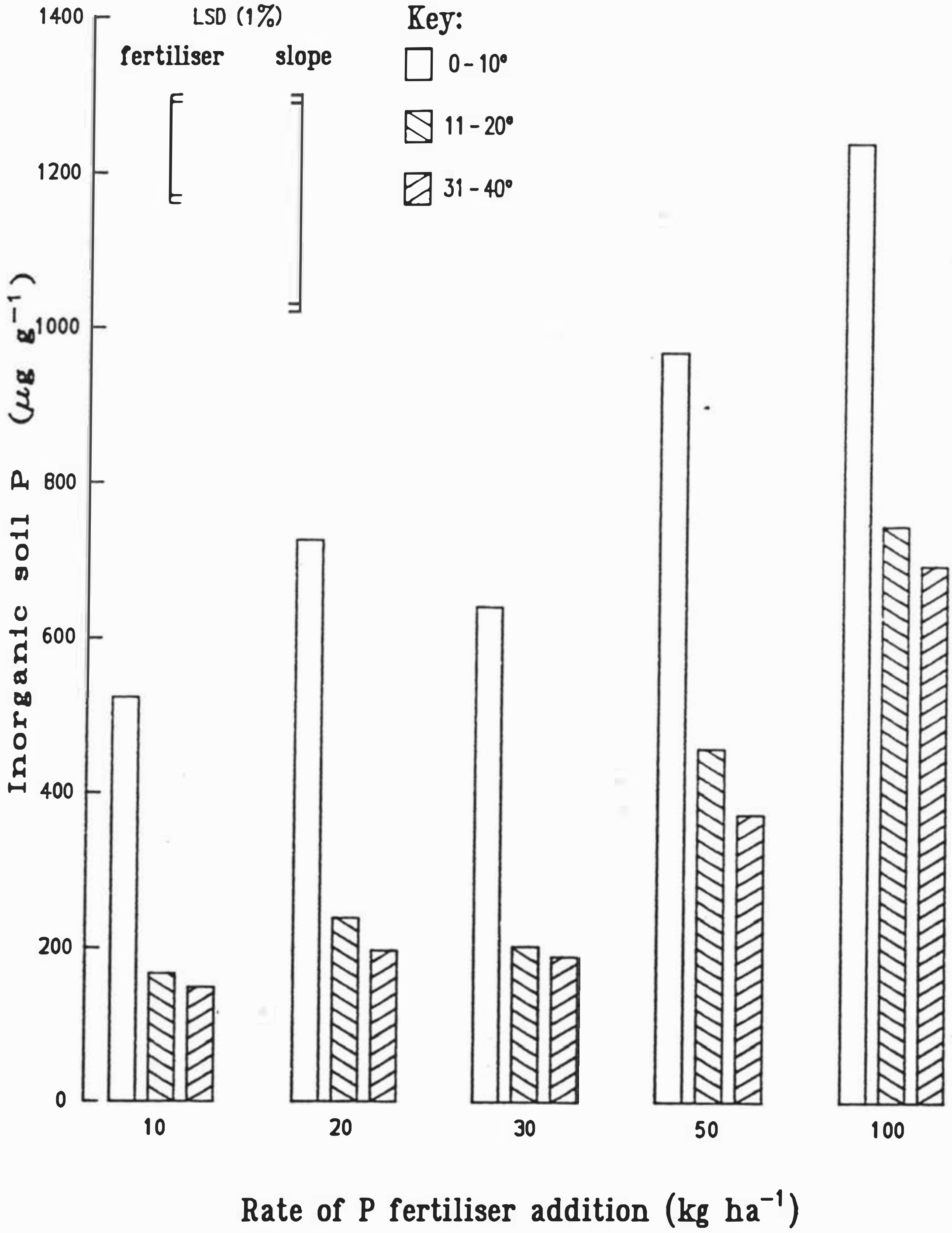

Figure 3.18 Relationship between levels of inorganic P and fertiliser rate after four years of differential fertiliser P addition. Results are presented for 0-3 cm depth on three slope categories.

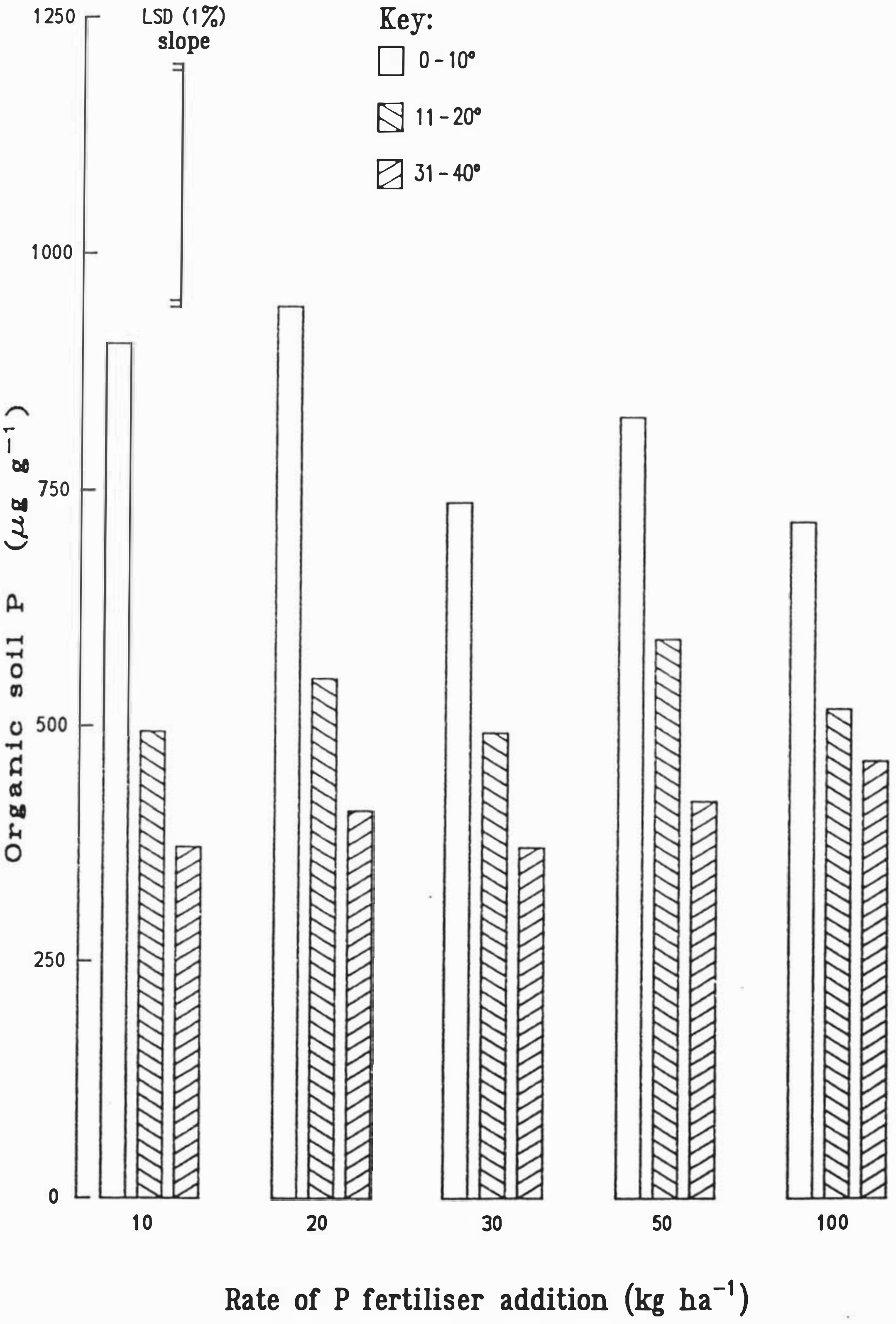

Figure 3.19 Relationship between levels of organic P and fertiliser rate after four years of differential fertiliser P addition. Results are presented for 0-3 cm depth on three slope categories.

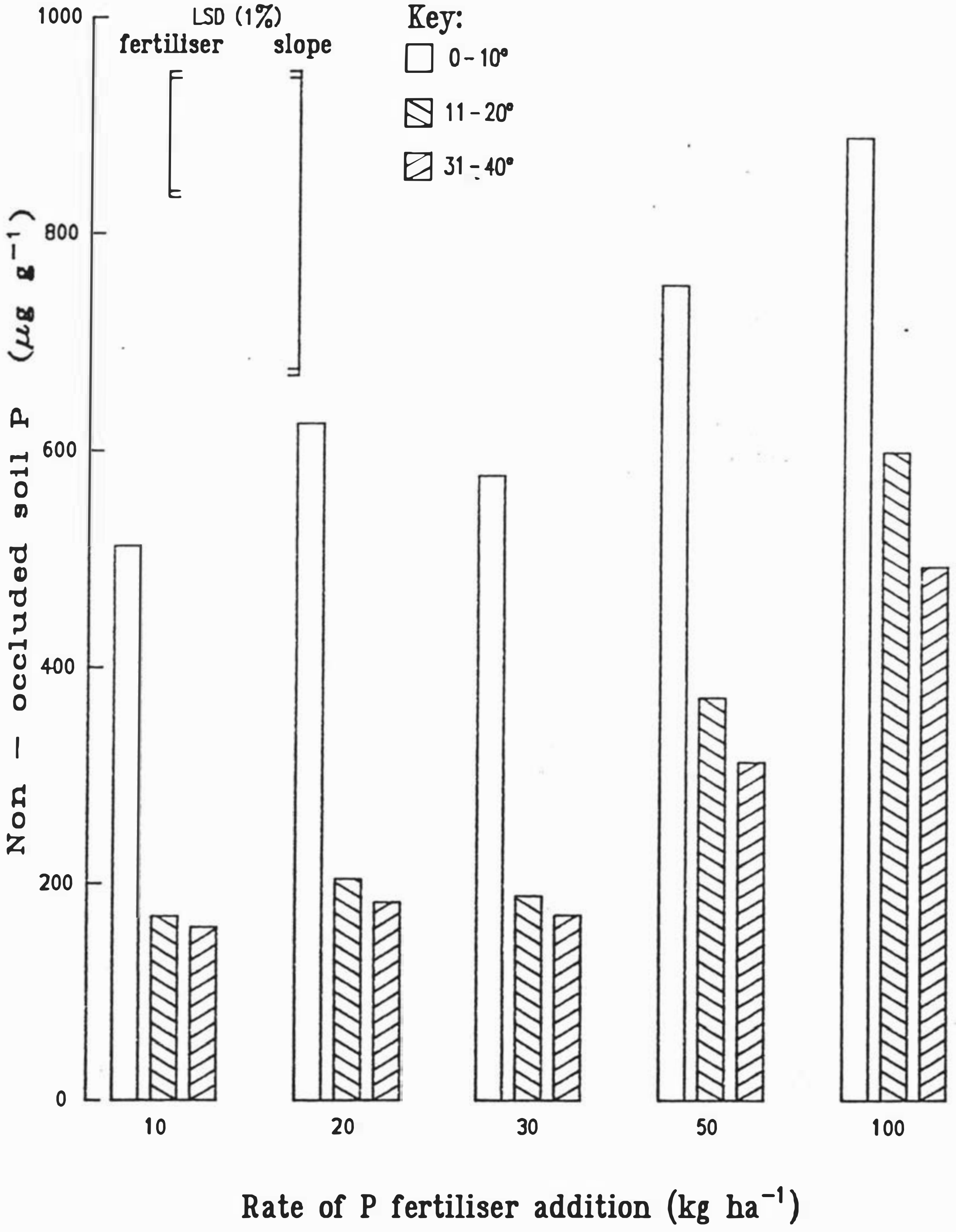

Figure 3.20 Relationship between levels of non-occluded P and fertiliser rate after four years of differential fertiliser P addition. Results are presented for 0-3 cm depth on three slope categories.

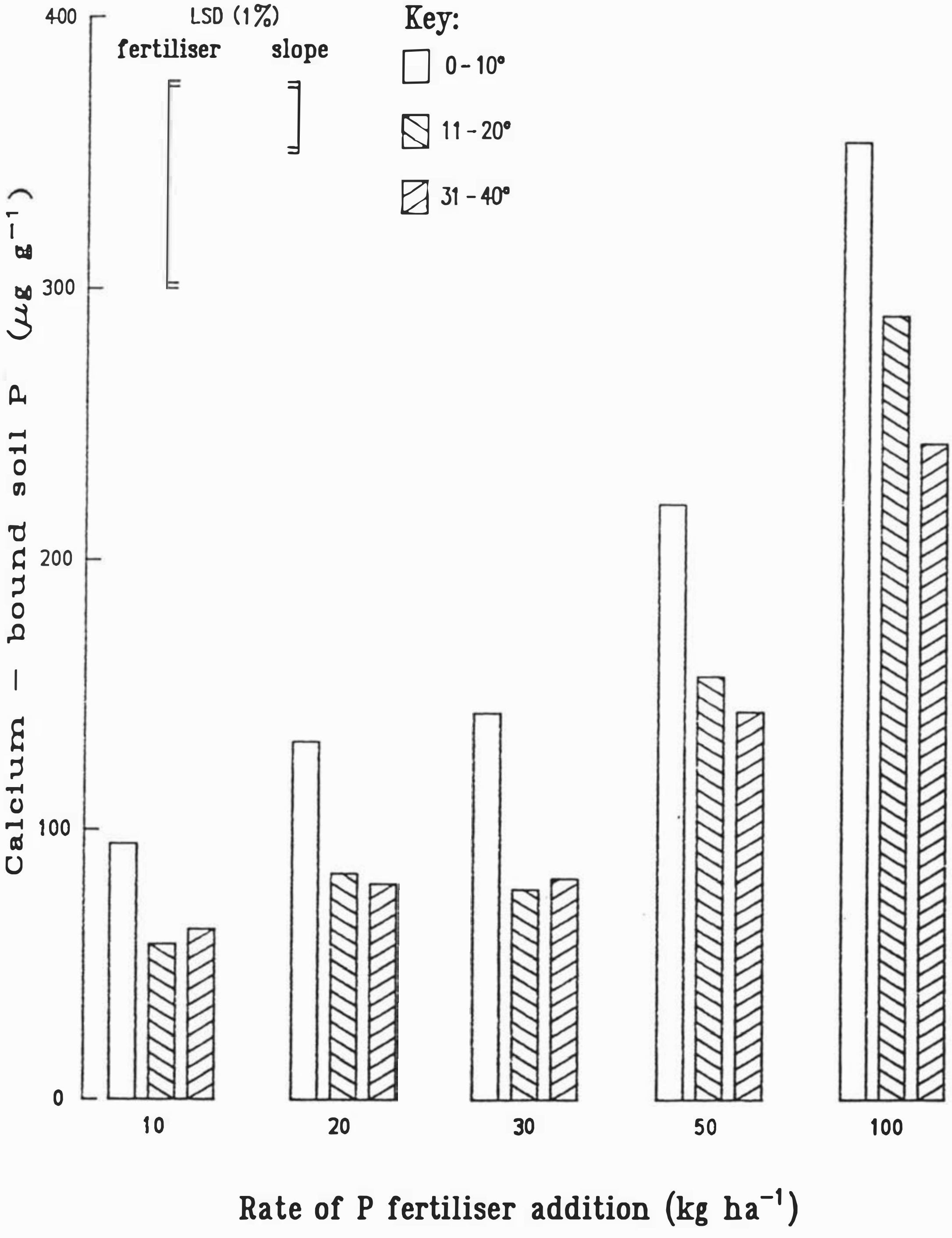

Figure 3.21 Relationship between levels of calcium-bound P and fertiliser rate after four years of differential fertiliser P addition. Results are presented for 0-3 cm depth on three slope categories.

from occluded-P (Fig. 3.22). For all three fractions the concentrations in the campsite soils were significantly ($P<0.01$) higher than in soils from steeper slopes.

It is interesting to note that the difference between campsites and steeper slopes was much greater for the non-occluded P fractions than it was in either of the other two fractions, particularly for calcium-bound P. This suggests that the non-occluded P fraction was playing a more active role in P cycling associated with nutrient transfer from steeper slopes onto campsites.

3.4 CONCLUSIONS

After three years of differential fertiliser P addition, total P was higher at high rates of fertiliser P than it was at low rates of fertiliser P. This was the result of an increase in the P_I fraction rather than the P_O fraction. Organic P accumulation was greatest at low rates of P addition. This is presumably due to an increase in mineralisation rate and organic matter turnover rate under the higher fertility conditions induced by high rates of P addition. For both P_I and P_O fractions, P levels were significantly higher in campsite soils than soils from steep-slopes. This corroborates findings by Gillingham (1978) on a similar hill-country site.

Fractionation of the soil P_I showed that non-occluded P, calcium-bound P and, to a lesser extent, occluded P, increased with increasing fertiliser P rate. The increase in occluded P may, however, have been an artefact induced by an unbuffered citrate-dithionite extraction.

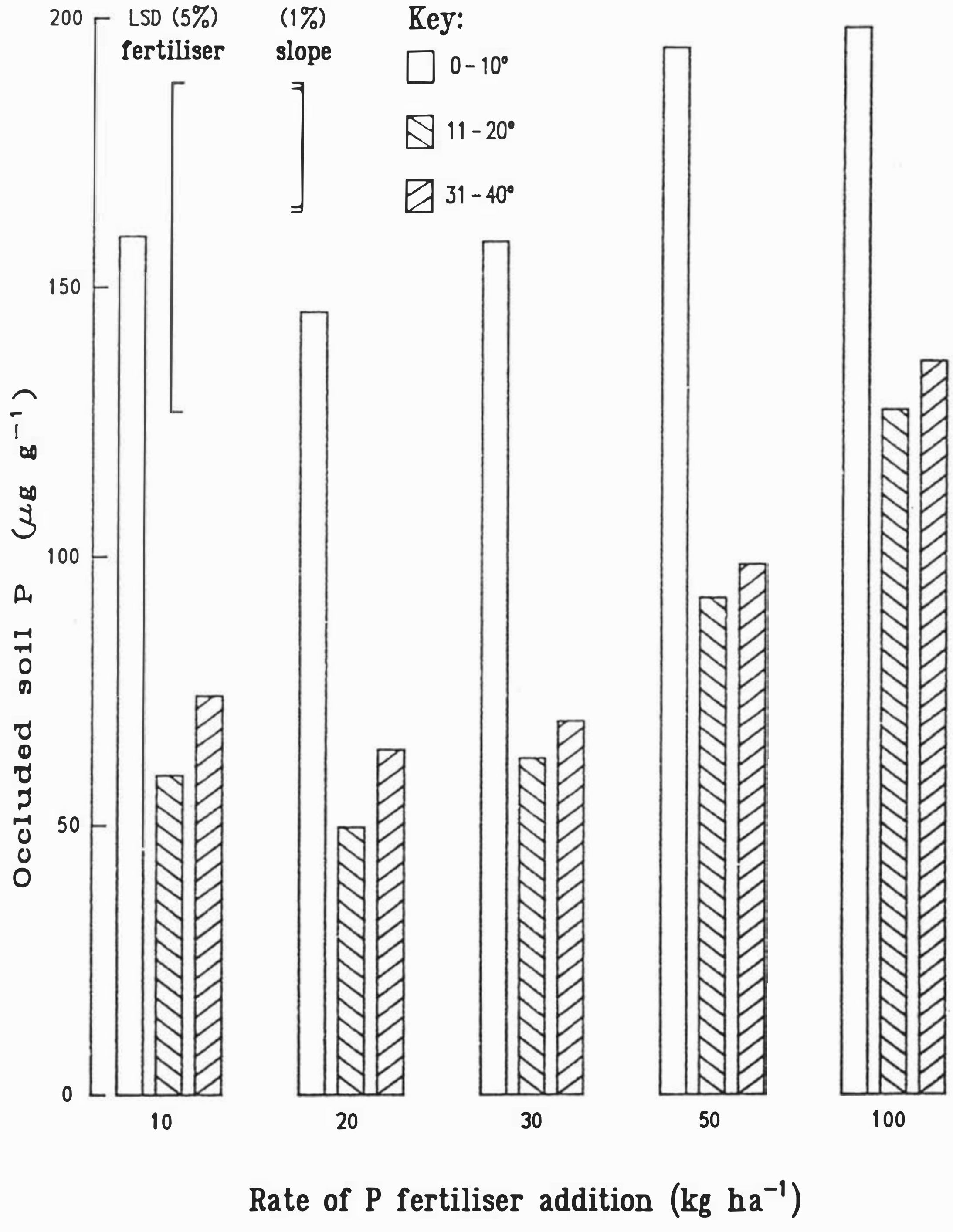

Figure 3.22 Relationship between levels of occluded P and fertiliser rate after four years of differential fertiliser P addition. Results are presented for 0-3 cm depth on three slope categories.

Non-occluded P was the largest P_I fraction and was markedly higher on campsites than on steeper slopes. This suggests that this fraction is involved in active P cycling and P transfer, and provides field evidence to support Grigg (1968) who concluded that non-occluded P (comprising aluminium-P and iron-P) is likely to be the plant-available form in the weakly weathered soils of New Zealand.

In contrast, the amount of calcium-bound P was more affected by fertiliser P rate than by slope, which suggests that this fraction is less actively involved in P cycling and is accumulating either as an insoluble residue from fertiliser or as a stable reaction product after the addition of superphosphate.

The soil type and environmental conditions of the present trial are considered to be conducive to the dissolution of phosphate rock (McKay et al., 1986; Quin et al., 1987) and are not, therefore, likely to favour the formation of calcium-bound P as a reaction product of superphosphate. Thus it seems likely that calcium-bound P is accumulating in the soil as an insoluble residue.

Investigations into the changes in P fractions during a period of two years confirmed the above results. Continuing P application, whether by chemical fertiliser or animal and plant returns, appears to have a major effect on two P_I fractions : non-occluded P and calcium-bound P, with the larger increase occurring in the non-occluded P pool. Once again, calcium-bound P increased more evenly across all slopes, suggesting that this form of P was not entering the cycling pool. These findings have implications to the quality of superphosphate as it would appear that less soluble calcium-P compounds are unlikely to become plant available in the short or medium term as long as soluble fertiliser P additions are maintained. Although this fraction could act as a long term reserve of P, it is likely that there would be little change in it until other, more available P fractions were depleted. Thus the P in any unreacted rock phosphate in superphosphate is unlikely to become plant available and is not considered to be "effective". Superphosphate of poor quality containing unreacted rock phosphate will have a smaller "effective" P content than high quality superphosphate though the total P content of the two fertilisers may be the same.

During the period of this trial, year to year variation in mean Olsen P levels for a range of slopes and rates of P fertiliser was marked. This variation occurred despite the fact that sampling was carried out in a careful manner and that many replicates were included within the trial. Thus it was not possible to tell, at least over a four year period, which, if any, of the slopes fertilised at different rates of P were at equilibrium. This is important because a prerequisite for determining whether maintenance conditions exist in the Ministry of Agriculture and Fisheries' Computerised Fertiliser Advisory Scheme model is that the grazing system be at equilibrium from year to year as defined by an unchanging Olsen P test.

Furthermore, results from the present trial indicated that the effect of changing the rate of P fertiliser addition would probably not become significant in the 0-7.5 cm sampling depth until after two to three years of the new fertiliser regime had passed. This has direct implications to the application of the modifying factor within the CFAS model, used to calculate short term P requirements. Whereas the modifying factor is relatively sensitive to changes in Olsen P, the latter is not a sensitive measure of soil P.

Notwithstanding the problem of year to year variation in the definition of equilibrium, results from the present trial showed clearly that Olsen P values increased on slopes at high rates of P fertiliser addition (50 and 100 kg ha^{-1}) and decreased on easy- and steep-slopes at medium and low rates of P fertiliser addition. On a per paddock basis (0-15 cm depth) Olsen P decreased slightly each year at low rates of P fertiliser addition, but increased at high rates. These results indicated that the amount of P fertiliser required for maintenance or equilibrium of Olsen P was probably around 30 kg ha^{-1} at a stocking rate of nineteen.

Having quantified the major "below-ground" components of the P cycle and hypothesised which of these components may be involved in active P cycling it is clear that further work investigating the relationship between these soil fractions and plant growth is required to determine which soil P fraction or fractions is most affected by plant P uptake. This would give information on the agronomic implications of the changes in soil P fractions observed in the present trial.

CHAPTER 4

PLANT AVAILABILITY OF P IN HILL-COUNTRY SOILS AS AFFECTED BY P FERTILISER ADDITION AND SLOPE

4.1 INTRODUCTION

The increasing cost of on-ground fertilisers coupled with lower product returns, has forced farmers to review their fertiliser policies. In many cases the result has been a drastic reduction in the amount of fertiliser applied. Consequently, there is increasing concern about the effect of withdrawal of fertiliser on dry matter production and available soil P levels.

Recent work in New Zealand by O'Connor et al. (1985) has shown that the effects of withholding fertiliser on hill-country farms are more immediate and severe than had been realised previously. On soils with a moderate to low Olsen P value (i.e., <15) and medium P retention (50%) a 4-5% decline in pasture production was found in the first year without fertiliser; in the second year the decline was 20-25%. On soils with medium to high Olsen P values (i.e., >15) and low to medium P retention there was no reduction in pasture production for two years after stopping fertiliser and only a small reduction in the third year. From these results it was concluded that the effects of withholding fertiliser would be most noticeable on soils with low Olsen P values, a high P retention and in the period of rapid growing conditions, i.e., spring. The comment was made that the decrease in pasture production observed was not necessarily accompanied by a decrease in Olsen P. The evidence suggested that, in the short term, Olsen P values did not reflect accurately a decline in available soil P status as a result of stopping fertiliser application.

The apparent insensitivity of the Olsen P test is likely to be due to a combination of several factors. In common with most soil-testing procedures the Olsen extraction measures a varying proportion of all the P compounds in the soil which have either a high solubility or high specific surface area (Chang and Jackson, 1957), i.e., it does not measure a single chemical fraction of P. Furthermore, although Olsen P is a useful indicator for predicting a possible plant response to fertiliser P, it does not measure the total amount of plant-available P in the soil. Perhaps most importantly, the Olsen P test is subject to sampling errors. These may assume disproportionate importance relative to the generally small size of the plant-available P pool measured by the Olsen extraction. Thus field variability can render the detection of a significant change in Olsen value extremely difficult.

In the past there have been many attempts to characterise plant-available P in soils (e.g., Bowman et al., 1978; Novais and Kamprath, 1978; Adepoju et al., 1982). Much of this work has been carried out in the glasshouse and laboratory, and most studies have involved extracting an arbitrary fraction of P that correlated well with plant response. Thus most of the studies have been concerned with predicting plant response to fertiliser P.

Bowman et al., (1978) conducted glasshouse trials on twenty-three high-P calcareous and neutral soils from northern Colorado. Plant-available P was found to correlate well with the amounts of exchangeable P, resin-extractable P, Olsen P and Colwell P in the pre-cropped soil. Similarly, Adepoju et al. (1982) found that plant P uptake correlated well with P extracted by an anion-exchange resin, and by the Olsen reagent.

In neither of these studies was any attempt made to investigate the chemical fractions within the available pool that were being affected by plant P uptake. In contrast, Novais and Kamprath (1978) did investigate the changes in soil P fractions. They found that on weakly acid soils "aluminium-P" (NH_4F-P) and "iron-P" (NaOH-P) were the main forms of P_I affected by plant P uptake. The relative contribution of these two fractions depend on soil type. Very little contribution to plant P uptake was made by calcium-bound P. This has been discussed in more detail in section 2.2.2.

In Chapter 3 the effect of P transfer and fertiliser P addition on the accumulation and depletion of soil P fractions on different slopes in grazed hill country was discussed. The trial produced a range of soil conditions which varied not only in P levels but also, to some extent, in physical properties. In this study the plant availability of the P fractions measured in Chapter 3, was assessed in an exhaustive cropping study, carried out in the glasshouse. The measurement of cumulative P uptake during the trial enabled a direct comparison of the amount of P made available with the depletion of the soil P fractions measured. In this way it was considered that the effect of

P transfer and fertiliser P application on plant-available P could be evaluated more fully as results from this study would allow further interpretation of results from Chapter 3. As well as measuring the main forms of soil P removed by cropping, the effects of cropping on extractable-P levels measured by common soil testing procedures were determined. Thus the relationships between changes in the main forms of soil P and in water-extractable P and Olsen-extractable P could be investigated.

4.2 MATERIALS AND METHODS

4.2.1 Soils

Soil samples for the glasshouse study were collected from three slopes (campsites, 0-10^{o}; easy, 11-12^{o}; steep, 31-40^{o}) in the paddocks in the major trial described in section 3.2.1.

Topsoil from areas selected according to Olsen P status and P-sorption capacity, was excavated to a depth of 3 cm and the area beneath was excavated to a depth of 7 cm. This method of collection differed from that described in the preceding chapter as large quantities of soil were required.

The paddocks had received differential P fertiliser rates (10, 20, 30, 50 or 100 kg ha^{-1}) for four years prior to sample collection. The samples were bulked on a depth basis, air-dried, and sieved to pass through an 8 mm mesh. A portion of each soil was ground more finely (<2 mm) and was used subsequently to form a seed bed in the pots.

4.2.2 **Soil properties**

Phosphorus-sorption capacities (Saunders, 1965) were measured on soil samples before commencing the pot trial. Measurements of soil pH, Olsen-extractable P (Olsen et al., 1954), water-extractable P (Sornsrivichai, 1985), total P, P_I and P_O (Walker and Adams, 1958), and non-occluded P, occluded P and calcium-bound P (Chang and Jackson, 1957) were made before and after the pot trial. All methods were as described in section 3.2.4.

Soils were prepared for analysis after the trial by air-drying, dividing each pot into quarters, and sieving a quarter of the soil to pass through a 2 mm or 0.152 mm mesh sieve according to the analysis being performed.

4.2.3 **Glasshouse study**

The amounts of plant-available P in the thirty samples of soil from the grazing trial were determined in a glasshouse experiment using an exhaustive cropping technique. Plant-uptake of P by plant tops was used in this study as a measure of plant-available P in the soil. The air dried soils (250 g; <8 mm) were hand packed into pots measuring 10 x 10 x 9 cm. Finer soil (50 g; <2 mm) of the appropriate type was spread on top to provide a seed bed; the total weight of soil in each pot was 300 g. Five pots of each soil type (four replicates plus one control) were prepared. At this stage the soils were watered to field capacity. Perennial ryegrass (*Lolium perenne L.*, Grasslands "Nui") was used as the test plant. Approximately thirty seeds were sown per pot.

A minus-P nutrient solution (Middleton and Toxopeus, 1973) was applied regularly. Ammonium nitrate in the nutrient solution was replaced by potassium nitrate to reduce the acidity produced by nitrification of added ammonium-nitrogen.

Moisture was maintained at 90% field capacity by daily overhead watering. Pots were completely randomised and were repositioned each week to minimise any effects of uneven environmental factors, such as light and temperature.

Ten harvests were taken at approximately five week intervals. Plants were cut to a level of 10 mm above the soil surface. After drying at 65^{o} C for 24 h, the herbage was weighed and analysed for P by the method of Twine and Williams (1971) after a Kjeldahl-type digestion.

One pot of each soil received complete nutrient solution as a control. In this way it was possible to determine whether or not the experimental pots were becoming P deficient and also whether there were any physical limitations imposed by the different soils.

The trial commenced in February 1984 and was terminated in January 1985 after ten harvests had been taken. By this time the herbage P concentration from all but two of the treatments had fallen below 0.2% (Table 4.1).

Table 4.1 Effect of slope, depth and rate of P fertiliser addition (kg ha^{-1}) on herbage P concentration (µg g^{-1}) at harvest ten.

		Rate of P fertiliser addition (kg ha^{-1})				
Slope	Depth (cm)	10	20	30	50	100
0-10°	0-3	1649	2136	1730	1644	2060
	3-7	992	1148	1160	1142	1626
11-20°	0-3	1029	1534	1315	1038	1937
	3-7	888	746	919	902	1278
31-40°	0-3	957	1076	1030	1201	1442
	3-7	980	773	956	978	915

4.3 RESULTS AND DISCUSSIONS

4.3.1 Soil properties

The effect of P fertiliser rate on soil P pools has been discussed in detail in section 3.3. Although the samples in this pot trial were necessarily collected in a different manner (Section 4.2.1), trends in the results were similar.

4.3.1.1 Phosphorus-sorption capacity

Phosphorus-sorption capacities (Table 4.2) tended to:

(i) be highest on easy-slopes
(ii) be lowest on steep-slopes
(iii) increase with depth.

Between-paddock variation was lowest on steep-slopes and highest on campsites. Most soil P-sorption capacities fell into the medium range (Saunders, 1965). High P-sorption capacities indicated the presence of volcanic ash on campsites and easy-slopes in the 20 kg ha^{-1} P paddock and easy-slopes in the 50 kg ha^{-1} P paddock. This influenced the interpretation of results from these soils.

Table 4.2 Effect of slope, depth and rate of P fertiliser addition (kg ha^{-1}) on P-sorption capacities (%) of soil used in the glasshouse study.

		Rate of P fertiliser addition (kg ha^{-1})				
Slope	Depth (cm)	10	20	30	50	100
0-10°	0-3	46	79	50	65	62
	3-7	49	87	55	65	70
11-20°	0-3	57	85	67	73	62
	3-7	59	92	70	76	70
31-40°	0-3	56	58	44	63	48
	3-7	64	61	49	67	53

4.3.1.2 **pH.**

Initial pH values decreased with depth and with increasing slope but were not affected by increasing P fertiliser rate (Table 4.3). In the majority of treatments soil acidity did not increase during the pot trial, despite its lengthy duration.

4.3.1.3 **Soil P fractions prior to the glasshouse trial**

All soil P fractions decreased with depth and increasing slope, and increased with increasing rate of P fertiliser addition. Differences between easy- and steep-slopes, particularly in the 3-7 cm depth, were small at the lower rates of fertiliser (Figs. 4.1 - 4.6).

The high levels of P in soils from the campsites and easy-slopes (0-3 cm depth) from the 20 kg ha^{-1} P paddock are thought to be a consequence of the very small area (only 9%) occupied by campsites in this paddock. As explained in section 3.3.4 a small campsite area implies intense faecal return to that area, with a consequent build-up in P. It is also likely that there is increased faecal return to adjacent easy-slopes (a spillover effect).

The fact that the increase in P in the 20 kg ha^{-1} P paddock was only slightly apparent in the Olsen P fraction (Fig. 4.1) and was not observed in results for water-extractable P (Fig. 4.2) is thought to be a consequence of the higher P-sorption capacity of these soils (Table 4.2). This is consistent with the results of Fox and Kamprath

Table 4.3 Effect of slope, depth and rate of P fertiliser addition (kg ha^{-1}) on pH measured before (a) and after (b) the glasshouse study. Post study results are the means of four replicates.

			Rate of P fertiliser addition (kg ha^{-1})				
	Slope	Depth (cm)	10	20	30	50	100
(a)	0-10°	0-3	5.6	5.7	5.8	5.8	5.7
		3-7	5.4	5.3	5.4	5.5	5.3
	11-20°	0-3	5.3	5.6	5.7	5.6	5.8
		3-7	5.3	5.4	5.5	5.5	5.5
	31-40°	0-3	5.2	5.3	5.3	5.4	5.1
		3-7	5.2	5.4	5.3	5.4	5.0
(b)	0-10°	0-3	6.2	5.9	6.2	5.6	6.1
		3-7	6.1	5.4	5.9	5.6	5.9
	11-20°	0-3	6.0	5.3	5.9	5.6	6.0
		3-7	5.3	5.3	5.7	5.5	6.1
	31-40°	0-3	5.6	5.9	5.7	5.6	5.7
		3-7	5.5	5.4	5.6	5.3	5.7

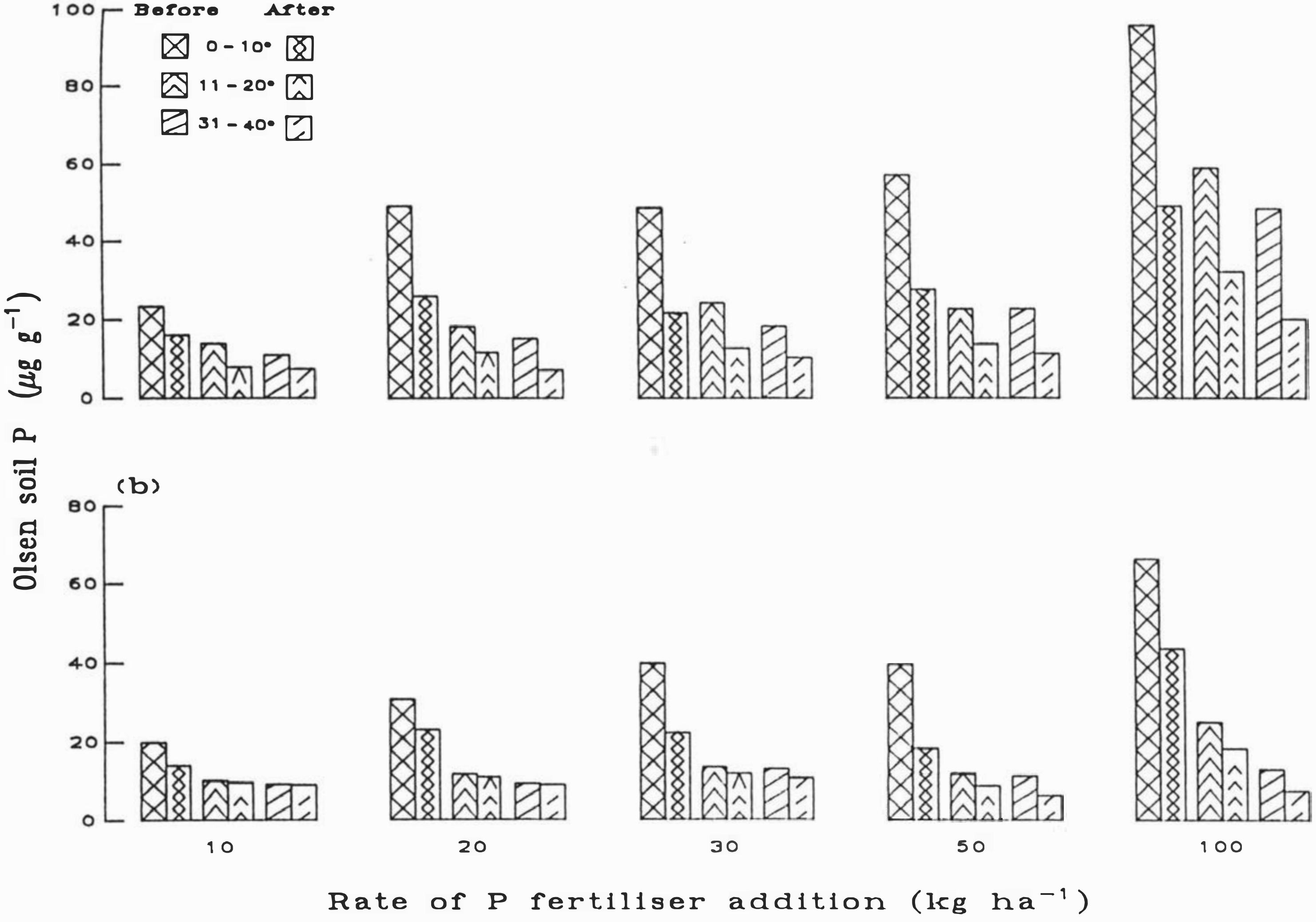

Figure 4.1 Effect of slope, sampling depth and P fertiliser rate on amounts of Olsen-extractable P in soil before and after the glasshouse trial; 0-3 (a) and 3-7 (b) cm depth.

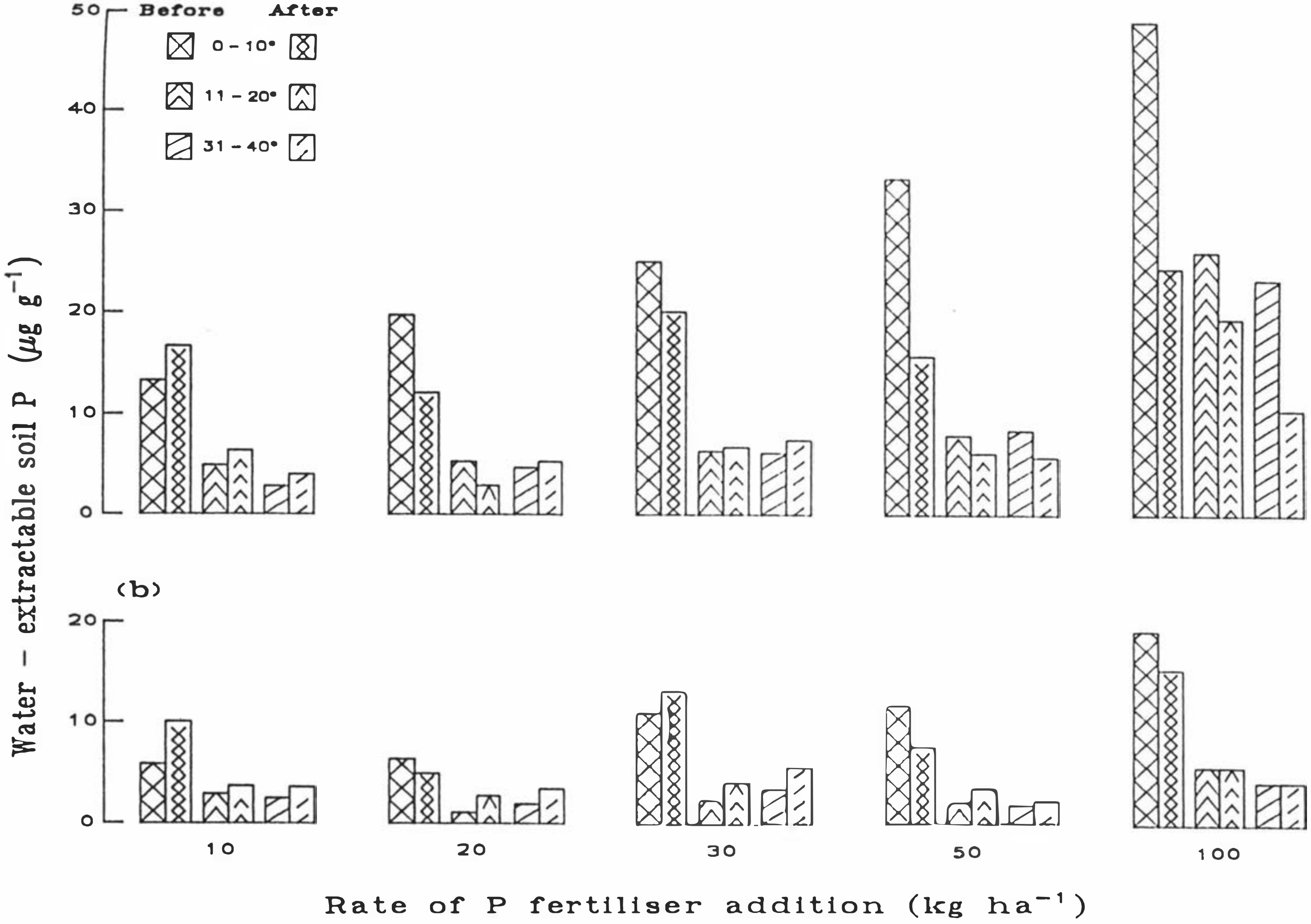

Figure 4.2 Effect of slope, sampling depth and P fertiliser rate on amounts of water-extractable P in soil before and after the glasshouse trial; 0-3 (a) and 3-7 (b) cm depth.

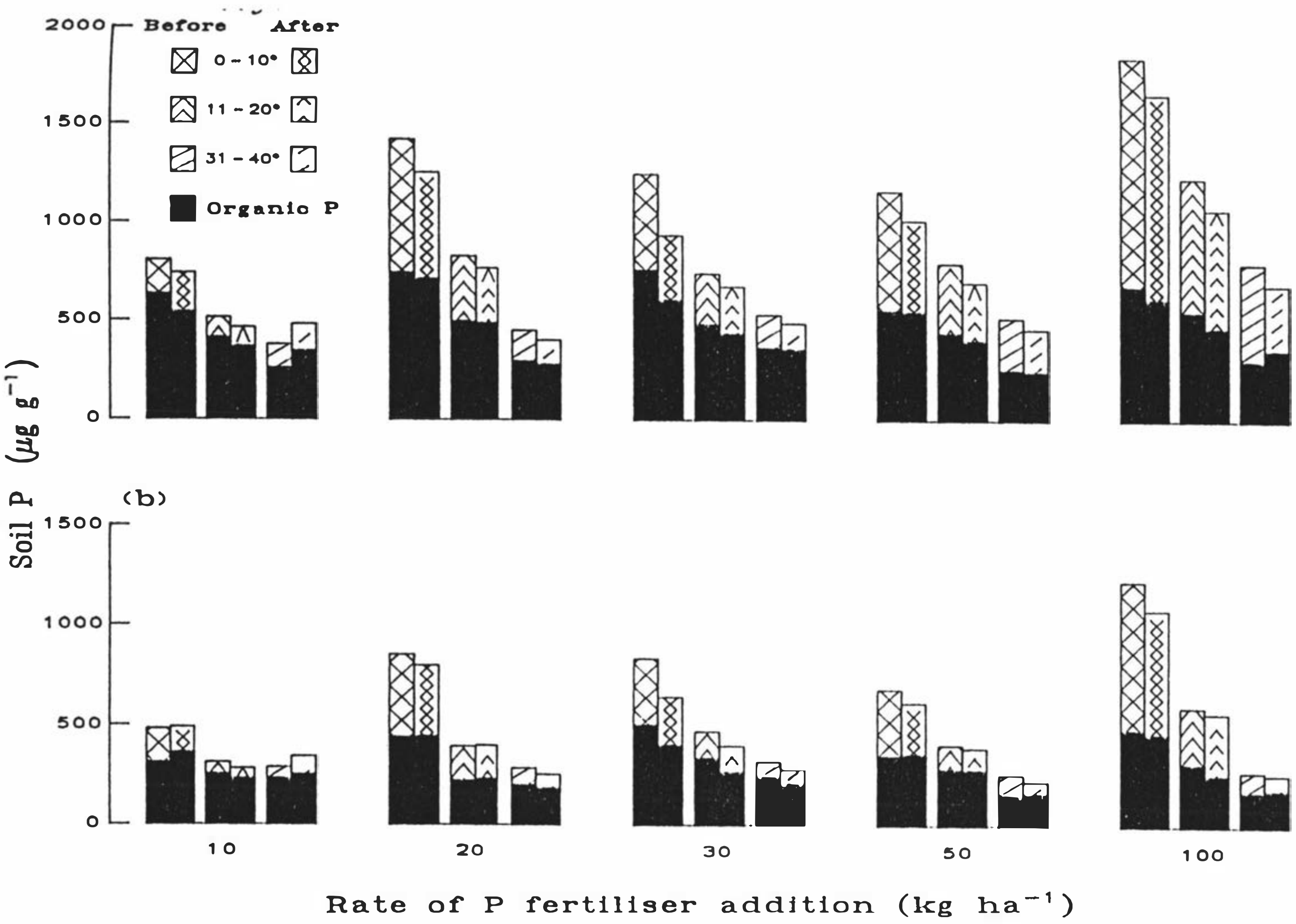

Figure 4.3 Effect of slope, sampling depth and P fertiliser rate on amounts of total P, inorganic P and organic P in soil before and after the glasshouse trial; 0-3 (a) and 3-7 (b) cm depth.

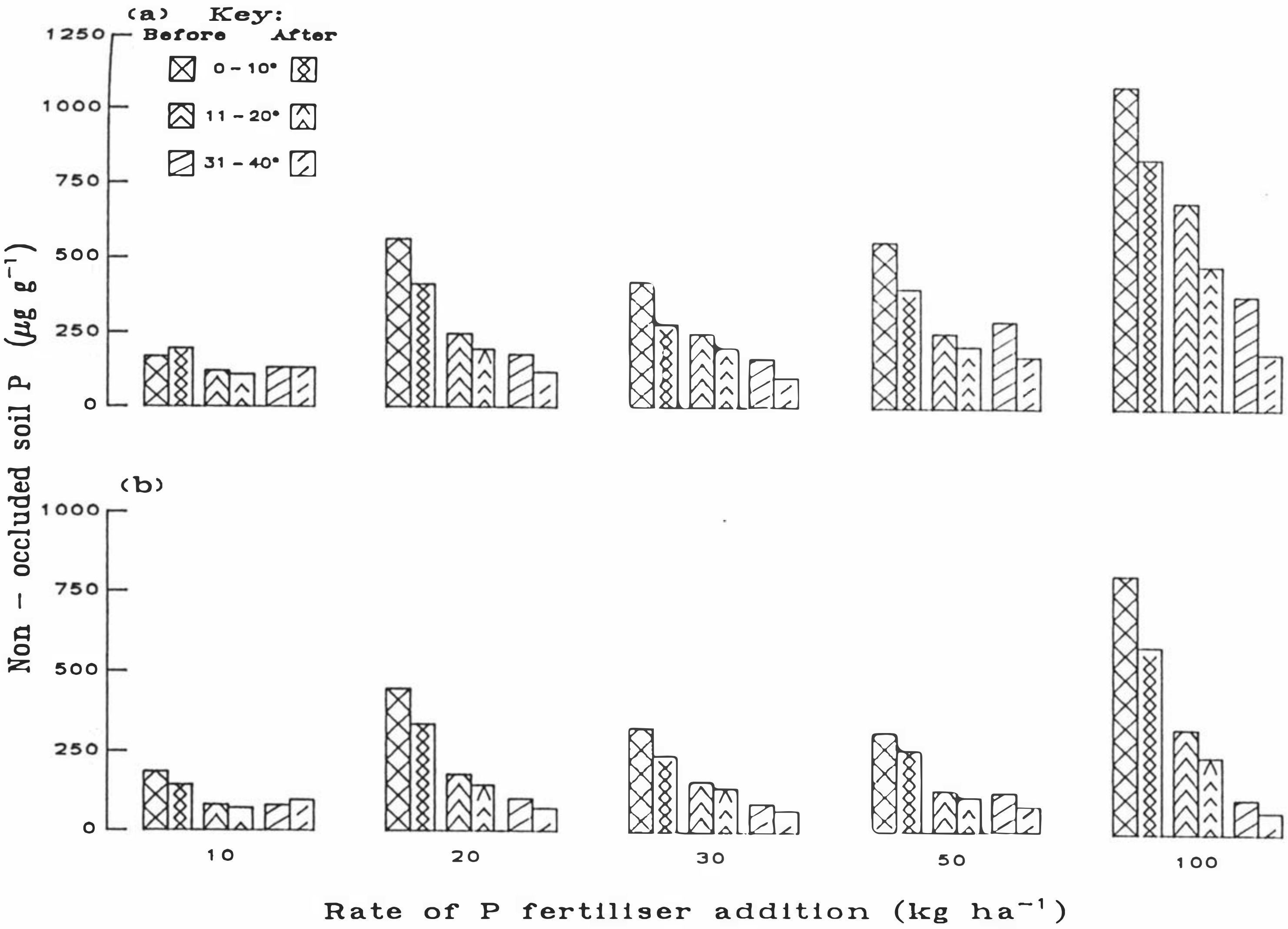

Figure 4.4 Effect of slope, sampling depth and P fertiliser rate on amounts of non-occluded P in soil before and after the glasshouse trial; 0-3 (a) and 3-7 (b) cm depth.

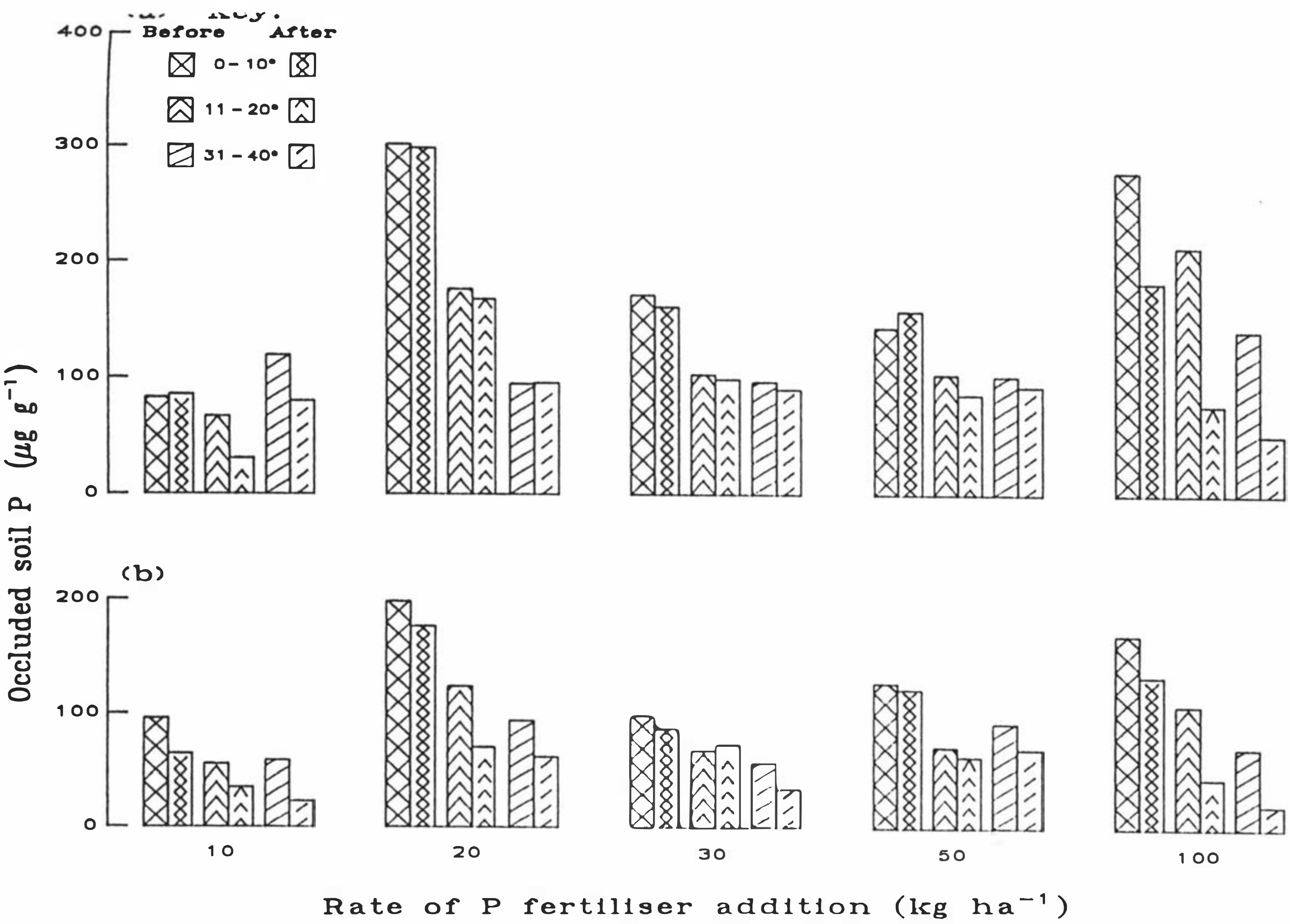

Figure 4.5 Effect of slope, sampling depth and P fertiliser rate on amounts of occluded P in soil before and after the glasshouse trial; 0-3 (a) and 3-7 (b) cm depth.

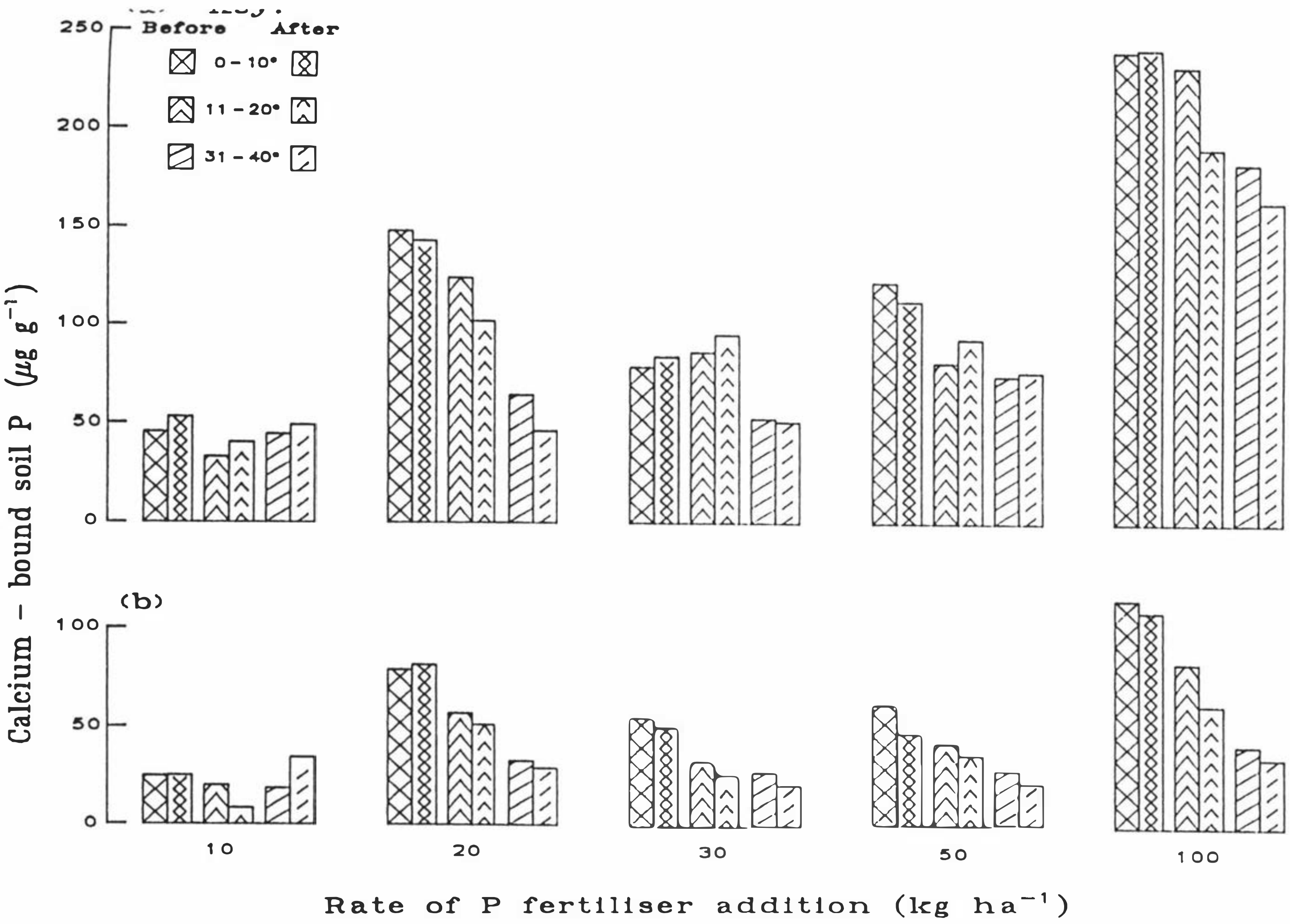

Figure 4.6 Effect of slope, sampling depth and P fertiliser rate on amounts of calcium-bound P in soil before and after the glasshouse trial; 0-3 (a) and 3-7 (b) cm depth.

(1970) who found that to reach a given level of solution P, larger quantities of P would have to be added to soils with a high P-sorption capacity than to soils with a low P-sorption capacity.

It is interesting to note that the soil samples collected for the trial showed a decrease in P_O with increasing depth and slope, but no effect of fertiliser rate on P_O. Thus the increase in total P was a function of increasing inorganic P_I, as discussed in section 3.3.6.

4.3.2 **Dry matter yield**

At harvest ten, dry matter yield (DMY) relative to control pots (in which non-limiting conditions in terms of nutrient supply were maintained)(Table 4.4) ranged from 85% (campsite, 0-3 cm depth, 100 kg ha^{-1}) to 11% (easy-slope, 3-7 cm depth, 10 and 50 kg ha^{-1}).

In the 3-7 cm depth on all steep-slope treatments and all but the 100 kg ha^{-1} P treatment on easy-slopes, production was below 16% of the control pots. This marked decrease in production was taken as an indication that the plants were severely P deficient.

In terms of DMY, campsites produced more than easy- or steep-slopes at corresponding depths. In most treatments, easy-slopes (0-3 cm depth) produced more than corresponding steep-slopes (Fig. 4.7). This was not the case for the 10 and 50 kg ha^{-1} P fertiliser rates where production from the steep-slopes exceeded that from the easy-slopes. Olsen-extractable P values for easy- and steep-slope soils (0-3 cm depth) receiving 50 kg ha^{-1} P fertiliser were the same (22.6 µg g^{-1}

Table 4.4 Effect of slope, depth and rate of P fertiliser addition (kg ha^{-1}) on relative dry matter yield (%) at harvest ten.

		Rate of P fertiliser addition (kg ha^{-1})				
Slope	Depth (cm)	10	20	30	50	100
0-10°	0-3	31.4	56.6	60.1	76.5	84.8
	3-7	38.9	39.2	28.3	45.6	53.0
11-20°	0-3	17.3	33.2	26.5	30.3	80.1
	3-7	11.4	13.4	15.1	11.4	27.3
31-40°	0-3	30.5	20.4	24.1	43.1	53.0
	3-7	15.8	13.1	14.4	11.5	15.7

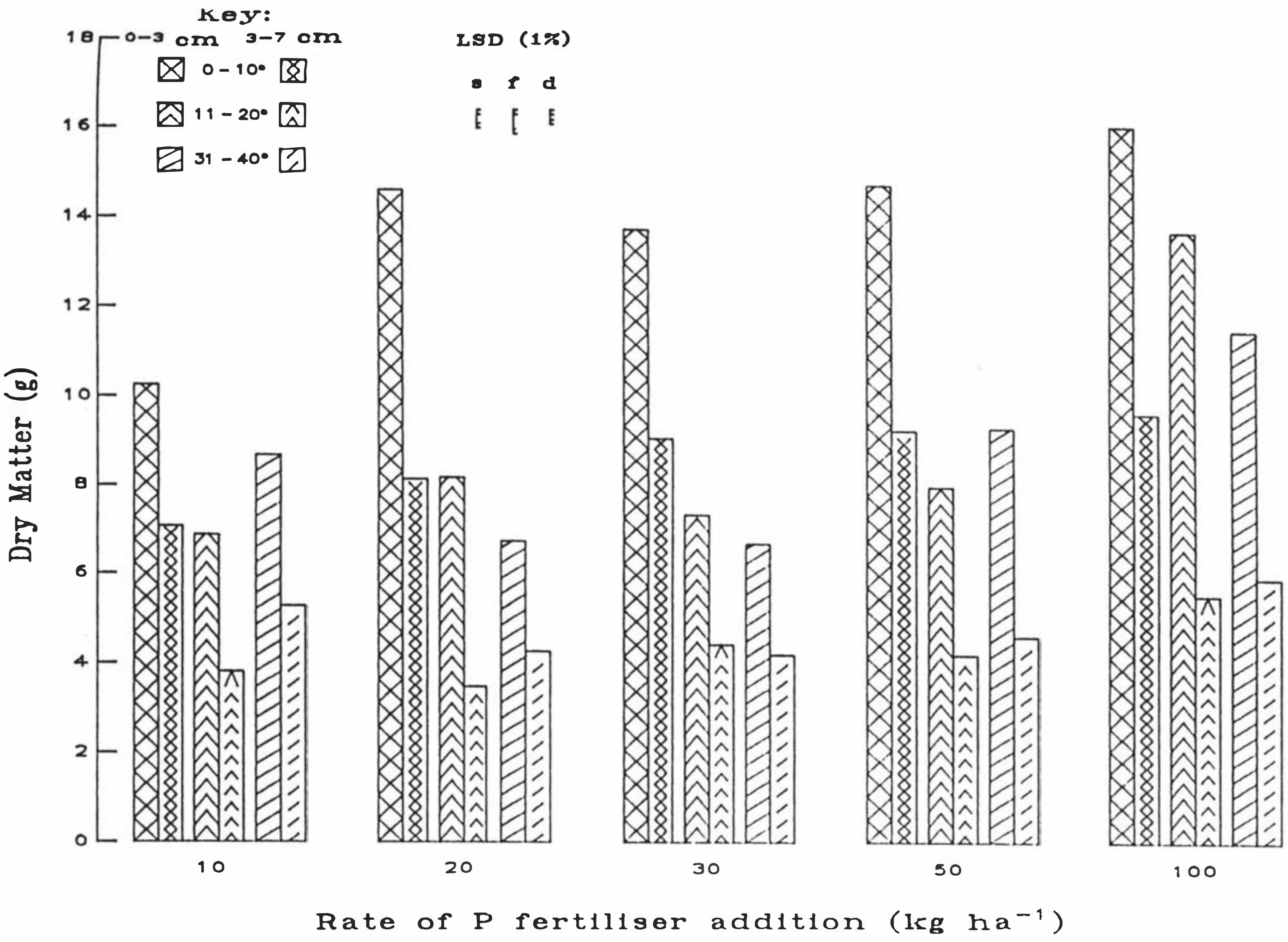

Figure 4.7 Effect of slope, sampling depth and P fertiliser rate on cumulative dry matter (g) at the tenth harvest.

soil) (Fig. 4.1). However, the P retention for the easy-slope (74%) was higher than that for the steep-slope (63%) (Table 4.2).Although it has been suggested by Fox and Kamprath (1970) that for soils with equal Olsen P values, the one with the higher P-sorption capacity will have a larger ability to supply P to the plant, during this trial more P was made available to the plant by the soil with the lower P-sorption capacity. This observation supports work by During (1968) who found that the availability of fertiliser P for plant uptake was larger on soils with a low P-sorption capacity than it was for soils with a higher P-sorption capacity at comparable Olsen values.

In the 3-7 cm depth treatments for all but the 30 kg ha^{-1} P paddock, steep-slopes outyielded easy-slopes. This was probably a consequence of physical factors such as texture and structure, and their effect upon other parameters, such as aeration, porosity, and water-holding capacity, and is substantiated by evidence from cumulative dry weights from control plants which received complete nutrient solution (Table 4.5), i.e., in the cases mentioned, the control plants grew better on the steep-slope soil than they did on the easy-slope soil. As neither P nor any other nutrient was limiting growth in these pots, and as all environmental factors were equal, the difference in growth was probably due to the physical nature of the soil.

In the 20 kg ha^{-1} P fertiliser treatment, the yield from the campsites and easy-slopes at both depths was somewhat higher than might have been expected from the trends indicated by other treatments (Fig. 4.7). This is thought to be due to high P levels resulting from intense P transfer, as explained in section 4.3.1.3.

Table 4.5 Effect of slope, depth and rate of P fertiliser addition (kg ha^{-1}) on cumulative dry matter yield (g) of control pots.

		Rate of P fertiliser addition (kg ha^{-1})				
Slope	Depth (cm)	10	20	30	50	100
0-10°	0-3	20.0	20.5	18.0	17.8	20.5
	3-7	13.3	13.5	15.1	15.1	13.0
11-20°	0-3	14.9	16.9	16.2	14.6	16.5
	3-7	13.0	10.9	10.7	10.6	11.2
31-40°	0-3	17.0	14.0	13.6	13.9	17.5
	3-7	14.0	13.0	9.4	13.7	12.6

Dry matter yield was closely related to Olsen-extractable P, water-extractable P, total P, P_I and non-occluded P (Table 4.6). This is discussed further in section 4.3.3.

4.3.3 **Total P uptake**

Total P uptake over ten harvests was highest at the maximum P addition rate for all slopes and both depths (Fig. 4.8). For each slope within each fertiliser rate P uptake was approximately twice as high from the 0-3 cm depth as it was from the 3-7 cm depth ($P<0.01$). Plants grown on campsites at both depths removed more P than from easy- or steep-slopes at the corresponding depths ($P<0.01$). In general, P uptake on easy-slopes exceeded that on steep-slopes. Exceptions to these trends have already been discussed in section 4.3.2.

At the end of the trial, P uptake was only a small fraction of that maintained by plants growing in pots receiving a complete nutrient solution (Table 4.7) and the P concentration in the herbage had, in all but two treatments, fallen below 0.2% (Table 4.1). Consequently, it was believed that the pool of plant-available P in most of the soils was nearing exhaustion after forty-eight weeks. In soils of high P status, however, the pool was unlikely to have been exhausted completely.

Total P uptake was strongly related to water-extractable P in the soils (Fig. 4.9; Table 4.8). The high correlation supports the work of others who have found that water extraction provides a good

Table 4.6 Correlation coefficients for dry matter yield and various soil P fractions. Results are presented for treatments separated according to depth (a) and for all treatments analysed together (b).

	Depth (cm)		
	a		b
Soil P fraction	0-3	3-7	0-7
Olsen-extractable	0.81	0.89	0.86 **
Water-extractable	0.86	0.90	0.91 **
Total	0.80	0.84	0.90 **
Inorganic	0.80	0.84	0.90 **
Non-occluded	0.73	0.79	0.80 **

** All treatments were significant at the 1% level.

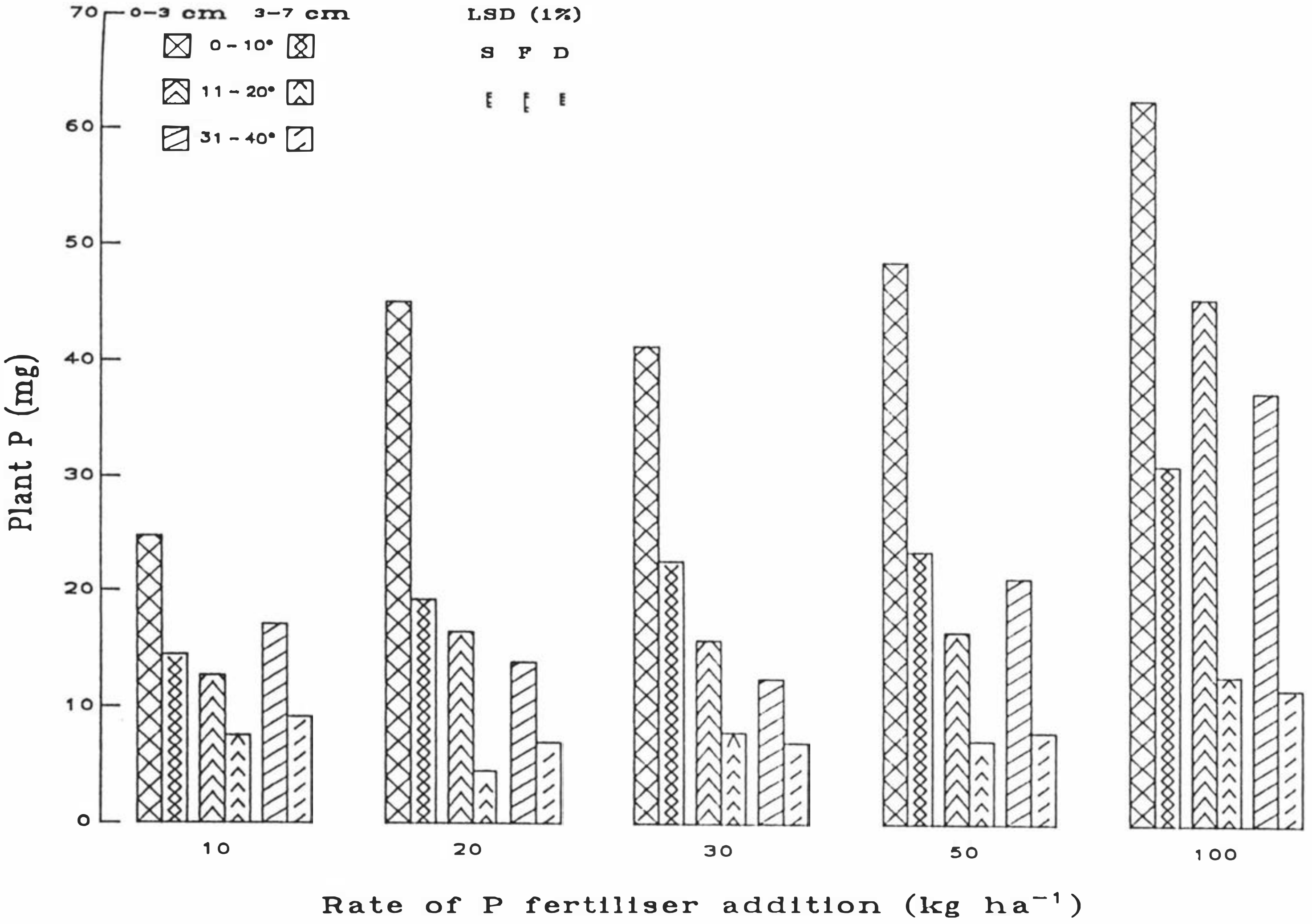

Figure 4.8 Effect of slope, sampling depth and P fertiliser rate on cumulative plant P uptake (mg) at the tenth harvest.

Table 4.7 Effect of slope, depth and rate of P fertiliser addition (kg ha^{-1}) on relative P uptake (%) at harvest ten.

		Rate of P fertiliser addition (kg ha^{-1})				
Slope	Depth (cm)	10	20	30	50	100
0-10°	0-3	11.6	28.2	25.1	35.2	45.2
	3-7	11.4	16.4	8.7	17.3	25.1
11-20°	0-3	5.2	14.8	9.9	10.4	52.8
	3-7	3.1	3.8	5.1	4.5	12.0
31-40°	0-3	6.8	6.2	6.0	16.8	16.4
	3-7	4.8	3.2	4.2	3.3	4.2

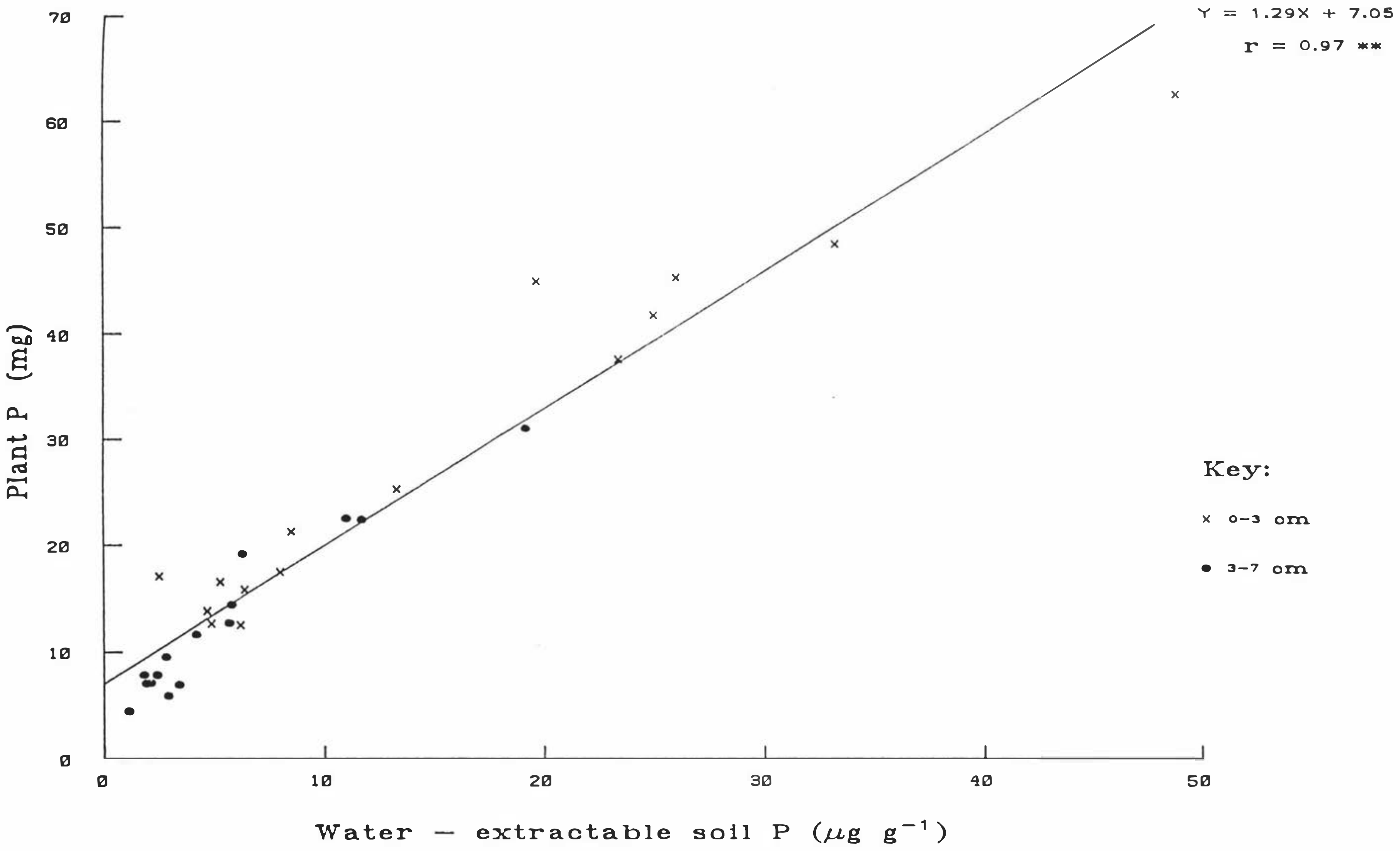

Figure 4.9 Relationship between plant P uptake (mg) and initial levels of water-extractable P.

Table 4.8 Regression equations and correlation coefficients for cumulative P uptake (Y) and initial amounts of various soil P fractions (x).

Soil P fraction	Depth (cm)	Regression equation	r
Olsen-extractable	0-3	$Y=0.66\ x + 5.76$	0.96 **
	3-7	$Y=0.46\ x + 2.71$	0.96 **
	0-7	$Y=0.66\ x + 2.08$	0.93 **
Water-extractable	0-3	$Y=1.17\ x + 10.29$	0.96 **
	3-7	$Y=1.50\ x + 4.47$	0.96 **
	0-7	$Y=1.29\ x + 7.05$	0.97 **
Non-occluded	0-3	$Y=0.06\ x + 8.40$	0.92 **
	3-7	$Y=0.04\ x + 4.37$	0.89 **
	0-7	$Y=0.05\ x + 4.36$	0.82 **
Total	0-3	$Y=0.03\ x - 1.74$	0.91 **
	3-7	$Y=0.03\ x - 0.71$	0.92 **
	0-7	$Y=0.03\ x - 3.56$	0.92 **
Inorganic	0-3	$Y=0.05\ x + 8.56$	0.93 **
	3-7	$Y=0.04\ x + 4.44$	0.91 **
	0-7	$Y=0.05\ x + 4.63$	0.91 **

indication of P availability in a wide range of soils and is not substantially affected by soil type (e.g., Thompson et al., 1960; Ryden et al., 1976; Luscombe et al., 1979; Sorn-srivichai, 1985).

Total P uptake was also strongly related to Olsen P (Fig. 4.10), total P, P_I and non-occluded P (Table 4.8). This means that, knowing the relationship for a particular soil type, total P uptake can be predicted from what are comparatively simple chemical soil tests. The same is true for DMY, but as this parameter does not allow for variations in P content between plants, the relationship is not as good as it is for total P uptake.

It is interesting to note that, in contrast to water-extractable P, the regression equations for Olsen-extractable P and total P uptake account for more variation if the two depths are considered separately than if all values are considered together. Although the intercepts of the two lines are not statistically different, the slopes are ($P<0.01$). This means that for a given Olsen value, the 0-3 cm depth soil is able to supply more P to the plant than is the 3-7 cm depth. The disparity increases as Olsen P increases. The present results suggest the Olsen test is affected by depth and consequent changes in organic matter, structure, and texture.

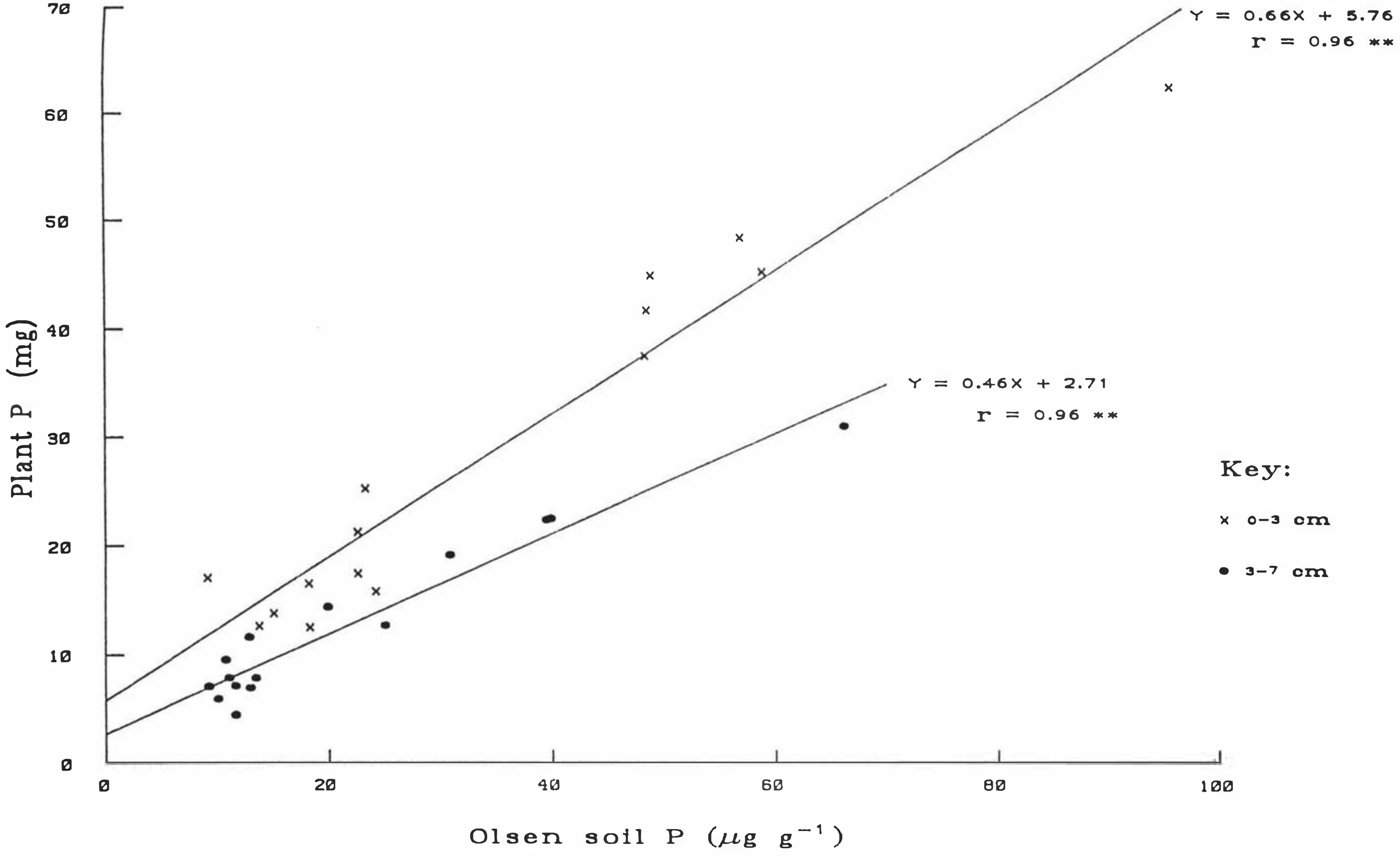

Figure 4.10 Effect of sampling depth on the relationship between plant P uptake (mg) and initial levels of Olsen-extractable P.

4.3.4 **Changes in soil P fractions during plant growth**

4.3.4.1 **Olsen-extractable P**

Measurements of Olsen P made after completion of the glasshouse trial showed that initial trends were still present (Fig. 4.1), i.e., Olsen P increased with increasing fertiliser P addition and decreased with increasing depth and slope. However, the amount of P was reduced by approximately 50% on campsites at both depths and easy-slopes at the 0-3 cm depth. On the steep-slopes (3-7 cm depth) at low rates of fertiliser P there was little change. With the remaining treatments Olsen P was reduced by approximately 33%.

At the end of the trial almost a third of the soils had Olsen P values decreased to a level below that thought to indicate responsiveness to P (During, 1984). All soils had Olsen P values of higher than 6, indicating that P was still available (though under field conditions it would be considered to be very low) yet the herbage P concentration and dry matter yield indicated severe P deficiency. This would suggest that at low levels of P, the Olsen-extraction technique does not reflect accurately the ability of plants to take up P under the conditions of high P demand generated in the glasshouse.

4.3.4.2 **Water-extractable P**

The effect of growing ryegrass was to reduce water-extractable P values in soil where they had been high initially (Fig. 4.2). For soils with low water-extractable P there was little or no change.

This can be explained by the shape of the sorption isotherm for P concentration which indicates that at a high solution P concentration a given amount of P uptake will cause a large reduction in solution P concentration (Ryden et al., 1977). In contrast, at a low solution P concentration the same amount of P uptake will result in a much smaller reduction in solution P concentration.

For some soils, particularly those with very low initial water-extractable P values, such as the steeper slopes (3-7 cm depth), there appeared to be slightly more water-extractable P in the soil after the glasshouse trial than before. As the differences were very small (generally less than 2 µg g^{-1} soil) they can probably be ascribed to experimental error.

4.3.4.3 **Total, inorganic and organic P**

The effect of taking ten harvests of ryegrass from the soil was to reduce total P by 7 to 25% in the 0-3 cm depth treatments and by 4 to 23% in the 3-7 cm depth treatments (Fig. 4.3). Reductions tended to be larger at the higher rates of fertiliser P addition with flatter slopes than at the lower rates of fertiliser P addition and with steep-slopes.

The changes in total P (Fig. 4.11) were significant for most treatments. The very large reduction in the 30 kg ha^{-1} P treatment was a consequence of a large drop in P_O content, as will be discussed later.

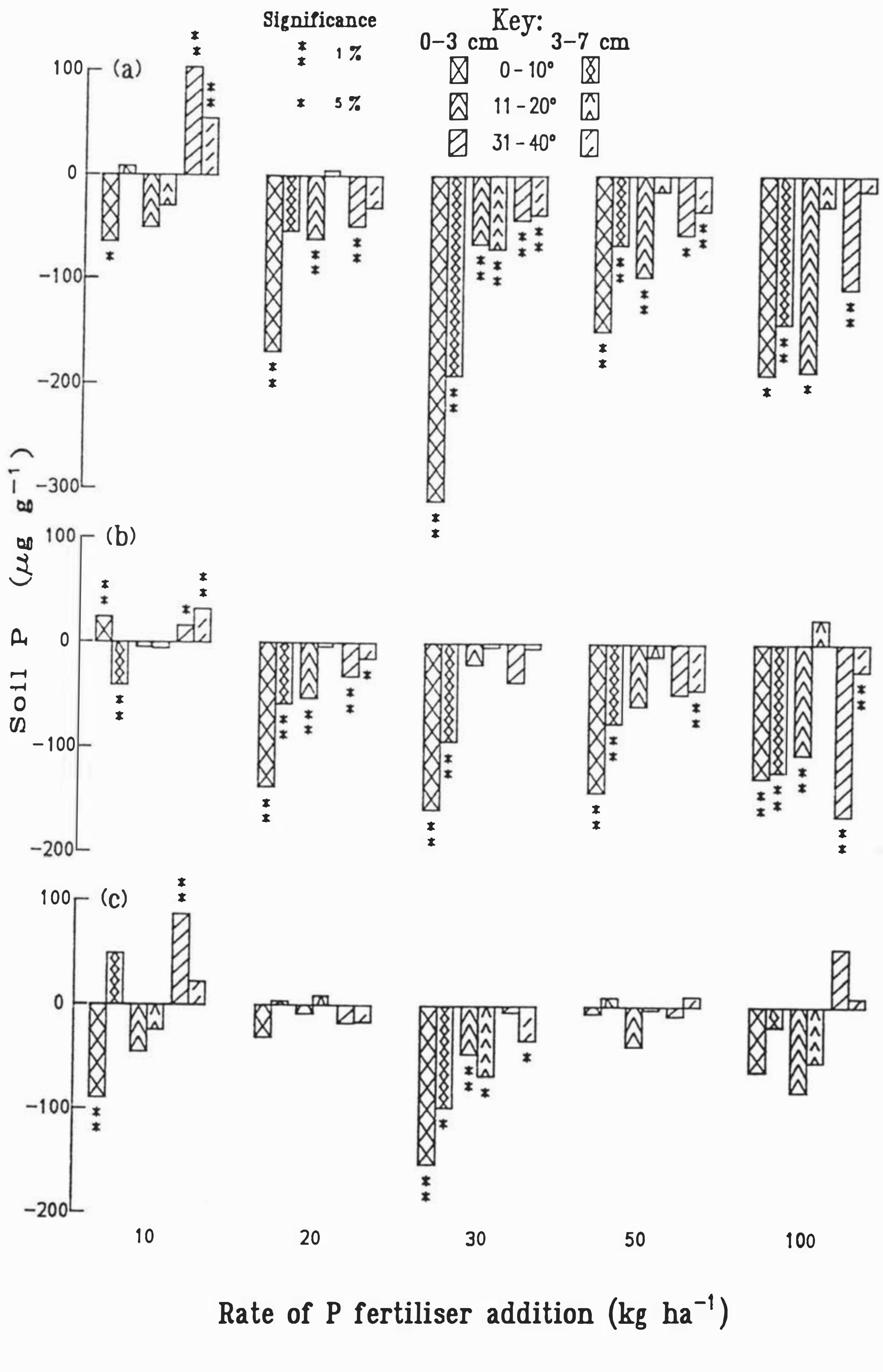

Figure 4.11 Change in total P (a) inorganic P (b) and organic P (c) measured as the difference in P levels before and after the glasshouse trial.

At the lowest rate of fertiliser P addition at both depths on the steep-slope soils there appeared to be more total P after the glasshouse trial than before. It is well established that "total P" measured by ashing does not give a complete estimate of total P in some soils (Sherrell and Saunders, 1966; Syers et al., 1968; O'Connor and Syers, 1975; Gillingham, 1978). Under conditions of high production with daily wetting and drying cycles, warm temperatures and intense exploration and exploitation of the soil by roots it may be possible that a fraction of P not previously extracted in 0.2 N H_2SO_4 became available.

A second, and more plausible possibility, is that the inclusion of root material in the soil after the glasshouse trial was responsible for the increase. Gillingham (1978) showed that variation in soil organic matter accounted for approximately 30% of the variability in total P content measured by ashing.

A third possibility is that there was an initial sampling error. A thorough re-analysis and investigation into experimental procedures and analysis techniques, however, failed to reveal any experimental error.

There were significant differences in P_I between pre- and post-glasshouse trial values (Fig. 4.11). Inorganic P was reduced by 5 to 33% in the 0-3 cm depth soils and 3 to 43% in the 3-7 cm depth treatments (Fig. 4.3). The actual change in P_I (Fig. 4.11) was little affected by fertiliser P addition, even on campsite soils, but did show an effect of slope and depth.

Organic P pre- and post- the glasshouse trial was reduced by 1 to 20% for both depths (Fig. 4.3). The reduction was largest for the 30 kg ha^{-1} P fertiliser addition for all soils. The significance of the reduction at this fertiliser rate (Fig. 4.11) probably reflects the comparatively low P_I levels in this paddock. The lack of significance with most of the other treatments is due not only to the fact that changes were small, but also to the fact that P_O is measured by difference. This means that experimental variations in the measurement of total P and P_I can be compounded. The increase in P_O in some soils may be due to this experimental variation, or to the inclusion of root material, as mentioned earlier. Although the soils were sieved (<2 mm) before analysis, it is extremely difficult to remove all root material from the soil particularly after a long-term glasshouse trial where root exploration has been intense.

4.3.4.4 **Non-occluded P**

The effect on non-occluded P of ten harvests of ryegrass was to diminish this P pool by 7 to 50% for the 0-3 cm depth and 9 to 32% for the 3-7 cm depth (Fig. 4.4). Easy-slope soils were less affected than campsite or steep-slope soils except at the highest rate of P fertiliser addition where non-occluded P decreased more for the steep-slope soils than easy-slope soils. Reductions for most soils were statistically significant (Fig. 4.12a).

In general, the pattern of reduction in non-occluded P follows that of total plant P uptake (Fig. 4.8) and initial non-occluded P values (Fig. 4.4). As discussed in section 4.3.4.3 there was an increase in

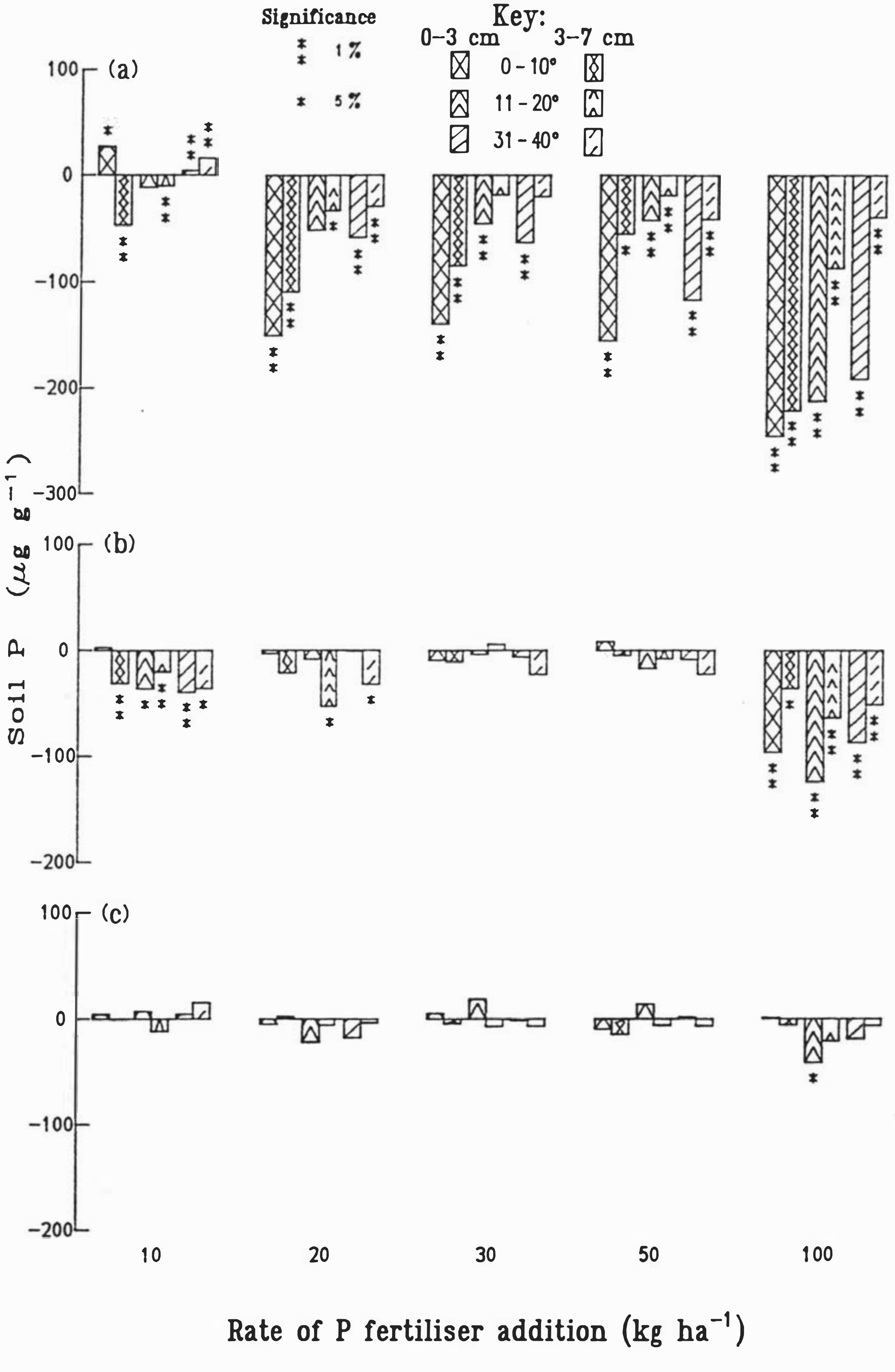

Figure 4.12 Change in non-occluded P (a) occluded P (b) and calcium-bound P (c) measured as the difference in P levels before and after the glasshouse trial.

total P on the steep-slope at the lowest rate of P addition. The fact that the increase was noticed in two fractionation schemes (fractionation of total P and fractionation of P_I) substantiates the hypothesis that analytical error was not responsible for the increase.

The reduction in non-occluded P in this trial supports conclusions by Du Plessis and Burger (1966), Grigg (1968), Martens et al. (1969), and Novais and Kamprath (1978) that it is the non-occluded P fraction within the total soil P pool that supplies P for plant uptake in weakly-acid soils.

4.3.4.5 **Occluded P**

After the glasshouse-trial, occluded P had been reduced in soils from nearly all slopes. These reductions were significant at the lowest and highest rate of P fertiliser addition, which had comparatively low and high initial levels of occluded P, respectively (Fig. 4.12b).

At the lowest rate of P fertiliser addition other "more available" P pools (e.g., Olsen and water-extractable P) were also low at the beginning of the glasshouse trial, and so would have been exhausted rapidly. The intensive growing conditions and extensive exploitation of soils by roots might have had an effect on the release of occluded P. It is, perhaps, significant that the treatment at this low fertiliser rate with the highest levels of "more-available P" (i.e., campsite, 0-3 cm depth) did not undergo a reduction in occluded P during the trial.

Significant reductions in occluded P also occurred at the highest rate of fertiliser P where initial levels of occluded P were comparatively high. It is possible that at this high rate of fertiliser (1) not all the non-occluded P was removed by the sodium-hydroxide extraction and (2) some P was present in hydrous ferric oxides which would have been removed during extraction for occluded rather than non-occluded P, but would have been available for plant-uptake given the timespan of the trial.

At moderate rates of fertiliser P addition there was very little change in occluded P. This is consistent with the work of Du Plessis and Burger, (1966), Grigg (1968), Martens et al. (1969) and Novais and Kamprath (1978) which suggested that occluded P was not generally plant-available.

4.3.4.6 **Calcium-bound P**

The amounts of calcium-bound P after the glasshouse trial were in most cases, similar to the initial values (Fig. 4.6). The changes in calcium-bound P were small and, in all but one case, nonsignificant (Fig. 4.12c). This supports the work of Grigg (1968) who concluded that calcium-bound P is only slowly available for plant P uptake.

4.3.5 **Plant-available P**

Plant-available P (the amount of P taken up by plants per g of soil from each pot) ranged from 15 $\mu g\ g^{-1}$ soil (easy-slope, 3-7 cm depth, 20 kg ha^{-1}) to 208 $\mu g\ g^{-1}$ soil (campsite, 0-3 cm depth, 100 kg ha^{-1}).

Regression of plant-available P against changes in various soil P fractions measured as the difference in the fractions before and after the glasshouse trial (Table 4.9) showed that plant-available P was strongly related to changes in Olsen-extractable P (Fig. 4.13), non-occluded P (Fig. 4.14), P_I (Fig. 4.15) and total P (Fig. 4.16).

Regression equations for these relationships (Table 4.9) show that, although a change in Olsen-extractable P gave the highest correlation with plant-available P, rather more P (4 and 3 times as much P from the 0-3 cm and 3-7 cm depths, respectively) was taken up by the plants than was indicated by change in Olsen P.

Depletion of the P_I fraction almost equalled total plant P uptake, particularly in the 0-3 cm depth. When P_I was fractionated, most of the plant-available P appeared to be derived from the non-occluded P fraction; contribution from the other two fractions was not significantly related to plant-available P.

Results from this glasshouse trial tend to confirm the suggestion (Grigg, 1968) that the NaOH extraction for non-occluded P removes a pool of P_I which is largely, but probably not totally, plant-available. Non-occluded P is thought to comprise surface-bound "aluminium-P" and "iron-P" (Williams et al., 1967) which are considered to be plant-available P compounds (Du Plessis and Burger, 1966; Martens et al., 1969; Novais and Kamprath, 1978). However, due to smaller, statistically insignificant, contributions from other P_I fractions, the total change in P_I gave a better indication of plant-available P than did any single P_I fraction.

Table 4.9 Regression equations and correlation coefficeints for plant-available P (Y) and changes in soil P fractions (x) measured as the difference in the fractions before and after the glasshouse trial.

Soil P fraction	Depth (cm)	Regression equation	r
Olsen-extractable	0-3	Y= 4.13 x + 26.4	0.95 **
	3-7	Y= 3.17 x + 21.2	0.93 **
	0-7	Y= 4.44 x + 17.3	0.98 **
Total	0-3	Y= 0.55 x + 35.6	0.76 **
	3-7	Y= 0.38 x + 22.4	0.72 **
	0-7	Y= 0.58 x + 18.3	0.80 **
Inorganic	0-3	Y= 0.87 x + 27.3	0.85 **
	3-7	Y= 0.69 x + 16.4	0.96 **
	0-7	Y= 0.96 x + 16.9	0.91 **
Organic	0-3	Y= 0.59 x + 77.4	0.43
	3-7	Y= 0.26 x + 33.3	0.27
	0-7	Y= 0.54 x + 57.2	0.37
Non-occluded	0-3	Y= 0.71 x + 18.3	0.92 **
	3-7	Y= 0.41 x + 19.0	0.85 **
	0-7	Y= 0.68 x + 16.1	0.91 **
Occluded	0-3	Y= 0.63 x + 83.9	0.47
	3-7	Y= 0.85 x + 27.8	0.37
	0-7	Y= 0.75 x + 60.7	0.46
Calcium-bound	0-3	Y= 0.63 x + 97.8	0.16
	3-7	Y= -3.24 x + 64.0	-0.25
	0-7	Y= 0.55 x + 75.4	0.11
Calcium-bound + occluded	0-3	Y= 0.50 x + 84.5	0.44
	3-7	Y= 0.76 x + 24.4	0.33
	0-7	Y= 0.59 x + 60.9	0.43

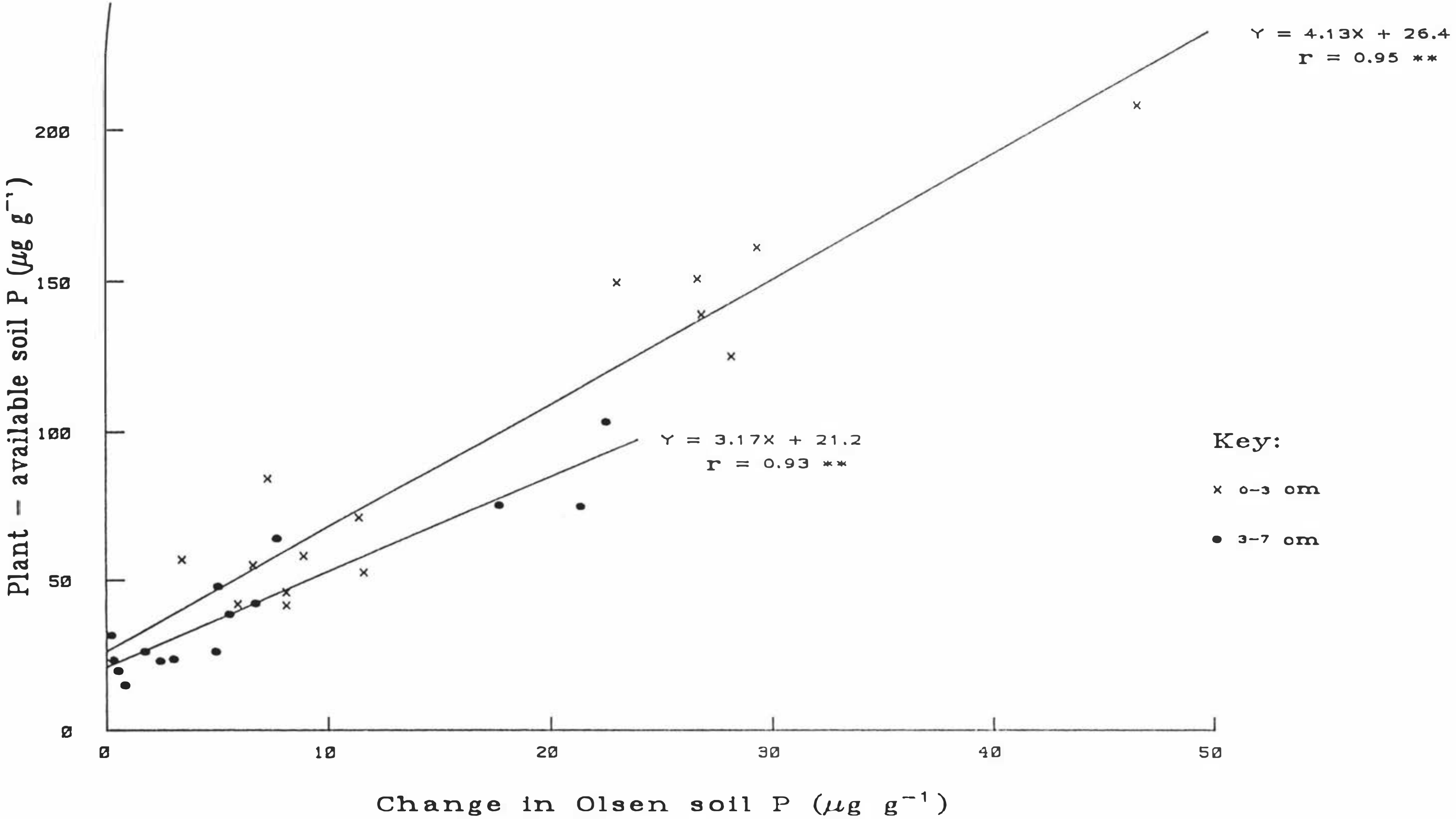

Figure 4.13 Effect of sampling depth on the relationship between plant-available soil P (µg g^{-1}) and change in Olsen-extractable P during the period of the glasshouse trial.

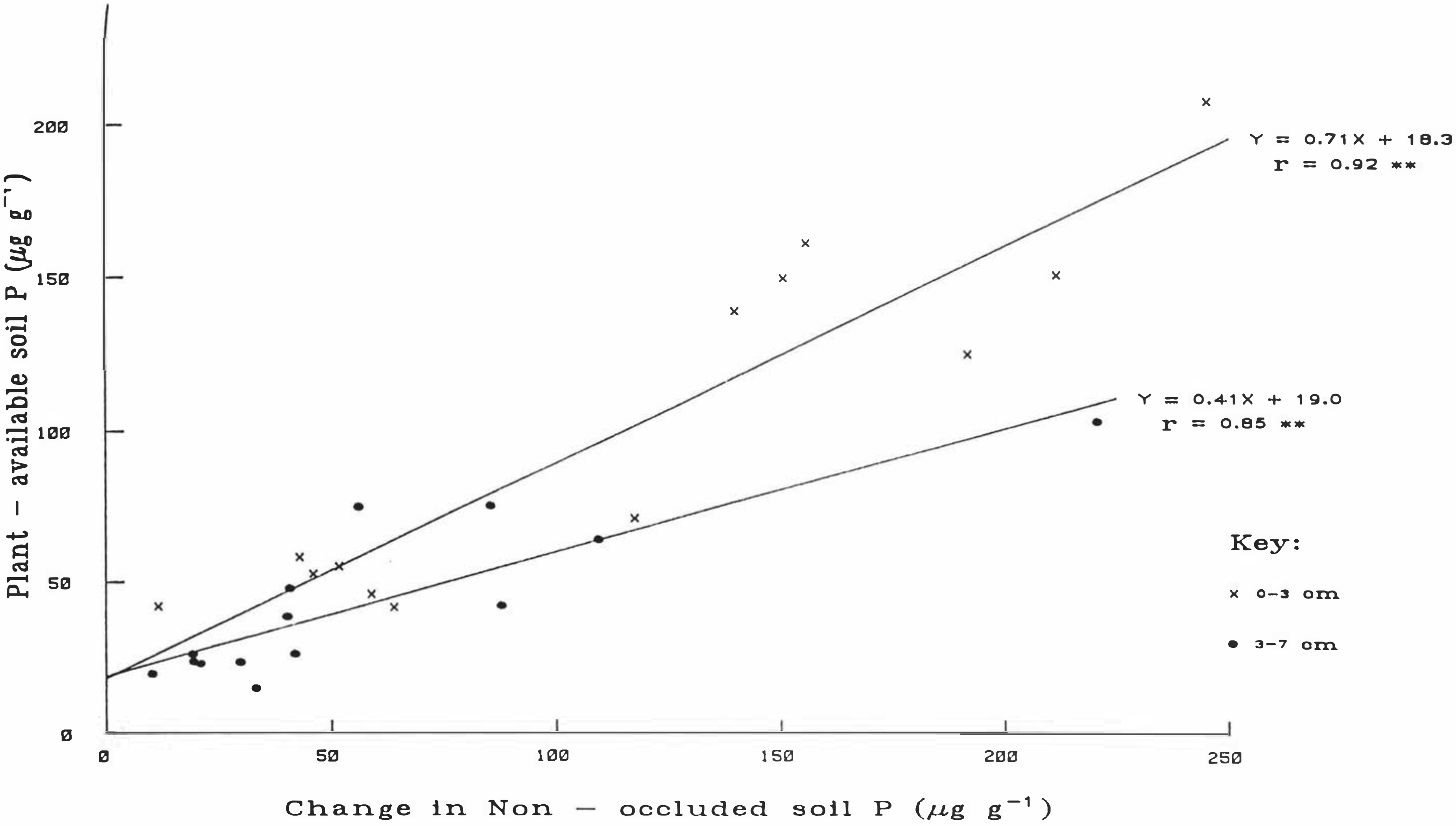

Figure 4.14 Effect of sampling depth on the relationship between plant-available soil P (µg g^{-1}) and change in non-occluded P during the period of the glasshouse trial.

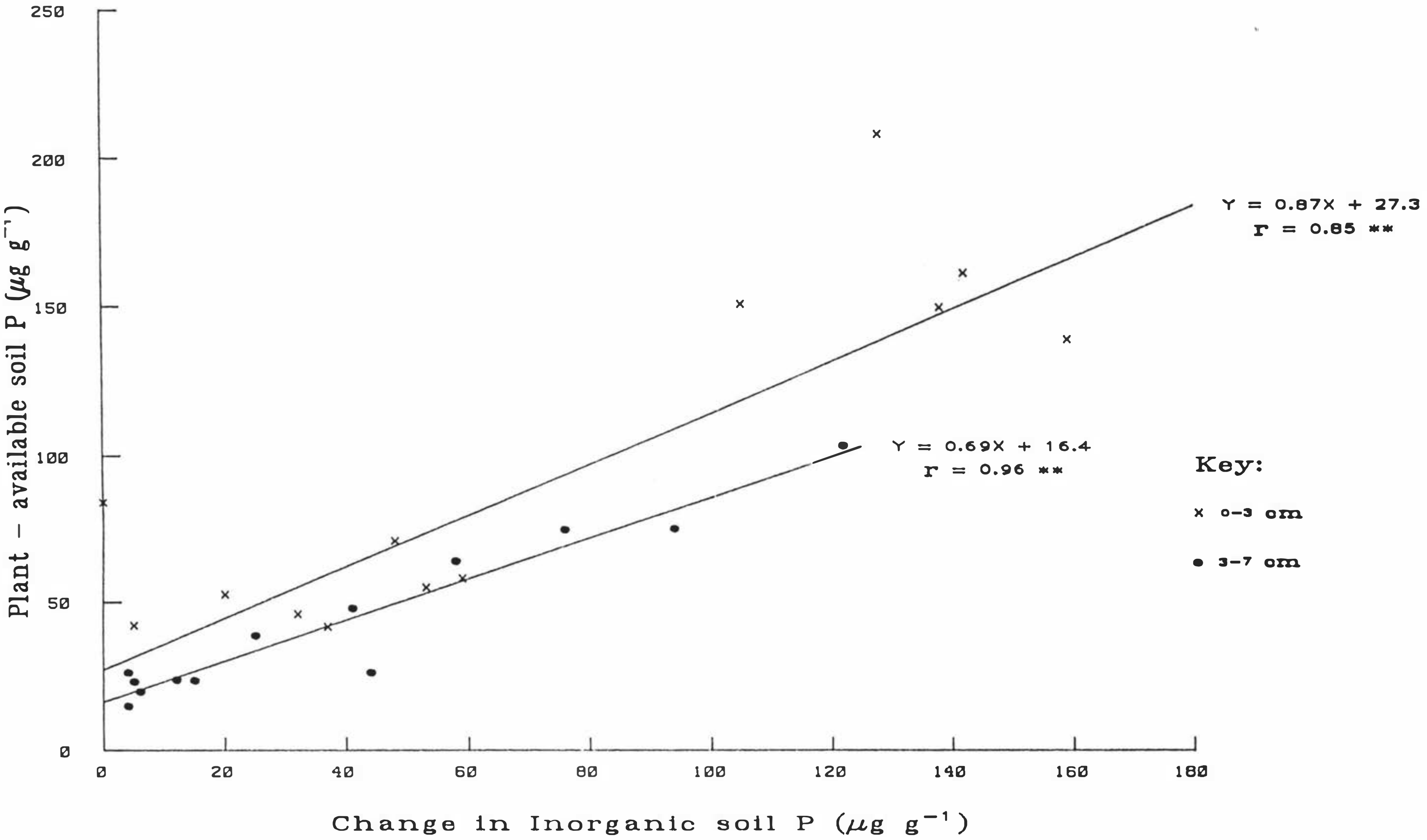

Figure 4.15 Effect of sampling depth on the relationship between plant-available soil P (μg g^{-1}) and *change*
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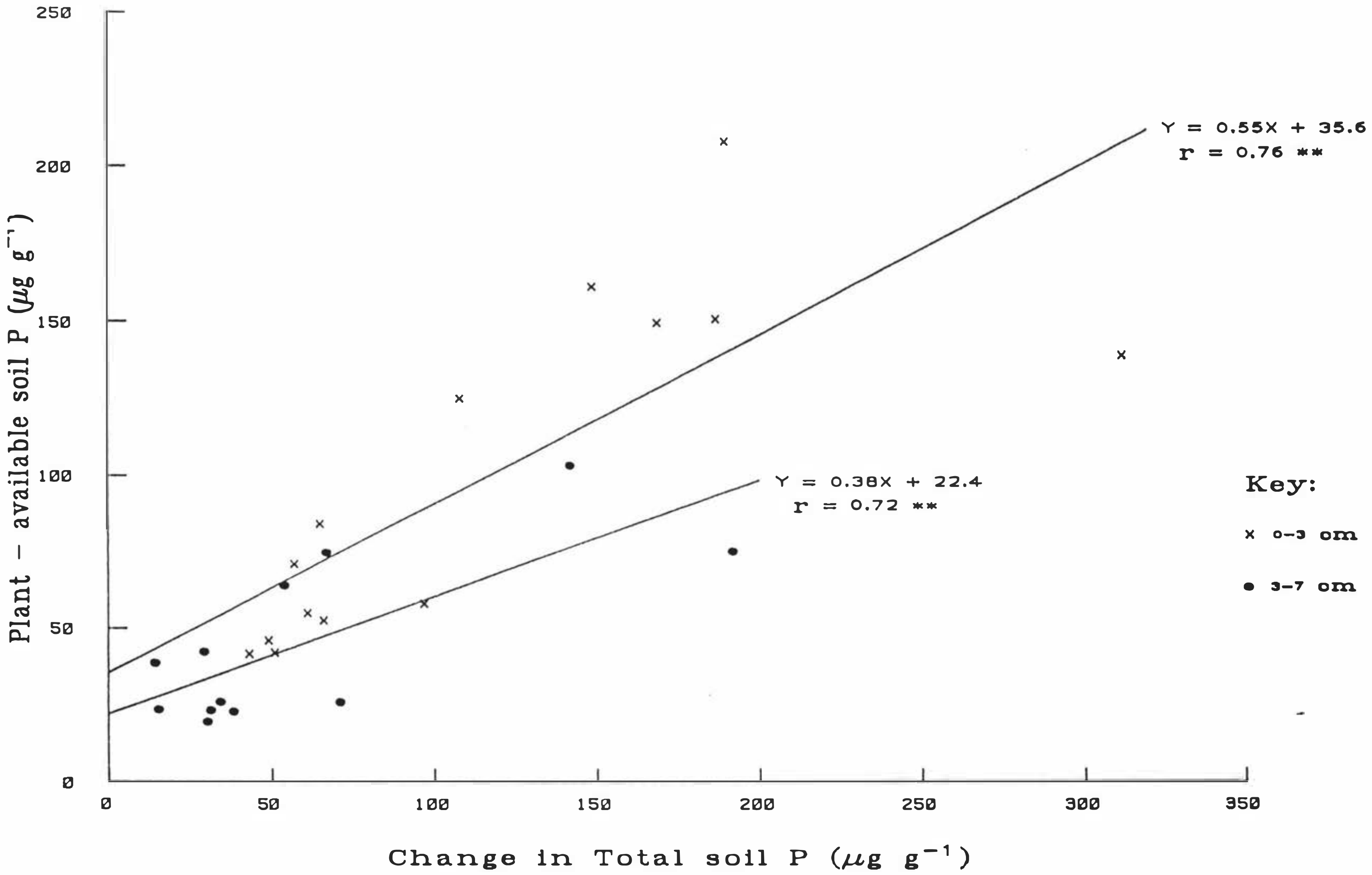


Figure 4.16 Effect of sampling depth on the relationship

The extremely high correlation of plant-available P with changes in Olsen P and P_I is promising in terms of P modelling for possible fertiliser P response as it means that plant-available P can be predicted from changes in Olsen P and P_I, thereby circumventing the need for measuring DMY and herbage P concentration. However, the technique is restrictive in that it requires the isolation of a portion of soil so that the amount of soil P before and after plant P uptake can be measured. Of more use in terms of P modelling are the regression equations discussed in section 4.3.3, where cumulative P content was seen to be closely related to an initial soil parameter rather than to a change.

4.4 CONCLUSIONS

The soil P pool which most accurately predicted total plant P uptake was that pool measured by water extraction. The water-extraction method is believed to measure "more physically-sorbed P" and is thought to reflect both intensity and capacity factors of the soil (Sorn-srivichai, 1985). Advantages of the water-extraction method lie not only in the high correlation with total plant P uptake and its apparent independence of soil type, but also in the fact that it is a simple technique to perform.

Plant-available P was highly correlated with the change in Olsen-extractable P measured as the difference in this pool before and after the glasshouse trial. The fact that plant-available P was four times larger than the change in Olsen P in the 0-3 cm depth, and three times larger than the change in Olsen P in the 3-7 cm depth suggests (a) that P was cycling through the Olsen P pool from a larger soil P pool to the plant and (b) that the capacity of the soil to supply P to the plant was reduced by depth.

Changes in P_I and non-occluded P were correlated not only with plant-available P but also with each other ($r = 0.96$ **). Thus it appeared that most of the P taken up by the ryegrass was derived from the non-occluded P fraction.

The positive effect of P transfer and P fertiliser application on P_I and non-occluded P can be seen on campsites and at high rates of P fertiliser, respectively. Results from this trial indicate that plant-available P will also be high in these areas.

High levels of P_O are also likely to be found on campsites. However, P_O is unlikely to make a significant contribution to P_I (and thus plant-available P), at least within the short term, as it made no contribution to P_I in this study despite the intense growing conditions in the pot and glasshouse environment.

At present in New Zealand recommendations for rate of fertiliser P addition and advice for withholding P fertiliser are based to some extent on the Olsen P soil test. Results from this glasshouse study would suggest that water-extractable P was a slightly better indicator of plant-available P than Olsen P. For fertiliser P recommendations, particularly in the cases where farmers are trying to save money by withholding fertiliser, it is possible that an improved indication of plant-available P reserves in the soil could be gained by using the water-extractable P test instead of the Olsen P test.

Soil P_I could also be used as a measure of plant-available P reserves in hill country. The advantage of P_I over Olsen P is that the former measures a complete P pool and is, therefore, independent of soil type. The latter measures a smaller P fraction through which P cycles to the plant. This rate of cycling is affected by soil depth.

CHAPTER 5

"ABOVE-GROUND" COMPONENTS OF THE P CYCLE AS AFFECTED BY P FERTILISER ADDITION AND SLOPE

5.1 INTRODUCTION

In pastoral systems, under maintenance conditions, applications of P fertiliser are made to replace losses of P due to animals and in the soil.

Losses of P in animal products have generally been assumed to approximate 10% of animal P intake (Karlovsky, 1966). For flat paddocks calculation of animal losses is relatively simple; for hill-country paddocks, comprising land in different slope categories, the problem is more complex because (a) P uptake by plants decreases with increasing slope (Gillingham, 1980a; Lambert et al., 1983) and (b) faecal P is not returned in proportion to the amount of plant P removed from a particular area. Although limited studies have been carried out on these two aspects of the P cycle, it would seem that the shortfall between plant P uptake and removal, and faecal P return increases markedly with increase in slope (Gillingham et al., 1980). On areas designated as campsites, which are usually flat and occupy less than 15% of the total area within a paddock, more P is returned than is taken up by pasture (Gillingham et al., 1980). Thus for hill country the maintenance P requirement to replace 'animal' losses will be different for each slope category under consideration.

From this it is clear that to identify maintenance P requirements in hill country a considerable amount of information is necessary not only on the effect of slope on P uptake by pasture and pasture utilisation (PU) by the grazing animal but also on faecal distribution and the relationship between plant P and faecal P. With the exception of the initial study of Gillingham et al., (1980) few published data are available to enable estimates of maintenance P requirements in hill country to be made.

This chapter reports on some of the data collected from the long term, large scale grazing trial at Whatawhata Hill Country Research Station described in Chapter 3. Results from measurements of dry matter yield (DMY), pasture P concentration and PU are recorded but are not examined in depth. Instead, discussion will concentrate on results from measurements of dry matter production and on distribution of faeces and faecal P concentration. Very little work of this nature has been carried out previously.

5.2 MATERIALS AND METHODS

5.2.1 Sample collection and analysis

5.2.1.1 Pasture dry matter yield

Three methods of estimating DMY were used by the Ministry of Agriculture and Fisheries at different stages during the course of the trial.

For the period 3 March 1981 to 26 January 1982, visual rating estimates of standing pasture DM (kg ha^{-1}) were made pre- and post-grazing on the permanent sampling sites in the rotationally-grazed paddocks. Ratings were calibrated against 0.18 m^2 quadrats of pasture cut to ground level.

On continuously-grazed paddocks five cages per slope were used to protect pasture from grazing. Pasture growth after spelling was assessed visually within the cages, and also in the unprotected paddock on twenty-five sites per slope prior to relocating cages for the next regrowth period.

From 26 January 1982 to 9 June 1983 the cage system was used on rotational as well as continuously-grazed paddocks. The change was made in order to determine whether or not cage shelter effects were the cause of the higher pasture DMY measured from the continuously-grazed paddocks during the previous period. At the same time, slope categories on the rotationally-grazed paddocks were reduced from five to four (0-10, 11-20, 21-30 and 31^{o}+) as no significant differences in DMY, or pasture P concentration had been found between the 31-40 and 41^{o}+ slopes.

For the remaining harvests a trim system (Lynch, 1947) was used in both grazing regimes to circumvent the problem of estimating negative growth rates which occurred in autumn and early winter when the dead-matter decomposition rate was faster than pasture growth rate. This new system involved visual assessment of DM cover on twenty-five sites per slope to then derive and select an average cage site. Cages were positioned after pre-trimming and after a regrowth period the pasture was cut to measure DMY, which was taken as the mean of five measurements per slope. Throughout the trial measurements of DMY were made at each grazing for easy- ($11-20^{o}$) and steep-slopes (31^{o}+) and once each season on the other slopes (campsites, and $21-30^{o}$). This was necessary to keep the workload to manageable proportions.

Annual pasture production was measured on easy- and steep-slopes as the accumulated difference per growth period between a post-grazed pasture level and the subsequent pre-grazing pasture level for years one and two, and as the accumulated amount of DM cut at each harvest in year three.

As only one assessment of pasture growth rate was made per season on the campsites and $21-30^{o}$ slopes, a somewhat different method of assessing annual production had to be employed. A graphical interpolation method was used to connect the periods of actual measurement and, at the same time, to preserve relativity with the two slopes that were measured continuously. The annual production was then assessed as the area under this pasture growth rate curve.

Each growth period was four-six weeks, according to season. Consequently, measured DMY underestimated actual growth by the amount of DM that decomposed and disappeared from the sward during the regrowth phase. This underestimation may have varied according to season and is likely to have been largest in autumn when warm, moist conditions would have been conducive to decomposition of the large amounts of dead material present in the sward during summer and autumn (A.G. Gillingham, pers. comm.). In addition, during the first two years of the trial, the technique used for the assessment of post-grazed pasture included the litter which had been severed from the plant during grazing but which had not yet decomposed. This inflated the residual DM figure after each grazing and led to an underestimation of the pasture accumulation during the next growth period.

The methods of assessing pasture growth during years one and two effectively indicated the pasture eaten by stock rather than total production, as they discounted the litter component. In the third year of the trial the technique used would have approximated actual dry matter production more closely, but it was not possible to assess the degree pasture was utilised by animals.

5.2.1.2 **Pasture utilisation**

Pasture utilisation (PU) was assessed on easy- and steep-slopes for each grazing in the first two years of the trial as the difference between pre-grazed DMY and post-grazed DMY expressed as a proportion of the pre-grazed DMY. The amount of DM that grew during the grazing period of two to three days was not included in the calculation which means that, at each grazing "PU" would have been slightly underestimated.

It must be stressed that the method used in the first two years of this study to assess pasture growth rates has, by definition, an associated "PU" of 100% when accumulated over a year. Thus actual "PU" in the normal sense could not be measured. This influenced later interpretation of results (Chapter 8).

5.2.1.3 **Pasture P concentration**

Subsamples of pasture were collected from the pegged or caged areas for each measured pre- and post- grazing period.

Samples were bulked, oven-dried at 65° C and ground to pass through a 2 mm sieve before analysis for P using a modification of the method of Twine and Williams (1971), following a Kjeldahl-type digestion.

5.2.1.4 Faecal dry matter distribution

Weight of faecal DM within a 0.25 m^2 quadrat positioned beside each peg after grazing was assessed by eye and then calibrated to give faecal deposition on each slope (g m^{-2}). The calibration involved eye assessment then drying at 65° C of portions of faecal matter. The calibration procedure was not carried out in the vicinity of soil and pasture measurement sites.

5.2.1.5 Faecal P concentration

Faecal samples for analysis of P concentration were collected directly from pastures at each grazing during the first year of the trial and thereafter once per season, corresponding with pasture collection. Five freshly-voided bulk samples were selected at random from each of the ten experimental paddocks. Samples were not collected from the pegged areas.

Faecal samples were oven-dried at 65° C and ground to pass through a 2 mm sieve before analysis. Total P was measured on a 0.2 g subsample of prepared faeces ignited for 1 h at 550° C and extracted with 100 ml 0.1 M H_2SO_4 for 16 h on an end-over-end shaker (Walker and Adams, 1958). Inorganic P was extracted by the same procedure on a comparable sample of unignited faecal matter and determined colorimetrically in both samples using the method of Murphy and Riley (1962). Organic P was calculated by difference.

5.3 RESULTS AND DISCUSSION

5.3.1 Pasture

5.3.1.1 Dry matter yield

When the data from the five intensively sampled paddocks were averaged over three years, annual pasture DMY was found to increase with increasing rate of fertiliser P addition and decrease with increasing slope (Fig. 5.1). On all slopes, at all rates of fertiliser, approximately 40% of the annual total of DM was produced in spring. Summer DMY exceeded that of autumn which, in turn, exceeded that of winter (Table 5.1). These results corroborate the findings of Gillingham (1980a), Radcliffe (1982) and Lambert et al. (1983) whose work was also carried out in New Zealand hill country.

However, DMY's in the present trial were higher, particularly on campsites, than those recorded by Gillingham (1980a) whose work was also carried out on Whatawhata Hill Country Research Station. Gillingham (1978) made the comment that as climatic conditions were extremely favourable during the one year of his trial, the DMY's achieved should be considered as being higher than average. The higher DMY's achieved in the present trial probably reflect the higher overall nutrient status which in turn, perhaps through improved nutrient cycling, is a reflection of the fact that whereas Gillingham's trial took place on moderately steep hill country, the present trial was carried out on easy hill country.

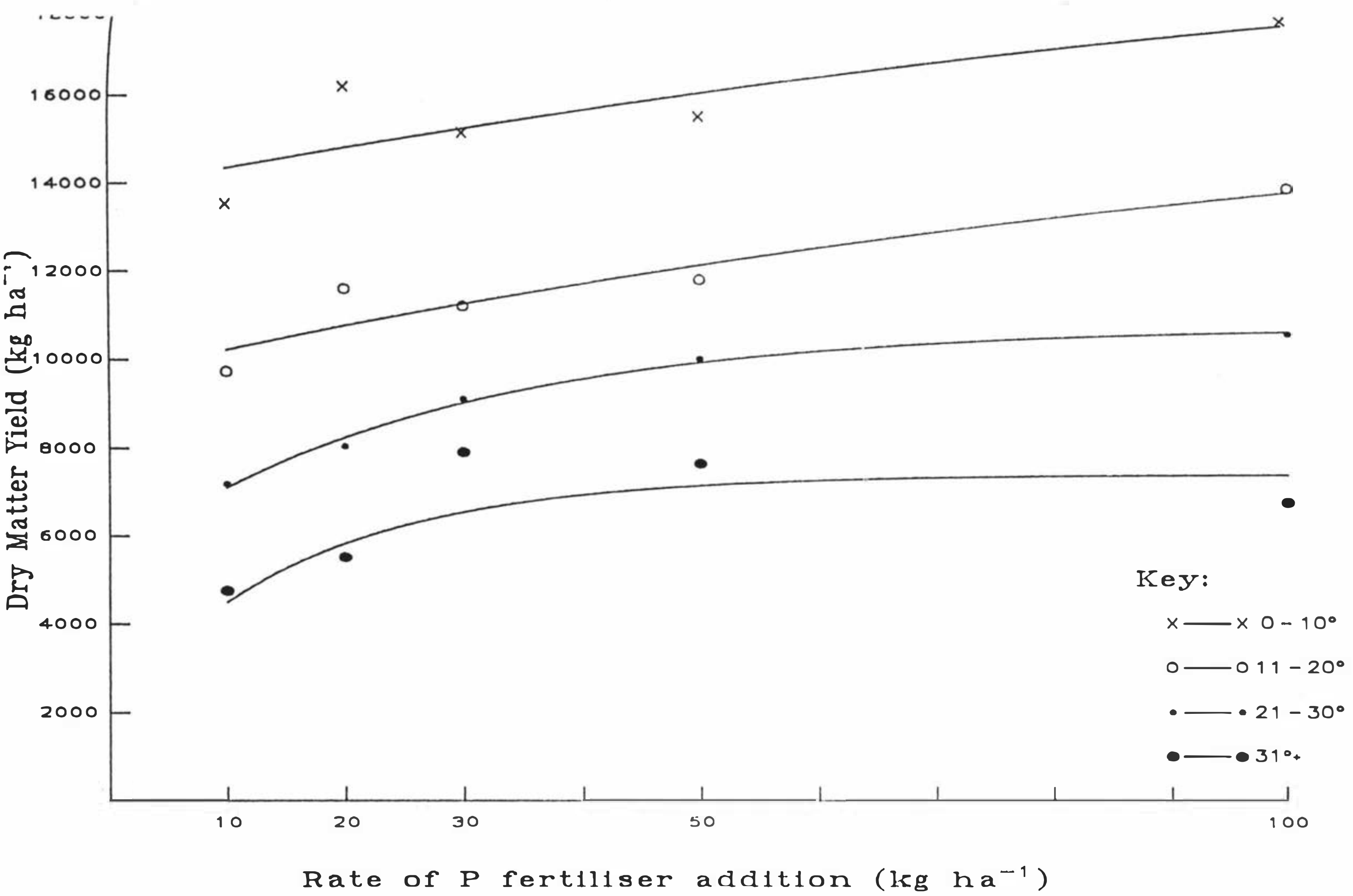


Figure 5.1 Effect of P fertiliser addition and slope on average annual dry matter yield (kg ha^{-1}). Data presented are the averages of three years measurements from the five intensively sampled paddocks.

Table 5.1 Effect of season, rate of P fertiliser addition (kg ha^{-1}) and slope on pasture dry matter yield. Results are presented as the average of three years data.

		Rate of P Fertiliser addition (kg ha^{-1})				
Season	slope	10	20	30	50	100
Winter	$0-10^{\circ}$	1079	878	1062	1069	1427
	$11-20^{\circ}$	820	975	1065	889	1307
	$21-30^{\circ}$	901	754	1054	932	1140
	$31^{\circ+}$	622	370	768	304	619
Spring	$0-10^{\circ}$	5169	6554	5823	6013	6545
	$11-20^{\circ}$	4269	4906	4591	5145	5896
	$21-30^{\circ}$	3176	3467	4132	4171	4169
	$31^{\circ+}$	1991	2345	3094	2978	2833
Summer	$0-10^{\circ}$	4692	5785	5155	5438	6089
	$11-20^{\circ}$	2967	3175	3392	3869	4038
	$21-30^{\circ}$	1897	2311	2601	3166	3149
	$31^{\circ}+$	1238	1410	2739	2382	2037
Autumn	$0-10^{\circ}$	2566	2953	3091	2964	3669
	$11-20^{\circ}$	1666	2524	2134	1870	2582
	$21-30^{\circ}$	1215	1511	1317	1734	2088
	$31^{\circ}+$	901	1261	1213	1542	1016
Annual	$0-10^{\circ}$	13506	16170	15131	15484	17730
	$11-20^{\circ}$	9722	11580	11182	11773	13823
	$21-30^{\circ}$	7189	8043	9104	10003	10546
	$31^{\circ}+$	4752	5515	7907	7640	6751

It is interesting that the DM response curves generated from DMY at five different rates of P fertiliser addition do not level off on campsites and easy-slopes at high rates of fertiliser P addition. On the campsites, which had high initial Olsen P values (>20) and which received large inputs of faecal P in addition to fertiliser, this continuing response is surprising. It can, however, be explained by considering the design of the trial. Unlike normal fertiliser trials in which differential rates of P are applied to adjacent plots of land of similar topography and aspect, in this trial the fertiliser rates were applied to whole paddocks. Slope categories were then identified in each paddock and response curves constructed by comparing production on land of similar slope but in different paddocks. In this trial design production on a given slope may be influenced not only by the rate of P fertiliser addition to that slope but also by production on the rest of the paddock as it influences P and nitrogen return to that slope in faeces and urine. For instance, clover growth on any one slope group was much more vigorous in the paddocks receiving high rates of P fertiliser (A.G. Gillingham pers. comm.) and, in time, this would have lead to increased nitrogen return to the campsites and easy-slopes. It is this increased nitrogen, therefore, which is likely to be responsible for the apparent P responsive nature of campsite areas. From this it is evident that the conventional calibration of Olsen P values (i.e., "low", "medium" or "high") was carried out under lower nitrogen status than existed in this trial at high rates of P fertiliser addition. This may mean that Olsen P should be calibrated for associated nitrogen status. Furthermore, consideration of the effect of slope relationships in a paddock influences interpretation of data from small-scale field trials investigating P response in hill country. The significance of any response in either DMY or P uptake to fertiliser P application may have a much larger influence on paddock productivity than that assessed from the trial site.

A second point of interest concerning the DM response curves (Fig. 5.1) was that in some cases (e.g., the campsite and easy-slope points for the 20 kg ha^{-1} P paddock) the fact that the DMY points were slightly higher than might be expected from trends exhibited in other paddocks can be explained by considering the topography of the paddock. The 20 kg ha^{-1} P paddock had, as discussed in Chapter 3, a very small area of campsites (only 9%) in comparison with other paddocks. Thus, faecal P return was likely to be intense in this area, and there was also likely to be increased spillover of faecal P to adjacent areas. These areas thus receive higher inputs of P than suggested by the fertiliser P rate, and DMY was slightly higher than might be expected.

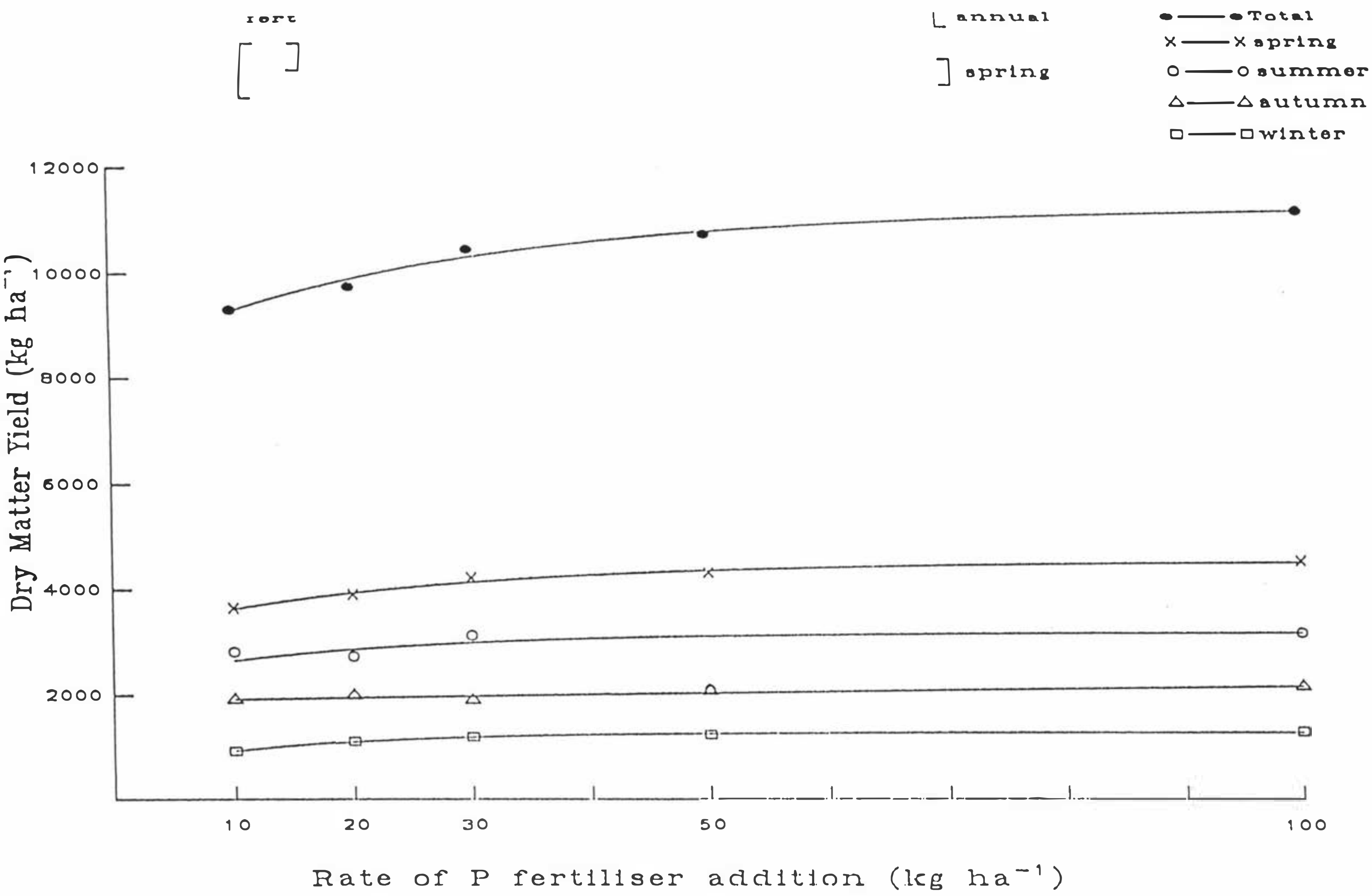
From this it is clear that if fencing is carried out to separate topographically different areas with the aim of stopping P transfer due to stock camping on flat areas, the latter should probably occupy less than about 10% of the paddock. As most easy hill country comprises an inextricable mixture of land in different slope categories, it is unlikely that fencing to stop P transfer could be carried out with effect.

Statistical analysis of DMY data was carried out on individual cuts. Statistical analysis of annual and seasonal data are available only for the final year of the trial and only for easy- and steep-slopes as the other slopes were not monitored continuously.

A pasture DM response to autumn applied fertiliser P was observed in each year of the trial. Analysis of the 1984 data (Fig. 5.2) indicated that this response was statistically significant ($P < 0.05$). The response was largely due to extra growth in late winter and early spring each year. Growth responses in these seasons were statistically significant for each cut in each year of the trial (data not presented).

Pasture DMY was higher on easy-slopes than steep-slopes throughout the trial (Fig. 5.3) and statistical assessment in 1984 indicated that the difference was significant ($P < 0.01$) in all seasons. Differences in DMY between easy- and steep-slopes tended to be less in autumn (when soil moisture was lacking) and in winter (when soil temperatures were low).

There was no consistent effect of grazing regime on DMY in winter and spring during the three years of the trial (Fig. 5.3 a and b). During the first summer of the trial, however, production from continuously-grazed (CG) paddocks was considerably greater than that achieved by rotationally-grazed (RG) paddocks (Fig. 5.3c). This is considered to have been a result of an excessively high grazing pressure on the RG paddocks (A.G. Gillingham pers. comm.). With the onset of dry conditions the over-grazed pasture took a long time to recover. In addition, the harvesting techniques used for the two grazing regimes (Section 5.2.1.1) may have caused some of the difference. In years



Fiugre 5.2 Main effects of P fertiliser addition on seasonal and accumulated annual dry matter yield (kg ha^{-1}) in the final year of the trial (1984). Data presented are the averages of all paddocks and both easy- and steep-slopes.

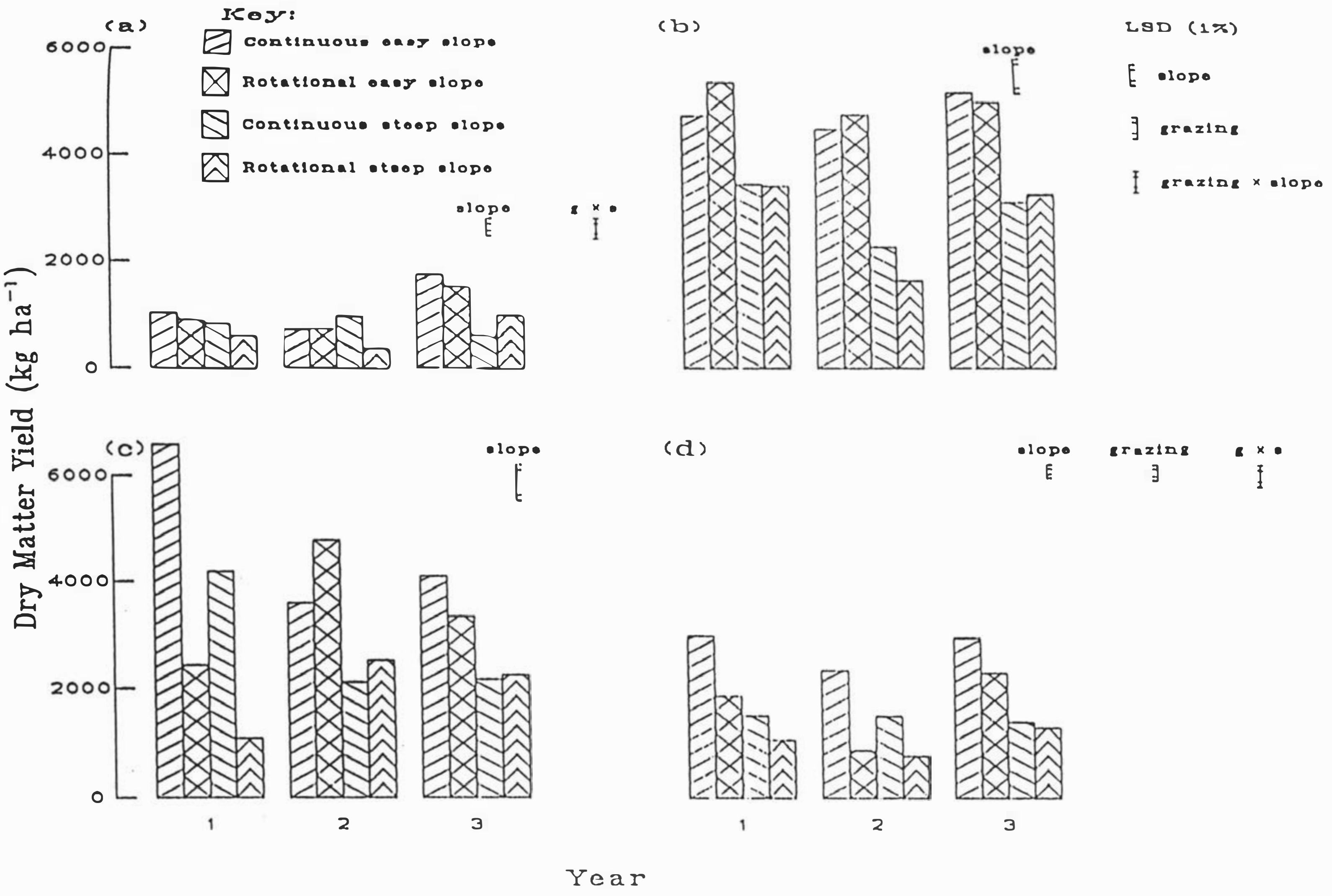


Figure 5.3 Effect of grazing regime and slope on seasonal dry matter yield (kg ha^{-1}) in winter (a) spring (b) summer (c) and autumn (d). Results are expressed as the average dry matter yield from all fertiliser rates within each grazing regime.

two and three of the trial, when RG stocking rates were decreased and the method of assessing DMY was the same for both grazing regimes, production from CG and RG paddocks was similar.

Production from CG paddocks in autumn was consistently higher than from RG paddocks during the three years of the trial (Fig. 5.3d). This may be a reflection of shoot and root growth patterns. In CG paddocks pasture DM was maintained at approximately 2 cm pasture height. The dense, short sward which developed was probably balanced by a shallow root system (Troughton, 1960). In contrast, in RG paddocks the higher, more open pasture was likely to have been balanced by a deeper rooting system. This means that the rooting system in CG paddocks was better placed to take advantage of autumn rain showers than was the rooting system in RG paddocks. Furthermore, as a short dense sward has more 'growing points' than an open sward CG pasture has the potential to grow more quickly, than RG pasture. As soil moisture is the major factor limiting production in late summer and early autumn, the proximity of the rooting system of CG pastures to the surface could explain the higher DMY.

A significant interaction ($P<0.01$) on DMY was noted between grazing regime and slope during winter and autumn in the final year of the trial (Fig. 5.3). In these seasons the difference in DMY between easy- and steep-slopes was greater for CG than RG paddocks. The trend was apparent in autumn in all years of the trial and is likely to be a reflection of relative overgrazing of easy-slopes in RG paddocks in summer, resulting in reduced DMY on those slopes in autumn.

The interaction between grazing and slope in the winter of the final year was not adumbrated by a similar trend in previous years. In contrast to results from autumn, the difference in DMY between CG and RG paddocks was mostly on the steep- rather than easy-slopes. This may reflect preferential grazing of easy- rather than steep-slopes in CG paddocks, which would allow more pasture on steep-slopes than on easy-slopes to enter a reproductive phase in late spring and summer. This would have a carryover effect in winter in comparison with RG paddocks because in the latter, more controlled grazing should have kept pasture in the actively growing vegetative phase.

The relatively small seasonal differences induced little consistent difference in annual DMY between the CG system and the intensively managed RG system. This does not support the findings of Lambourne (1956) and Lambert et al. (1983) who concluded that RG systems resulted in the production of more DM compared with CG systems. It does, however, support the work of Chapman et al. (1983) who found that leaf production on an area basis was similar under both managements as leaf and litter size and leaf extension rates are inversely related to tiller density.

Production during the second year of the trial was less than for years one and three for most seasons, slopes and grazing regimes. Part of the difference between years two and three may be attributed to differences in measurement technique (section 5.2.1.1) but there was probably also an effect due to reduced rainfall in year two, particularly in late spring, in comparison with other years (Appendix II). The fact that steep-slope production was more affected by reduced late spring rainfall than production on easy-slopes (Fig. 5.2b) was probably a reflection of the fact that steep-slopes tend to dry out more rapidly than easy-slopes (i.e., water-holding capacity is lower on steep-slopes than easy-slopes which is a reflection not only of the higher ash component on easy- than steep-slopes but also of the higher organic matter status).

5.3.1.2 **Pasture utilisation**

The proportion of total DMY which is consumed during a year is termed pasture utilisation (PU). In any single grazing event PU may be only 30-40% of the pasture on offer but, as pasture uneaten at one grazing period may be largely consumed at the next, over a year PU may be equal to 90% of grown pasture in an intensively managed system (Scott et al., 1980).

In this trial PU was calculated at each grazing as the difference between the level of pre-grazed pasture and the subsequent post-grazed level on easy- and steep-slopes as discussed in section 5.2.1.2. Although this utilisation at each grazing could be summed over a year to give annual animal intake, no absolute measure of DMY was made (Section 5.2.1.1) and so annual PU could not be calculated. Therefore, PU recorded on only easy- and steep-slopes at each harvest during the first year of the trial is considered.

Pasture utilisation at individual harvests throughout the year ranged from 5% (steep-slope, 10 kg ha^{-1} P paddock in December) to 71% (steep-slope, 100 kg ha^{-1} P paddock in October) (Table 5.2). Except in the October harvest, PU was significantly greater ($P<0.01$) on easy- than on steep-slopes, throughout the year; average PU for each harvest was 58% and 36% on easy- and steep-slopes, respectively. This is likely to be a reflection of standing DM on these two slopes. At most times of the year, DMY on easy-slopes exceeds that on steep-slopes. Given that sheep do not tend to graze below a certain level (e.g., 2 cm height), the potential exists for higher PU on easy-slopes than on steep-slopes. Differences in pasture type on the two slopes also contributes to differences in PU. As discussed earlier in the study of the "below-ground" components of the P cycle (Chapter 3), easy-slopes have a higher soil nutrient status than steep-slopes and support ryegrass-clover swards rather than swards composed of lower fertility species such as browntop, weeds and moss (A.G. Gillingham pers.comm.). Sheep tend to graze more palatable and digestible plants selectively (Meyer et al., 1957) and so are likely to eat grass from easy-slopes in preference to that on steep-slopes.

Pasture utilisation generally increased with increasing rate of fertiliser P addition (partly as a result of increasing standing DM as discussed above) but the effect was significant ($P<0.05$) only at the October harvest during the year. Examination of results shows that the trend of increasing PU with increasing P fertiliser addition was more apparent on the steep- rather than the easy-slopes. This is a reflection of the improvement in pasture species, particularly in clover levels, on steep-slopes at high rates of P addition.

The effect of grazing regime on PU was significant at several times of the year, i.e., November (P<0.01) and September, December and January (P<0.05). On each of these occasions PU for equivalent slopes was higher on CG than RG paddocks. However, PU was very much an artefact of grazing management in that stock were removed from RG paddocks when standing DM on easy-slopes was grazed to a height of approximately 2 cm. More "efficient" PU, on steep-slopes could have been obtained by allowing the stock to graze for longer, but this would probably have been achieved at the expense of overgrazing on easy-slopes. At certain times of the year (e.g., summer) overgrazing could prove extremely detrimental to pasture growth during subsequent weeks.

The significant interaction observed between slope and grazing regime at several harvests is subject to the same *caveats* as for grazing alone. Notwithstanding this problem it is of interest that in June (P<0.01) and January (P<0.05) the interaction was due to poor utilisation on steep-slopes in RG paddocks. This indicates that easy-slopes had been grazed to the pre-determined level of DM before very much grazing had occurred on steeper slopes. As discussed earlier this is a result of differences in standing DM on the two slopes.

Table 5.2 Effect of slope and month of harvest on pasture utilisation (%). Data presented were taken from all paddocks in year one of the trial.

		Rate of P fertiliser addition kg ha^{-1}					x		Stat			
Month of harvest	Slope	10	20	30	50	100	C	R	F	S	G	SxG
June	11-20°	47	52	53	61	58	51	58	NS	**	NS	*
	31-40°	20	29	29	36	33	37	22				
Aug.	11-20°	58	62	59	62	65	60	63	NS	**	NS	NS
	31-40°	47	49	50	50	55	49	51				
Sep.	11-20°	55	51	56	56	56	58	52	NS	**	*	NS
	31-40°	40	40	42	43	40	43	39				
Oct.	11-20°	62	65	62	66	66	69	59	*	NS	NS	**
	31-40°	54	64	62	70	71	57	71				
Nov.	11-20°	49	48	49	46	43	56	38	NS	**	**	NS
	31-40°	18	9	40	28	28	40	16				
Dec.	11-20°	47	59	62	56	61	65	49	NS	**	*	NS
	31-40°	5	37	48	33	36	42	22				
Jan.	11-20°	56	67	69	69	72	69	64	NS	**	*	*
	31-40°	12	21	35	25	30	38	11				
Mar.	11-20°	51	53	51	57	54	61	45	NS	**	NS	**
	31-40°	20	16	28	26	25	14	32				

x = means of treatments; F, fertiliser; C, continuous grazing; R, rotational grazing.
stat = statistical significance of treatments; F, fertiliser; S, slope; G, grazing.
S x G, interaction between slope and grazing.
NS = not significant.
*= $P<0.05$
**= $P<0.01$

5.3.1.3 Pasture P concentration

Increasing the rate of fertiliser P addition generally caused an increase in pasture P concentration (Fig. 5.4; Table 5.3). This effect was not significant in the first year of the trial, although the pasture P concentration in the 100 kg ha^{-1} P paddock did reflect the large input of P in the autumn immediately after the first application of fertiliser (Fig. 5.5a). After three years of differential fertiliser addition the P response in pasture P concentration was significant ($P<0.01$) (Fig. 5.5b).

The seasonal fluctuations in P concentrations were marked throughout the trial and have also been noted by McNaught et al. (1968), McNaught (1970), Saunders and Metson (1971) and Metson and Saunders (1978). The fluctuations in this trial were larger at high rates of fertiliser (Fig. 5.4a) than at low rates (Fig. 5.4c), i.e., the minimum pasture P concentrations were similar in dry seasons, but the maximum values increased with increasing P fertiliser rate in wet seasons.

Overall, P concentrations in summer were approximately half those in late autumn following annual application of P fertiliser in autumn.

Increasing slope within a paddock generally resulted in a decrease in pasture P concentration (Fig. 5.4; Table 5.3), which supports work by Gillingham et al. (1980) on similar hill country. In the present trial, however, pasture P concentrations were considerably lower than those recorded by Gillingham et al., (1980). Gillingham's trial was

Table 5.3 Effect of rate of P fertiliser addition (kg ha^{-1}) and slope on pasture P concentration (%). Results are a production-weighted average of three years data.

slope	Rate of P fertiliser addition kg ha^{-1}				
	10	20	30	50	100
0-10°	0.32	0.31	0.36	0.36	0.39
11-20°	0.28	0.29	0.32	0.33	0.37
21-30°	0.25	0.26	0.29	0.32	0.36
31°+	0.28	0.28	0.27	0.33	0.35

Table 5.4 Main effect of grazing regime on pasture P concentration. Data are presented only for harvests where significant differences in main effect occurred or where there was a significant interaction

Harvest		Pasture P concentration %		Significance		
Year	Month	Continuous	Rotational	G	SxG	FxG
1	August	0.38	0.34	*		
	November	0.34	0.28	**		
	December	0.34	0.29	**		
	March	0.24	0.22		**	
2	September	0.37	0.33	**		
	October	0.35	0.31	*		
	November	0.27	0.31	*		
	March	0.21	0.18	**	*	
3	August	0.42	0.37	**	**	
	September	0.45	0.42			*
	October	0.50	0.48		**	
	January	0.20	0.18	**		
	May	0.39	0.36		**	

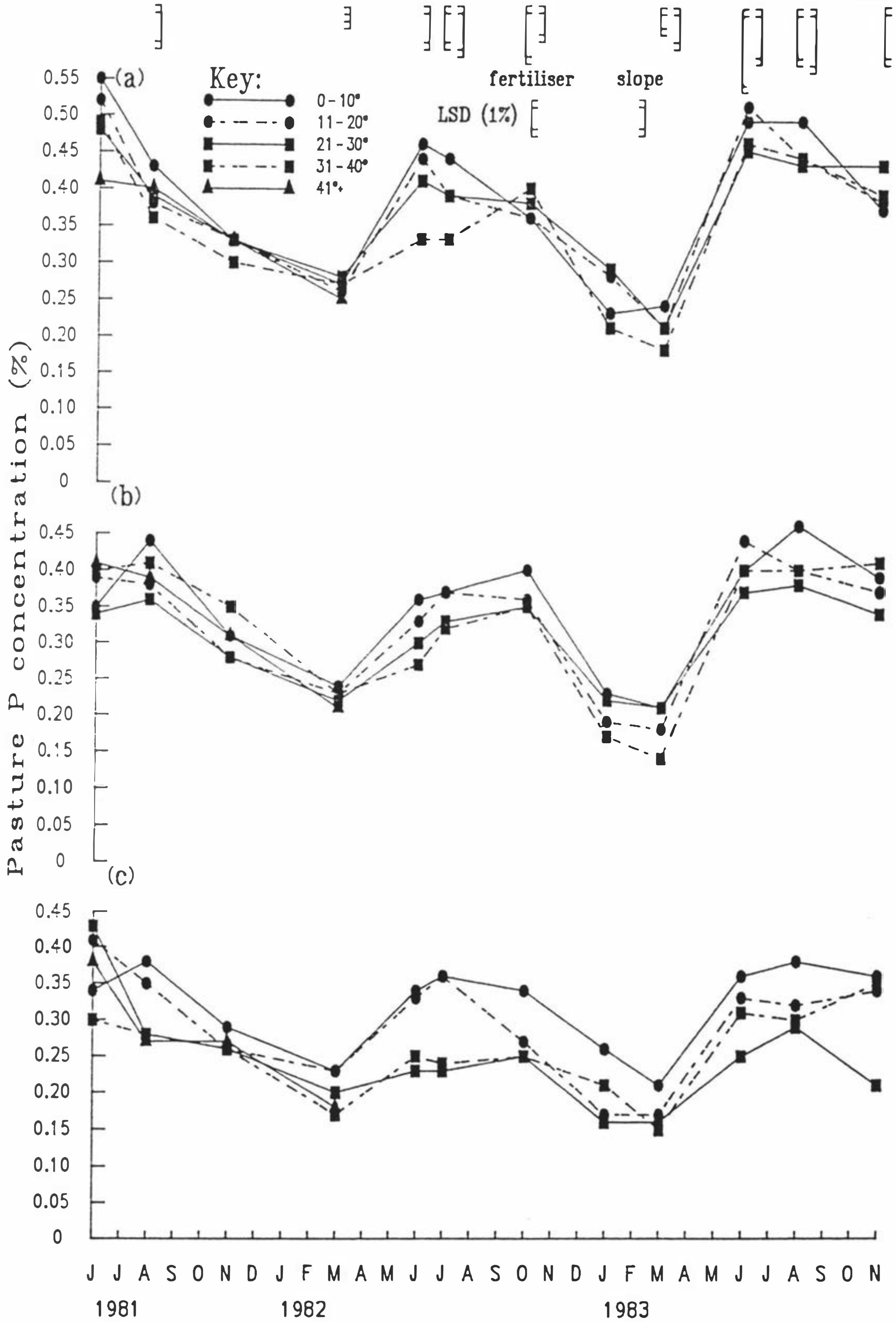


Figure 5.4 Effect of slope and P fertiliser addition on pasture P concentration (%) during the period of the trial; 100 (a) 50 (b) and 10 (c) kg ha^{-1} P fertiliser.

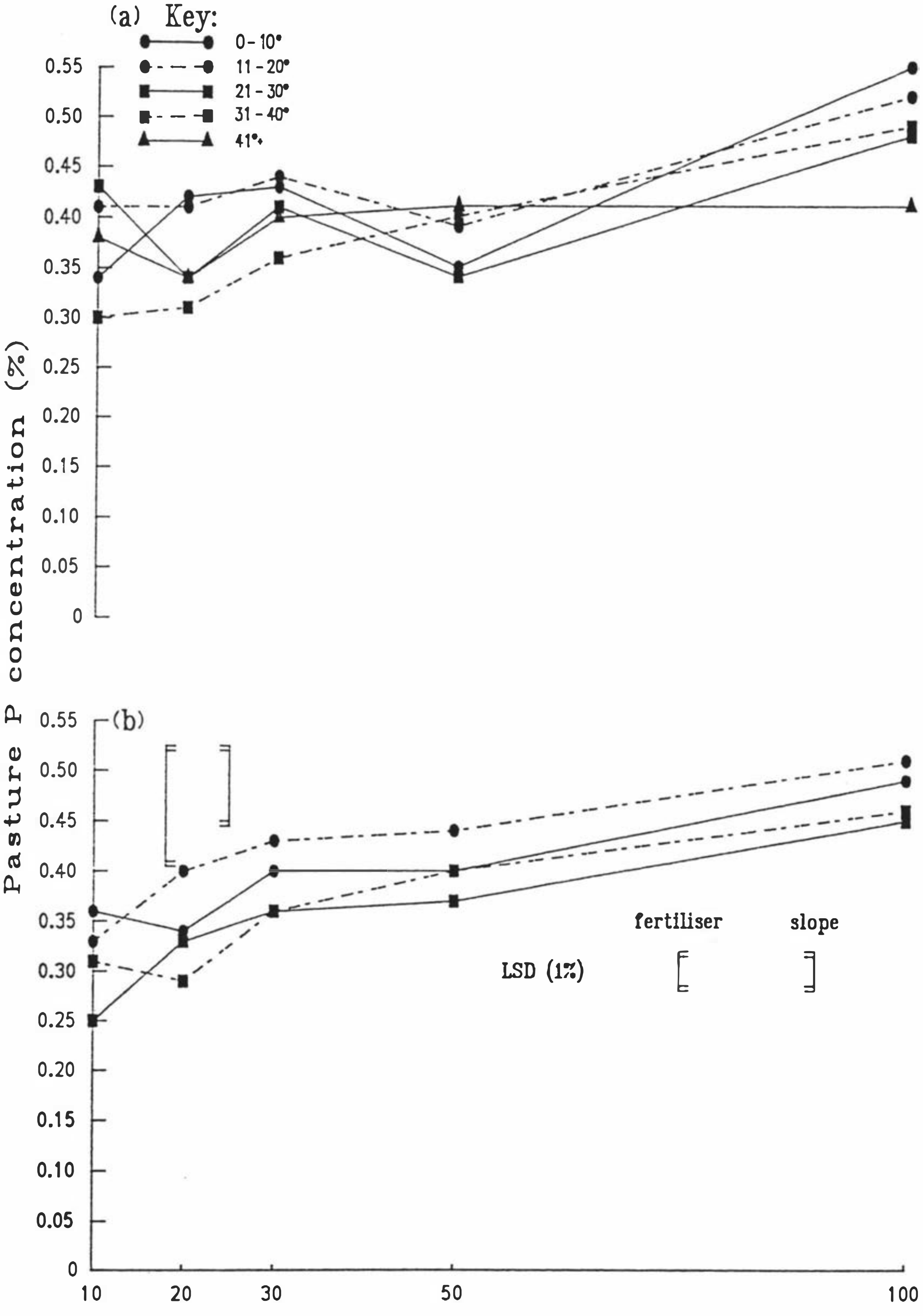


Figure 5.5 Effect of slope and P fertiliser addition on pasture P concentration (%) in June at the beginning (a) and towards the end (b) of the trial.

run under conditions considered to be non-limiting for P (the pasture had been topdressed annually with 315 kg ha^{-1} of single superphosphate). Dry matter yields recorded in his trial were comparatively low (as discussed in section 5.3.1.1) and it appears that "luxury" P uptake was occurring, i.e., more P was available to the plants than was actually necessary for growth. The effect of slope was significant ($P<0.01$) in winter each year of the present trial but was less consistent in other seasons. It was, however, noticeable that the effect of slope was significant in a dry summer (1982), when there was a very low level of P uptake on the steepest slopes, particularly at the lowest level of fertiliser P addition (Fig. 5.4c).

For a given fertiliser P rate, pasture P concentration tended to be slightly higher in the CG paddocks than the RG paddocks (Table 5.4). Differences were usually significant in the main winter and spring cuts occurring each year, and also in March and January after a dry February or December (Appendix II). This may have been a result of repeated defoliation in CG pastures causing more root death than occurred in RG pasture. The increased root death in CG pasture would lead to more rapid P cycling (Evans, 1973; Troughton, 1981) and a resultant more shallow root exploration in a zone of higher P status than deeper soil. This effect was most pronounced at higher rates of P fertiliser addition although on only one occasion was there a significant interaction ($P<0.05$) between fertiliser and grazing. At low rates of P fertiliser addition there was little difference in P status with depth as discussed in Chapter 3.

An interaction between slope and grazing regime (i.e., the difference between RG and CG paddocks was greater on easy- than steep-slopes) was apparent during late winter in the second and third years of the trial and in summer each year (Table 5.4). Removal of more DM from easy- than steep-slopes would mean the root death phenomenon discussed earlier would be exaggerated. In RG paddocks, where sheep are mob-stocked, grazing pressure is such that preferential grazing of one slope category is reduced. The interaction was significant in summer when there was very little DM on steep-slopes to be consumed and in late winter when growth on easy-slopes was both more abundant and more palatable than on steep-slopes (A.G. Gillingham pers. comm.)

The P concentration of post-grazed pasture was significantly ($P<0.01$) related to P concentration of pre-grazed pasture:

$$\text{Post-grazed pasture P\%} = 0.92 \text{ pre-grazed pasture P\%} + 0.02$$

$$r = 0.98^{**}$$

As indicated by the regression coefficient, pre-grazed pasture generally had a higher P concentration than subsequent post-grazed pasture. However, in late summer, when pasture P concentration fell below 0.16% (Fig. 5.6), post-grazed pasture often had a higher P concentration than pre-grazed pasture. This can be explained by considering seasonal growth patterns. In summer months, ungrazed pasture which has accumulated during the spring flush tends to be in a "hayed-off" state. With the majority of the pasture in a mature state, pre-grazed pasture P concentration will also be low. New shoots at the base of the sward or clover plants in a low-growing form

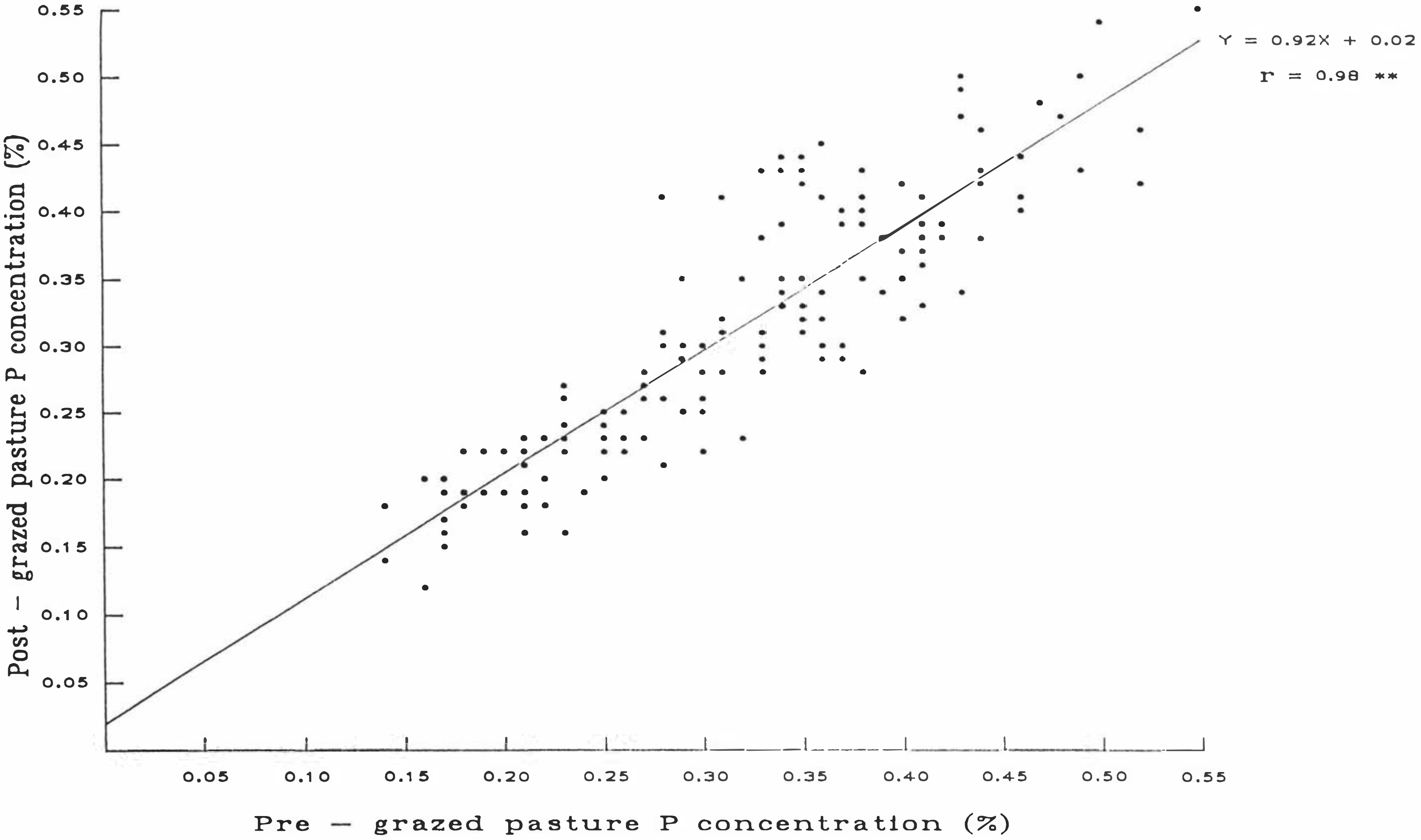


Figure 5.6 Relationship between pre-grazed and post-grazed pasture P concentration (%).

will have a higher P concentration than the rest of the pasture and, after grazing has occurred, will make proportionately greater contribution to the remaining DM concentration. Thus post-grazed pasture is likely to have a higher P concentration than pre-grazed pasture during dry times of the year, e.g., late summer and early autumn.

The significance of the relationship between pasture P concentration pre- and post-grazing in terms of P intake and utilisation by sheep will be discussed in Chapter 8.

5.3.1.4 **Total plant P uptake**

Total plant P uptake (DMY x pasture P concentration) increased with increasing rate of fertiliser P addition and decreased with slope (Fig. 5.7). This is to be expected from the trends in DMY and pasture P concentration discussed in preceding sections.

Seasonal plant P uptake was greatest in spring and least in winter. On all slopes P uptake in summer exceeded that in autumn (Table 5.5). As plant P uptake is governed mostly by DMY (Gillingham et al., 1980) it is possible that in a wet season, summer P uptake could exceed that of spring.

The trends in P uptake found in this trial were similar to those reported by Gillingham et al.,(1980).

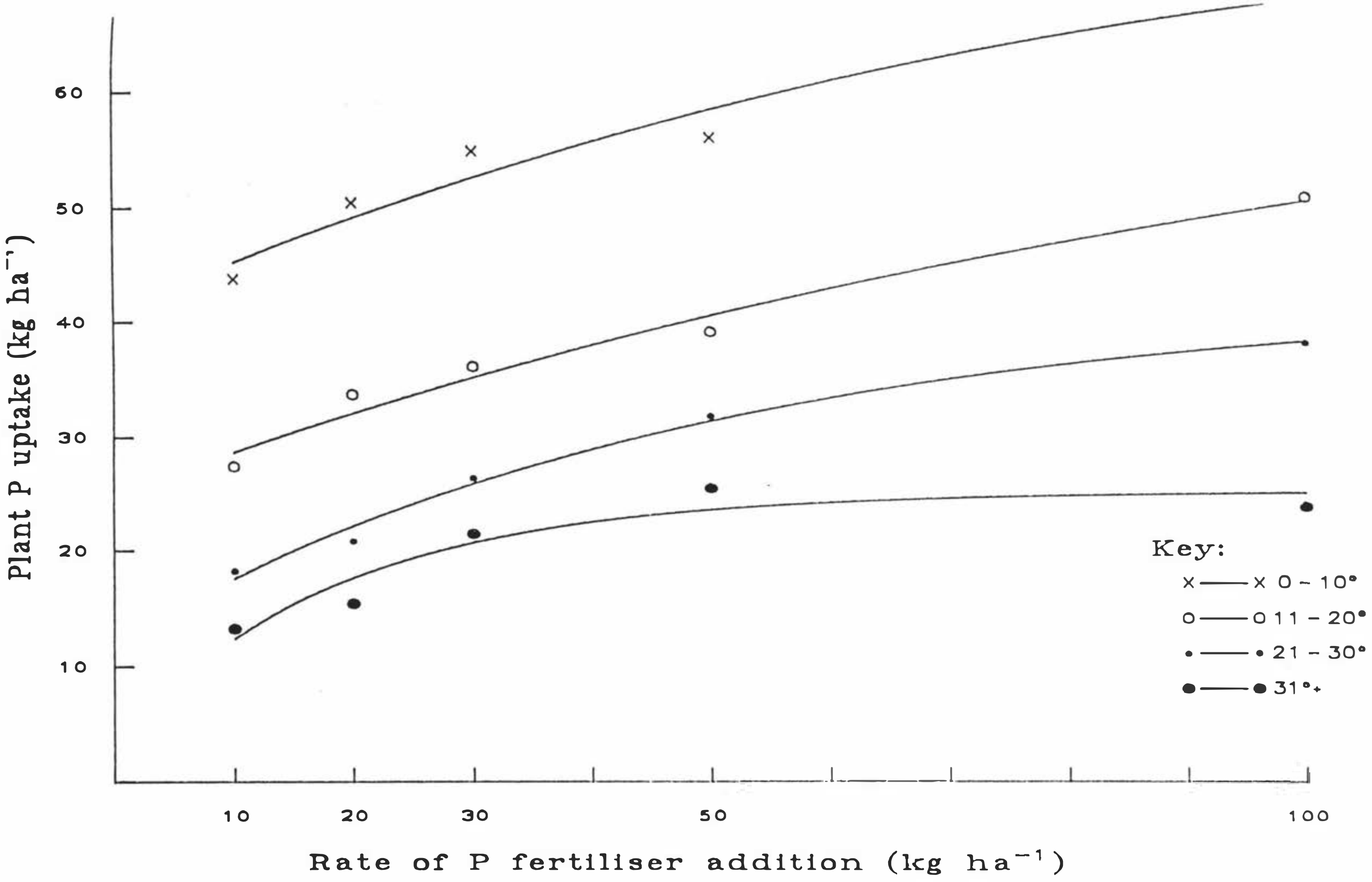


Figure 5.7 Effect of P fertiliser addition and slope on average annual plant P uptake (kg ha^{-1}). Data presented are the averages of two years measurements from the five intensively sampled paddocks.

Table 5.5 Effect of slope and rate of P fertiliser addition (kg ha^{-1}) on seasonal and annual P uptake (kg ha^{-1}). Data presented are the averages of three years results from the five intensively sampled paddocks.

		Rate of P fertiliser addition kg ha^{-1}				
Season	slope	10	20	30	50	100
Winter	0-10°	4.0	3.4	4.3	4.7	6.6
	11-20°	2.8	3.2	3.7	3.4	5.3
	21-30°	2.4	2.2	3.5	3.4	4.7
	31°+	1.8	1.6	2.8	2.8	3.4
Spring	0-10°	18.6	22.8	23.4	25.2	29.3
	11-20°	13.9	16.3	17.4	19.7	24.2
	21-30°	9.3	10.3	10.2	15.0	18.9
	31°+	6.9	7.2	10.1	12.0	11.6
Summer	0-10°	12.9	14.4	15.3	15.3	19.4
	11-20°	6.3	6.8	8.2	9.6	11.6
	21-30°	3.9	4.5	5.9	7.9	9.2
	31°+	2.5	3.3	5.2	5.7	5.3
Autumn	0-10°	8.2	9.8	11.8	10.7	13.4
	11-20°	4.4	7.3	6.7	6.3	9.5
	21-30°	2.5	3.9	3.4	5.5	6.7
	31°+	2.1	3.3	3.3	4.9	3.4
Annual	0-10°	43.7	50.4	54.8	55.9	68.6
	11-20°	27.4	33.6	36.0	39.0	50.6
	21-30°	18.2	20.8	23.0	31.7	39.5
	31°+	13.2	15.4	21.4	25.4	23.7

5.3.2 FAECES

5.3.2.1 Distribution of faeces

A study of the total amount of faecal material deposited on each slope was carried out during the first year of the trial. Subsequently, faecal collections were made at one grazing per season. These measurements of faecal DM distribution were made by MAF research staff and statistical analyses of the results are not available.

Increasing slope resulted in a decrease in deposition of faecal material (Table 5.6). The amount of faeces (kg ha^{-1}) on a slope was reduced by at least half by moving from one slope category to the next in order of increasing steepness. The 20 kg ha^{-1} P paddock had the smallest area of campsites (9%) and easy-slopes (29%) and these areas had the highest rate of faecal DM return. Apart from this, however, there appeared to be no close relationship between faeces deposited on each slope and the area occupied by each slope in the paddock. This lack of relationship is thought, to some extent, to have been an artefact of trial design in that all areas 0-10° in slope were designated campsites. In earlier studies (Hilder and Mottershead, 1963; Gillingham and During, 1973) campsites were found to occupy less than 10% of the paddock. In this trial it is likely that sheep camped within the 0-10° areas and that where the 0-10° slopes formed a large part of the paddock, only a portion was actually used by sheep as campsites. This means that in relatively flat paddocks the

Table 5.6 The effect of slope and area occupied by that slope (as % of total paddock area) on the amount of faecal material (kg ha^{-1}) deposited on each slope in the first year of the trial in the five intensively monitored paddocks.

Slope	Area of slope (%)	Amount of faecal material (kg ha^{-1})	Av faecal for each slope (kg ha^{-1})
0-10°	26	118	
	9	123	
	13	86	
	17	92	
	18	93	102
11-20°	42	36	
	29	42	
	47	35	
	36	38	
	33	48	40
21-30°	16	20	
	33	21	
	29	21	
	28	16	
	25	23	20
31-40°	11	13	
	18	9	
	9	7	
	13	5	
	18	8	8
41°+	5	4	
	11	5	
	2	2	
	6	5	4
	6	3	

measured amount of faecal material returned may not be a true reflection of intensity of deposition on actual campsites.

In this trial approximately 60% of the total faecal material deposited in a paddock was found on flat areas which occupied, on average, 17% of the paddock. This is a less intense return than that recorded by Gillingham (1980a), who found that 88% of the total faecal material was returned to 20% of the paddock and may be a reflection of the fact that paddocks in this trial were generally less steep than those used by Gillingham (1980a). Furthermore, whereas Gillingham (1980a) recorded eight times as much faecal material returned to 25° slopes as 45° slopes, in this trial only five times as much faecal material was returned to $21\text{-}30^{\circ}$ slopes as $41^{\circ}+$ slopes. The significance of the more uniform faecal distribution measured in this trial will be examined more fully in section 5.3.3.

Analysis of the amount of faecal material deposited on a particular slope within each paddock as a percentage of the total amount of faecal material deposited within the paddock revealed a distinct relationship with the area occupied by that slope within the paddock (Fig. 5.8). This relationship was different for each slope. From the relationships generated it is possible to predict the proportion of faecal material (as a percentage of the total deposited in the paddock under consideration) that will fall on any particular slope group from the area the slope occupies within the paddock. With the exception of easy-slopes the variance accounted for by those relationships is quite high ($r^2 = 0.88 - 0.98$).

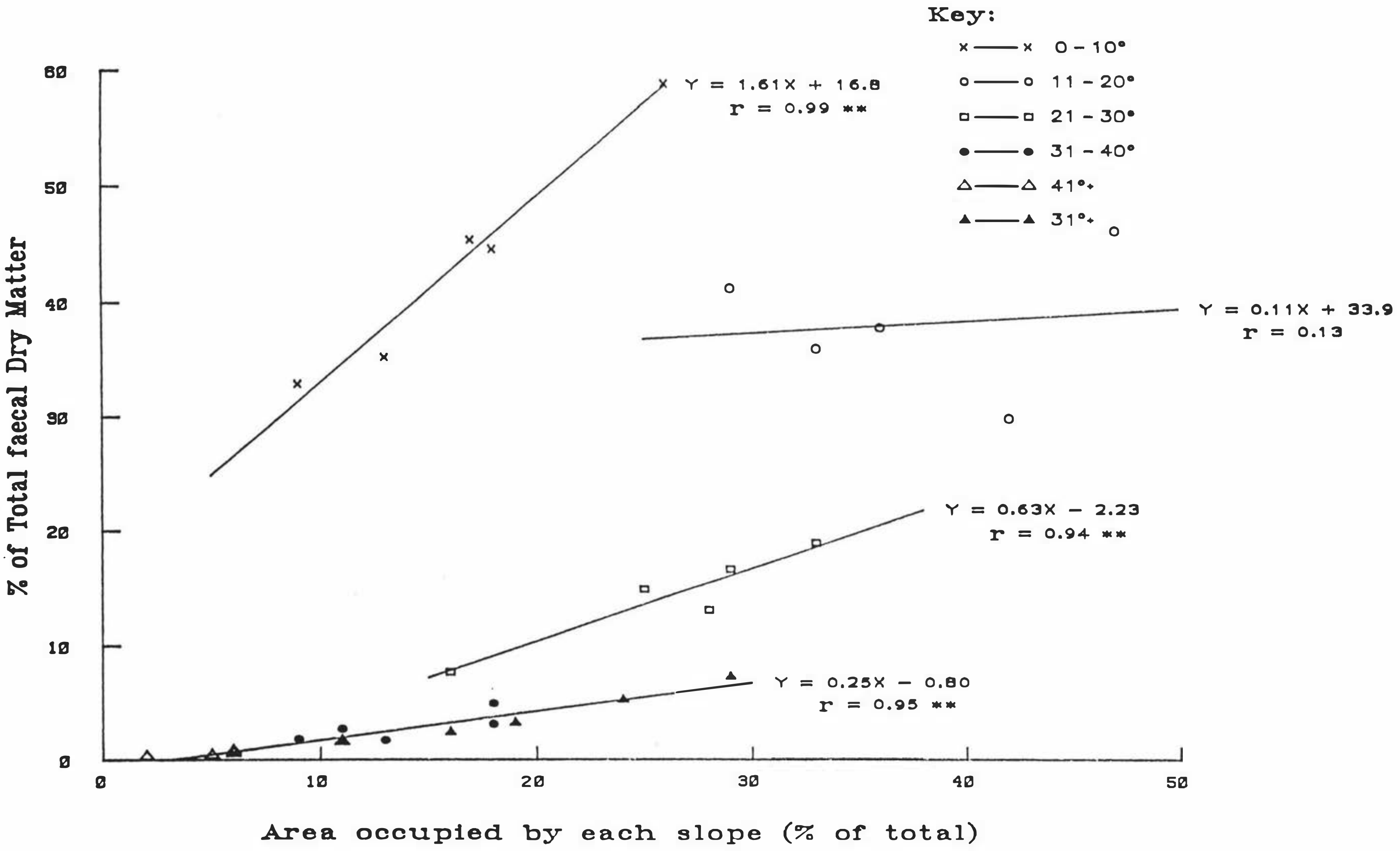


Figure 5.8 Effect of slope on the relationship between faecal dry matter return to each slope as a percentage of the total area occupied by each slope.

5.3.2.2 **Faecal P concentration**

The total P concentration of faeces increased significantly ($P<0.01$) with increasing rate of P fertiliser addition (Fig. 5.9a). Similar trends have been noted by Bromfield (1961), Floate (1970a) and Floate and Torrance (1970) in that faecal material from improved pasture has a higher P content than that collected from unimproved pasture. Seasonal variation in faecal P concentration (Fig. 5.9) reflected the seasonal variation in pasture P concentration (Fig. 5.4). The changes were, however, more marked.

At most harvests faecal P concentration was significantly higher ($P<0.01$) from CG paddocks than RG paddocks (Fig. 5.9b). This reflected the higher pasture P concentrations in CG than RG paddocks.

Faecal inorganic P, as a proportion of total faecal P, increased as the total P content increased, and followed the same annual pattern as total faecal P. Organic faecal P, calculated as the difference between inorganic and total P, did not appear to be affected by fertiliser rate or grazing regime. It did, however, tend to be slightly higher in late winter and early spring than in autumn (Fig. 5.10). Thus changes in total P level occur predominantly as a result of changes in the inorganic P fraction. This finding has also been reported by Bromfield (1961) and Barrow and Lambourne (1962).

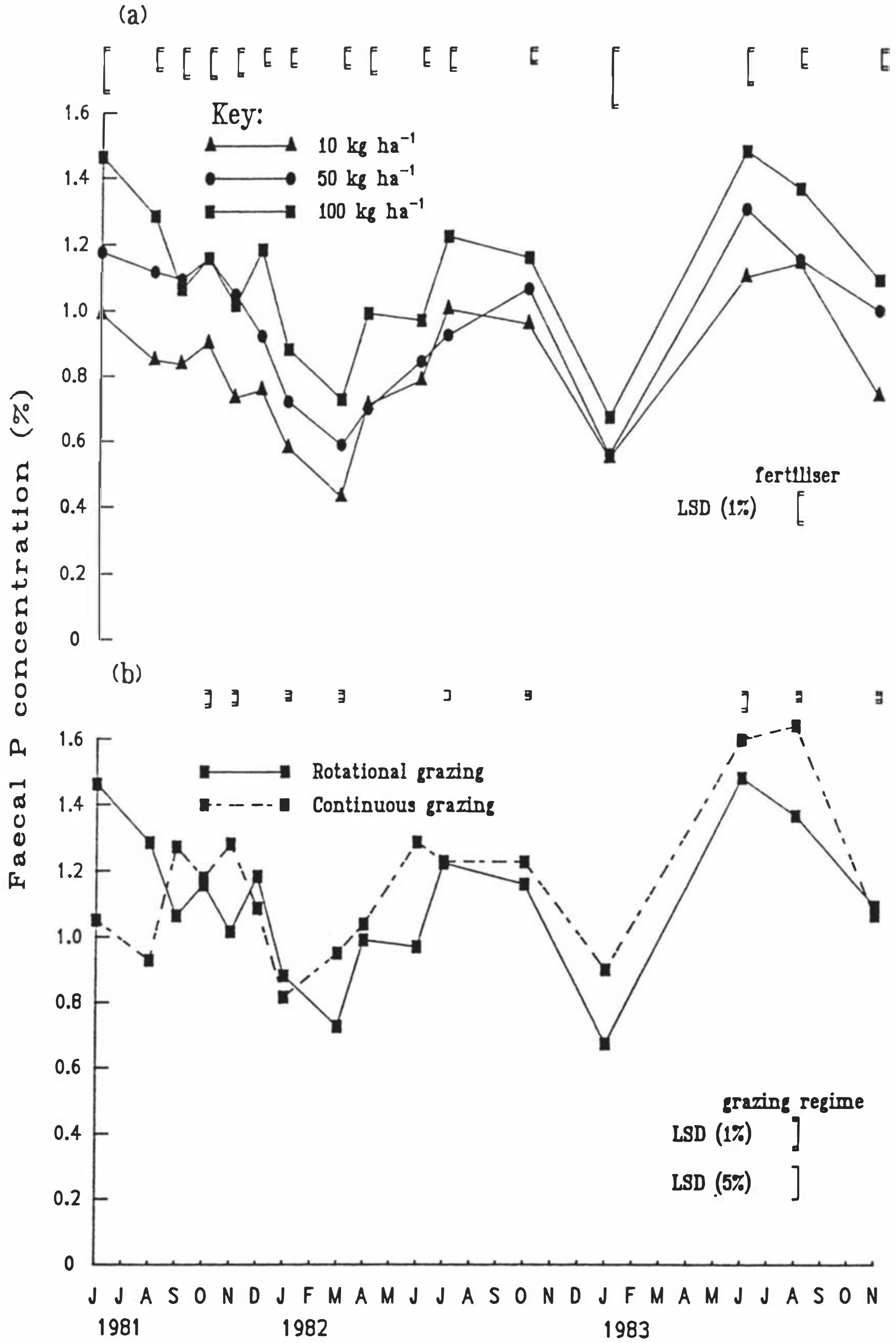


Figure 5.9 Effect of P fertiliser addition (a) and grazing regime (b) on faecal P concentration (%) measured over the period of the trial.

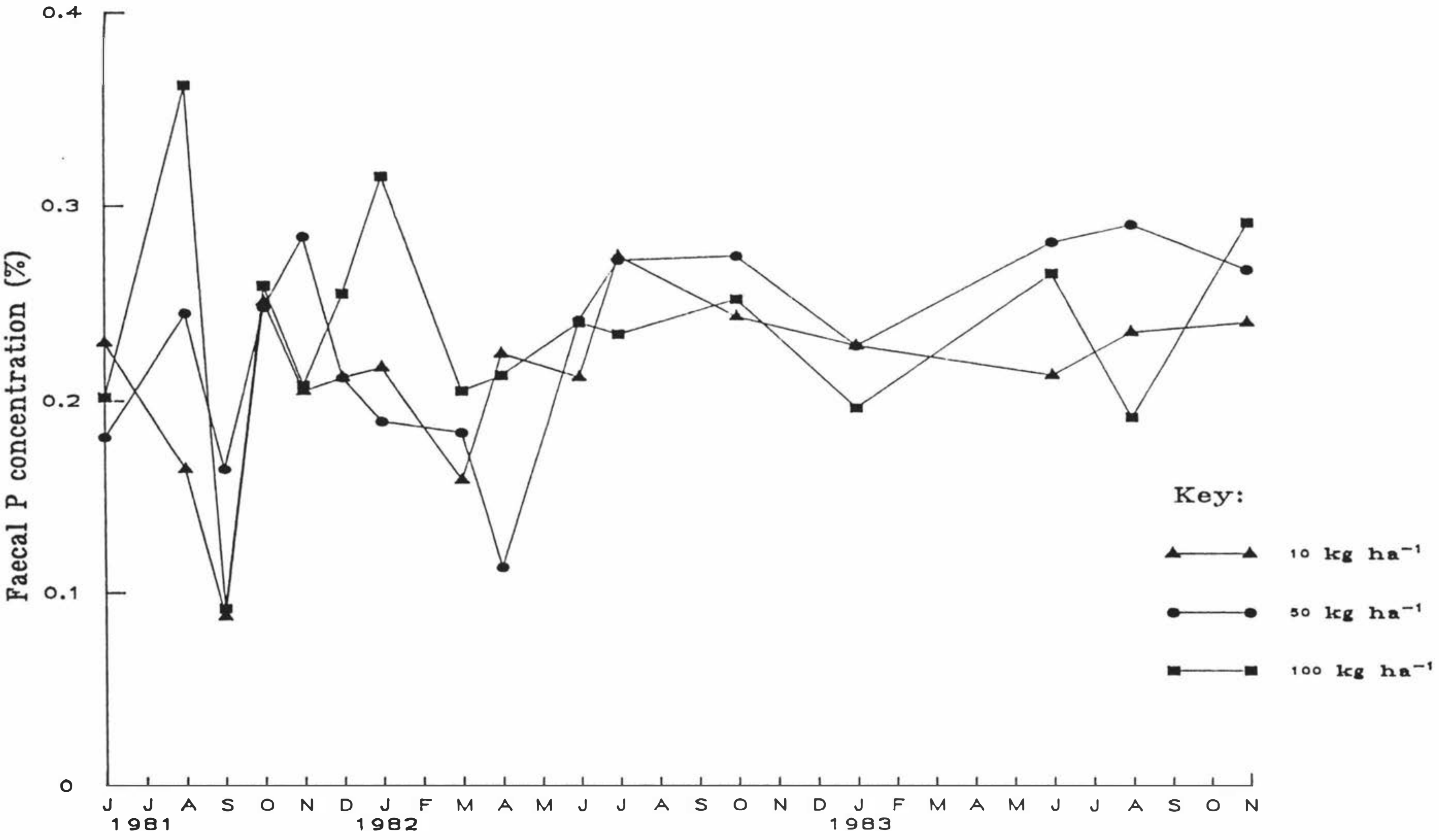


Figure 5.10 Effect of P fertiliser addition on faecal organic P concentration (%) measured over the period of the trial. Results are presented from the rotationally-grazed paddocks.

5.3.2.3 **Faecal P distribution**

Faecal P distribution was calculated from measurements of DM and faecal P concentration. As no statistical analyses, were available for faecal DM distribution (Section 5.3.2.1), no statistical analyses were carried out for faecal P distribution. For each slope, total faecal P return tended to increase with increasing rate of fertiliser P addition (Table 5.7). For each fertiliser rate, total faecal P return decreased with increasing slope. As faecal P concentration was not affected by slope, this decrease was a result of a reduction in faecal deposition on steeper slopes.

On a per paddock basis, measured faecal P return varied from 76% to 106% of plant P uptake (Table 5.8). The average figure of 86% is only slightly less than that of 90% suggested by Karlovsky (1966).

The apparent importing of nutrients at the lowest rate of fertiliser P addition (106% of plant P uptake was returned as faecal P) occurred despite precautions taken in grazing sheep on pre-treatment paddocks and means that effective P addition to that paddock was slightly higher than 10 kg ha^{-1}.

Although on average only 14% of plant P uptake was lost on a per paddock basis, losses for individual slopes (greater than 10^{o}) were much higher and increased with steepness (Table 5.8). This was because return of faecal P was not spread uniformly across the paddock but was concentrated on the flatter campsite areas.

Table 5.7 Effect of rate of fertiliser P addition (kg ha^{-1}) and slope on the annual balance between plant P uptake and faecal P return (kg ha^{-1}). Data presented are averages of three years results from the five intensively sampled paddocks.

		Rate of fertiliser P addition kg ha^{-1}				
Slope	P pool kg ha^{-1}	10	20	30	50	100
0-10°	Plant	43.7	50.4	54.8	55.9	68.7
	Faeces	61.5	73.5	69.0	78.3	94.7
	Surplus	17.8	23.1	14.2	22.4	26.0
11-20°	Plant	27.4	33.6	36.0	39.0	50.6
	Faeces	25.2	28.0	26.0	33.3	43.6
	Deficit	-2.2	-5.6	-10.0	-5.7	-7.0
21-30°	Plant	18.2	20.8	26.3	31.7	37.9
	Faeces	12.4	12.4	14.4	12.7	21.1
	Deficit	-5.8	-8.4	-11.9	-19.0	-16.8
31°+	Plant	13.2	15.4	21.4	25.4	23.7
	Faeces	5.9	5.0	4.4	4.4	7.3
	Deficit	-7.3	-10.4	-17.0	-21.0	-16.4
Whole Paddock (adjusted for topography)	Plant	27.9	25.6	34.0	37.3	44.2
	Faeces	29.5	20.3	25.9	29.7	38.5
	Surplus/ deficit	1.6	-5.3	-8.1	-7.6	-5.7

Table 5.8 Effect of slope and rate of P fertiliser addition (kg ha^{-1}) on faecal P return expressed as a percentage of plant P uptake. Data presented are averages of three years results from the five intensively sampled paddocks.

	Rate of P fertiliser addition (kg ha^{-1})				
Slope	10	20	30	50	100
0-10^{o}	141	146	126	140	138
11-20^{o}	92	83	72	85	86
21-30^{o}	68	59	55	40	55
31^{o} +	45	32	21	17	31
whole paddock (adjusted for topography)	106	79	76	80	87

5.3.2.4 Relationship between faecal P and pasture P concentration

A close, linear relationship was found to exist between the P concentration of faeces and the overall mean pasture P concentrations on offer in each paddock (Fig. 5.11):

$$\text{faecal P concentration} = 3.19\ \text{MPP} - 0.09;\ r = 0.94^{**}$$

where MPP = mean pasture P concentration. The latter was calculated using topographical data (i.e., the % area of each paddock occupied by each slope category; Appendix I), dry matter on offer within each slope category (kg ha^{-1} of DM, Table 5.1), and the pre-grazing P concentration of that pasture (Table 5.3), i.e.,

$$\text{MPP\%} = \frac{(\text{DM}_1 \times \text{P conc}_1\ \% \times \text{area}_1\ \%) + (\text{DM}_2 \times \text{P conc}_2\ \% \times \text{area}_2\ \%) + \ldots}{(\text{DM}_1 \times \text{area}_1\ \%) + (\text{DM}_2 \times \text{area}_2 \%) + \ldots}$$

This relationship does not take into account any effect of differences in levels of PU by sheep, which occurred on contrasting slopes. From discussions in section 5.3.1.2 it is known that PU on steep-slopes tends to be lower than on easy-slopes. This means that the pasture P concentration on steep-slopes, which is generally lower than that on easy-slopes, will make less of a contribution to faecal P than that of easy-slopes. However, the relationship derived assuming PU to be equal on all slopes appears to account for a considerable proportion

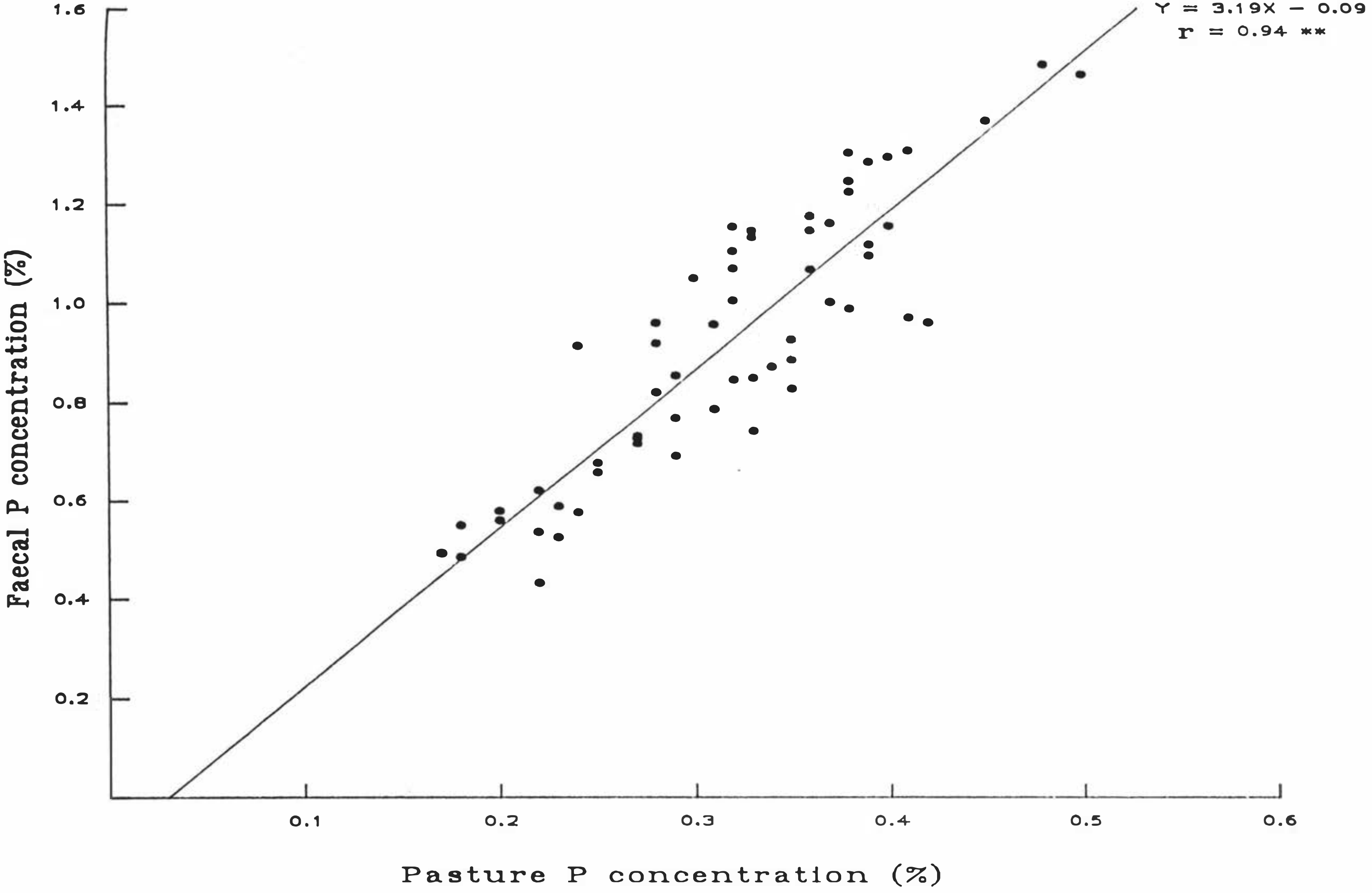


Figure 5.11 Relationship between faecal P concentration (%) and pasture P concentration (%).

of the variation ($r^2 = 0.88$), and as PU's for campsites and 21-30^o slopes were not measured in the trial attempts at refining the relationship are unlikely to improve it.

A second point to consider is that the above relationship does not allow for the fact that in RG pasture, P concentrations of residual post-grazed pasture are generally lower than in pre-grazed pasture, due to the higher proportion of stem and dead material found at the base of the sward (Section 5.3.1.3). This means that the pasture actually ingested by sheep has a slightly higher P concentration than the pasture on offer in each paddock. The true relationship, therefore, probably has a slightly lower slope. However, since the P concentration in pre-grazed pasture is a more easily measured factor the relationship established is of more practical value.

5.3.3 Phosphorus balances

5.3.3.1 Effect of P fertiliser addition and slope on "above-ground" P balances

At a given site the proportion of P taken up in pasture that is returned to that site depends on the degree of PU and the amount of faecal P return. The latter is affected by the degree of retention of ingested P by the grazing animal and by factors affecting the physical distribution of faeces. Barrow and Lambourne (1962) have found that the proportion of ingested P retained by sheep varies according to pasture P concentration. Below a pasture P concentration of approximately 0.22% sheep will excrete more P than they ingest due to endogenous supplementation. Though pasture P concentration can fall below this critical level during summer months, particularly on steep-slopes (Fig. 5.4) on an annual basis pasture P concentrations were above this level even at the lowest rate of P fertiliser addition (Table 5.3). It is thus considered unlikely that stock would be in negative P balance for very long when grazing pasture on New Zealand soils. Thus faecal P return is dependent solely upon factors such as topography and grazing management which affect the distribution of faeces.

In this trial, for a given fertiliser rate, the "shortfall" between plant P uptake and faecal P return (which must be compensated for in a maintenance P situation by addition of fertiliser P) increases with increasing slope (Table 5.7) as was defined by Gillingham et al., (1980) (Table 5.9b).

The shortfall (or surplus on campsites) tends to increase with increasing rate of P fertiliser addition. This is due to the increased stock numbers necessary at higher rates of DM production and also to the higher P concentration in herbage at high rates of P addition.

When faecal P return is expressed as a percentage of plant uptake (Table 5.8) the decrease with slope is still apparent but the fertiliser effect is no longer present. This indicates that P loss

Table 5.9 Effect of slope on faecal P return expressed as a percentage of plant P uptake. Data presented in (a) are the average returns to each slope from all rates of P fertiliser additon (Table 5.8). Data in (b) is recalculated from results presented by Gillingham (1980b).

	slope	Faecal P return (%)
(a)		
	0-10°	138
	11-20°	84
	21-30°	55
	31°+	29
(b)	slope	
	0-15°	244
	25° (15-35°)	39
	45° (35°+)	7

via animal transfer is not a function of rate of P fertiliser addition and so will not be increased by increasing productivity.

The proportion of plant P returned to campsites in this study was somewhat less than that recorded by the one study carried out on similar hill country (Gillingham, 1980a and b; Gillingham et al., 1980). A comparison of figures (Table 5.9) shows that whereas return to campsites was less in this study than that carried out by Gillingham (1980b) the reverse was true for steeper slopes. The range of plant P uptakes in Gillingham's trial was encompassed by that obtained in the present trial. It would seem, therefore, that in the present trial faecal P distribution was more uniform than that measured by Gillingham. The significance of the more uniform faecal P distribution recorded in this trial is that animal transfer losses from steeper slopes to campsites will be reduced. The importance of this will be discussed in detail in Chapter 8.

5.3.4.2 **Effect of P fertiliser addition and slope on "above-" and "below-ground" P balances**

Combining results from the preceding section with those from the study on "below-ground" changes in the P cycle (Chapter 3) it was possible to examine the total effect of slope and fertiliser P addition on the "above-" and "below-ground" components of the P cycle.

The difference between faecal P return and soil and plant P "uptake" was calculated for each slope at each rate of P fertiliser addition. In theory, this "difference" should be equal to the amount of fertiliser P added, thereby providing a simple method for validating analysis techniques used within the trial. In practice it can be seen (Table 5.10) that although on slopes other than campsites the measured deficit did approximate the amount of P added, on campsites results were highly variable. Most of this variation appeared to be occurring in the soil pool. (An internal "check" on the "above-ground" components was provided by the fact that on a per paddock basis faecal P return plus expected losses, balanced the amount of P consumed by the grazing animal). Soil samples were bulked for analysis of total P which meant that it was not possible to estimate field variability in this pool. It was known, however, that field variability in Olsen P was particularly high on campsites (A.G. Gillingham pers. comm.) hence the large number of replicates used in the trial as explained in Section 3.2.3. It can then be inferred that field variability in total P would have been high.

On slopes other than campsites the fact that the annual P deficit in the sum of the "above-" and "below-ground" P pools approximated the appropriate fertiliser P input was taken as an indication that the various sampling and analysis techniques used within the trial did not contain any major systematic errors.

Table 5.10 Effect of slope and rate of P fertiliser addition on the annual shortfall (kg ha^{-1}) in the sum of the "above-" and "below-ground" components of the P cycle. Data presented are annual averages of the results from the five intensively sampled paddocks.

		Rate of P fertiliser addition kg ha^{-1}				
slope	P pool (kg ha^{-1})	10	20	30	50	100
0-10°	Soil	124.8	109.1	54.2	80.5	68.8
	Plant	43.7	50.4	54.8	55.9	68.7
	Faeces	61.5	73.5	69.0	78.3	94.7
	Deficit	-107.0	-86.0	-40.0	-58.1	-42.8
11-20°	Soil	5.9	11.1	15.7	67.4	93.5
	Plant	27.4	33.6	36.0	39.0	50.6
	Faeces	25.2	28.0	26.0	33.3	43.6
	Deficit	-8.1	-16.7	-25.7	-73.1	-102.5
21-30°	Soil (interpolated)	-2.6	14.8	12.3	52.0	77.2
	Plant	18.2	20.8	26.3	31.7	37.9
	Faeces	12.4	12.4	14.4	12.7	21.1
	Deficit	-3.2	-23.2	-24.2	-71.0	-93.9
31°+	Soil	-11.1	18.4	8.9	36.6	58.8
	Plant	13.2	15.4	21.4	25.4	23.7
	Faeces	5.9	5.0	4.4	4.4	7.3
	Deficit	+3.8	-28.8	-25.9	-57.6	-75.2

5.4 CONCLUSIONS

Results of this study on the "above-ground" components of the P cycle in a hill-country grazing system indicate clearly that areas in different slope categories within a paddock may have different P maintenance fertiliser requirements due to differences in P demand (plant P uptake) and P supply (faecal P return). Whether or not fertiliser requirements are different will depend to a great extent on the effect of slope on soil P loss. This will be investigated in Chapter 8.

The disproportionate return of faecal P to campsites means that P is not a limiting factor in these areas. In contrast, insufficient faecal P is returned to steeper slopes to compensate for plant P uptake and removal. This means that these areas are dependent upon fertiliser P input in order to maintain production. The significant transfer of P from steeper slopes to campsites explains, to a great extent the widely recognised fact that in many hill-country pastures, improvement by topdressing can be a slow process (During, 1972).

In maintenance conditions where, as defined by the MAF CFAS model, fertiliser P inputs are made to compensate for losses of P in animal products and the soil, the availability of P in faeces is of importance. The model assumes that a unit of faecal P has the same ultimate value as a unit of fertiliser P; results from the literature vary widely in their indications of the time scale of availability. In this trial the fate of faecal P could be interpreted to some extent in conjunction with results from Chapters 3 and 4.

On campsites, where large amounts of faecal matter were deposited, an increase in soil P_O was measured (section 3.3.6). The increase appeared to be larger at low rates of fertiliser P addition than at high. This is thought to be a reflection of the higher amounts of nitrogen returned via urine at high levels of P addition (as a result of increased stock numbers) and a consequent stimulation of the P cycle resulting in increased mineralisation. Organic P was found to be largely unavailable during the period of the glasshouse study (section 4.3.4.3). This means that at low rates of P fertiliser addition much of the added P became unavailable. At high rates of fertiliser P addition the unavailable pool was tending to increase more on easy-slopes than on campsites, partly because of higher additions of nitrogen to campsites and partly because of more uniform grazing in these paddocks (section 5.3.1.2). From this it can be concluded that in all paddocks transfer of P was occurring via the medium of faeces from an available form on steeper slopes to a less available form on easier slopes. The addition of nitrogen in urine appeared to prevent some of the faecal P immobilisation. Recent work (Ledgard et al., 1987 in press) has revealed an increase in C:N with increasing slope.

From these results it would appear that whether faecal P does or does not have the same "ultimate" value as fertiliser P depends upon where the faecal P was deposited plus the general level of fertility of the paddock. On campsites, where the biological activity is likely to be higher than in the rest of the paddock, the balance between immobilisation and mineralisation appears to depend, at least to some extent, on the return of nitrogen. At high rates of P fertiliser addition, with associated higher nitrogen return to campsites and, possibly, easy-slopes, immobilisation appeared to be reduced in comparison with that occurring at low rates of P fertiliser addition. Thus, more faecal P was remaining in an available form at high rates of P fertiliser addition than at low rates of P fertiliser addition.

On easy- and steep-slopes, the amount of faecal P deposited was considerably less than on campsites, but the increase in organic P recorded in Chapter 3 (Fig 3.9) was only slightly less in many cases. As litter was not measured in this trial, it is not possible to say how much faecal P became available or unavailable. However, if it is assumed that annual PU (%) was approximately uniform throughout the paddock, for which there is some evidence (Gillingham, 1978), then it can be seen that proportionately more faecal P is rendered unavailable with increasing slope. This is likely to be due in part to a decrease in soil moisture with increasing slope, affecting not only faecal breakdown but also mobility of faecal P.

From this it would appear that more faecal P becomes available in the areas where P uptake is high (i.e., campsites) than in areas where P uptake is low (i.e., steep-slopes). However, the time span of the "ultimate" availability of faecal P cannot be determined from this work. In order to validate the CFAS assumption that faecal P and fertiliser P have the same ultimate value detailed studies of the physical and chemical breakdown of faecal material are necessary.

Overall, results from this trial would tend to suggest not only that different slope groups within a paddock may have different fertiliser P requirements but also that true maintenance equilibrium on a paddock scale (a condition required for the maintenance definition of the CFAS model) will be impossible to obtain. The latter is a corollary of the former given that aerial topdressing does not allow for the addition of different rates of fertiliser to small areas within a paddock. The implications of this slope difference in paddocks will be discussed further in Chapter 8.

CHAPTER 6

RELEASE OF P FROM SHEEP FAECES AS AFFECTED BY SLOPE, SEASON AND FORM OF FAECAL MATERIAL

6.1 INTRODUCTION

The return of P to the soil in faeces is, as discussed in section 2.5.1, an important pathway in the P cycle in grazed pasture. Two pieces of information are required before this pathway can be quantified:

(1) How much faecal P is returned to the soil?

(2) How quickly does this faecal material decompose and the P become available for plant uptake?

The first question has been researched in Chapter 5. This chapter addresses the second question.

Studies of the physical breakdown of faeces have been carried out in Britain (White, 1960) and Australia (Bromfield and Jones, 1970; Rixon and Zorin, 1978). Results of the British trials, performed in the Pennines, showed that the faecal material deposited on moorland decomposed less rapidly than that deposited on grassland, and that at each site, samples deposited in summer remained longer than those deposited in winter. Breakdown in summer was attributed almost entirely to earthworm activity, whereas in winter, when animal activity is at a minimum, wind and precipitation were believed to be responsible for removal of 30-50% of the faeces.

In the drier conditions of Australia, Bromfield and Jones (1970) found that a 40% weight loss from faecal samples occurred over the two year period of their trial. Rixon and Zorin (1978) found that after twenty months, 50% of the faecal sample in an irrigated location remained, whereas 54% of the faecal material placed between bushes in saltbush rangeland, and 62% of the material placed under bushes was still present. They concluded that the rate of loss of dry weight from faeces in the dryland location was not greatly influenced by climatic conditions, and that the regular addition of moisture at the irrigated location did not result in a substantial increase in the rate of disappearance of faecal material.

The possibility that chemical decomposition occurs before physical disappearance of the faecal material in the field was investigated by both groups of Australian workers. In sequential leaching experiments, Bromfield (1961) showed that a proportion of total inorganic P could be removed by extensive leaching. Further work by Bromfield and Jones (1970) showed that the total amount of P leached depended on the number of leachings, not the intervening incubation time, and that the amount of P released decreased during successive extractions. A field investigation showed that over two years, total P concentration of faecal samples decreased by 60%. Similarly, Rixon and Zorin (1978) noted a decrease of 50% in the initial P concentration in samples placed under bushes in the saltbush rangeland for twenty months. The decrease was 70 and 80% for faecal samples placed between bushes and on irrigated pasture respectively. There has been little comparable work done in New Zealand.

The trials described in this section were conducted to provide information on the effect of surface area, initial P content, slope and season on the release of P from sheep faeces.

6.2 MATERIALS AND METHODS

The trial site has been described in section 3.2.1.

6.2.1 Winter trial

This study investigated the influence of slope where deposition occurred (campsites (0-10^{O}), easy-slopes (11-20^{O}), or steep-slopes (31-40^{O})), surface area (pads or pellets,) and initial P concentration on physical and chemical decomposition of faecal samples.

Freshly voided faecal pads (low surface area) and pellets (high surface area) were collected directly from pasture on soils of known and varied P content (Table 6.1). The pads and pellets were bulked separately and then subsampled. The initial wet weight of the pellet subsamples was 25 g (7.8 g dry weight for low P samples and 6.4 g dry weight for high P samples) and of the pads was 20 g (4.4 g dry weight for low P samples and 4.2 g dry weight for high P samples).

Table 6.1 Initial total P concentration of faecal samples used in the winter trial.

P content	Pellets ($\mu g\ g^{-1}$)	Pads ($\mu g\ g^{-1}$)
High	10130	11810
Low	6750	8050

Each subsample was sealed in a mesh bag (10 x 15 cm) made from woven polyethylene. The mesh holes (approximately 4 x 3 mm) were sufficiently large to allow access by small insects and soil-incorporating fauna, and ready passage of fragments of faecal material into the underlying soil (Rixon and Zorin, 1978).

The bags were pegged out on each site at the beginning of August 1982, and four replicates of each treatment were collected after each major rainfall event during the six weeks which followed. Sufficient bags were pegged out to allow six collections of pellets and seven of pads. Daily rainfall was recorded nearby. Soil moisture was measured gravimetrically at each collection date (Table 6.2); two bulked samples were taken from within each trial area and the moisture was determined for the 0-3 cm soil depth.

6.2.2 **Summer trial**

This trial was established at the beginning of March 1983. Modifications included increasing the number of replicates at each sampling to six, taking soil samples from beneath the mesh bags, and using faeces of only one P concentration. As breakdown was slower than in winter, sampling was carried out on an increasing elapsed time scale so that at the last collection the material had almost or totally disappeared. The last collection was made one hundred and six days after the start of the trial.

6.2.3 **Phosphorus analysis**

Analysis of total, inorganic and organic P has been described in section 5.2.1.5. Water-extractable P in faecal samples from the summer trial was determined on duplicate 1 g samples subjected to four successive extractions with 40 ml distilled water. The samples were shaken for a total of 6 h (2 x 1 h and 2 x 2 h shaking periods) and were centrifuged and filtered between each successive extraction. Total dissolved P was determined in a sulphuric-perchloric acid digest of the extracts (Environmental Protection Agency, 1971). Dissolved inorganic P was determined directly on the extract, and dissolved organic P was calculated by difference.

6.2.4 **Soils**

In an attempt to follow the movement of dissolved inorganic P from faecal material into the soil during the summer trial, cores were taken at 0-3 cm depth from the soil underlying the mesh bags after their removal. Fifteen soil samples from areas between the bags were taken at the same time and used as controls. The cores were bulked, sieved to pass through a 2 mm mesh, and air-dried. Samples (2 g) of the air-dry soil were shaken in 240 ml distilled water on an end-over-end shaker for 1 h. Dissolved inorganic P was measured colorimetrically using the method of Murphy and Riley (1962).

6.3 RESULTS AND DISCUSSION

6.3.1 Physical decomposition

Under winter conditions, faecal samples underwent rapid physical decomposition. Pellet samples decomposed completely within twenty days (Fig. 6.1), whereas some pad samples remained for approximately thirty days (Fig. 6.2). The rate of disappearance of the samples from the bags varied depended upon:

(1) surface area - i.e., pellets decomposed at a faster rate than pads; and

(2) slope - i.e., samples on campsites disintegrated faster than those on easy-slopes, which in turn disintegrated faster than those on steep-slopes.

Under summer conditions the faecal material persisted for over seventy-five days. Pellets decomposed marginally faster than pads, and material on campsites disappeared at a faster rate than that on the steeper slopes. The differences, particularly between pellets and pads, were less marked than in the winter trial, possibly because persistent rain, cloudy conditions, and high soil moisture during winter prevented the faecal samples from drying out. In their moist state they would have been susceptible to physical breakdown from raindrop impact (consequently the surface area of the sample would be important) and to biological action (faster breakdown on campsites probably reflected the higher biological activity observed in those

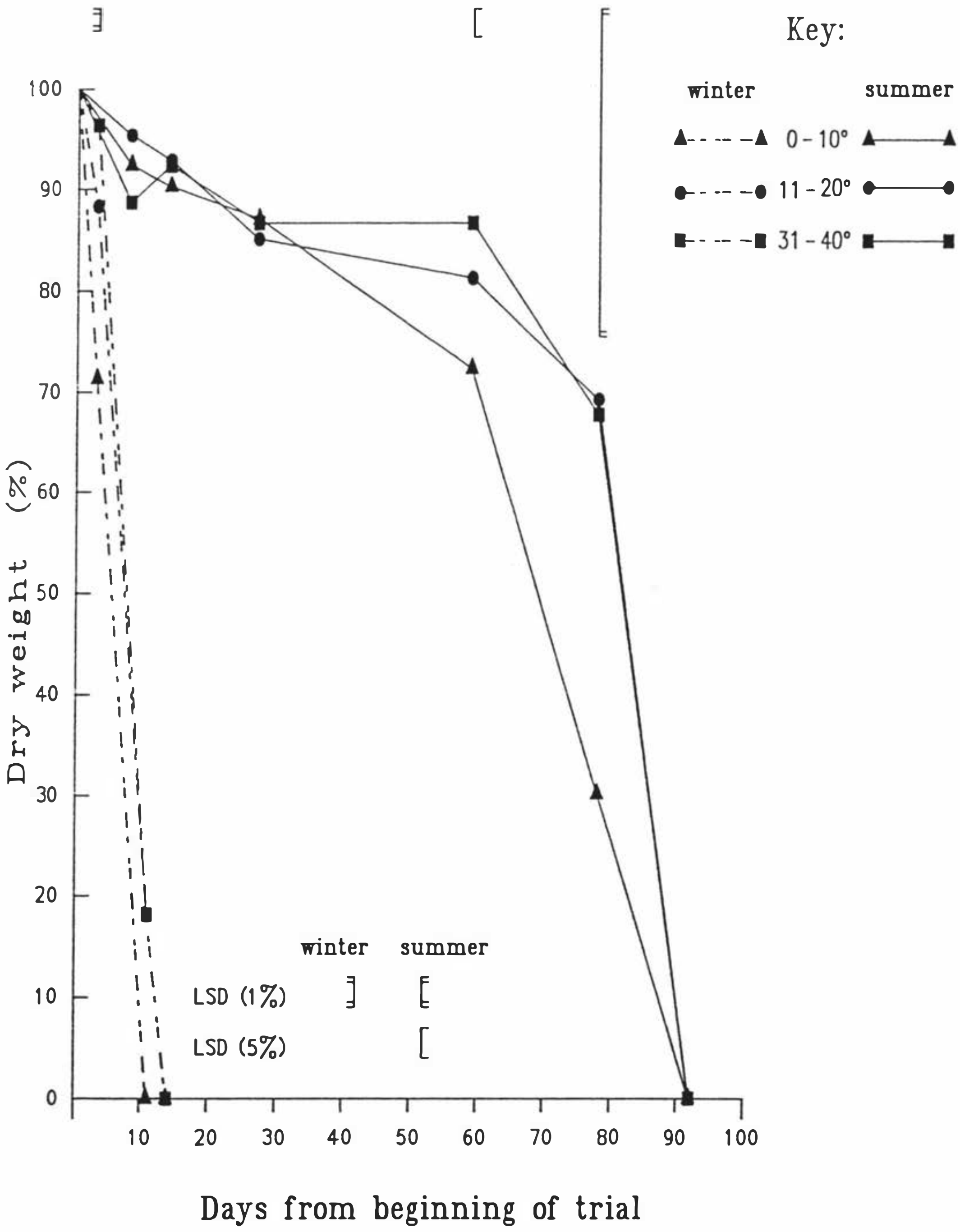


Figure 6.1 Change (%) in dry weight of faecal pellets as a function of time under winter and summer conditions. Values are the means of four and six samples for the winter and summer trial respectively.

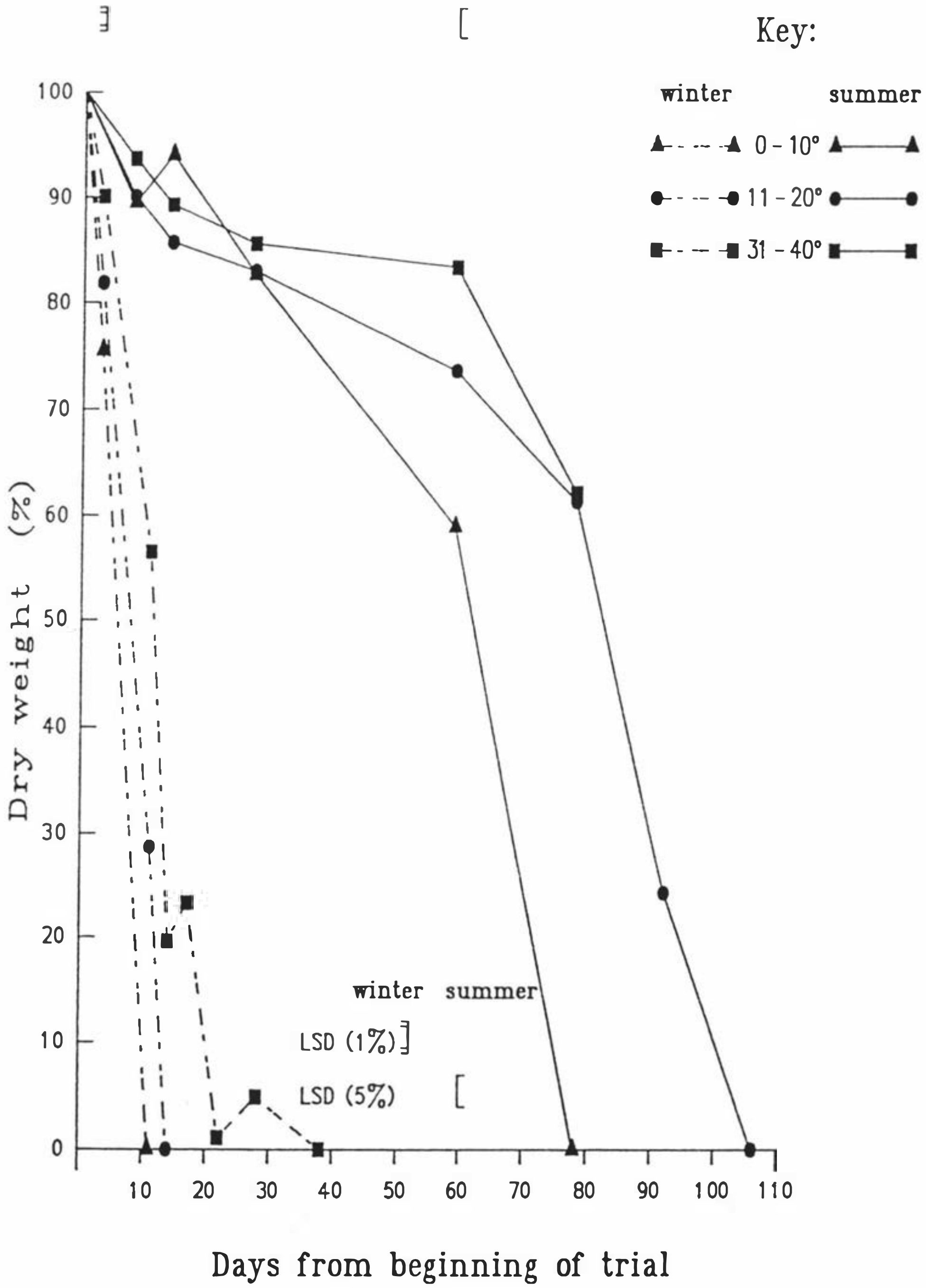


Figure 6.2 Change (%) in dry weight of faecal pads as a function of time under winter and summer conditions. Values are the means of four and six samples for the winter and summer trial, respectively.

areas in comparison with steeper slopes). Total rainfall was higher during the summer trial than the winter trial, but the days with rain were fewer, soil moisture was lower (Table 6.2) and conditions were more conducive to the drying out of the faecal samples.

The apparent increase in soil moisture content in the latter half of the summer trial is a result of the sampling procedure used. Faecal samples and soil cores were collected immediately after heavy rainfall events. As the soil had not had time to drain, the soil moisture content measured at each collection date was higher than at times between collections.

Once the samples had dried they appeared to be more resistant to physical breakdown. This, coupled with lower activity of earthworms under dry conditions (Sharpley and Syers, 1977), was probably of major importance in the slower rate of breakdown of samples during the summer trial. Pad material remained almost twice as long as that in the winter trial, and pellet material three times as long.

6.3.2 **Chemical decomposition**

6.3.2.1 **Total phosphorus**

Faecal samples collected during each trial showed no significant change in total P concentration with time (Fig. 6.3). Thus the decrease in the amount of total P contained in the bag with time (Fig. 6.4) was caused by physical, not chemical decomposition. As data for pads and pellets were similar, pad data are not presented.

Table 6.2 Soil moisture at 0-3 cm depth, measured during faecal sampling. Values given are the means of two replicates.

		Soil moisture (% dry weight)		
		Slope		
Season	Days from initiation	0-10°	11-20°	31-40°
Winter	0	77.1	77.2	47.1
	3	77.3	73.3	51.1
	11	83.5	75.8	48.4
	14	82.3	72.0	42.0
	17	75.4	65.0	37.2
	22	74.5	52.7	31.1
	28	82.3	67.6	38.1
	38	76.4	70.5	33.3
Summer	0	20.4	19.3	13.9
	8	43.1	36.1	26.1
	14	52.4	42.4	28.6
	27	67.8	57.3	42.8
	59	71.2	81.2	44.6
	78	68.5	58.4	38.9
	92	83.4	87.8	45.4

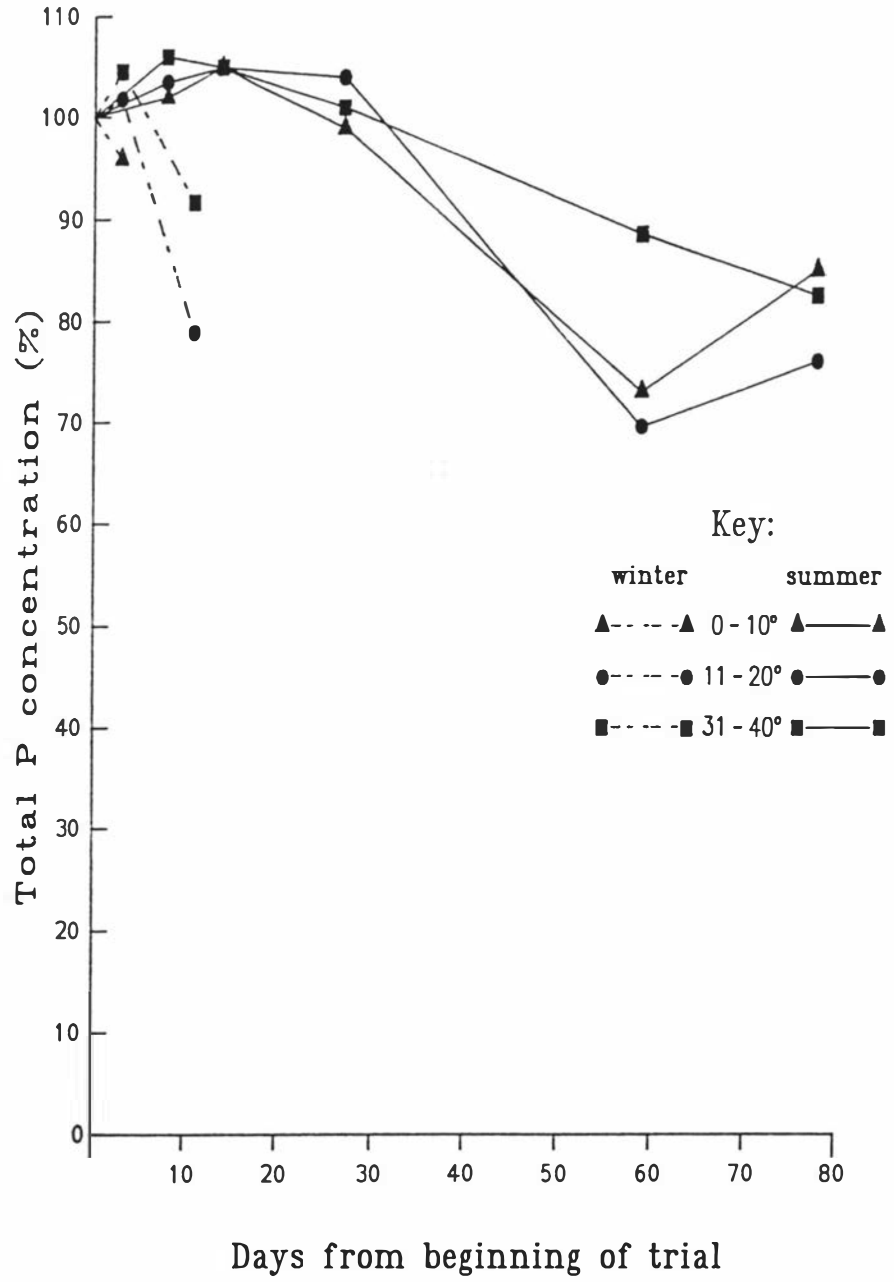


Figure 6.3 Change (%) in total P concentration in faecal pellets as a function of time under winter and summer conditions. Values for the winter trial are the means of four samples; for the summer trial they are the result of six samples bulked.

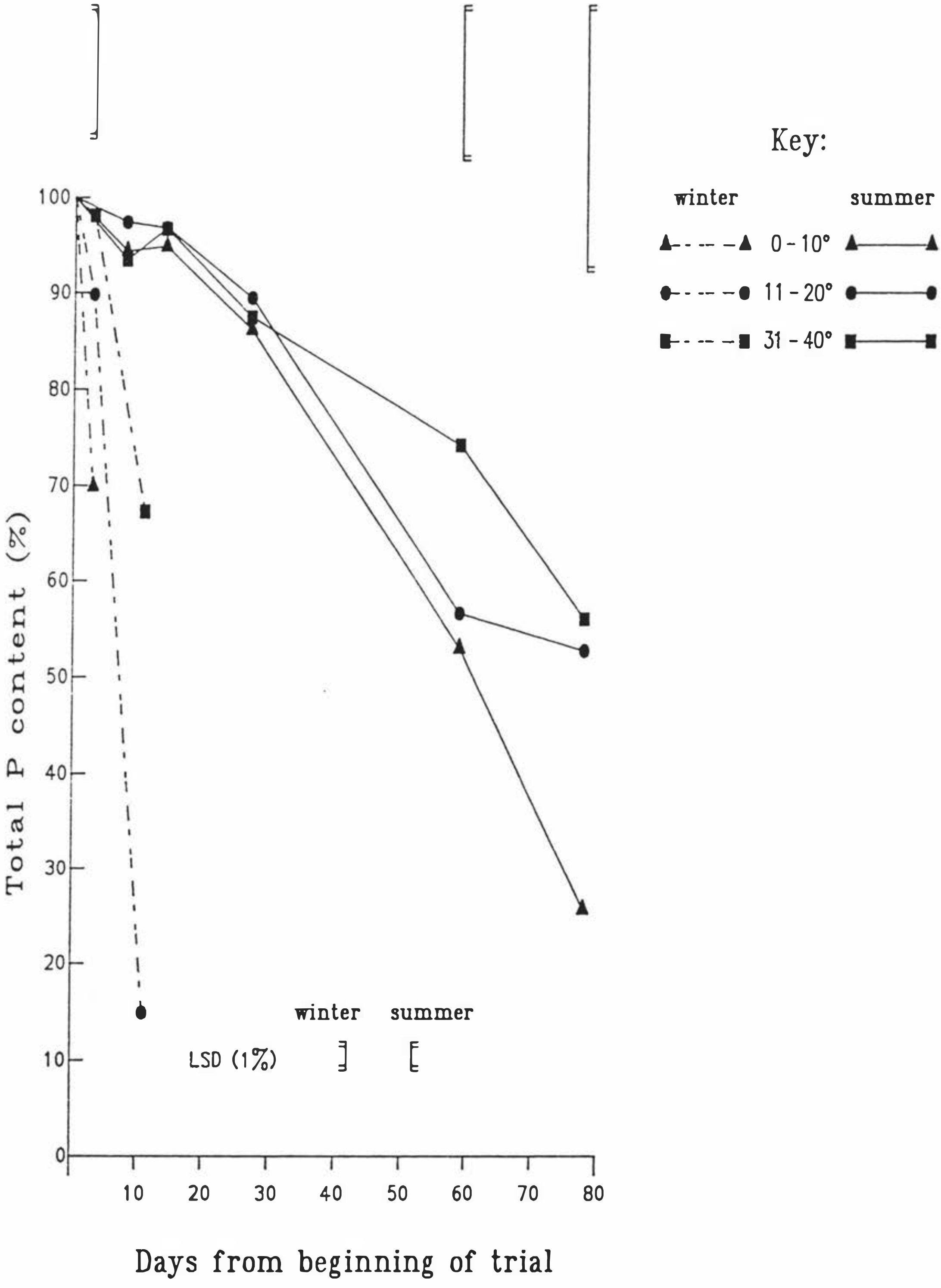


Figure 6.4 Change (%) in total P content of faecal pellets as a function of time under winter and summer conditions. Values for the winter trial are the means of four samples; for the summer trial they are the result of six samples bulked.

These results contradict the findings of Bromfield and Jones (1970) and Rixon and Zorin (1978). However, in the former study, 450 g air-dry samples were used and observed over a two year period during which 1092 mm rain fell. In the latter study, 40 g samples of air-dry, faecal pellets were used and collected over a period of twenty months in an area with an annual rainfall of 335 mm. Thus the sample size was much larger and rainfall was much lower than in the present study, and, most importantly, both studies used air-dry samples.

6.3.2.2 **Sequential extractions of faecal samples**

Considerable dissolved inorganic P was extracted from both pad and pellet faecal material by sequential extraction (Table 6.3). The dissolved inorganic P content of the fourth extraction was appreciable, indicating that further P release was probable if the extraction procedure had been continued.

The cumulative dissolved inorganic P extracted from both pad and pellet samples, expressed as a proportion of the total inorganic P level, was 61% on average. In contrast the amount of dissolved organic P extracted, expressed as a proportion of the total organic P level, was 21% for pads and 10% for pellets (data not presented). The amount of dissolved organic P in the fourth extract was very low, suggesting that much faecal organic P is not water soluble and so resists leaching. This supports the findings of Bromfield and Jones (1970) and Rixon and Zorin (1978).

Table 6.3 Water-extractable P removed by repeated extractions (2 x 1 h and 2 x 2 h) from faecal pellets exposed to the elements for increasing periods during summer. Values given are the means of six replicates.

		Water-extractable P ($\mu g\ g^{-1}$)				
Days from initiation	Slope	Extract 1	Extract 2	Extract 3	Extract 4	Total
0		950	440	350	220	1960
8	0-10°	990	470	360	210	2030
	11-20°	1110	470	380	220	2180
	31-40°	1010	460	370	230	2070
14	0-10°	1280	320	350	220	2170
	11-20°	1090	370	370	240	2070
	31-40°	1120	440	360	240	2160
27	0-10°	1020	340	340	200	1900
	11-20°	1270	310	370	250	2170
	31-40°	1340	310	350	240	2240
59	0-10°	730	260	270	150	1410
	11-20°	690	270	270	160	1390
	31-40°	720	310	340	220	1590
78	0-10°	840	290	250	180	1560
	11-20°	790	270	260	160	1480
	31-40°	830	310	290	180	1610

Although large quantities of inorganic P can be leached from prepared faecal samples under laboratory conditions, there was only a relatively small decrease in the concentration of inorganic P in samples which had been exposed to field conditions for increasing periods of time (Table 6.3). This contrasts with findings of Bromfield and Jones (1970) and Rixon and Zorin (1978).

6.3.3 **Soil analysis**

Analysis of soil collected from under the faecal samples during the summer trial showed no consistent change in water-extractable P concentration with time (Table 6.4). Calculation of P input to the soil from the faecal samples and uptake from the soil by pasture indicated a P surplus of about 80 $\mu g\ g^{-1}$ for pellets and 60 $\mu g\ g^{-1}$ for pads. A surplus of this order should have been detectable if it had remained in a water-extractable form.

In contrast, Rixon and Zorin (1978) reported a rapid increase in the amount of Truog P in the soil under faeces on irrigated pasture, the increase being closely related to the rapid decrease in inorganic P in the faecal samples during the first six months of the trial.

Table 6.4 Water-extractable P removed from soil sampled at a depth of 0-3 cm under bags of sheep faeces at the time of collection of the bags. Values are for single determinations on bulked samples.

		Water-extractable P (μg g^{-1})		
Days from Initiation	Slope	Control	Pellet	Pad
0	0-10°	28.0		
	11-20°	13.9		
	31-40°	19.4		
8	0-10°	36.6	28.2	32.9
	11-20°	20.0	15.0	21.0
	31-40°	23.8	20.5	22.4
14	0-10°	30.6	18.3	23.1
	11-20°	16.9	17.7	19.4
	31-40°	19.1	17.5	25.8
27	0-10°	36.0	40.5	36.2
	11-20°	13.7	18.7	18.9
	31-40°	14.6	15.8	15.6
59	0-10°	34.9	22.1	7.8
	11-20°	23.9	16.7	24.8
	31-40°	13.9	19.2	13.9
78	0-10°	11.8	12.8	11.4
	11-20°	11.5	6.3	8.8
	31-40°	13.8	12.7	11.7
92	0-10°	28.1	22.3	38.6
	11-20°	13.1	17.7	18.6
	31-40°	18.5	24.7	20.0

6.4 CONCLUSIONS

Faeces deposited on hill-country pasture in summer disappeared completely within 106 days; 25 and 13% had gone from campsites and steep-slopes respectively after 58 days. In winter, the average persistence of the samples was 10 days on campsites and 17 days on steep-slopes. These results indicate that the rate of loss of dry weight from faeces is greatly influenced by climatic conditions, presumably by rainfall. Earthworm activity is influenced by soil moisture and soil temperature (Sharpley and Syers, 1977) and this would affect the incorporation of faeces into the soil.

Results of the present study support trends in faecal decomposition observed in the temperate climate of Britain (White, 1960) but are in marked contrast to those recorded in the much drier climate of Australia (Bromfield and Jones, 1970; Rixon and Zorin, 1978). In these reports, faeces were considered to decompose at a linear rate whereas results from this trial indicate that the rate of decay is exponential.

The relatively slow breakdown of faecal material during summer means that there is little input of P from faecal matter. During winter when breakdown is rapid, the plant-available P pool will be supplied with faecal P from the breakdown of recently deposited faeces as well as that deposited in previous seasons. In areas where defaecation occurs frequently, such as campsites, the soil should have a P surplus. The magnitude of the deficit or surplus will vary not only according to season, but also according to slope where deposition is taking place. The P deficit on steep-slopes will be greater than on flatter areas not only because less faecal material is deposited there but also because the rate of decomposition is slower. This will modify interpretation of the estimates of P losses and gains reported by Gillingham et al. (1980).

The fact that physical disintegration of faeces occurs so rapidly under New Zealand conditions suggests that there is little chance for prior chemical decomposition to occur, thus the return of faecal P to the soil is directly related to the physical breakdown of the faecal material.

CHAPTER 7

PLANT UPTAKE OF P AS AFFECTED BY SLOPE, SEASON AND SOURCE OF P

7.1 INTRODUCTION

The contribution of sheep faeces and urine to the maintenance of soil fertility and the yield of high producing pastures has been studied extensively in both New Zealand and Britain.

Under highly intensive grazing conditions, Sears et al. (1948) found that as much as 90% of the phosphorus (P) in pasture was returned in faeces. The rate was high and equivalent to 700 kg ha^{-1} of superphosphate per annum.

Many of the studies by Sears and co-workers (e.g., Sears and Newbold, 1942; Sears et al., 1948; Melville and Sears, 1953; Sears, 1953a, 1953b and 1953c; Sears and Evans, 1953) showed that, under intensive grazing, withholding of faeces and urine from pastures resulted in lower yields and nutrient uptake, and a decline in the amounts of soil nutrients. These workers did not, however, draw any conclusions about the actual contribution to the nutrition of the pasture of the large amount of P being returned in faeces.

In some studies, withholding excreta for up to four years did not decrease yield (Sears and Thurston, 1953; Wheeler, 1958b) nor affect the amount of readily-extractable soil P (Wolton, 1955). This has lead to the conclusion by some workers (Anderson and McLachlan, 1951; Wolton, 1955) that P in faeces is of little immediate value to the pasture.

In order to measure the plant availability of faecal P, compared with that of fertiliser P, several glasshouse studies involving incorporation of the P source with soil have been carried out (McAuliffe et al., 1949, Bromfield, 1961; Gunary, 1968; Batten, 1976). Results showed that the inorganic P fraction in faeces was as available, or nearly as available, as that in superphosphate.

Gunary (1968) investigated the difference in availability of faecal P when incorporated into the soil, as opposed to surface application. He concluded that the usefulness to crops depended on the probability of contact between plant roots and faecal P, and commented that the speed with which contact occurs could be important.

A study of seasonal net P balances in grazed hill-country pastures in New Zealand (Gillingham, 1978) showed that the largest proportion of the net total P losses from slopes occurred in spring and summer. The net total P surplus on campsites accumulated largely during the same period, but was also high in autumn.

These calculations were based on the assumption that the P returned in litter and faeces became available for plant uptake within the season under consideration. If a three month delay in availability was assumed instead, the estimated seasonal net P balances were found to alter considerably. On campsites there was a net P loss in spring, with autumn being the season of largest net P surplus. On 25° slopes, net P losses occurred in spring and summer, but a P surplus occurred in autumn and winter. In contrast, 45° slopes were little affected by the modified calculation.

From the above discussion it can be seen that the rate of turnover of P from faeces to pasture is dependent not only on the rate of incorporation of faecal P into the soil, as discussed in Chapter 6, but also on the rate at which the faecal P becomes available again for plant uptake. How quickly these two processes occur is the subject of much debate. Various attempts have been made at measuring turnover of faecal P with the use of radioactive tracers (McAuliffe et al., 1949; McAuliffe and Bradfield, 1955; Gunary, 1968). Studies have involved labelling P sources such as faecal P and superphosphate P (McAuliffe et al., 1949; McAuliffe and Bradfield, 1955) and labelling the soil (Gunary, 1968). Although the latter is relatively easy to achieve in that uniform physical distribution of radioactive material can be obtained by thorough mixing of soil plus radioactive P source, uniform labelling of faecal P is more difficult. A study by McAuliffe and Peech (1949) revealed that organic P in faeces was difficult to label even when sheep were fed with radioactive $KH_2{}^{32}PO_4$. Labelling was even less successful when faeces were incubated with radioactive $KH_2{}^{32}PO_4$.

Notwithstanding these problems, a major drawback of the aforementioned studies was that they were not carried out under field conditions. In glasshouse studies (McAuliffe et al., 1949; Gunary, 1968), environmental conditions are likely to be optimised for rapid growth of plants and mineralisation of faecal P. Thus results from these trials should not be extrapolated directly to the field. Similarly, though the study by McAuliffe and Bradfield (1955) (which involved cattle manure) was carried out in field conditions, it involved disturbed soil in large containers and, therefore, can not be considered to fully simulate field conditions.

For a field trial, as in a pot experiment, uniform labelling of either the added P source or of soil P is required so that the source of plant P can be identified. Uniform labelling of faecal P is, as discussed earlier, difficult to obtain (McAuliffe and Peech, 1949). It is probable that more uniform labelling of faecal P could be obtained by feeding sheep with uniformly labelled pasture. However, to grow sufficient pasture from seed in a radioactive medium would take a considerable amount of both time and radioactive isotope. Difficulties such as the relatively short half-life of ^{32}P and the high cost of ^{33}P render this technique impractical. Due to the problems associated with non-uniform labelling of faecal P it is generally preferred to label soil P, and so use the inverse isotope dilution technique (Larsen and Sutton, 1963) which has been shown to be superior to other methods (Mekhael et al., 1965). However, this technique involves disturbing the soil profile and although operable for pot trials, does not lend itself to field experiments.

The recent development of an isotope injector (Hedley and Tillman, 1987) overcomes some of these problems as it allows the soil profile to be labelled *in situ* via the spatially uniform injection of radioactive source.

The objective of this trial was to compare plant P uptake from surface applications of two P sources (monocalcium phosphate and sheep faeces) in the field using the technique of inverse isotope dilution. Investigations were also made into the effect on plant P uptake of factors associated with increasing slope (i.e., decreased biological activity and moisture and nutrient status, plus consequent changes in pasture sward composition, all of which result in decreased pasture growth).

7.2 MATERIALS AND METHODS

7.2.1 Trial site

This has been described in section 3.2.1.

7.2.2 Trial design

7.2.2.1 Autumn

This trial was established at the beginning of February 1985. Thirty cylinders, 15 cm in diameter and depth, were hammered into the soil on two slope sites (camp (0-10^{o}) and easy (11-20^{o})). An isotope injector was then used to label fifteen of the soil cores on each slope with ^{32}P.

The injector (Hedley and Tillman, 1987) consisted of a series of fifteen needles located evenly across a metal disc of 15 cm diameter. A template with similarly positioned probes was used to prepare the soil before insertion of the more fragile needles. Slow withdrawal of the needles from the soil was effected using a screw mechanism; as withdrawal occurred, carrier-free ^{32}P was injected into the vacated needle space. The ^{32}P was then free to exchange with soil P. Thus the soil core was labelled with minimum disturbance to the profile. Although this technique resulted in uniform injection of radioactive material on a physical or spatial basis, it is possible that uniform chemical labelling was not achieved, i.e., some P fractions within the soil may have equilibrated more rapidly than others. It was hoped that this problem could be overcome to some extent by allowing an equilibration period (Larsen, 1952).

After one month, the remaining fifteen cores on each slope were injected with ^{32}P. At the same time, 20 g samples of faeces (containing 74 mg inorganic P) were placed on one third of the cores and samples of monocalcium phosphate containing the same amount of inorganic P were placed on another third of the cores.

Injections of isotope were carried out at two times in order to investigate the effect on mineralisation of the presence of fresh faeces. It was thought possible that fresh faeces could enhance (or "prime") the mineralisation of soil organic P. If this had happened, plant uptake from the "original" soil inorganic P pool would have been diluted, leading to false conclusions regarding the availability of faecal P. In the event, conditions were too dry for substantial microbial activity to occur.

Pasture was trimmed from the plots before each injection to encourage new growth and minimise the effect of P already present in the plant. Harvests were taken seven and seventeen weeks after emplacement of P sources.

7.2.2.2 **Spring**

This trial was established at the end of September 1985. Because of lack of time, no equilibration period was included in this study and this enabled the number of cores on each slope to be halved to fifteen.

After injecting ^{32}P into the cores (as described in the preceding section), 30 g samples of faeces each containing 83 mg inorganic P were placed on one third of the cores. Samples of monocalcium phosphate containing the same amount of inorganic P as in faeces, were placed on another third of the cores.

Trimming of the plots prior to injection was not necessary as there had been little regrowth since the last grazing event several weeks earlier. One harvest was taken eight weeks after the trial commenced. This time period was necessary to allow breakdown of faecal material and growth of pasture in what were, initially, poor growing conditions due to moisture limitations (Appendix II).

7.2.3 **Pasture P analysis.**

Pasture samples were dried at 65° C for 24 h, weighed and, after kjeldahl digestion, samples were analysed for P by the method of Twine and Williams (1971).

For scintillation counting, 4 ml aliquots of the digest (which had been diluted to 25 ml) were transferred to vials containing scintillation cocktail (Patterson and Green, 1965). An external standard was used with an automatic quench correction to ensure that all samples exhibited similar counting efficiencies.

7.3 **RESULTS AND DISCUSSION**

7.3.1 **Dry matter**

Within-treatment dry matter (DM) production was highly variable (standard deviations of up to 49% were recorded). This was due in part to the relatively small surface area of the cores (only 176.7 cm^2), and the non-uniform nature of hill-country pasture. It is possible that variability could have been reduced in the second trial by increasing the size of the cores being sampled or by increasing the numbers of replicates. Unfortunately, the former was impossible as the isotope injector was designed for 15 cm cores only, and the latter was not carried out due to lack of time. It was hoped that the improved growing conditions likely to be encountered in spring would result in a more uniform pasture growth. In the event, the reduction in variability was marginal.

During the autumn trial, conditions were very dry (Appendix II), which resulted in very low DM production (Table 7.1a). In general, faeces treated plots yielded more than the fertiliser plots or controls, and campsite plots yielded more than easy-slope plots.

Wet conditions during the latter half of the spring trial resulted in a much higher DM yield (Table 7.1b) than in autumn. Campsite treatments yielded significantly more than easy-slope treatments ($P<0.01$), which is consistent with the results discussed in section 5.3.1. The low yield on the campsites control plots is thought to be a reflection of small plot sizes and experimental error in trial layout. The Olsen P levels for this area were high (approximately 20) and so a response to additional P was unlikely.

7.3.2 **Pasture P concentration**

Pasture P concentrations at harvest one in the autumn trial ranged from 0.22% (control, easy-slopes) to 0.36% (fertiliser treatment, campsite) (Table 7.2). These values are within the normal range for hill-country pasture (Gillingham, 1978; During, 1984). Although there was no significant effect of P source, campsite pasture P concentrations were significantly higher ($P<0.01$) than easy-slope pasture P concentrations.

Table 7.1 Effect of P source (monocalcium phosphate or faeces) and slope (0-10° or 11-20°) on pasture production (g DM) in autumn and spring.

Harvest	Injection	Slope	Treatment		
			Control	Faeces	Fertiliser
(a) Trial 1 (autumn)					
1	1	0-10°	2.7A*	2.2A	1.8A
		11-20°	1.5A	1.8A	1.1A
	2	0-10°	2.0AB	1.9A	2.1AB
		11-20°	1.3AB	1.5B	1.5AB
2	1	0-10°	1.2A	1.8A	1.5A
		11-20°	1.7A	2.0A	1.3A
	2	0-10°	1.7A	2.2A	2.1A
		11-20°	1.7A	2.0A	2.1A
(b) Trial 2 (spring)					
		0-10°	7.5AB	9.2A	9.8A
		11-20°	7.0AB	5.8B	6.4B

* Duncan's lettering (Duncan, 1955). For comparisons within a given harvest and injection, slopes without a common letter (e.g., A or B) are significantly different. Capital letters indicate a significant difference at the 1% level of probability; small letters indicate a significant difference at the 5% level of probability.

Table 7.2 Effect of P source (monocalcium phosphate or faeces) and slope (0-10° and 11-20°) on pasture P concentration (%) in autumn and spring.

Harvest	Injection	Slope	Treatment		
			Control	Faeces	Fertiliser
(a) Trial 1 (autumn)					
1	1	0-10°	0.34A*	0.34A	0.36A
		11-20°	0.25B	0.25B	0.30B
	2	0-10°	0.33A	0.32A	0.34A
		11-20°	0.22B	0.23B	0.28B
2	1	0-10°	0.40A	0.42A	0.48A
		11-20°	0.34B	0.33B	0.37B
	2	0-10°	0.38AL	0.42Ahi	0.45Ai
		11-20°	0.31Bj	0.31Bj	0.38Bk
(b) Trial 2 (spring)					
		0-10°	0.39A	0.37A	0.34A
		11-20°	0.33A	0.36A	0.36A

*Duncan's lettering (Duncan, 1955). For comparisons within a given harvest and injection (1) slopes without a common letter (i.e., A or B) are significantly different (2) treatments without a common letter, (i.e., h, i, j or k) are significantly different. Capital letters indicate a significant difference at the 1% level of probability; small letters indicate a significant difference at the 5% level of probability.

The fact that the control plots were significantly different between the two slopes suggests that there is an inherent difference in pasture species composition on the two slopes, due to differences in moisture and nutrient status. This was visible at the time of harvest in that the easy-slopes had a much higher proportion of weeds and poorer-producing species, such as browntop and yarrow (which tend to have low P concentrations) than the campsite areas. The latter supported a predominantly ryegrass-clover sward which tends to have a high P concentration. Again, this corroborates findings discussed in section 5.3.1.3.

Differences in pasture P concentration for the second harvest were significant for slope ($P<0.01$) and P source ($P<0.05$). On both slopes, the monocalcium phosphate plots had significantly higher P concentrations than the control plots; on the easy-slope, pasture P concentrations on the monocalcium phosphate plots were also significantly higher than on the faecal P plots.

Pasture P concentrations in the spring trial (Table 7.2b) ranged from 0.33 to 0.39% (control plots, campsite and easy-slopes, respectively). There were no obvious trends in the data.

7.3.3 **Pasture P uptake**

Within treatment pasture P uptake was extremely variable in both trials. On the campsite plots, at both harvests and both injection times in the autumn trial, plant P uptake was generally higher than on the faeces and fertiliser treatments than on the control plots

(Table 7.3). This was also true for the second injection on the easy-slope at both harvests. For the first injection on the easy-slope at both harvests, plant P uptake from the faeces plots exceeded that from the control plots which was, in turn, higher than that from the fertiliser plots. Plant P uptake was higher on the campsite plots than on the easy-slope plots. This is consistent with higher production and higher pasture P concentration on campsites than easy-slopes as discussed in Chapter 5.

Plant P uptake was much higher in the second trial than in the first trial. Again, this is consistent with increased dry matter production in spring (section 5.3.1). On the campsite treatments, plant P uptake on the faeces and fertiliser treatments exceeded that of the control plots, as was the case in the first trial. In contrast, on the easy-slopes plant P uptake was highest on the fertiliser treatment and lowest on the faeces treatment.

7.3.4 **Specific activity**

In both trials, specific activity (SA), calculated as ^{32}P counts g^{-1} herbage, divided by herbage ^{31}P concentration was generally higher on easy-slopes than on campsites (Table 7.4). Although these differences were not significant, the trend is a reflection of the higher amount of P found in exchangeable forms on campsites than on steeper slopes. The exception to this trend was seen in the autumn trial at harvest one with the second injection treatment. As there was no equilibration period with this treatment it is possible that in the

Table 7.3 Effect of P source (monocalcium or faeces) and slope ($0-10^{\circ}$ and $11-20^{\circ}$) on plant P uptake (mg) in autumn and spring.

Harvest	Injection	Slope	Treatment		
			Control	Faeces	Fertiliser
(a) Trial 1 (autumn)					
1	1	$0-10^{\circ}$	6.33A*	7.41A	6.25A
		$11-20^{\circ}$	3.99B	4.64B	3.12B
	2	$0-10^{\circ}$	6.52A	8.80A	8.12A
		$11-20^{\circ}$	2.85B	3.43B	4.02B
2	1	$0-10^{\circ}$	4.59A	7.37A	7.18A
		$11-20^{\circ}$	5.82A	6.62A	4.99A
	2	$0-10^{\circ}$	6.54a	9.35a	9.36a
		$11-20^{\circ}$	5.22b	6.25b	7.82b
(b) Trial 2 (spring)					
		$0-10^{\circ}$	28.52A	33.70A	33.25A
		$11-20^{\circ}$	22.63B	22.15B	23.14B

*Duncan's lettering (Duncan, 1955). For comparisons within a given harvest and injection (1) slopes without a common letter (i.e., A or B) are significantly different (2) treatments without a common letter, (i.e., h, i, j or k) are significantly different. Capital letters indicate a significant difference at the 1% level of probability; small letters indicate a significant difference at the 5% level of probability.

Table 7.4 Effect of treatment (monocalcium phosphate and faeces) and slope (0-10° and 11-20°) on specific activity in autumn and spring.

Harvest	Injection	Slope	Treatment		
			Control	Faeces	Fertiliser
(a) Trial 1 (autumn)					
1	1	0-10°	14.4	17.1	12.9
		11-20°	19.4	21.9	14.2
	2	0-10°	42.9	35.3	33.2
		11-20°	33.8	31.9	27.2
2	1	0-10°	2.0hi	2.1h	1.6i
		11-20°	2.7j	2.0k	1.7k
	2	0-10°	6.1	5.4	4.3
		11-20°	6.8	6.3	5.5
(b) Trial 2 (spring)					
		0-10°	130.8A	115.1A	97.2A
		11-20°	272.0Bh	233.03hi	204.1Bi

*Duncan's lettering (Duncan, 1955). For comparisons within a given harvest and injection (1) slopes without a common letter (i.e., A or B) are significantly different (2) treatments without a common letter, (i.e., h, i, j or k) are significantly different. Capital letters indicate a significant difference at the 1% level of probability; small letters indicate a significant difference at the 5% level of probability.

dry conditions experienced at the time of the trial, incomplete equilibration caused rather more ^{32}P to be taken up from the soil pool than would be expected if complete equilibration had occurred.

At both harvests on both slopes for both injections in the first trial, SA was lower for the fertiliser treatment than for the corresponding faeces treatment or control. This indicates that fertiliser P was making a positive contribution to plant P. In the second harvest (first injection) the difference was significant at the 5% level on both slopes. It should be noted that the SA values were very low. Counts were only just above background due to radioactive decay, relatively low plant P uptake, and, possibly, to the fact that the dilution pool was comparatively large. Results were also very variable (+ 35% at the extreme) and conclusions made from the data are therefore tentative.

Specific activities for the second injection at harvest two were higher than for the first injection, but were equally variable. Trends on both slopes suggest that fertiliser P was making a larger contribution to plant P uptake than was faecal P, but that both were having some effect.

Examination of the proportion of P derived from soil, fertiliser, and faecal sources is possible if it is assumed that the P taken up from each control plot was derived entirely from soil P and was representative of the amount of P available on that slope at that harvest. Thus the differences in SA for each slope at each harvest are due to P source, and thus the relative contribution of P from that source can be calculated.

In the autumn trial, on the campsite at harvest one, 18% of the plant P came from faeces and 25% from fertiliser. By harvest two the proportions had changed to 11% from faeces and 30% from fertiliser. On the easy-slope plots contributions were similar for harvests one and two. Faecal P accounted for 6 and 7% of plant P at harvests one and two respectively; fertiliser P accounted for 20 and 19% at harvests one and two respectively. This adds further evidence for the suggestion made earlier that fertiliser P was more available than faecal P during dry autumn conditions. On easy-slopes, where biological activity is minimal during dry periods (Sharpley and Syers, 1977) and faecal decomposition is slow (as discussed in section 6.3.1), faecal P made little contribution to plant P. The decrease in contribution of faecal P with time observed on the campsite treatments was also noticed by Kaila (1950) and Gunary (1968). The latter proposed that the reduction in availability of faecal P was due to the formation of more crystalline phosphates, akin to apatite, from what were initially finally divided calcium phosphates. The presence of calcium phosphates in faeces has been suggested by Barrow (1975).

In the second trial, SA values were much higher than in the first trial (Table 7.4b) due to a much higher uptake of P (and ^{32}P) in the moister, better growing conditions of spring.

Values of SA were significantly higher ($P<0.01$) on easy-slopes than on campsites for all treatments, which confirmed the previous suggestion that the exchangeable soil P pool was smaller on the easy-slopes than on campsites. Treatment trends were obvious in that on each slope the control plots had the highest SA and the fertiliser plots had the lowest. The effect of P source was significant at the 5% level.

The proportions of P derived from faeces and fertiliser were little affected by slope (12 and 14% from faeces on campsite and easy-slope plots, respectively; 26 and 25% from fertiliser on campsite and easy-slope plots, respectively). This was probably because very favourable growing conditions towards the end of the trial resulted in rapid uptake of any P which became available; under these conditions easy-slope treatments were not limited by moisture or nutrient status as was likely in the autumn trial.

As a source of plant P, fertiliser P appeared to be twice as effective as faecal inorganic P in the two month period considered. This difference is probably a reflection of the fact that faecal P dissolution rates were somewhat slower than fertiliser P dissolution rates. This difference in physical dissolution was apparent as some faecal material was recovered from the plots at the end of the trial whereas no fertiliser remnants could be discerned. Gunary (1968) found similar results in that contact with the soil for two months reduced the effectiveness of faecal P from approximately 70% (after one month) to 50% of that of superphosphate. In that study surface applied faeces appeared to be more effective, supplying 85 and 60% of the P taken up by the test crop on two different soils; this represented 20 and 13% respectively, of the total P applied as faeces. In contrast, McAuliffe and Bradfield (1955) found total faecal P to be more available than superphosphate after the first harvest, although they did notice a decrease with time in the proportion of P in the plant which had been derived from added fertiliser. In their trial the proportion of P in the test crop derived from added faeces and superphosphate varied from 15 to 40% in the first harvest and from 9 to 37% in the third, being dependent upon soil as well as past fertiliser application. In all harvests, plant P derived from faeces was higher than that derived from superphosphate, but their results were confounded by the fact that slightly more inorganic P was placed on plots in the form of faeces than in the form of superphosphate.

The results from the present study are consistent with those of McAuliffe and Bradfield (1955) but are in disagreement with those of Gunary (1968). Given that the trial of McAuliffe and Bradfield (1955) involved the incorporation of faecal material into the soil, this is somewhat surprising. However, the trial run by Gunary (1968) was carried out in the glasshouse, where environmental conditions are optimised, and this may have enhanced plant P uptake. Furthermore, under glasshouse conditions, root exploration of the soil is intensive. This would have increased the likelihood of contact with the faeces. Thus the relevance of the trial to field conditions is questionable.

The recovery by plants of applied P in the trial of McAuliffe and Bradfield (1955) was less than 10%. In the glasshouse trial run by Gunary (1968) the recoveries were 20 and 13% according to soil type.

In the autumn trial of the present study the two harvests recovered 1.9 and 0.9% of the inorganic P added as faeces on campsite and easy-slopes, respectively. The recovery from monocalcium phosphate was 5.8 and 2.6% on campsites and easy-slopes, respectively. The lower recovery of P on easy-slopes than on campsites for both P sources is probably a consequence of poorer growing conditions, as already discussed.

In the spring trial 10.5 and 7.0% of the fertiliser P on campsites and easy-slopes, respectively, was recovered in one harvest. The recovery of the inorganic P added as faeces was 4.8 and 3.5% on campsites and easy-slopes, respectively. However, not all of the faecal material added had decomposed (dry conditions at the beginning of the trial meant that the faeces dried out and became more resistant to physical processes of decomposition as discussed in section 6.3.1). If the total inorganic P which had been washed into the soil is considered, then the percentage recovery of faecal P was 5.4 and 4.5% on campsites and easy-slopes, respectively, which is just over half that recovered from monocalcium phosphate. Again, the recoveries agree better with the results of McAuliffe and Bradfield (1955) than with those of Gunary (1968).

7.4 **CONCLUSIONS**

During the relatively short time span of the two field experiments, inorganic P in fertiliser appeared to be approximately twice as effective as inorganic P in faeces as a source of P for pasture. Unfortunately, due to lack of growth in the first trial and lack of time in the second it was not possible to continue harvesting over sufficient time to determine whether faecal P was becoming more or less available than fertiliser P. However, by combining results from this study with those from the study of the physical and chemical decomposition of faecal material (Chapter 6) it was possible to draw some conclusions on the likely availability of faecal P in hill country.

Fresh faecal material disintegrates very rapidly in wet weather (section 6.3.1). Any dissolved inorganic P washed into the soil should have a high availability (Gunary, 1968) and, as indicated by results from the present study, will supply P for pasture growth. Faecal material disintegrates faster on campsites than on steeper slopes (section 6.3.1) and, consequently, faecal P is more available for plant P uptake on campsites than on steeper slopes (section 7.3.3). Thus faecal P has the highest availability on the area where P uptake is highest due to the presence of fast growing, high P-demanding species such as ryegrass and clover.

In drier weather (or on steeper slopes) the breakdown of faecal material is slower and there is a decrease in the availability of faecal P. Thus it is unlikely that the P in faeces deposited during the dry summer and early autumn months will be utilised in the short term.

It would seem that faecal P is most available during late winter and spring when, in New Zealand, pasture growth rate is high and faecal production and faecal P concentrations (section 5.3.2) are at a maximum. Conversely, faecal P is least available during dry summer and early autumn months when pasture growth rate is low and faecal P concentration is at a minimum.

Given that steeper slopes are generally drier and support poorer quality pasture than campsites, this study provides further evidence to support the proposal made earlier (section 5.4) that the rate of P cycling is more rapid on campsites than it is on steeper slopes. The results also indicate that the attempt to calculate net P balances by Gillingham (1978) was an oversimplification as the basic proposition that returns will become available either within the season or after a delay of three months is not valid. In the field both situations can occur.

Results from the studies discussed in Chapters 6 and 7 indicate that faecal P deposited in spring will probably be available within the season. In contrast, faecal material deposited in summer and early autumn is unlikely to undergo physical decomposition before late autumn, when temperatures will be sufficiently low to encourage net immobilisation rather than mineralisation of P.

Using this information, the data of Gillingham (1978) can be recalculated. The result is a P deficit on all slopes (including campsites) during summer, autumn and winter, ranging from 2.5 to 12 kg ha^{-1} of P. In spring there is a large surplus of P in campsites, a zero balance on easy-slopes and a small deficit (3.8 kg ha^{-1} of P) on steep-slopes.

This information supports the limited amount of field trial evidence (Saunders et al., 1963) that autumn applications of superphosphate are likely to generate more of a relative DM response than are spring applications. In spring there is a release of P (due to microbial activity) which can, except on steep-slopes, supply plant requirements.

CHAPTER 8

PARAMETER VALIDATION OF THE CFAS MODEL

8.1 INTRODUCTION

As discussed in Chapters 1 and 2 a pre-requisite for creating efficient use of fertiliser in an agricultural system is a knowledge of the processes and interactions occurring within that system. In the past, two distinct approaches have been taken in studying nutrient cycling in agricultural systems. In the first, results of detailed studies of parts of the chosen system, often studied under controlled conditions (sections 2.2 - 2.7) are combined to build up a picture of the complete system. Blair et al. (1977), provide an example of this approach whereby information available in the literature has been collated to create a complete picture of the P cycle under grazed pasture. The second approach is to examine a whole system in terms of fertiliser input and product output relationships (section 2.8), i.e., it is a balance sheet approach studying net gains or losses. The Computerised Fertiliser Advisory Scheme (CFAS) model (Cornforth and Sinclair, 1984) currently used in New Zealand by the Ministry of Agriculture and Fisheries (MAF) to determine fertiliser requirements of P, potassium and sulphur, is an example of such an approach.

The structure of the CFAS model has been described in some detail in section 2.8. Essentially, the model assumes that in a particular grazed pasture system at maintenance, the relationship between production and annual P fertiliser addition is described by a Mitscherlich-type curve. This curve passes through the origin and asymptotes at a value corresponding to maximum production or "carrying capacity". A third point is also required to allow calculation of the appropriate curve in any given situation. This curve will depend on type of animal, soil type and topography. In the CFAS model the point chosen to define the curve is that corresponding to 90% of maximum production.

At the point equivalent to 90% of maximum production it is assumed that the P required to maintain both the level of production and the size of the P cycling pool is equal to the sum of the P losses occurring within the soil and those due to the grazing animal. These losses are calculated using information on soil group, class of animal, land slope, grazing management and carrying capacity.

Once the appropriate set of response curves for a particular area has been identified it can be used to predict the fertiliser P required to maintain any desired level of production not exceeding the carrying capacity. All that is required is knowledge of the stocking rate of the area under consideration and the level of pasture utilisation.

The CFAS model has proved to be an excellent framework for collating and organising the vast amount of trial data available in New Zealand. There are, however, some difficulties associated with both the application of the model and its formulation.

In practice, on a farm scale it has proved difficult to obtain reliable estimates of some of the input parameters required in the model. In particular, stocking rate and pasture utilisation have been identified (Parker, 1982) as being difficult to quantify.

The accuracy of the animal loss factors (ALF's) and soil loss factors (SLF's) used in the model and described in section 2.8 can also be questioned. In particular, estimates of animal losses in hill country are based largely on a single trial (Gillingham et al., 1980) and further work is required to confirm the universality of the findings of that trial.

Soil loss factors were derived by "difference", rather than by direct measurement, on a series of mowing trials covering a wide range of New Zealand soil groups with an associated range of slopes. However, few of these trials were carried out in hill country. In the trials DMY, pasture P concentration and hence P uptake were measured at different rates of P fertiliser.

On treatments where annually measured Olsen P did not appear to be changing, any fertiliser P not accounted for in plant P uptake was considered to have become unavailable (as the Olsen P level had not increased) and, therefore, lost from the cycling P pool. This fraction, expressed as a percentage of plant P uptake at 90% of maximum yield was deemed the soil loss factor for the soil. No measurements of actual changes in total P, inorganic P (P_I) or organic P (P_O) were made. This means that total reliance was being placed on the Olsen test as a sensitive indicator of changes in available P or of equilibrium conditions. However, Olsen P is neither particularly reliable nor particularly sensitive in that it has a 20% temporal variability and 10% spatial variability associated with any value (Wheeler pers.comm.). If the Olsen P test was not reflecting an increase or decrease in available soil P, SLF's within the CFAS model could have been overestimated and underestimated respectively.

A further factor to consider is that SLF's were measured under a mowing regime with removal of clippings. Whether a similar magnitude of soil loss would occur in the presence of the grazing animal with the associated P return to the soil remains to be determined.

The results from the large-scale grazing trial, described in detail in previous chapters, provided a rare opportunity to test some of the assumptions and predictions of the CFAS model. In particular, data on faecal P distribution and soil P fractionation were used to check the ALF's and SLF's used in the model.

8.2 **Validation of selected factors within the model**

The first way in which data from the trial were used to validate the model involved measuring the actual losses due to animals and in the soil, and comparing these with values suggested by the model.

8.2.1 Animal loss factor

As explained earlier, the ALF is P lost from the system in animal produce and via animal transfer (at a pasture production of 90% of the maximum) expressed in kg P per stock unit (SU).

Animal faecal P return, and the effect of slope on faecal distribution, has been discussed in Chapter 5. Animal loss per SU for each slope in each paddock was calculated from the difference between plant P removed and faecal P returned, as shown in Appendix III. This derivation of animal loss per SU for each slope involves calculation for that slope of:

(i) Stocking Rate

(ii) % of pasture P uptake not returned in faeces

(iii) Total P uptake

(iv) P transfer (kg) = (iii) x (ii)

(v) P transfer SU^{-1} = (iv) ÷ (i)

Within a fertiliser rate, animal loss per SU increases with increasing slope (Table 8.1). This finding is in agreement with results by Gillingham et al., (1980). The effect of increasing fertiliser P addition on animal loss per SU is generally to increase losses on steeper slopes but not on easy-slopes. This probably reflects the fact that at high rates of P fertiliser addition (i.e., 50 and 100 kg ha^{-1}) both pasture production and pasture P concentration from steep-slopes is increased. Some of the associated increase in faecal production through associated high stocking rate is likely to be

Table 8.1 Effect of slope and rate of P fertiliser addition on (kg ha^{-1}) animal loss P per SU.

	Rate of P fertiliser addition kg ha^{-1}				
Slope	10	20	30	50	100
0-10°	0	0	0	0	0
11-20°	0.12*	0.27	0.50	0.27	0.28
21-30°	0.44	0.58	0.71	1.05	0.89
31°+	0.84	1.04	1.17	1.52	1.33

* Calculations were made as described in Appendix III using information on pasture production, total P uptake, estimated SR and faecal P return appropriate to the fertiliser P rate and slope under consideration from Chapter 5.

transferred to easy-slopes rather than deposited on steep-slopes. The increased "camping behaviour" that occurs on easy-slopes at high rates of fertiliser addition (i.e., high stocking rates) has been discussed in the studies on the "above-" and "below-ground" components of the P cycle (Chapters 5 and 3 respectively). The reduced animal loss per SU (calculated on a whole paddock basis) at very high rates of P fertiliser addition (100 kg ha^{-1}) provides further evidence for this observation. The comparatively low animal losses per SU on the 10 kg ha^{-1} P paddock are probably a result of imported P from the pre-treatment paddock. The straight-line relationship between faecal P concentration and pasture P concentration discussed in section 5.3.2.4 indicates that pre-conditioning of the sheep was effective, i.e., the P concentration of faeces brought onto the experimental paddocks was appropriate for paddock pasture P concentration. Thus the importing of P that occurred was probably a result of "extra" faecal DM.

When estimates of animal losses for individual slopes are combined, using topographic survey data (Appendix I), to give an average animal loss per SU for a paddock, it can be seen (Table 8.2) that, other than in the 10 kg ha^{-1} P paddock, there is relatively little effect of increasing P fertiliser. Increasing rate of P fertiliser in this trial was associated with an increase in SR. Thus, for the range of SR's in the trial (16.5 - 22 SU ha^{-1}) the amount of P lost per SU remained relatively constant. This supports the use of a common ALF for a range of SR's (and a given topography) in the CFAS model, which had not previously been confirmed. Any increase in total losses per SU with increasing SR, as indicated in the CFAS model, is, therefore,

Table 8.2 Effect of rate of P fertiliser addition (kg ha^{-1}) on loss per SU calculated over a whole-paddock.

Rate of P fertiliser addition kg ha^{-1}				
10	20	30	50	100
0.17	0.45	0.52	0.57	0.48

associated with an increase in soil loss. Thus as DMY increases with increasing rate of P fertiliser, P losses in the soil will increase.

A direct comparison between animal losses per SU obtained in this trial and the ALF designated for "Easy" hill country in the CFAS model (Table 8.3) is possible only at the fertiliser rate giving 90% relative yield (RY). As explained in the study on the "above-ground" components of the P cycle (Chapter 5) it was not possible to pinpoint where maximum production (and, hence, 90% RY) occurred due to the probable confounding effect of nitrogen via urine.

Although a direct comparison is not possible it can be seen (Table 8.2) that for "Easy" hill country the animal loss figure of 0.7 kg SU^{-1} designated by the CFAS model (Cornforth and Sinclair, 1984) was not confirmed in this trial. The significance of a lower ALF (0.5 kg SU^{-1} of P) is illustrated by considering the maintenance P fertiliser requirements of a "typical" high producing sheep farm on similar country to that used in the trial. For a potential CC of 18, SR of 15, PU of 80% and SLF of 0.25, reducing the ALF from 0.7 kg SU^{-1} to 0.5 kg SU^{-1} would decrease the CFAS maintenance P recommendation from 20 kg ha^{-1} to 17 kg ha^{-1}, i.e., a 15% reduction.

There are at least two reasons for the difference between measured and suggested ALF's. In this trial there was less animal transfer of P to campsites particularly from easy-slopes (Chapter 5), than was measured in the trial from which the CFAS ALF's were derived. This may have been due in part to the fact that most of the intensively monitored paddocks in the trial were topographically "flatter" than the notional

Table 8.3 Topographies for "Easy" and "Steep" paddocks as designated by the CFAS Model (Cornforth and Sinclair, 1984).

	Slope			
Paddock type	0-15° (campsites)	0-15° (flat)	25° (15-35°)	45° (35°+)
"Easy"	10	40	40	10
"Steep"	10	-	57	33

"Easy" paddock defined in the CFAS model (Table 8.3). Also, the extent to which differences in grazing management and paddock size (paddocks in the present study were smaller than those used in the trial from which the CFAS ALF's were derived) may have influenced camping behaviour of stock is not known.

Secondly, two assumptions incorporated into CFAS in calculating ALF's for all situations (A.G. Gillingham pers.comm.) were probably not strictly true or applicable in this trial. These two assumptions are:

(i) mean pasture P content at 90% of maximum production varies according to actual production levels.

(ii) annual pasture utilisation is equivalent to annual P utilisation.

The effect of changes in these assumed relationships was examined.

(i) Pasture P concentration.

The CFAS model assumes that pasture P concentration increases with increasing carrying capacity; the derived relationship is:

$$\text{pasture P\%} = 0.005 \times \text{CC} + 0.275$$

Thus for a range in CC of 8-32 SU ha^{-1}, pasture P is assumed to range from 0.315 to 0.435%.

The relationship was formulated for use only at production levels equivalent to 90% of maximum yield. As this level was difficult to define in this trial, pasture P% measurements are shown for contrasting fertiliser input levels (Table 8.4) and can be compared with derived estimates (Table 8.5). Estimates of CC required for calculation of pasture P% were calculated from average maximum DMY from the trial (Chapter 5).

Actual values measured over a three year period were lower than respective calculated values except on the steep-slope at the highest rate of fertiliser. The original estimates of the ALF's in the CFAS model (Cornforth and Sinclair, 1982b) were derived for hill country, under intensive rotational grazing, estimating (from one year's data) a mean pasture P concentration of 0.35% (A.G. Gillingham pers.comm.). Table 8.6 shows that this figure is reached on an annual basis only at excessively high rates of P fertiliser. Results from the present trial suggest that a value of 0.30% would be more realistic.

Substituting 0.30 for 0.35% in the original calculations for ALF's would reduce the magnitude of P loss from 25^{o} slopes from 1.13 to 0.97 kg SU^{-1} and for 45^{o} slopes from 1.71 to 1.46 kg SU^{-1}. From Table 8.1 it can be seen that these "new" ALF's are similar to those measured on corresponding slopes in the 50 kg ha^{-1} P paddock but are still somewhat higher than those measured at more commonly used rates (i.e., 20 - 30 kg ha^{-1}) of P fertiliser addition.

Table 8.4 Effect of slope and rate of P fertiliser addition ($kg\ ha^{-1}$) on average pasture P concentration (%). Data presented are the averages of three years results from the five intensively sampled paddocks.

	Rate of P fertiliser addition $kg\ ha^{-1}$				
Slope	10	20	30	50	100
0-10°	0.32	0.31	0.36	0.36	0.39
11-20°	0.28	0.29	0.32	0.33	0.37
21-30°	0.25	0.26	0.29	0.32	0.36
31°+	0.28	0.28	0.27	0.33	0.35

Table 8.5 Effect of slope on CC* and pasture P% as calculated by the equation pasture P% = 0.005 x CC + 0.275.

Slope	CC	Pasture %
0-10°	32.2	0.44
11-20°	25.1	0.40
21-30°	19.2	0.37
31°+	14.4	0.35

* CC for each slope was calculated from maximum DMY achieved on that slope in the grazing trial divided by 550 kg SU^{-1}.

Table 8.6 Effect of rate of P fertiliser addition (kg ha^{-1}) on pasture P concentration (%). Data presented are the averages of three years results from the five intensively sampled paddocks.

Rate of P fertiliser addition kg ha^{-1}				
10	20	30	50	100
0.29	0.28	0.31	0.34	0.37

On a per paddock basis, using a mean pasture P concentration of 0.30% in calculations (whilst holding all other factors constant) reduces the ALF for "Easy" hill country from the original (trial determined) 0.9 to 0.8. Substituting this value in the CFAS tables for a "typical" hill-country farm (as described earlier) reduces the maintenance fertiliser P recommendation by 1.5 kg ha^{-1} y^{-1}. In other "realistic" situations maintenance fertiliser P recommendations can be reduced by 2.5 kg ha^{-1} y^{-1}. The relatively small decrease in P requirements indicates that pasture P concentration is a relatively insensitive parameter within the CFAS model.

(ii) Pasture DM utilisation : pasture P utilisation.

Inherent within the CFAS model is the assumption that pasture DM utilisation is synonymous with pasture P utilisation. However, pasture P concentration is generally measured on herbage samples trimmed to near ground level (i.e., 1-2 cm height). Under the grazing regimes in the present study, stock did not always graze to such a low level (Chapter 5). Given that pre-grazed pasture has a higher P concentration than post-grazed pasture at most times of the year (section 5.3.1.3), P utilisation calculated as the difference between pre-grazed pasture DMY x P% and post-grazed pasture DMY x P% will be higher than that predicted by the model (calculated from pasture utilisation x pasture P concentration).

In the CFAS calculation of ALF's a P utilisation that is higher than pasture utilisation will effectively increase animal intake of P per unit of dry matter. This in turn will increase ALF's in the model.

At most times of the year pre-grazed pasture is about 0.02 - 0.03% higher in P content than post-grazed pasture (section 5.3.1.3). If a pasture P concentration of 0.30% is considered, a decrease of 0.02 - 0.03% represents a proportional difference of 7 - 10%.

The effect of decreasing the ALF from 0.9 to 0.8 (i.e., 11% proportional decrease) was shown earlier to represent a decrease in recommended maintenance fertiliser P rate of 1.5 to 2.5 kg ha^{-1} y^{-1}. Increasing the ALF by 7 - 10% would increase recommended maintenance fertiliser P rate by 1 to 2 kg ha^{-1} y^{-1}.

In summary, modifying the CFAS calculations to include realistic pasture P levels reduces ALF's and will thus have an effect on reducing fertiliser P rate recommendations. In contrast, modifying assumption (ii) to include more efficient P utilisation than pasture utilisation would cause an increase in ALF's and hence on fertiliser P recommendations. When the two effects are combined they tend to cancel each other out. The small resultant change in recommended maintenance P of approximately 0.5 kg is negligible in comparison with the effect on ALF's of the markedly different pattern of faecal P return observed in this trial, as described earlier in this section for a typical hill-country farm.

8.2.2 **Soil loss factor**

In the context of the CFAS model, P is considered to be lost from the cycling pool when organic or inorganic P compounds from which P cannot be extracted by plant roots accumulate in the soil.

As has been discussed earlier in this chapter, the soil losses used in the derivation of the CFAS model were measured as the difference between "above-ground" P input and P output in pasture products at 90% maximum yield. Soil loss factors were then calculated by expressing the soil loss as a percentage of the P taken up by plants in pasture maintained at 90% maximum yield.

Data from this trial discussed in Chapters 5 and 3 provided information with which to validate the CFAS SLF's in several ways. However, before comparisons between the suggested SLF of 0.25 for this soil group could be made with "measured" SLF's several difficulties had to be considered.

Firstly, DMY as such was not measured in this trial; DM intake, as discussed in Chapter 5, was measured instead. Dry matter yield is used to calculate total P uptake figures for each slope. These are required for the conversion of "soil losses" to "soil loss factors".

In order to overcome this problem PU's (Table 8.7) obtained in a similar hill-country grazing trial under an intensive rotational grazing management (Gillingham, 1978) were used to adjust the DM pasture intake figures actually measured to give an indication of likely DMY from each slope at each fertiliser rate (Table 8.8).

Table 8.7 Effect of slope on pasture utilisation*.

Slope	PU%
0-15°	78
15-35°	85
35°+	79

*Data from Gillingham (1978)

Table 8.8 Effect of slope and rate of P fertiliser addition ($kg\ ha^{-1}$) on DMY*.

	Rate of P fertiliser addition $kg\ ha^{-1}$				
Slope	10	20	30	50	100
0-10°	17315	20731	19399	19851	22731
11-20°	11438	13624	13155	13851	16262
21-30°	8458	9462	10711	11768	12407
31°+	5795	6726	9643	9317	8233

*DMY is calculated from animal intake measured in this trial and pasture utilisation from Gillingham (1978).

Secondly, 90% maximum production could not be identified. During the construction of the CFAS model soil losses were measured on soils supporting pasture at 90% maximum production and SLF's were calculated by expressing soil loss as a proportion of P uptake at that 90% production level. It was decided that in this trial soil losses at all rates of fertiliser application be converted to SLF's by expressing them as a percentage of the appropriate P uptake for the slope and fertiliser rate under consideration (Table 8.9). Although the actual point of 90% relative yield could not be pinpointed, the range of values obtained should bracket the correct value.

Thirdly, during the construction of the CFAS model SLF's were calculated for maintenance of a certain production level. By definition (Cornforth and Sinclair, 1982a) this means that available soil P, as measured annually by the Olsen P test, is not changing.

Using Olsen P data from all the paddocks in the trial (Fig. 8.1) an attempt was made to identify a maintenance rate of fertiliser (i.e., a paddock where the Olsen P was static from year to year). Trends in Olsen P examined in Chapter 3 on a paddock basis indicated that the 30 kg ha^{-1} P paddock might be near equilibrium.

When the data were subjected to statistical analysis (paired "t" tests, the pairs being the Olsen P level for a particular paddock in 1981 and 1984) it was clear (Fig. 8.1) that Olsen P on easy- and steep-slopes was rising significantly ($P<0.01$) at excessively high rates of P fertiliser (i.e., 100 kg ha^{-1}). At low rates of P

Table 8.9 Effect of slope and rate of P fertiliser addition (kg ha^{-1}) on P uptake* (kg ha^{-1}). Data presented are the averages of three years results taken from the five intensively sampled paddocks.

	Rate of P fertiliser addition (kg ha^{-1})				
Slope	10	20	30	50	100
0-10°	56.05	64.58	70.24	71.65	88.01
11-20°	82.24	39.55	42.36	45.87	59.47
21-30°	21.40	24.47	30.99	37.32	44.60
31°+	16.13	18.76	26.11	30.98	28.87

* P uptake is calculated from animal intake measured in this trial and pasture utilisation from Gillingham (1978).

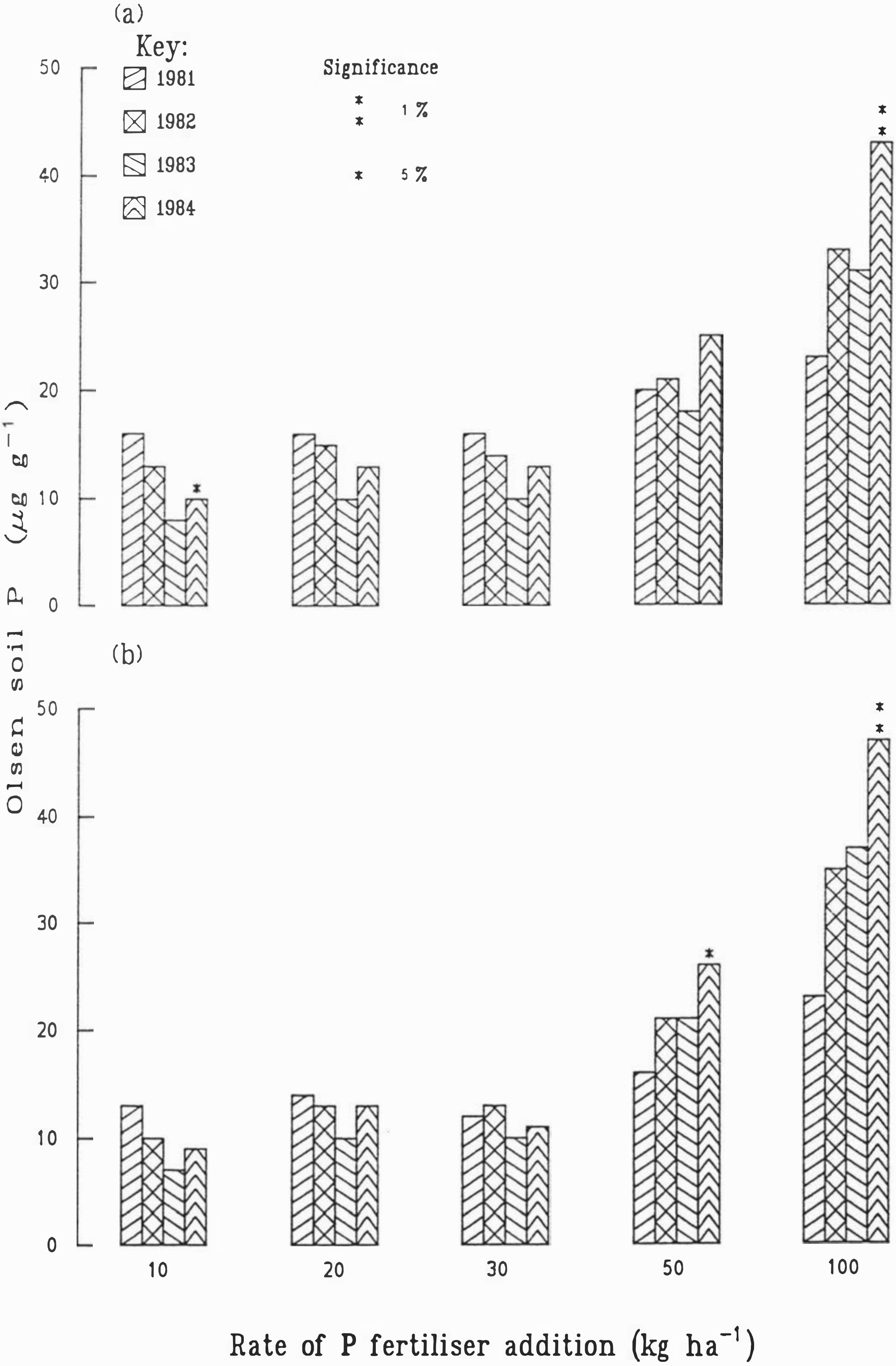


Figure 8.1 Effect of P fertiliser rate and time on Olsen-extractable P on easy-slopes (a) and steep-slopes (b). Data presented is from all paddocks.

fertiliser (i.e., 10 kg ha^{-1}) Olsen P was decreasing significantly on easy-slopes ($P < 0.05$). However, at moderate rates of P (20-30 kg ha^{-1}) no significant differences existed.

Based on Olsen P analyses for easy- and steep-slopes, results from this trial would tend to indicate that on this soil type, under the intensive management conditions of this trial where the highest SR (22) is considered to be the potential CC, maintenance P fertiliser requirements may be in the range of 20 - 30 kg ha^{-1} for SR's of between 16.5 and 19.5. It is not possible to be more specific because the Olsen P test, used to define equilibrium conditions, is not sufficiently sensitive in the short term (four years) to measure whether annual P inputs of either 20 or 30 kg ha^{-1} are creating equilibrium conditions for the associated SR's. It should be emphasised that maintenance P requirements are related to SR and it is, therefore, possible for both the 20 and 30 kg ha^{-1} P paddocks to be at equilibrium given their respective SR's. A further consideration that should be made in terms of the concept of equilibrium is that of time. During the four years of the trial the 20 and 30 kg ha^{-1} P paddocks probably approached equilibrium. Given longer, it is probable that the 10 kg ha^{-1} P paddock would also have reached an equilibrium. At the higher rates of P fertiliser, however, it is possible that equilibrium is unattainable as losses of P are unlikely to be able to account for additions of P in fertiliser. That is, due to limiting factors other than P, it is unlikely that DMY and hence plant P uptake, could ever account for very large additions of P (e.g., 100 kg ha^{-1}) and so, as seen in the present trial, available soil P (as measured by Olsen P) will continue to increase and equilibrium will not be reached.

Statistical analysis of Olsen P on three slope groups during the period of the trial (Fig. 3.3) suggested that a change in Olsen P of 6 $\mu g\ g^{-1}$ would be significant. The relationship between Olsen P and plant P uptake derived in section 4.3.5 indicates that the addition of surplus plant-available P at the rate of 4.0 $\mu g\ g^{-1}$ soil would be required to effect an increase in Olsen P of 1 $\mu g\ g^{-1}$. This means that 24 $\mu g\ g^{-1}$ of plant-available P would have to be added to effect a significant increase, which, for the 0-3 cm depth in a paddock, would mean 4 - 6 kg ha^{-1} extra plant-available P.

The paddock receiving 50 kg $ha^{-1}\ y^{-1}$ of P fertiliser was probably receiving very much more than 6 kg $ha^{-1}\ y^{-1}$ of P in excess of maintenance P requirements (in relation to SR) and yet no significant increase in Olsen P could be discerned on easy-slopes even after four years.

Alternatively, using data from the glasshouse study (Chapter 4) it is possible to derive a relationship between Olsen P and non-occluded P:

change in non-occluded P = 5.73 x change in Olsen P + 6.05 $r = 0.94^{**}$

This means that an increase in soil non-occluded P of 40 $\mu g\ g^{-1}$ is required for an increase in soil Olsen P of 6 $\mu g\ g^{-1}$. This amount of non-occluded P is equivalent to 6 - 8 kg ha^{-1} of P for the top 0-3 cm. Increases of greater than 40 $\mu g\ g^{-1}$ of P did occur in the non-occluded fraction on most slopes in the 30, 50 and 100 kg ha^{-1} P paddocks during the period of the trial. However, only in the 100 kg ha^{-1} P paddock, and the steep-slope of the 50 kg ha^{-1} P paddock were these increases reflected in Olsen P. This suggests that non-occluded P is a more sensitive indicator of changes in soil P than Olsen P.

The fact that the expected Olsen P increase did not occur may be due to a certain extent to microbial activity and the immobilisation of P in the organic form. Hence the build up of P_O on campsites, constituting a loss of P in the soil from the cycling P pool.

A further factor to consider is that the relationships between changes in Olsen P and plant-available P or non-occluded P were derived from a depletion curve. This curve is not necessarily the same shape as that derived from a situation where P is being increased. As monitoring of soil test results is the only practical way of monitoring the CFAS recommendations, considerably more work needs to be done in this area in order to develop an understanding of the response in Olsen P to above- or below-maintenance rates of fertiliser P addition.

A further attempt at defining maintenance conditions was made by examining the status of P pools other than the Olsen P pool. Evaluation of changes in "below-ground" P pools, including changes in non-occluded P and P_I, both of which correlated well with plant P uptake in the glasshouse trial discussed in Chapter 4, did not assist in the decision as to which, if any, paddock was at equilibrium. This was because variability in measurement was high in all soil P fractions, not just in the Olsen P fraction.

Variability was also a feature in measurements of the "above-ground" components of the P cycle. For the three years of the trial, spring DMY on easy-slopes were least variable (± 9-18% for the two "equilibrium paddocks", i.e., the 20 and 30 kg ha^{-1} P paddocks). Pasture P concentration in spring showed similar variability (± approximately 15%). This parameter was relatively consistent in summer and early autumn on an annual basis, but there was no effect of P fertiliser, i.e., droughty conditions limited P uptake on all P fertiliser rates. Pasture P uptake in spring (calculated from DMY x pasture P concentration) was considerably more variable than either of the components alone. Although P in sheep grazing the trial were not examined it is considered unlikely that P in wool or blood, for instance, could assist in the determination of a paddock at "equilibrium" as sheep tend to excrete P surplus to requirements.

These results tend to suggest that the concept of equilibrium may not be applicable to the individual components of the P cycle in individual slope groups in hill-country pasture, although it may apply to a hill-country paddock considered as a whole.

An alternative method of defining maintenance P for the conditions of the trial involved use of the CFAS model itself. For an SLF of 0.25 and an ALF of 0.7 (as recommended by the CFAS model (Cornforth and Sinclair, 1984) for the soil type and grazing regime of the trial) plus a CC of 22 and assuming a PU of 80% the maintenance P recommendations are 17, 20 and 30 kg ha^{-1} respectively. These P recommendations are reduced to 14, 16 and 21 kg ha^{-1} if PU is assumed to be 90%. In the present trial a fertiliser P addition of 20 kg ha^{-1}

supported an SR of 16.5, and of 30 kg ha^{-1} supported an SR of 19.5. This suggests not only that the CFAS model provides a good estimate of maintenance P at this site but also that 80% PU is a reasonable estimate for that being achieved.

Having attempted to define maintenance P requirements for SR's associated with the present trial, the next step was to use data from the trial to calculate SLF's associated with a range of P fertiliser rates or SR's. The trial data used was from the five intensively sampled paddocks where P fractionation data were available. For this reason the significance of any difference between sampling periods could not be evaluated.

Initially, results from the present study were used to calculate SLF's in the same way as originally carried out for the CFAS model, i.e., by difference. In the CFAS approach P fertiliser is added to balance losses under equilibrium conditions. Fertiliser P which neither appears in the available P pool (as measured by the Olsen test) nor is taken up by plants (measured by DMY x P concentration) is assumed to be lost in the soil. This P loss is then divided by plant P uptake to give an SLF value.

At the P fertiliser rates closely approximating the probable maintenance requirement and possible equilibrium conditions (i.e., 20 and 30 kg ha^{-1}) the SLF's (Table 8.10) are considerably higher than the figure of 0.25 used for this site in the CFAS model. These higher values are a consequence of the lower animal losses described in the previous section. That is, if, for example, 20 kg ha^{-1} of P

Table 8.10 Effect of slope and rate of P fertiliser addition ($kg\ ha^{-1}$) on SLF's*.

	Rate of P fertiliser addition ($kg\ ha^{-1}$)				
Slope	10**	20	30	50	100
0-10°	0.50	0.67	0.63	1.01	1.43
11-20°	0.24	0.36	0.47	0.97	1.56
21-30°	0.20	0.47	0.58	0.83	1.86
31°+	0.17	0.51	0.50	0.93	2.90

* SLF's calculated from P uptake (Table 8.9) and P return data presented in chapter 5.

** SLF's for other than "maintenance" paddocks presented for purposes of comparison.

fertiliser is the true maintenance rate for an SR of 16.5 at this site, and animal losses are smaller than predicted, it follows that soil losses must be greater than predicted.

The CFAS model assumes that the magnitude of soil loss is linearly related to plant P uptake through the SLF. It also assumes that this relationship is constant on different slopes despite differences in pasture P composition, soil water, physical properties and the status of other nutrients. It was clear (Table 8.10) that the SLF's calculated in this trial did vary with slope but since equilibrium conditions were not apparent, no firm conclusions could be drawn on the validity of the assumptions relating plant P uptake to SLF.

Another way in which data from this trial were used in attempting to validate the CFAS SLF was to recalculate SLF's for the trial using figures for actual soil P changes. These values were taken from the study on the "below-ground" components of the P cycle (Chapter 3).

For a paddock at equilibrium (as measured by the Olsen P test) any increase in total soil P at yearly intervals must constitute a soil P loss because, by definition, no net change in the available P pool is occurring. The average annual increase in total soil P was calculated for each slope at each rate of fertiliser P addition, and was then expressed as a proportion of the appropriate plant P uptake (Table 8.11).

Both total soil P in the 0-15 cm depth (i.e., to root depth) and the SLF's were found to increase with increasing rate of fertiliser P addition on easy- and steep-slopes, but decrease with increasing rate

Table 8.11 Effect of slope and rate of P fertiliser addition (kg ha^{-1}) on (a) change in total soil P (kg ha^{-1}) and (b) soil loss factor calculated from (a). Data presented are the averages of two years results from the five intensively sampled paddocks (0-15 cm depth).

	Rate of P fertiliser addition (kg ha^{-1})				
Slope	10	20	30	50	100
(a) 0-10°	124.8	109.1	54.2	80.5	68.8
11-20°	5.9	11.1	15.7	67.4	93.5
31°+	-11.1	18.4	8.9	36.6	58.5
(b) 0-10°	2.23	1.69	0.77	1.12	0.78
11-20°	0.18	0.28	0.37	1.47	1.57
31°+	0.69	0.98	0.34	1.18	2.03

of fertiliser on campsites (Table 8.11). Again, slope had a marked but inconsistent effect.For the two paddocks receiving close to maintenance P (20 and 30 kg ha^{-1}) it could be seen that SLF's calculated from total P accumulation were somewhat higher than suggested by the CFAS model.

Results from the glasshouse study (Chapter 4) on the availability of P fractions indicated that within the total P pool, occluded P, calcium-bound P and P_O were relatively unavailable for plant P uptake during the long term trial. Using the sum of these three soil fractions from the trial data (Table 8.12), similar trends in soil P and SLF's were observed as with total P. At low additions of P fertiliser SLF's on easy-slopes were higher than when calculated using total soil P figures. This was due to the fact that at low levels of P addition increases in levels of unavailable forms of P occurred at the expense of decreases in levels of available forms. This can be seen on a per paddock basis in Fig. 3.13.

In comparison with the CFAS SLF of 0.25, figures obtained from the combination of "unavailable-P pools" at approximately maintenance rates of P addition were much larger. These appear high (at or near equilibrium) as they indicate that in any year almost as much P will be locked up in the soil as taken up by the plant.

Another attempt at validating the CFAS SLF was made using changes in occluded P and calcium-bound P, i.e., those fractions of P_I thought to be least plant available. The same trends in results were obtained (Table 8.13) as for the other two data sets, but the values were much

Table 8.12 Effect of slope and rate of P fertiliser addition ($kg\ ha^{-1}$) on (a) change in unavailable soil P ($kg\ ha^{-1}$) and (b) soil loss factor calculated from (a). Data presented are the averages of two years results from the five intensively sampled paddocks (0-15 cm depth).

	Rate of P fertiliser addition ($kg\ ha^{-1}$)				
Slope	10	20	30	50	100
(a) 0-10°	118.1	61.4	49.6	86.2	22.2
11-20°	17.1	19.7	13.0	39.2	65.6
31°+	0.5	34.4	22.9	44.3	39.1
(b) 0-10°	2.11	0.95	0.71	1.20	0.25
11-20°	0.53	0.50	0.31	0.85	1.10
31°+	0.03	1.83	0.88	1.43	1.35

Table 8.13 Effect of slope and rate of P fertiliser addition (kg ha^{-1}) on (a) change in unavailable soil inorganic P (kg ha^{-1}) and (b) soil loss factor calculated from (a). Data presented are the averages of two years results from the five intensively sampled paddocks (0-15 cm depth).

	Rate of P fertiliser addition (kg ha^{-1})				
Slope	10	20	30	50	100
(a) 0-10^{o}	33.2	29.3	16.8	28.0	18.6
11-20^{o}	6.0	2.8	3.0	15.6	31.7
31^{o}+	- 4.2	9.8	10.8	11.4	16.6
(b) 0-10^{o}	0.59	0.45	0.24	0.39	0.21
11-20^{o}	0.18	0.07	0.07	0.34	0.53
31^{o}+	-0.26	0.32	0.41	0.37	0.57

lower. In fact, combining these SLF's to give a "paddock" SLF gives results (i.e., 0.25 for the 20 kg ha^{-1} P paddock and 0.19 for the 30 kg ha^{-1} P paddock) which are comparable with the SLF of 0.25 derived for the CFAS model.

Using least plant-available soil P_I fractions thus provides a more realistic SLF (as defined by the CFAS model) than the other two methods. The fact that such similar results were obtained using only these least available P_I fractions of total soil P in the calculations of SLF's throws some doubt on whether or not an increase in P_O implies a soil loss. It is possible that any increase in P_O should be considered as a P reserve rather than as a P loss. If input conditions are altered (e.g., nitrogen is added via improved pasture fertility or P fertiliser additions are reduced) the balance between immobilisation and mineralisation is likely to change and net mineralisation can occur, thus releasing P in a form available for plant P uptake. As neither the interaction between nitrogen and P nor the residual availability of P fertiliser are fully understood in hill country these aspects need further research to determine the quantities of P that might be involved and the sensitivity of the reactions to changes in inputs. Such manipulations cannot be made to release calcium-bound P or occluded P; an increase in P in these two soil fractions can probably be said to constitute a true soil loss.

8.2.3 Combined effect of changes in ALF and SLF

Despite the fact that the CFAS and trial estimates of SLF and ALF's cannot be compared directly it can be seen that whereas estimates of ALF's in this trial are lower than those used in the CFAS model, trial estimates of SLF's are similar when based on increases in "non-available" inorganic P. The net effect of the two is a slightly lower P requirement than suggested by the CFAS model.

8.3 SHORT-TERM P REQUIREMENTS

The significance of the Olsen P findings in this study have implications in the determination of short term P requirements of a given situation in hill country.

Short-term P requirements are calculated in the CFAS model using a "modifying factor" which either increases or decreases the amount of P recommended depending upon whether the Olsen P status of the area under consideration is lower or higher than that considered appropriate for the stocking conditions in existence. Additional information used to choose the appropriate "modifying factor" is the soil group and the level of relative yield currently being achieved.

The structure of the graphs used within the CFAS model to give "modifying factors" is such that they are relatively sensitive to changes in Olsen P. For instance, assuming a relative yield of 85% (which was achieved on a paddock basis at 30 kg ha^{-1} of P) on a medium

P loss soil with an Olsen P status of 18 the associated "modifying factor" is 0.4. For this paddock and SR, plus PU of 80% it was established in section 8.2.2 that 30 kg ha^{-1} of P was probably appropriate. The "modifying factor" calculated for short-term P requirements suggests that only 12 kg ha^{-1} of P fertiliser are necessary as the Olsen P status is higher than that thought necessary to support an RY of 85%. However, a 30% error in Olsen P due to temporal and spatial variability could mean that the "true" Olsen P was between 13 and 23. These values are associated with "modifying factors" of approximately 1.1 and 0 respectively. Thus the short-term P recommendation is likely to be between 33 and 0 kg ha^{-1}.

In the paddock receiving 30 kg ha^{-1} P fertiliser the overall paddock average for Olsen P was 15 in the final year of the trial, which is associated with a "modifying factor" of approximately 0.8. Thus only 24 kg ha^{-1} P fertiliser are required for maintenance. However, a drop in Olsen to 12 (which would occur if campsites were omitted from soil sampling) would mean an increase in the "modifying factor" to approximately 1.2 and in short-term fertiliser P recommendations to 36 kg ha^{-1}. Given the inherent variability of both the Olsen P test and hill-country soils, plus the sensitivity of the modifying factor it is possible that improved recommendations for short-term maintenance P requirements could be made by sampling only easy-slopes, i.e., those slopes most P responsive.

The incorporation of short-term P recommendations or adjustments to maintenance P recommendations in the CFAS model is likely to be beneficial to farmers as it provides a "fail-safe" mechanism, preventing exploitation of soil P reserves, evident in a rapidly decreasing Olsen P, or "unnecessary" investment in soil P (or fertiliser), evident in a rapidly increasing Olsen P. However, the sensitivity of the model to changes in Olsen P means that large errors could be introduced into P requirement calculations very easily.

8.4 MAINTENANCE P REQUIREMENTS FOR INDIVIDUAL SLOPES WITHIN A PADDOCK

Throughout this chapter it has been suggested that different slopes within a paddock may have different fertiliser P requirements as plant P uptake and faecal P return varied. This hypothesis was examined using data collected from the study on the "above-ground" components of the P cycle (Chapter 5) and information on losses within the soil.

The P deficit on slopes (other than campsites) generated by plant P uptake and inadequate faecal P return has been discussed in detail in section 5.3.4.1 and is represented in Table 8.14. In summary, a P surplus was measured on campsites. On steeper slopes the P deficit increased with increasing degree of landslope.

It is expected that soil losses will exhibit the opposite trend, as the CFAS model suggests that soil loss is linearly related to P uptake. Thus the greater P uptake on easy- than steep-slopes indicates a higher soil P loss on the easy-slopes. Previous sections have discussed the difficulties in measuring soil losses in grazed hill country.

Table 8.14 Effect of slope and rate of P fertiliser addition ($kg\ ha^{-1}$) on the difference ($kg\ ha^{-1}$) between annual P uptake and annual P return. Data presented are the averages of three years results from the five intensively sampled paddocks.

	Rate of P fertiliser addition ($kg\ ha^{-1}$)				
Slope	10	20	30	50	100
0-10°	17.8	23.1	14.2	22.4	26.0
11-20°	-2.2	-5.6	-10.0	-5.7	-7.0
21-30°	-5.8	-8.4	-11.9	-19.0	-16.8
31°+	-7.3	-10.4	-17.0	-21.0	-16.4

To determine maintenance P requirements for each slope the SLF recommended by the CFAS model (0.25) was used with plant P uptake data (Table 8.9) to calculate the magnitude of soil loss. Soil losses were found to increase with increasing rate of fertiliser and decrease with increasing slope (Table 8.15). This is to be expected because plant P uptake follows the same trends and the conversion factor was the same for all slopes and P fertiliser rates.

Combination of annual animal and soil losses (Table 8.16) produces annual P deficits on each slope which, excluding campsites are remarkably similar within a single paddock. This is particularly the case at moderate to low rates of fertiliser P addition.

This use of the CFAS SLF to estimate losses in soils at levels of production other than at 90% of maximum is not strictly correct. It does, however, serve to illustrate in this trial situation that although production may vary considerably on different slopes, the magnitude of P deficits can be similar.

In contrast, it is possible that short-term P requirements may vary between slopes. As explained in the previous section, an Olsen P higher than that deemed appropriate for a given production level represents an inefficient investment in soil P. This can be exploited, thereby increasing production efficiency, by reducing P fertiliser inputs. If Olsen P is lower than that considered appropriate for a particular level of production, maintenance P recommendations must be increased to compensate.

Table 8.15 Effect of slope and rate of P fertiliser addition (kg ha^{-1}) on soil P loss (kg ha^{-1}). Data presented are the averages of three years results from the five intensively sampled paddocks.

	Rate of P fertiliser addition (kg ha^{-1})				
Slope	10	20	30	50	100
0-10°	14.0*	16.2	17.6	17.9	22.0
11-20°	8.1	9.9	10.6	11.5	14.9
21-30°	5.4	6.1	7.8	9.3	11.2
31°+	4.0	4.7	6.5	7.8	7.2

* Data were calculated from adjusted plant P uptake figures (Table 8.9) modified by the CFAS SLF of 0.25.

Table 8.16 Effect of slope and rate of P fertiliser addition (kg ha^{-1}) on annual P requirements (kg ha^{-1}). Data presented are the averages of three years results from the five intensively sampled paddocks.

	Rate of P fertiliser addition (kg ha^{-1})				
Slope	10	20	30	50	100
0-10°	3.8*	7.0	-3.4	4.5	4.0
11-20°	-10.3	-15.5	-20.6	-17.2	-21.9
21-30°	-11.2	-14.5	-19.7	-28.3	-28.0
31°+	-11.3	-15.1	-23.5	-28.8	-23.6

* Data were calculated from Tables 8.14 and 8.15.
Positive sign indicates a P surplus.
Negative sign indicates a requirement for P

In the present study, DMY tended to be higher from the 30 kg ha^{-1} P paddock than the 20 kg ha^{-1} P paddock (as discussed in Chapter 5) but Olsen P values were often lower (Table 8.1). The CFAS "modifying" graphs for the appropriate soil group and RY were used to determine short-term P requirements on a per slope basis for the two "equilibrium" paddocks. Relative yields were calculated from DMY data, presented in Table 8.8, assuming 100% RY to be that achieved on the 100 kg ha^{-1} P paddock.

Olsen P data from 1984 indicated that apart from on campsites, where Olsen P levels were considerably higher than appropriate, Olsen P levels on slopes were within one or two units of that deemed appropriate for the associated RY. This was not the case in 1983 (an indication of temporal variability in Olsen P).

In 1983, Olsen P levels were higher than appropriate on campsites, but lower than appropriate on steeper slopes. "Modifying factors" were found to decrease with increasing slope. This suggests that for a given unit area easy-slopes require more P fertiliser than other slopes within a paddock and are likely to be the most P responsive. This is shown to some extent in DMY curves discussed in Chapter 5, but the fact that easy-slopes are the most P responsive is somewhat obscured by the campsite response to nitrogen.

This information could be of importance when considering P fertiliser application on a farm scale. Given that easy-slopes are the most P responsive areas, efficiency of use of P will be higher on those areas than others. Therefore, farmers should apply fertiliser preferentially to these areas. For example, using data from the 20 kg ha^{-1} P paddock presented in Table 8.16, maintenance P requirements for areas other than campsites approximate 15 kg ha^{-1}. However, whereas the "modifying factor" for the easy-slope is approximately 2, it decreases to approximately 1.2 and 1.1 for the steeper slopes. Thus 30 kg ha^{-1} P is required on easy-slopes, 18 kg ha^{-1} on 21-30^{o} slopes and 16.5 kg ha^{-1} on steep-slopes. In an "Easy" paddock (CFAS topography) this would mean topographically adjusted P requirement of 21 kg ha^{-1}. In a "Steep" paddock, the P requirement would be reduced to 16 kg ha^{-1}.

Within most New Zealand hill country it is unrealistic to expect farmers to topdress individual slopes within a paddock at different rates of P fertiliser. However, a modification of the CFAS model to include topography could allow adjustment of overall rates to a block of land which, for a fixed P fertiliser budget, could allow more P to be applied to areas which would be more responsive, i.e., those areas with the greatest proportion of easy-slopes. Ultimately, this would lead to improved efficiency of use of P fertiliser.

8.5 CONCLUSIONS

The evaluation of the effect of rate of P fertiliser addition and slope on changes in or size of the "above-" and "below-ground" components of the P cycle has enabled a greater understanding of the P cycle in grazed hill-country pasture. Knowledge of the P cycle offers

one of the most useful methods for assessing P fertiliser requirements. Results from this study were used in an attempt to validate input data used to determine maintenance and short-term fertiliser P requirements in the MAF CFAS model.

Three major conclusions were formulated.

(1) Animal losses were lower in this study than suggested by the MAF CFAS model.

(2) Soil losses of P were extremely difficult to measure because of the high associated field variability and the difficulty in establishing the existence of "equilibrium" in terms of available soil P as measured by the Olsen test.

(3) Excluding campsites (which had a zero requirement for P fertiliser) P deficits on other slopes appeared to be little affected by degree of slope.

With respect to conclusion (1), the comparatively large reduction in animal losses per SU measured on each slope in the present trial in comparison with the trial from which the CFAS ALF's were derived (Gillingham et al., 1980) appeared to be due mainly to a more uniform distribution of faecal material. Although both trials were run under an intensive rotational grazing regime, paddocks in Gillingham's trial were both larger and steeper than those used in the present trial, allowing less uniform return of faecal P. The earlier trial may relate more closely to a farm-scale operation than the present trial. As only two sets of data on faecal distribution in New Zealand hill country are available, it is not possible to make firm conclusions on the effect of paddock size.

Results from the present trial in comparison with those from the trial from which CFAS ALF's were derived (Gillingham et al., 1980) illustrate the dangers of extrapolating results from one situation to another without having a detailed knowledge of the causes of specific results (as indicated by Mohammed et al., 1984). In this case it is not merely the topography that changes between a steep and an easy paddock, but also faecal distribution. Therefore, to transfer results from one situation to another successfully requires an appreciation of this relationship.

Faecal P return is one of the three major factors used to calculate maintenance P requirements for a particular area, thus a change in faecal P return could have an important effect on the P budget. For this reason considerably more research needs to be carried out in order to determine the effect of paddock size and contrasting topography on the distribution of faecal material within a paddock.

For conclusion (2), establishing causes of soil P loss proved to be difficult. Within the objectives of the present trial it was hoped to both define changes in soil P related characteristics and identify those soil pools which reflected changes in the "above-ground" compartments of the P cycle. For these reasons, soil sampling involved many replicates and was carried out in a careful manner. In spite of this it was found that variability in P fractions in field samples was extremely high. The CFAS model relies heavily on the identification of "equilibrium" in available soil P, as measured by the Olsen test, in order to establish maintenance rates of fertiliser. It also relies on Olsen P to indicate short-term P requirements.

The fact that "equilibrium" could not be defined by this method in the present trial rendered validation of the CFAS SLF for this soil group difficult. It will, therefore, be even more difficult under "routine" soil-testing procedures. It was possible to observe, however, that SLF's calculated in the same way as the CFAS SLF's were similar if changes in only those P_I pools found to be least plant available (Chapter 4) were considered. Inclusion of changes in P_O due to net immobilisation, which the CFAS model defines as a loss, increased the calculated SLF's considerably, but unrealistically. These results suggest that the inclusion of net immobilised P_O as a soil loss in the CFAS model may not be valid. An alteration of SR or P fertiliser addition could affect the ratio of mineralisation to immobilisation rapidly and dramatically, which would then affect maintenance P requirements; it is unlikely that the same could be said for the reactions causing the formation of occluded P and calcium-bound P.

A second factor to consider is that the variability associated with Olsen P values observed in this trial will also be present in routine soil sampling associated with the use of the CFAS model. Thus, it will be difficult to establish whether or not the correct "maintenance" rate of P fertiliser is being applied and to make short-term P fertiliser recommendations.

Other P fractions measured in this trial showed as much variability as Olsen P. The use of water-extractable P instead of Olsen P could offer some advantages. Although field variability in the water-extractable P fraction is as high as that of Olsen P, and seasonal variability is slightly higher (Sorn-srivichai, 1985), it was found in Chapter 4 that water-extractable P provided a slightly better indicator of plant-available P than Olsen P. Furthermore, the interpretation of water-extractable P levels is not greatly influenced by the buffering capacity of soils and appears to be largely independent of soil-type (Sorn-srivichai, 1985). As it is possible to model changes in water-extractable P in soils following superphosphate fertiliser addition (Sorn-srivichai, 1985) a water-extraction procedure may offer some advantages if incorporated into the CFAS model as a replacement for Olsen P. However, because of the seasonal variability in water-extractable P (also apparent in Olsen P) routine soil sampling for each farm would have to be carried out at the same time each year.

Results from the present trial tend to indicate that a routine soil test, either of Olsen P or water-extractable P, is likely to provide the "best" (i.e., they are simple to perform and are not more variable than any other parameter considered) estimate of equilibrium. However, extreme care needs to be taken in order to ensure that soil sampling occurs from representative portions of the paddock under consideration. As campsites do not require P fertiliser, and tend to have extremely high variability in soil tests, these should be excluded from soil sampling. In fact, given that easy-slopes are probably the most P responsive areas within a hill-country paddock, and tend to occupy the largest area, it is likely that an improved representative and less variable soil test could be gained by concentrating soil sampling on these slopes in similar type hill country as studied in this trial.

In an attempt to find an indicator of "equilibrium" the "above-ground" components of the P cycle (e.g., DMY, pasture P concentration and P uptake) were examined. This was not successful as these components were found to be as variable as the "below-ground" components. Furthermore, it is considered unlikely that an improved estimate of equilibrium could be obtained by monitoring the animal (e.g., P levels in the wool or blood). Given the variability of the "above-ground" components of the P cycle and the consequent relatively large changes in annual plant P uptake it is not surprising that Olsen P also undergoes relatively large annual changes. As annual fluctuations in Olsen P have been found to occur under the intensive sampling regime of the present study and are to be expected it is, perhaps, unrealistic that one of the assumptions of the CFAS model is that the area under consideration is at "equilibrium" as defined by a stable Olsen P. The use of the "modifying factor" for short-term P requirements renders the assumption unnecessary.

From this it would seem that equilibrium within a hill-country ecosystem or macropool is not necessarily reflected by equilibrium in a single P compartment or micropool. In hill country the P compartments and sub-compartments undergo complex interactions and although, in the present trial, paddocks as a whole may have been at equilibrium, this did not appear to be the case for any one P pool within the paddock. It seems likely that, given the constant transfer of P in faeces from steeper slopes to easier slopes, individual hill-country slopes may not reach equilibrium at all.

With respect to conclusion (3), apart from campsites, maintenance P fertiliser requirements of other areas in any given paddock in this trial were found to be remarkably similar, regardless of slope. The balance between soil P, plant P uptake and faecal P return was probably, in part, a function of topography. On dominantly steep paddocks, where there is likely to be far greater P transfer via animals, P requirements may not balance out across slopes in quite such an even fashion. Recalculation of data from the trial from which ALF's were derived (Gillingham et al., 1980), using the CFAS SLF of 0.25, indicates that P requirements may be greater on easy-slopes than steep-slopes. Again, this calculation is based on the premise that the SLF is not affected by slope. It remains to be established whether or not this is so.

Short-term P requirements were found to be markedly affected by slope as "modifying factors" for easy-slopes tended to be larger than for steep-slopes. This has implications to the use of P fertiliser. Given that pasture on easy-slopes is more responsive to P than pasture on other slopes it is clear that, with a limited P fertiliser budget, improved efficiency of use of P fertiliser could be obtained by topdressing easy-slopes preferentially. As hill country generally consists of an amalgam of land in different slope categories, the most efficient rate of topdressing can be calculated using a topographical survey plus the individual P requirements of each slope group. Thus the effect of the easy-slopes within a paddock can be gauged. In this way P "saved" from steeper paddocks can be applied to easier paddocks. The total amount spent on P fertiliser need not be changed, but efficiency of use of that fertiliser will be much improved.

Results from the present trial have identified that further research is necessary to establish how soil P losses occur. Although sampling was intensive, replication was relatively high and monitor sites were used, results were inconclusive. Thus it is clear that the problem of determining what soil P losses are and how they occur must be examined in a different way. The use of ^{33}P offers a possible solution to this problem. Although the radioisotope is expensive, it is relatively safe to use and has a comparatively long half-life (25.2 days). The ^{33}P could be used directly in the field via the isotope injector (Hedley and Tillman, 1987) as described in Chapter 7, or to label fertiliser P before application. In the first case the amount of radioactive P in each soil P fraction after equilibration would reflect the size of that fraction. The amount of time taken to reach equilibrium would reflect the rate of turnover of that fraction. In the second case the use of radioactive fertiliser could allow the fate of the fertiliser P to be traced in the field. Both techniques could greatly improve the present understanding of P cycling in hill country.

Unless it can be established how soil losses occur, ways and means of improving the efficiency of P cycling and associated means of testing or refining the CFAS model cannot be formulated.

CHAPTER 9

SUMMARY

A review of literature revealed that information on the P cycle in grazed hill-country pastures in New Zealand in terms of size of compartments and rates of transfer of P between the compartments is scarce. In particular, knowledge of the effect of the grazing animal on redistributing P from the plant via faeces and the availability of faecal P to pasture plants is lacking. Furthermore, the effect on soil P fractions of continual P additions and the plant availability of P in those fractions is not clearly understood.

The P fertiliser requirements of New Zealand pastures are determined currently by MAF advisory officers by the use of a model constructed on the basis that P inputs balance P outputs under equilibrium conditions. An increased understanding of the P cycle offers an opportunity to refine the model and improve the precision of P fertiliser requirements. This would lead to increased efficiency of P fertiliser use, particularly in hill country where the economies of fertiliser use are marginal.

A basic requirement for a study of the P cycle under field conditions is a well conducted grazing trial. The large-scale grazing trial established at Whatawhata Hill Country Research Station offered an ideal opportunity to study all components of the P cycle at one site. The trial had been set up to provide information on the effect of grazing regime, land-slope and P fertiliser addition on pasture production and pasture P concentration. The effect of slope on the distribution of faecal material and the effect of slope and P fertiliser addition on Olsen P levels were also monitored.

More detailed studies included investigations into the distribution and plant availability of faecal P, and the effect of slope and fertiliser P addition on changes in a range of soil P fractions.

"Above-ground" compartments of the P cycle.

Two major "above-ground" compartments of the P cycle were studied, i.e., pasture P uptake and P return to soil via faeces. Results were combined to enable investigation of animal losses.

Pasture components.

Dry matter yield and P uptake increased with increasing rate of P fertiliser and, within a fertiliser rate, decreased with increasing slope. Response curves to increasing rate of P fertiliser reached a maximum on steeper slopes but did not reach a maximum on campsites and easy-slopes. This was due to the effect of increased nitrogen return via urine to these slopes at high rates of P fertiliser (associated with high stocking rates). This nitrogen/P interaction may mean that the Olsen P test requires recalibration with reference to nitrogen status for these areas.

Dry matter yield and plant P uptake followed a seasonal pattern in the order spring ≥ summer > autumn > winter. In contrast, pasture P concentration was highest in autumn (following application of P fertiliser) and lowest in summer.

A highly significant relationship ($P < 0.01$) was measured between pre-grazed and post-grazed pasture, i.e., post-grazed pasture P% = 0.92 pre-grazed pasture P% + 0.02 $r = 0.98^{**}$. This relationship indicates that at most times of the year (when pasture P concentration is above 0.16%) P intake by animals will be slightly higher than that indicated by conventional measurements of pasture P concentration. As a consequence P utilisation will be slightly higher than pasture utilisation which will, effectively, increase the animal P losses described for the Computerised Fertiliser Advisory Scheme (CFAS) model.

Faecal components

Faecal distribution was found to be strongly influenced by slope. The amount of faecal material (kg ha^{-1}) per slope category declined by approximately half in moving from one slope category (10^{o} range) to the next in order of increasing steepness.

Total P and inorganic P concentration of faeces increased with increasing rate of P fertiliser, but organic P was little affected. Similarly, there was a marked seasonal variation in total and inorganic faecal P but not in organic faecal P. The fluctuations in total and inorganic P followed the same pattern as pasture P concentration and a close linear relationship between plant and faecal P (i.e., faecal P concentration = 3.19 mean pasture P concentration - 0.09 r = 0.94**) was found.

The physical and chemical decomposition of faecal material was studied in the field during winter and summer. Faecal material decomposed physically before doing so chemically, i.e., P was not leached from faeces in the field as the material tended to disintegrate before this could occur. In winter, disintegration occurred within a month of deposition due to conditions of high rainfall and biological activity. In summer, disintegration took up to three months due to dry conditions and low biological activity. Faecal material in the form of pellets disintegrated more rapidly than pad material. The larger surface area of pellet material with an associated increased potential for "attack" by earthworms or raindrops was probably responsible for this difference. The difference in rate of breakdown of pad and pellet material means that in summer, when the faecal material tends to be in the form of pellets, it is "predisposed" to physical attack. In spring, when faecal material tends to be excreted in the form of pads, climatic conditions are such that breakdown will be rapid despite the form of the faeces.

Faeces on campsites disintegrated more rapidly than on steeper slopes. This was probably a reflection of higher macrofauna activity and moisture conditions on campsites than on steeper slopes. Not only was the faecal P input larger on campsites than on steeper slopes due to P transfer via animals, but also the rate of P release from faeces was faster on campsites than steeper slopes.

The plant availability of faecal inorganic P in comparison with fertiliser P was investigated under field conditions using the technique of inverse isotope dilution. Under autumn conditions of low pasture growth there was little uptake of either faecal P or fertiliser P. During spring, when conditions were conducive to plant growth and breakdown of faecal material, faecal inorganic P appeared to be approximately half as available as P derived from monocalcium phosphate during the relatively short time span of the trial (two months).

The relative availability of faecal P and fertiliser P were not examined over a sufficiently long time period to be able to resolve the debate on whether the former becomes more or less available with time than the latter. However, during the relatively short time span of the trial (two months) fertiliser P appeared to be approximately twice as available as faecal P. Further research is necessary in order to validate the assumption made within the CFAS model that faecal P has the same ultimate value as fertiliser P. It was suggested that use of the inverse isotope dilution in the field using ^{33}P instead of ^{32}P may assist this research.

Animal Losses

Losses of P due to animals measured in this trial were considerably lower (e.g., 40%) than those measured in the trial from which the CFAS animal loss factors (ALF's) were derived initially. Reasons for this difference included the fact that annual pasture P concentration in this trial did not reach the value assumed within the CFAS model. Another factor was that faecal distribution in the present trial was more uniform, and associated ALF values were therefore lower, than measured in the trial from which the CFAS animal loss factors were derived. This was probably due to differences in paddock size and topography. Further research on the effect of these factors on distribution of faeces was suggested as fertiliser P requirements are influenced greatly by faecal P return.

Results from the present trial suggest that for "Easy" hill country a lower animal loss factor than that currently used within the CFAS model is appropriate.

The ratio of faecal P return to plant P uptake was not affected by rate of P fertiliser addition (i.e., increasing stocking rate) but was found to decrease markedly with increasing slope.

Campsites received considerably more P in the form of faeces than could be utilised by plant P uptake whereas there was a deficit on all other slopes. This suggests that different slopes within a paddock may require different rates of P fertiliser addition if the objective is to balance losses. If this is the case, applying an average rate of P fertiliser to an entire paddock means that some areas will be receiving surplus P whereas others will be receiving insufficient P. Thus, although "equilibrium" or maintenance conditions may be achieved when the paddock as a whole is considered, that "equilibrium" will be compounded from increases and decreases in different areas of the paddock.

"Below-ground" compartments of the P cycle

The magnitude of soil P fractions, and the effect of slope and P fertiliser rate upon them, plus the plant availability of these soil P fractions was investigated. Results were combined to evaluate losses of P in the soil in comparison with those defined by the CFAS model as being due to immobilisation, runoff and leaching.

Soil P fractions

A study of the effect of P fertiliser addition and slope on the "below-ground" compartments of the P cycle was carried out by examining changes in P fractions over a four year period. With increasing rate of P fertiliser addition, increasing amounts of P were found in the non-occluded fraction (containing "aluminium-" and "iron-P") of the inorganic P pool. For a given fertiliser rate, the rate of increase in non-occluded P was much larger on campsites than steeper slopes, indicating that this fraction played an active part in P cycling in hill country.

In contrast, calcium-bound P appeared to be influenced more by P fertiliser rate than slope. The large increase in this fraction observed on all slopes at high rates of P fertiliser addition (50 and 100 kg ha^{-1}) suggested that the unreacted P rock component of superphosphate was accumulating as calcium-bound P and was playing a relatively inactive role in P cycling. An increase in this fraction was also apparent at moderate rates of P fertiliser addition on all slopes but because of variability and the lower magnitude of the increase no firm conclusions could be drawn.

An increase in organic P levels occurred on all slopes at all P fertiliser rates during the period of the trial. This increase decreased with increasing slope. On campsites the increase was higher at lower rates of P fertiliser than at high rates. An increased rate of P mineralisation was postulated to have occurred at high rates of P fertiliser.

In any one year Olsen P was found to increase with increasing rate of P fertiliser and decrease with increasing slope. Whereas the effect of slope was significant ($P<0.01$) from the beginning of the trial, the effect of P fertiliser rate did not become significant until after two to three years of differential topdressing had occurred. A high degree of variability occurred in Olsen P measurements which made it difficult to establish trends in Olsen P over the entire four year period. Although it was clear that Olsen P was increasing on easy- and steep-slopes at very high rates of P fertiliser (100 kg ha^{-1}) and decreasing at low rates (10 kg ha^{-1}) at moderate rates of P fertiliser (20 and 30 kg ha^{-1}) no clear trends were evident.

These findings for Olsen P have direct implications to the precision of the CFAS model as firstly, maintenance P recommendations are made on the basis that equilibrium conditions (as indicated by an Olsen P which is constant from year to year) exist within the system under consideration and secondly, short-term P recommendations are calculated using maintenance P requirements modified by a factor which is calculated from a knowledge of Olsen P levels and desired relative yield.

Results from the present trial indicated that it was extremely difficult to prove the existence of equilibrium conditions by the use of Olsen P. Also, Olsen P is unlikely to reflect changes in P fertiliser additions for at least two years and may take longer than four years depending on the rate of application. Furthermore, annual variability in Olsen P may result in the use of an inappropriate modifying factor.

Plant availability of soil P fractions

The plant availability of the P fractions monitored in the field trial was assessed in an exhaustive cropping glasshouse study over a period of eleven months. Under these intensive and exploitive conditions non-occluded P was found to be highly correlated ($r = 0.91^{**}$) with plant-available P. Organic P, occluded-P and calcium-bound P were considered unavailable. Therefore, any measured annual increases in these fractions may constitute a loss of P to the cycling pool.

At a similar depth of sampling (0-7 cm) both initial Olsen P and water-extractable P were found to be highly correlated ($r= 0.93$ ** and 0.97 **, respectively) with cumulative P uptake. Whereas the relationship for water-extractable P was found to be independent of soil depth, the relationship for Olsen P was improved (r = 0.96 **) if depths were considered separately (0-3 and 3-7 cm).

Soil P losses

Soil P losses due to immobilisation, runoff and leaching are an important component of the CFAS model. Figures for soil P losses used within the CFAS model were not calculated directly, but were estimated by difference between fertiliser P inputs and P output in pasture product.

Attempts were made to validate the CFAS soil loss for the soil group on which the trial was based. Indirect assessments were made using data collected from the 20 and 30 kg ha^{-1} P paddocks which, for several reasons, were considered to be near "equilibrium". It was found that soil "losses" due to increases in occluded P and calcium-bound P (i.e., those inorganic P pools thought to be least plant available) were similar to those inferred in the CFAS model. When increases in organic P were included, as implied by the CFAS model, the soil losses appeared to be unrealistically high for developed conditions. This cast doubt on whether or not an increase in organic soil P should be classed as a loss of P.

Fertiliser P requirements

Using data collected throughout this study, the effect of slope on both maintenance and short-term P fertiliser requirements was examined.

Maintenance P

Maintenance P requirements on various slope groups were calculated using plant P uptake and faecal P return data with soil losses calculated using the same CFAS soil loss factor for each slope group. It was found that maintenance P requirements varied little according to slope group. The use of the same soil loss factor on all slopes and the comparatively uniform return of faecal P in this particular trial limits the significance of this finding.

Short-term P

Short-term P requirements were calculated for each slope group in the same way as for maintenance P requirements but were modified according to whether the Olsen P value was higher or lower than that considered necessary to maintain the appropriate relative yield. Requirements were found to vary according to slope. Easy-slopes had the highest P requirement within a paddock, and P requirement decreased with increasing slope. Campsites, having a P surplus due to faecal P returns, had no requirement for P in the short-term.

This finding is of practical importance when considering P requirements on a paddock basis. Given that easy-slopes require most P, and tend to be the most P responsive areas within a paddock, paddocks or areas of a farm predominantly "easy" in nature should be topdressed at higher rates of P fertiliser than those areas predominantly "steep" in nature. Alternatively, if priorities need to be made, preference should be given to applying fertiliser to paddocks which have the largest proportion of "easy" areas.

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APPENDIX I

Topography of the individual paddocks within the trial.

Paddock Number	P Fertiliser rate (kg ha^{-1})	Grazing regime	Slope 0-10°	 11-20°	 21-30°	 31°+
1	10	R	9	57	29	5
2	30	C	11	59	26	4
3	20	C	11	32	29	29
4	100	C	12	51	28	9
5	50	C	36	39	17	8
6*	10	R	26	42	16	16
7	30	R	29	45	18	8
8	100	C	12	51	25	12
9	20	R	41	54	4	1
10	30	C	17	46	25	12
11*	50	R	17	36	26	19
12	10	C	19	40	24	17
13	100	R	7	27	30	35
14	20	C	12	46	27	16
15	50	C	9	39	31	21
16*	20	R	9	29	33	29
17*	30	R	13	47	29	11
18	10	C	9	32	33	26
19	50	R	6	32	37	25
20*	100	R	18	33	25	24

where R indicates rotational grazing
C indicates continuous grazing
* indicates paddocks in intensively sampled subtrial

APPENDIX II

Rainfall (mm)

Month

	J	F	M	A	M	J	J	A	S	O	N	D
1980												
Rainfall	150	112	175	113	50	188	163	125	125	63	213	138
Raindays	15	12	20	10	15	19	23	19	25	17	22	16
1981												
Rainfall	83	52	75	177	78	250	185	152	135	107	127	137
Raindays	8	12	15	14	15	23	17	20	25	12	13	13
1982												
Rainfall	74	96	124	135	112	93	106	65	79	161	42	115
Raindays	9	7	10	9	17	13	15	24	14	22	10	16
1983												
Rainfall	121	18	98	151	108	138	40	91	156	207	63	138
Raindays	17	6	14	15	18	18	5	13	20	19	11	16
1984												
Rainfall	129	118	166	59	115	106	159	229	109	38	117	160
Raindays	10	10	17	10	15	18	16	25	12	14	13	11
1985												
Rainfall	97	143	98	68	129	219	129	115	84	70	137	141
Raindays	NA	7	11	9	5	20	21	13	18	13	15	13

NA = data not available

APPENDIX III

Estimation of the Animal loss factor (ALF) as estimated for the CFAS (Gillingham, pers. comm.).

Calculations are shown for data from the 30 kg ha^{-1} P addition paddock.

Estimation of P transfer per SU per single slope category.

Campsites -

126% of P uptake returned in faeces, i.e., zero loss per SU.

11-20^{o} slopes
28% of pasture P uptake not returned in faeces pasture production = 11182 kg ha^{-1} of DM.

Total P uptake = 36.01 kg ha^{-1} at 100% PU and 550 kg SU^{-1} of DM
11182 kg DM = 20.3 SU ha^{-1}.

P transfer = 36.01 x 0.28 = 10.08 kg

P transfer SU^{-1} = $\frac{10.08}{20.3}$ = 0.50 kg SU^{-1} of P

21-30^{o} slopes
45% of pasture P uptake not returned in faeces.

Pasture production = 9103 kg ha^{-1} of DM
Total P uptake = 26.34 kg ha^{-1} of P
at 100% PU and 550 kg SU^{-1} of DM
9103 kg ha^{-1} = 16.6 SU ha^{-1}
P transfer = 26.34 x 0.45 = 11.85 kg
P transfer SU^{-1} = $\frac{11.85}{16.6}$ = 0.71 kg SU^{-1} of P

31+^{o} slopes
79% of pasture P uptake not returned in faeces
pasture production = 7907 kg ha^{-1} of DM
Total P uptake = 21.41 kg ha^{-1} of P
at 100% PU and 550 kg ha^{-1} of P
7907 kg DM = 14.4 SU ha^{-1}
P transfer = 21.41 x 0.79 = 16.91
P transfer SU^{-1} = $\frac{16.91}{14.4}$ = 1.17

On a per paddock basis ALF's are calculated using topographic survey data:-

For the actual topography of the paddock -

Slope	% area	Pasture production	Equivalent SU^{-1}
0-10°	13	15132	3.6
11-20°	47	11182	9.6
21-30°	29	9103	4.8
31°+	11	7907	1.6
			19.6

P transfer SU^{-1}

Slope		Total P loss
0-10°	0	0
11-20°	0.50 x 9.5	4.8
21-30°	0.71 x 4.8	3.4
31°+	1.17 x 1.6	1.9
		10.1

Total P loss = $\frac{10.1}{19.6}$ = 0.52

For "Easy" paddocks:

Slope	% area	Pasture Production	Equivalent SU ha^{-1}
0-10°	10	15132	2.8
11-20°	40	11182	8.1
21-30°	40	9103	6.6
31°+	10	7907	1.4

P transfer SU^{-1}

Slope		Total P loss
0-10°	0	0
11-20°	0.50 x 8.1	4.1
21-30°	0.71 x 6.6	4.7
31°+	1.17 x 1.4	1.6
		10.4

Total P loss = $\frac{10.4}{18.9}$ = 0.55