A COMPARISON OF TWO PHOSPHORUS SOIL TESTS AS INPUTS TO A PASTURE GROWTH MODEL

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ABSTRACT

Glasshouse and field studies were carried out to investigate relationships between plant growth and extractable soil phosphorus and between fertilizer phosphorus and extractable soil phosphorus respectively. The purpose of the studies was to provide information with which to quantify the parameters of a simple model designed to predict relative pasture yield as a function of soil and fertilizer phosphorus.

The relationship between yield and water-extractable soil P differed markedly between two soils of different P retention properties in glasshouse studies using both intact cores and conventional pots. To illustrate this difference, the levels of water-extractable P (0-8 cm depth) in intact cores required for 90% of maximum yield were 12.7 and 2.6 μg/g soil in the soils of lower and higher P retention respectively. In contrast, the relationship between yield and Olsen (bicarbonate-extractable) P was much less soil type dependent. The corresponding levels of Olsen P in intact soil cores required for 90% of maximum yield were 17.7 and 17.8 μg/g soil respectively. For modelling purposes, the Olsen procedure was therefore considered to provide a more suitable index of plant available soil P from which to predict pasture production on soils differing in P retention.

The proportion of yield variation accounted for by differences in extractable soil P was 25% or less in initial harvests from the intact cores, 50-75% in later harvests from the intact cores and 89-97% in the pot experiments. The results of the intact core experiments, however, were considered to be more directly applicable to the field situation than were the results of the pot experiments.

Seasonal changes in extractable soil P in Tokomaru silt loam included an increase during the dry season to reach a peak in late autumn followed by a decline in winter. The magnitude of these changes with respect to Olsen P was approximately 2.5 and 5 μg/g soil in the 0-8 cm and 0-4 cm depths respectively. A subsequent decline in extractable soil P during the spring and second summer was attributed largely to plant uptake of soil P and its loss in discarded clippings.

The application of superphosphate increased extractable soil P in proportion to the rate applied. The increases per unit of applied fertilizer P, in both absolute terms and relative to an initial (time-zero) increase, were greater in a soil of low P retention (Tokomaru) than in a soil of high P retention (Ramiha). Water-extractable P (0-8 cm depth) was increased on average by 2.3 and 0.2 μg/g in the Tokomaru and Ramiha soils respectively six months after the application of 40 kg P/ha as superphosphate. The corresponding average increases in Olsen P (2.7 and 1.1 μg/g) were greater, and differed less between the soils, than the increases in water-extractable P. Thus, neither soil P extraction procedure was independent of soil type in terms of the effects of applied fertilizer P. For modelling purposes the effects of applied fertilizer would need to be assessed in a wider range of soils.

The level of water-extractable P in stored, air-dry soils was found to undergo short-term fluctuations, apparently due to changes in the conditions of extraction such as variations in the pH of distilled water. Longer-term increases of 25-100% in the level of water-extractable P of stored soils also occurred. No reason for the latter changes was apparent.

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CHAPTER 1

INTRODUCTION

The use of fertilizer, particularly phosphate fertilizer, has played a vital role in the productivity of New Zealand agriculture. The total amount of fertilizer used has steadily increased over the years, surpassing one million tonnes per annum in the mid-1950's and two million tonnes per annum in the mid-1960's. During the last fifteen years, between 1.7 m and 2.5 m tonnes per annum have been applied to New Zealand soils (Ministry of Agriculture and Fisheries, 1978). Variation between years, sometimes considerable, has reflected the overriding influence of the financial state of the farming industry on fertilizer use.

Most fertilizer used on New Zealand farms is manufactured from imported raw materials, the balance being imported in manufactured form. The total value of imported fertilizer materials is currently of the order of \$100 m per annum, of which about 65% is for raw rock phosphate and other phosphatic fertilizers (Ministry of Agriculture and Fisheries, 1978). Phosphate fertilizer is therefore not only a very important resource in New Zealand agriculture, but is also a very expensive one. Despite this, phosphate fertilizer applied to grazed pastures in recent years appears to have exceeded the maintenance requirements of New Zealand's livestock population (Karlovsky, 1975). Syers (1974) similarly concluded that fertilizer usage may be excessive, at least on certain soils, and in view of the inevitable increases in the price of phosphate fertilizer, considered there was a need for further research on the efficiency of fertilizer use on many soils.

Technically, efficient fertilizer use requires that wastage of fertilizer through the application of excessively high rates is avoided. Optimum fertilizer rates can be determined in specific situations by conducting field trials to measure the response of pasture to various rates of application. Such trials are often used to calibrate soil tests which are then used to assess the nutrient status of soils in areas where there is no information available from field trials.

A largely untested method, particularly in New Zealand, of evaluating fertilizer use in relation to optimum rates, times and frequencies of application, is systems modelling or more specifically the mathematical simulation of soil-plant relationships. Systems modelling has been defined as an activity involving the construction of a mathematical model of a system, generally but not necessarily followed by manipulation or experimentation with the model (Wright, 1976). A recent example of systems modelling in New Zealand is the development of a simulation model of an intensive pastoral beef grazing system, including soil, pasture, animal and management components, by Wright et al (1976). In the pasture component of this model, the potential growth rate of ryegrass-white clover pasture on any given day is determined by time of year and accumulated level of dry matter. The estimated potential growth rate is then modified by a temperature factor and a soil moisture factor to give actual growth rate.

A deficiency of the pasture growth model, however, is the absence of any soil nutrient component. To enable evaluation of the effects of alternative phosphate fertilizer policies on simulated pasture production, an attempt was made to develop a simple phosphorus (P) submodel (Smith et al, 1977). The overall pasture model would then integrate the separate effects of soil moisture supply, temperature and phosphate supply on plant growth.

The P submodel is based on two basic assumptions. The first is that relative pasture yield can be predicted from the level of plant available soil P if the relationship between these two variables is known. Extractable soil P is used as an index of plant available soil P because of problems associated with the definition and rapid measurement of the latter fraction. The relationship between relative yield (RY) and the level of extractable soil P (x) is represented in the P submodel by an exponential equation of the form:

$$RY = 1 - \frac{Be^{-cx}}{A}$$

where A is maximum attainable yield, B is the difference between maximum yield and actual yield when $x = 0$, and c is the curvature coefficient. If yield is zero when $x = 0$, then the equation simplifies to:

$$RY = 1 - e^{-cx}$$

Ideally, the soil P extraction procedure should be independent of soil type so that the magnitude of the c coefficient does not vary between different soils.

The second assumption made in the P submodel is that the level of extractable soil P at any given time can be predicted if it is known how the level changes over time and in response to applied fertilizer P. The relationship between the amount of fertilizer P applied (F) and the level of extractable soil P is represented in the P submodel by a linear equation of the form:

$$x_2 = x_1 + bF$$

where x_1 and x_2 are levels of extractable soil P before and after fertilizer application and b is the unit change in x per unit of applied F. The magnitude of the b coefficient can be expected to decrease with time as the extractability of the applied P declines.

Before the P submodel can be used to evaluate alternative fertilizer policies, it is necessary to know what values should be assigned to the coefficients in the equations representing the relative yield-soil P and fertilizer-soil P relationships. Unfortunately, there is a distinct lack of this type of information in relation to phosphate fertilizer use on New Zealand pasture soils. The aim of this study was to quantitatively investigate the above relationships.

CHAPTER 2

LITERATURE REVIEW

2.1 RELATIONSHIPS BETWEEN PLANT GROWTH AND SOIL P STATUS

2.1.1 Plant available soil P.

Plants growing in soil meet their P requirements by absorbing inorganic P from the soil solution. The amount of P in the soil solution at any one time is very small and must be renewed several times each day during the growing season to meet normal plant uptake (Barber, 1962).

The factors considered important in determining the ability of soils to supply P include the intensity (I), quantity (Q), capacity ($\Delta Q/\Delta I$) and kinetic factors (Williams, 1967). The intensity factor reflects the ease, or difficulty, of P withdrawal; in its simplest form intensity is usually regarded as the P concentration in the soil solution. The quantity factor refers to the solid phase P that can replenish the soil solution and is often equated with the labile P pool. The capacity factor represents the ability of the soil system to maintain the solution P concentration during P withdrawal by plants (also termed buffering capacity). The kinetic factor refers to the rate of P release from the solid phase. Fried et al (1957) showed that P release was much more rapid than uptake by plants, so the kinetic factor is probably of lesser importance than the other P supply factors in most soils.

Precise measurement of plant available soil P would necessitate growing plants under conditions in which no other factor limits growth. Plant P uptake then provides a measure of the amount of soil P that is plant available. Under normal field conditions, however, plant growth and P uptake are usually modified by a number of other factors such as climate, disease or an inadequate supply of other nutrients. Actual plant P uptake in the field must therefore often be a poor approximation of that which would have been available for plant growth under more ideal growth conditions (Beckwith, 1963).

Since the measurement of plant P uptake only provides information regarding available soil P after the event , a large number of biological and chemical "soil test" procedures have been investigated in an attempt to find quicker and easier methods of assessing plant available soil P. Only the more commonly used chemical procedures will be considered in this review.

2.1.2 Chemical extraction of "available" soil P.

It is very difficult, if not impossible, to measure the soil P that is available to plant roots using a chemical extractant. The early use of dilute acids can in general be regarded as arising from the now largely abandoned idea of simulating the action of plant roots (Hesse, 1971). With most extraction methods the intention is therefore to remove amounts of soil P which can be correlated with that taken up by a test crop grown in the same soil. Chemical extraction thus provides only a "relative index" of available soil P, not an absolute measure of it (Beckwith, 1963; Thomas and Peaslee, 1973). In this review the term "extractable" will therefore be used in preference to "available" to describe those quantities of P which are chemically extracted from soils.

The relative importance of the intensity and quantity factors in controlling soil P supply can be expected to vary depending on the nature of the crop, particularly in relation to the size of the root system and whether the crop is fast or slow growing (Williams, 1962). Accordingly, a wide variety of chemical extractants and extraction conditions have been used in various parts of the world. Bingham (1962) described 31 chemical methods, involving 14 different extractants, which were in use throughout the USA. Over half of the methods were based on three extractants, these being 0.025N H_2SO_4 + 0.05N HCl (as used in the Mehlich method), 0.025N HCl + 0.03N NH_4F (Bray and Kurtz, 1945) and 0.5M $NaHCO_3$ solution (Olsen et al, 1954a).

Weak extractants such as distilled water (eg Bingham, 1949; van der Paauw, 1971) and dilute neutral salt solutions extract only small amounts of P and so mainly reflect P intensity. In contrast, strong extractants such as the acidic solutions used in the methods of Mehlich (see above) and Truog (1930) remove larger amounts of P and give predominantly quantity measurements. Lying between these extremes are a range of extractants that provide composite quantity-intensity indices and which include the Olsen bicarbonate reagent (Williams, 1967).

2.1.3 Soil test correlation studies.

The usefulness of any soil test index of available P depends on the extent to which it can account for variation in one or more plant criteria when plants are grown in soils which vary in terms of the amount of P extracted by the soil test in question (Dalal and Hallsworth, 1976). The plant criteria with which extractable P is usually correlated include actual yield, P uptake, relative (percentage) yield or yield response to added P. Sometimes extractable P is also correlated with plant percentage P content (Pack and Gomez, 1956; John et al, 1967) or with other available P indices such as "A" values or Neubauer values (Soil Test Work Group, 1956).

Relative yields are often used to reduce the scatter in soil test correlation data caused, for example, by differences in climate and other soil properties (Cate and Nelson, 1971). The plant criterion used, however, may influence the degree of correlation. Extraction methods which provide mainly P quantity measurements tend to correlate better with P uptake than with yield, while the reverse tends to be true of methods which measure mainly P intensity (Williams, 1962; Williams and Knight, 1963).

Most soil test correlation studies have been conducted under greenhouse conditions from which the most promising method(s) is selected for subsequent field calibration. The greenhouse gives much quicker results, involves less work and permits much more effective control of the many factors other than soil P which affect plant growth. Consequently, better soil test correlations are invariably obtained with greenhouse data than with field data (Soil Test Work Group, 1956).

It is commonly found that a particular extraction method provides a reliable index of plant available soil P for only a limited range of soils. In Scotland, Williams et al (1952) found that the Truog method correlated best with crop response to added P on soils derived from slate and basic igneous material, where as 2.5% acetic acid was best for soils of granitic origin and neutral ammonium fluoride for soils derived from sandstone. When all soils were considered as one group the Egner lactate method gave the best correlations with crop response.

In Canada, John et al (1967) found that Olsen-extractable P was best correlated with the P content of alfalfa on Chernozemic and Brunlisolic soils, while the Bray No 1 method was best on Regosolic and

Gleysolic soils. None of the soil test methods studied was satisfactory for Solonetzic and Podzolic soils. Only the Olsen and Bray methods gave satisfactory correlations with alfalfa P content when all soils were considered as one group.

The Bray No 1 method was developed in the USA by Bray and Kurtz (1945) for the extraction of adsorbed soil P and has often been found to correlate with plant growth better than other extraction methods (Olson et al, 1954; Baker and Hall, 1967; Martens et al, 1969). Smith et al (1957) concluded that the Bray method was superior to the Olsen method not only for acid soils but also for a range of calcareous soils in Western Kansas. The Bray method was also found to be satisfactory for New Zealand soils in both greenhouse (Grigg, 1968b; Sherrell, 1970) and field studies (Grigg, 1965b, 1972). The success of the Bray No 1 method is probably due to the test being relatively unaffected by other soil properties (Soil Test Work Group, 1956) or by secondary reactions during extraction (Olsen et al, 1954a) and because it extracts predominantly Al-P with minimal attack on unavailable forms of Ca-P despite the low pH of the extractant (Grigg, 1965a, 1972).

Prior to 1975, the standard test in New Zealand for soil P was the Truog method. It was selected on the basis of correlation of extractable P with the growth of oats in Mitscherlich - type pot experiments and with the results of observational field trials on pasture (Davies, 1952). The method extracts predominantly Ca-P (Grigg, 1965a) in contrast to the Bray No 1 method. Although the Truog method worked well on many soils (Grigg, 1968b; Sherrell, 1970), it failed on recent and gley soils in which essentially unavailable Ca-P often occurs in the silt and sand fraction (Grigg, 1968a,1972).

The Olsen bicarbonate procedure, which was originally developed for calcareous soils, has now replaced the Truog method in New Zealand. Since it involves desorption of part of the surface-held soil P, the Olsen method is preferable, at least in theory, to the dissolution-type extraction of the Truog test (Syers, 1974). The Olsen procedure extracts predominantly Al-P and Fe-P from acid soils (Grigg, 1965a,1972). The narrow soil:solution ratio (1:20) and short extraction time (30 minutes) favour intensity measurement, but in acid soils the high pH (8.5) of the extracting solution favours quantity measurement.

The Olsen method has been found to correlate well with crop performance in many field and greenhouse studies involving both calcareous and non-calcareous soils (Olsen et al, 1954a; Olson et al, 1954; Moser, 1957; Williams and Cooke, 1962; John et al, 1967; White and Haydock, 1967; Ogot, 1970; Grigg, 1972). Shifting the emphasis of the Olsen extraction further in favour of P quantity measurement, through using a wider soil:solution ratio (1:50) and longer extraction time (up to 16 hours), has been found to improve correlations with plant criteria in a number of studies (Colwell, 1963; McLachlan, 1965; Grigg, 1968a, 1972; Grigg and Stephen, 1974; Montgomery and Rubenis, 1978).

Although often found to be a more reliable index of available soil P than other methods, the Olsen procedure is not independent of soil type. Welch et al (1957) observed that the level of Olsen-extractable P required to give a certain percentage of maximum yield varied between soil types. Bishop et al (1967) and Helyar and Spencer (1977) fitted the Mitscherlich equation to soil test correlation data from field trials and found the c value varied with soil type. Matar and Samman (1975) obtained no correlation between Olsen-extractable P and P response of wheat grown on a wide range of Syrian soils in pots. However when the soils were divided into groups based on genetic origin, Olsen-extractable P and response to added P were highly correlated within individual soil groups.

The soil type dependence of the Olsen procedure has often been attributed to the effects of buffering capacity. In Australia, Barrow (1967) concluded from pot experiments with soft brome grass that the modified Olsen procedure overestimated the availability of P on soils of low buffering capacity and vice versa. The differential effects of buffering capacity were greatest initially but became smaller as the number of harvests increased.

Working with pastures, Ozanne and Shaw (1968) found the level of Olsen-extractable soil P needed for near-maximum production to vary widely in soils of different buffering capacity. When corrected for buffering capacity, Olsen P values were closely related to P requirements. The importance of buffering capacity in influencing both the plant availability of soil P and the fertilizer P requirements of plants has been demonstrated more recently in both field (Helyar and Spencer, 1977) and greenhouse studies (Holford and Mattingly, 1976; Holford, 1976). Unfortunately it is not possible to measure the buffering capacity of a soil with a chemical extractant.

A major disadvantage of the Olsen procedure, therefore, as with the Truog and other empirical soil testing procedures, is the need for extensive field calibration on a wide range of soils. Recently, Ryden et al (1976) proposed a non-empirical water extraction method, based on detailed P sorption isotherm studies, as an index of readily available P in soils. Since this method, which involves two one-hour extractions at a soil:solution ratio of 1:40, was shown to be essentially specific for more-physically sorbed P in contrasting subsoils and in a range of surface soils (Ryden and Syers, 1977b), it was considered likely to be independent of soil type. Limited evidence in support of this suggestion was provided by a preliminary greenhouse experiment involving the growth of ryegrass in three contrasting soil types (Luscombe, 1976).

A soil test method based on water extraction (one-hour shaking at a 1:60 soil:solution ratio following premoistening for 22 hours) has been in use for all arable soils in the Netherlands since 1970. Based on greenhouse studies with wheat grown on a wide range of soils from several countries, this method too is considered to be essentially independent of soil type (van der Paauw, 1971). On permanent grassland, however, better results have been obtained with stronger extractants such as 1% citric acid or an ammonium lactate-acetic acid mixture (van der Paauw, 1974).

Many other empirically-based water extraction methods have also been evaluated, some of which have given high correlations with the performance of various crops grown under greenhouse conditions (Bingham, 1949; Olsen et al, 1954b; Larsen et al, 1958; Thompson et al, 1960; van Diest, 1963; Blanchar and Caldwell, 1964; McLean et al, 1964; Williams, 1967).

A non-empirical soil test procedure based on interpretation of quantity-intensity relationships might be expected to most closely approximate the "ideal" method (Ryden et al, 1976), although Holford and Mattingly (1976) consider it impossible to set a universal "critical" value for any quantity or intensity parameter of available P which applies to all soils under all conditions.

2.1.4 Regression equations used to describe soil test - plant yield relationships.

The relationship between extractable soil P and plant yield is usually found to conform with the diminishing returns concept; ie as the level of extractable P increases the yield increment per unit of extra soil P decreases. Mitscherlich, in 1909, described the diminishing returns relationship by a first-order rate differential equation (Analogides and Rendig, 1972):

$$\frac{dy}{dx} = k(A - y)$$

This equation assumes that when only one nutrient factor (x) is limiting, the differential increase of yield (dy) with respect to differential increase of the nutrient factor (dx) is proportional to the maximum attainable yield (A) minus the actual yield (y). The more usual form of the Mitscherlich exponential equation is:

$$y = A(1 - e^{-cx})$$

which has the following linear form:

$$\log (A - y) = \log A - cx$$

where c is a curvature coefficient considered by Mitscherlich to be constant for any particular nutrient.

The Mitscherlich equation, in one form or another, has been widely used to describe soil test correlation data for a range of crops (Bray, 1944,1945; Smith and Sheard, 1957; Yurtsever et al, 1965; Bishop et al, 1967; Ozanne and Shaw, 1967; Helyar and Spencer, 1977; Peaslee, 1978). The curvature coefficient (c) is known to vary with a number of factors, including soil type (Helyar and Spencer, 1977), plant species and grazing management in the case of pasture (Bowden and Bennett, 1975). For grazed pastures, therefore, variation in the value of c is to a large extent a reflection of soil type differences (such as buffering capacity) providing pasture management is reasonably uniform.

Most non-linear sets of data can be accurately described by polynomial expressions (Landsberg, 1977), which have the basic form:

$$y = a + bx + cx^2 + \ldots..$$

where a, b and c are constants. Colwell (1963) favours polynomials over exponential functions because on average they tend to give a better regression fit of yield data and can accommodate a maximum yield. Quadratic polynomials were used to describe soil test - yield (or P uptake) data in the greenhouse studies of Ozus and Hanway (1966), Baker and Hall (1967), Grigg (1968a), Martens et al (1969), Sherrell (1970), Grigg and Stephen (1974) and Matar and Samman (1975). Landsberg (1977), however, describes polynomials as biologically undesirable since the constants seldom have any conceptual significance and the more constants there are, the less significant they become.

A third type of regression equation, used much less frequently than exponentials and polynomials, is the log function:

$$y = a + b \log x$$

where a and b are constants. Welch et al (1957) fitted this equation to yield-soil test data for Ladino clover grown on three different soil types. Grigg (1968b) similarly described yield-soil test data for ryegrass grown in pots using a log function.

The log function, in addition to the Mitscherlich equation and a quadratic polynomial, was used by White and Haydock (1967) to represent the relationship between extractable P (according to four soil test methods) and various plant criteria for lucerne and phaseolus grown on a range of soils in pots. The exponential function gave the best fit for relative yield on soil test, while the quadratic equation gave the best fit for P uptake on soil test. The correlation between absolute yield response and soil test was generally low, the best fit being given by the quadratic function. The only instance in which the log function gave the best fit was for the regression of Morgan's acetic acid-extractable P on absolute yield response to added P.

As with soil test extraction methods, there appears to be no single type of regression equation that is best in all situations. Personal preference often appears to play a large part in which type is selected, frequently no reason being given why a particular regression function was used. An advantage of the Mitscherlich model is that real meaning can be attached to the constants or coefficients. In addition, it appears to describe yield-soil test data even better than data expressing yield as a function of applied nutrient as originally proposed by Mitscherlich (Peaslee, 1978). Theoretical considerations aside, the most useful equation is likely to be that which most closely fits the data in question.

2.2 TEMPORAL VARIATION IN EXTRACTABLE SOIL P UNDER FIELD CONDITIONS

2.2.1 Field sampling procedures.

Few studies have been undertaken specifically to examine changes over time in the level of extractable soil P. Those which have been made have involved repeated sampling of a given area at intervals of one month (Blakemore, 1966; Garbouchev, 1966; Childs and Jencks, 1967; Saunders and Metson, 1971) or more frequently (Ball and Williams, 1968; Williams, 1968; Jessop et al, 1977). Some additional information is also available from a few studies carried out for purposes other than the investigation of seasonal variation in extractable soil P (Grigg, 1966; Sharpley et al, 1977).

Seasonal variation can be masked by spatial variation; ie variation in extractable soil P levels between different parts of a paddock or plot. Such variation tends to be high in grazed fields (McIntyre, 1967; Cameron et al, 1971) and has been shown to increase as mean levels of extractable P increase (During and Mountier, 1968). Ball and Williams (1968) were unable to detect any seasonal trends because of the extent of spatial variability. In many instances, this source of variation can be reduced to an acceptable level through intensive sampling of small replicated plots (Robertson and Simpson, 1954; Garbouchev, 1966; Mountier and During, 1966; Saunders and Metson, 1971; Jessop et al, 1977).

Other workers (eg Gallagher and Herlihy, 1963; Blakemore, 1966; Childs and Jencks, 1967) have preferred to sample whole fields, this being more representative of conditions encountered in normal soil testing. The results obtained from this latter type of approach might be expected to include a larger component of spatial variation than those obtained from more intensively sampled small plots.

Most investigators have used grazed pastures in preference to mown swards in assessing seasonal variation. Contamination of soil samples by animal excreta could contribute to the variation in extractable soil P between samplings. During and Mountier (1967) studied both grazed and mown swards and concluded that spatial variation in extractable soil P was not significantly greater for a grazed sward compared to one that was mown. Over the three year trial period, however, mean extractable soil P levels declined under the mown sward relative to those under the grazed sward, presumably as a result of P being removed in clippings from the mown sward.

2.2.2 Laboratory extraction procedures.

A variety of chemical extraction procedures have been employed in assessing seasonal variation. Soil P has been variously extracted with 0.2N HCl (Robertson and Simpson, 1954; Smith, 1959), Truog's 0.002N H_2SO_4 (Grigg, 1966; Mountier and During, 1966; Williams, 1968), Mehlich's 0.025N H_2SO_4 + 0.05N HCl (Childs and Jencks, 1967), Morgan's acetic acid (Gallagher and Herlihy, 1963), citric acid and water (van der Paauw, 1962), Olsen's 0.5M $NaHCO_3$ (Williams, 1968; Jessop et al, 1977) and 0.01M $CaCl_2$ and anion-exchange resin (Garbouchev, 1966; Saunders and Metson, 1971). Where more than one extraction procedure was used to analyse the same soil samples, broadly similar patterns of change in extractable soil P with time were usually observed (van der Paauw, 1962; Williams, 1968; Saunders and Metson, 1971), though not always (Garbouchev, 1966). Different methods tended to extract different amounts of P from the same soils, particularly in the case of 0.01M $CaCl_2$ and anion-exchange resin (Saunders and Metson, 1971).

2.2.3 Seasonal changes in extractable soil P.

A New Zealand study of the magnitude of errors associated with advisory soil test results (Mountier and During, 1966) found that the level of Truog-extractable P in Marton loam varied as much as 12 ppm between consecutive monthly samplings but showed no consistent trends with season. At sites on several other soils, however, temporal variance associated with extractable P values was smaller and not significantly greater than long-term laboratory variance. Similar results were obtained by Gallagher and Herlihy (1963) in Ireland for three unfertilized pasture soils sampled at four to six week intervals. Since whole paddocks were sampled in the latter study, though, any seasonal trends might have been masked to some extent by spatial variation.

Two Australian studies of seasonal variation employed 2-4 week sampling intervals. In the first study, Williams (1968) noted both short-term and long-term changes in extractable soil P. Between October and May, extractable P levels fluctuated about a fairly constant mean value, but during the subsequent winter-spring period, the mean level of extractable P declined to about half of its original value. Although he stated that the site was not grazed during the experiment, the author did not indicate how the pasture was managed or whether the decline in extractable soil P could have been caused by loss of P in discarded clippings.

In the second Australian study, Jessop et al (1977) observed that Olsen-extractable soil P fluctuated between samplings by up to 10 ppm, but showed no seasonal trends. Fluctuations were greater in the fallow and wheat sections of a cropping rotation than in the same soil growing medic pasture. Sudden increases in extractable P levels appeared to be related to previous periods of high rainfall. Mineralisation of organic P may partly account for such increases, since Thompson and Black (1947) found appreciable mineralisation occurred when air-dry soils were moistened.

A detailed study of seasonal variation in both soil and plant factors at seven pasture sites in New Zealand was undertaken by Saunders and Metson (1971). Significant temporal variation in the level of extractable soil P was detected at all sites though there were large differences between sites in the magnitude of these changes over time. The most consistent change was an increase in extractable soil P in summer. Similar observations during a particularly dry summer were made by Robertson and Simpson (1954) and Smith (1959) in the course of monitoring soil P levels over several years at five sites in East Scotland.

Grigg (1966) also noted indications of a seasonal increase in extractable P levels in summer, as did Yuen and Pollard (1951a, 1951b) in cultivated soils growing flax. Still other workers (Blakemore, 1966; Childs and Jencks, 1967) have found extractable P levels to be highest in the autumn. Saunders and Metson (1971) attributed increases in extractable soil P in summer to release of P from the decomposition of organic residues at a time when plant P uptake tends to be restricted by a soil moisture deficit.

A build-up of "available" soil P during the winter has been postulated (Scott and Cullen, 1965) to explain the general lack of pasture response to fertilizer P in spring. This has not been confirmed by P extraction data; often extractable soil P levels have actually been found to decrease during winter and, sometimes, early spring (Williams, 1968; Saunders and Metson, 1971; Sharpley et al, 1977). These observations are in line with the findings of Williams and Simpson (1965) that short periods of water-logging, as commonly occur in field soils in winter, reduced both extractable P and the availability of soil P to subterranean clover in pots.

A comprehensive study of changes in the level of extractable P in soils under various crops was carried out at Rothamsted and elsewhere in England (Garbouchev, 1966). The results were rather variable between different crops and different sites. Exchangeable soil P levels were generally highest in early spring and lowest in early autumn, while soil P soluble in 0.01M $CaCl_2$ tended to reach maximum values in late spring - early summer and minimum values in autumn in unfertilized plots. These latter findings contrast with those of Blakemore (1966) who obtained highest values for $CaCl_2$ - soluble P in autumn for grassland soils at Rothamsted and Woburn.

Van der Paauw (1962), in an analysis of rainfall patterns in the Netherlands, noted an association between cumulative rainfall and long-term trends in extractable P in soils of light texture. During periods (up to three years) of relatively low rainfall soil P levels increased, and conversely, in high rainfall periods the levels of extractable soil P declined. These long-term fluctuations appeared to be a reflection of the degree to which soil P was leached out of the soil sampling zone, and tended to be relatively greater for water-extractable P than for citric acid - extractable P.

Other than the observations of van der Paauw (1962), there is a lack of information regarding seasonal variation in water-extractable soil P. No field studies have yet been undertaken with the water extraction procedure proposed by Ryden et al (1976). Williams (1952) states that the concentration of P in water extracts of soils can be expected to vary widely during the year in response to seasonal changes in the electrolyte content of soils.

Although some of the reported changes in extractable P levels may not reflect real seasonal effects, certain trends are consistent in several studies. In particular, an increase during the dry season (summer and/or autumn) and a decline in the winter - early spring period have commonly been observed. In other studies no seasonal trends have been detected. Mountier and During (1966), for example, recorded some quite large short-term fluctuations in extractable soil P despite intensive sampling, suggesting that the data included a significant component of variation from some other source. In view of these inconsistent results, and the importance of soil testing as an aid in formulating fertilizer recommendations, there would appear to be a need for further investigation of seasonal variation in local pasture soils.

2.3 TEMPORAL CHANGES IN EXTRACTABLE P FOLLOWING P ADDITION TO SOILS

When a water-soluble P fertilizer, such as monocalcium phosphate, comes into contact with moist soil, it undergoes rapid dissolution (Lawton and Vomocil, 1954; Williams, 1969) which dramatically increases the soil solution P concentration. This effect is short-lived as various sorption and precipitation reactions result in the transfer of P from solution onto the solid phase of the soil in a labile form (Larsen, 1967). Slower changes follow which eventually give rise to less soluble and non-labile forms of P.

A large number of insoluble and sparingly soluble P forms may exist in soils, and the chemistry governing transformations between them and P in the solution phase is very complex (Larsen, 1967). It is mainly for this reason that studies investigating the nature of, and mechanisms involved in, the reactions that occur when P is added to soil, have often been conducted with individual soil components such as pure clays or oxides of aluminium and iron.

2.3.1 Changes in solution P concentration in shaken and incubated systems.

The decline in solution P concentration following P addition has invariably been found to follow a distinct pattern with an initial rapid decline preceding a much more gradual one. This two-stage process has been observed in many studies involving both soil components (Kuo and Lotse, 1972, 1973; Chen et al, 1973; Rajan et al, 1974) and whole soils (Rennie and McKercher, 1959; Hsu, 1964; Ryden et al, 1977). There appears to be general agreement that adsorption reactions are responsible for the initial rapid loss of added P from the solution phase (Rennie and McKercher, 1959; Hsu 1964; Munns and Fox, 1976), a process which may approach steady-state within a few hours.

In the second stage, loss of added P (immobilization) occurs very slowly and may take days or months to reach a true equilibrium, if ever (Kurtz et al, 1946; Hsu, 1964; Fox and Kamprath, 1970; Rajan and Fox, 1972). This slow reaction is not well understood nor is there complete agreement on the nature of the P compounds formed. Most investigators appear to favour sorption reactions, rather than precipitation reactions resulting in the formation of sparingly-soluble P compounds as advocated by Kittrick and Jackson (1956) and Talibudeen (1974).

Ryden et al (1977) recently concluded that slow immobilization results not only from an increase in the overall amount of P sorbed but also from an appreciable shift of sorbed P from the more physically sorbed form to the chemisorbed form. White and Taylor (1977), however, consider that neither sorption nor precipitation alone can adequately explain all aspects of P immobilisation, suggesting that both types of reactions may occur in soils. Evidence for both types of reaction was found by Gebhardt and Coleman (1974) in their allophanic tropical soils.

Concurrent with the decline in solution P concentration, it has been observed that the ease with which P may be desorbed by competing anions decreases (Evans and Syers, 1971; Barrow, 1974a; Ryden and Syers, 1977a). Isotopic exchangeability is also reduced (Talibudeen, 1958; Larsen and Widdowson, 1971; Barrow and Shaw, 1975b; Ryden and Syers, 1977a). The factors which affect the rate and extent of these reactions however, appear to have received only limited study. While temperature was shown to be important (Barrow and Shaw, 1975a, 1975b), the rate of the slow reaction between soil and added P did not differ greatly between a range of soils and was not related to the soils' short-term capacity to absorb P (Barrow, 1974b; Barrow and Shaw, 1975a). Munns and Fox (1976), on the other hand, observed different rates of P immobilisation between soils from two broad soil groups.

The reaction rate, or proportion of added P immobilized, was found to be independent of the amount of P added (Barrow, 1974a; Barrow and Shaw, 1975b). Similar results were obtained in the recent study of Rennes (1978) who concluded that for different rates of added P, there is a common "proportional decline" curve with respect to water-extractable soil P. These observations suggest that the overall immobilization reaction is first-order, and represents the sum total of a range of reaction rates each corresponding to a different soil surface (Barrow and Shaw, 1974).

The immobilization reactions which occur in soils have an important influence on the long-term effectiveness and residual value of added P. Although P interactions with both soils and soil components have been extensively studied, there still remains much uncertainty regarding the mechanisms involved. Temperature has been shown to be an important factor influencing the rate of immobilization of added P, but there are conflicting reports on whether the reaction rate differs between soils of contrasting sorption properties.

2.3.2 Changes in plant available and chemically extractable soil P following P addition.

2.3.2.1 Incubation and greenhouse studies.

A gradual decline in the effectiveness of added P for plant growth has been demonstrated by several studies in which P was added to soil in pots for various intervals prior to cropping (Devine et al, 1968; Massey et al, 1970; Barrow, 1973, 1974c). Barrow assessed the relative effectiveness of added P in terms of the ratio of the exponents in an exponential equation fitted to the various yield response data.

The rate at which the effectiveness of added P for plant growth declined was independent of the amount of P added (Barrow and Campbell, 1972) but very dependent on temperature (Barrow, 1974c). The rate of decline also tended to decrease with increasing ability to adsorb P in a wide range of soils studied by Barrow (1973). Devine et al (1968), on the other hand, found a tendency for the rate of immobilization to increase with increasing P adsorption capacity. Similarly, in more recent studies the immobilization rate was found to be highly correlated with the buffer capacity of four colliery shale soils (Fitter, 1974) and with the P sorption capacity of ten acid soils in the tropics (Enwezor, 1977).

Using a pot technique developed by Stanford and De Ment (1957), which provides a rapid measure of plant P uptake, Rennes (1978) was able to demonstrate that plant recovery of added P declined rapidly during the first ten days or so, then much more slowly up to 100 days. Rennes also showed that P removed in two sequential one-hour extractions with water (Ryden et al, 1976) similarly declined in a manner which corresponded closely to the decline in plant available P. Olsen-extractable P, however, showed no initial rapid decline, only a continuous gradual decrease over the 100 day period. Neither extraction method was considered to provide an accurate quantitative estimate of plant available P in the soil.

Borzsonyi and Fuleky (1978) also employed chemical extractants to follow changes in soil P levels after P addition to a range of Hungarian soils in pots. The pattern of decrease in soil P extracted by the Olsen method over 2½ years varied between soils, depending on soil pH and soil texture. In acid soils (pH < 7), Olsen P declined only gradually throughout the experiment, in contrast to calcareous soils, in which Olsen P initially fell rapidly and then more slowly during the next two years. The difference between these soils was attributed by Borzsonyi and Fuleky (1978) to the initial formation of readily soluble calcium phosphates in calcareous soils which were subsequently transformed rather quickly into a form much less soluble in Olsen bicarbonate solution.

In contrast to the study of Rennes (1978), short-term changes in extractable P levels were not assessed in the study of Borzsonyi and Fuleky (1978). The first samples were collected one week after P addition, at which time only 30-40% of the added P in the acid soils, compared to 60-70% in the calcareous soils, was Olsen-extractable.

The effect of soil texture in the study of Borzsonyi and Fuleky (1978) was illustrated by one calcareous soil of sandy texture. In this soil, Olsen P declined at a slower rate than in the other calcareous soils of finer texture, but still faster than in the acid soils. Kafkafi et al (1968) also found soil texture to have an important influence on the rate of decline in the Olsen extractability of added P. In a range of calcareous soils, Olsen P declined more rapidly in fine-textured than in coarse-textured soils.

2.3.2.2 Field studies.

Saunders et al (1963) measured the decline in effectiveness of applied fertilizer P for pasture growth on a high P-sorbing volcanic ash soil using a technique similar to that used by Devine et al (1968) and Barrow (1973, 1974c) in the greenhouse. P was applied in the form of granular double superphosphate at various rates up to 170 kg P/ha in each of four consecutive years. An important finding of the field study by Saunders et al (1963) was that the decline in effectiveness of applied P varied depending on the season in which it was measured. Fertilizer

P applied two, three and even four years earlier was almost as effective for pasture growth in spring and summer as newly applied P, but was much less effective in autumn. They attributed this to seasonal changes in the availability of soil P for pasture growth and discussed a number of possible factors involved.

In other field studies the rate of immobilization of fertilizer P applied at high rates has been measured for periods of up to five years. Larsen et al (1965), for example, applied up to 500 kg P/ha at 24 sites and then monitored changes in the L-value of samples taken from the field plots periodically for greenhouse study. Sadler and Stewart (1975) applied up to 1000 kg P/ha to three Canadian soils and measured changes in Olsen-extractable P levels for two years. Steele (1976) applied up to 500 kg P/ha to two sandy soils and measured changes in Truog and Olsen-extractable P levels over a one year period.

Larsen et al (1965) concluded from their five-year study that the loss of labile P by immobilization occurred exponentially. Calculated half-lives for the rate of fall in labile P content varied from one to six years. The rate of immobilization was found to be more rapid (ie short half-lives) in higher pH soils, as confirmed by Borzsonyi and Fuleky (1978) with Olsen-extractable P, but was unaffected by other soil properties such as clay content, organic matter content, extractable Fe and Al levels and unfilled sorption capacity.

Soil pH was also found by Sadler and Stewart (1975) to be directly related to the rate of decline in the availability of applied P as reflected by Olsen extraction. Although only three soils were studied, the rate of decline in the Olsen-extractability of added P between two months and two years was greatest in a calcareous soil and least (in fact undetectable) in an acid Gleysol.

In New Zealand, Steele (1976) found that the pattern followed by extractable P with time after applying fertilizer P to two soils derived from wind-blown sand, was essentially comprised of two phases. In the first, a more or less steady but quite rapid decline of about 30 weeks duration occurred, which was followed by apparently stable extractable P levels for the rest of the year. Unfortunately, no comparison was made with soils of finer texture.

In a recent New Zealand study, Rennes (1978) used water extraction to monitor the immobilization loss of fertilizer P applied at normal rates to soils in a cleared catchment area. The relative water extractability of soil P declined rapidly at first and then more slowly over an eight month period. The same pattern occurred in both aerially topdressed field soil and potted soil left in the field after mixing with fertilizer P. Variation in extractable P level between samples was, not surprisingly, much greater in the field soil than in the potted soil. No comparison was made in this study between Olsen and water extraction.

To summarize, both greenhouse and field studies have clearly demonstrated that soluble P applied to soils declines in plant availability and chemical extractability, at first rapidly and then more slowly. The rate at which this immobilization loss occurs has been shown to depend on several factors. Under greenhouse conditions, temperature, soil pH and soil texture were found to be important, with conflicting reports regarding the effect of P sorption capacity. Soil pH was also found to be important in one field study. It was shown that the decline in effectiveness of P applied to pasture varied depending on the season in which it was measured. However, very few field studies, and none at all in New Zealand, have compared soils of contrasting sorption properties. There is therefore a need to determine whether the P sorption capacity of New Zealand soils has an effect on the rate at which added P is immobilized in the soil.

2.3.3 Models used to simulate changes in soil P parameters following P addition to soils.

Mathematical simulation is a technique which has been used with increasing frequency in recent years to deal with certain problems involving soil-plant relationships. One reason for greater interest in mathematical modelling is the possibility it offers of making predictions about the behaviour of soil-plant systems in situations where direct measurement is unrealistic (Kline, 1973). At a more basic level than this, however, a model may be no more than one or more equations intended to describe a reaction or process such as the adsorption of P by soil or soil components when shaken with solutions in tubes in the laboratory.

2.3.3.1 Changes in solution P concentration.

Perhaps the simplest model capable of describing changes over time (t) in the amount of P adsorbed is a first-order kinetic equation of the type:

$$\frac{dx}{dt} = kC$$

where x represents adsorbed P, C is the solution P concentration and k is the specific reaction rate constant (Fried et al, 1957). According to this equation the rate of adsorption, or the rate of decline in solution P concentration, is directly proportional to the P concentration. Chen et al (1973) concluded that this simple model could describe the rate of P sorption by aluminium oxide and kaolinite over 60-day periods. In contrast, McLaughlin et al (1977) concluded that sorption of P by Fe gel did not obey first-order kinetics.

Other workers, particularly those concerned with describing the rate of isotopic exchange in soils and sediments, have used an equation composed of a sum of exponential terms, each representing a first-order reaction (Arambarri and Talibudeen, 1959; Li et al, 1972; Probert and Larsen, 1972). Probert and Larsen point out that as the time scale increases, the number of terms required to get a good fit to experimental data in a "sum of exponentials" model must also be increased.

The rate of decline in solution P concentration has not always been found to depend solely on the concentration itself, so that the use of first-order kinetics may often be an over-simplification (Larsen and Probert, 1968; Probert and Larsen, 1972; McLaughlin et al, 1977). Kuo and Lotse (1972) developed a second-order kinetic equation to describe adsorption which fitted the Langmuir isotherm. Their model described the rate of P adsorption by $CaCO_3$ and Ca-kaolinite as a function of both the concentration of P remaining in solution and the extent of surface saturation of the adsorbent.

Subsequently these workers developed a two-constant kinetic model, based on the Freundlich equation, to describe P adsorption by haematite and gibbsite (Kuo and Lotse, 1973) and lake sediments (Kuo and Lotse, 1974).

Barrow and Shaw (1974, 1975a) proposed a model in which soil inorganic P was allocated to compartments A, B and C, representing solution P, adsorbed P and "firmly held" P, respectively. The equilibrium between A and B was described by a Freundlich isotherm, while that between B and C was controlled by an empirical rate equation. Together the rate equation and adsorption isotherm were found to adequately describe changes over time in the solution P concentration of incubated soils after P addition.

In contrast to the Barrow and Shaw model, a kinetic model of steady state P fixation in solution, developed by Overman and Chu (1977), assumed Langmuir-type adsorption followed by a first-order chemical reaction with the solid phase of the soil. A different approach again was adopted by Helyar and Munns (1975) in developing a model to simulate not only changes in soil solution P concentration with time, but also uptake of P by plant roots. They used a function adopted by Gunary (1970) from the Langmuir equation to describe adsorption, while the subsequent slow reaction was represented by a simple nth order equation. A similar equation was investigated by Probert and Larsen (1972) who found it fitted their isotopic exchange data as effectively as a "sum of exponentials" model with four terms.

A rather more complex, mechanistic model was developed by Mansell et al (1977) to describe the fate of applied P in soils. Four phases of soil P (solution, adsorbed, immobilized and precipitated P) were assumed, with transformations between them determined by rate coefficients (of which there were six) and the amount of P in each phase. A series of equations were used to simultaneously describe rates of P transfer between the four phases.

2.3.3.2 Changes in plant available and chemically extractable soil P.

The results of a field study by Larsen et al (1965) suggested that the overall P immobilization reaction in soil could be described by first-order kinetics. This loss was subsequently treated theoretically by Larsen and Probert (1968) who proposed a simple exponential model to describe changes in "labile" soil P over time. Repeated, regular applications of fertilizer P were found to lead eventually to steady-state conditions, the equilibrium level of labile P depending on the rate and frequency of P applications and the rate of immobilization of labile P. Karlovsky (1962) has discussed similar concepts to these, based on measured changes in P soil test levels in New Zealand pasture soils.

In contrast to the theoretical approach of Larsen and Probert (1968) based on labile P, Rennes (1978) and Borzsonyi and Fuleky (1978) developed models to describe measured changes in extractable P levels after P addition to incubated soils. Rennes' kinetic model was based on the Langmuir equation and was found to satisfactorily predict the decline in the water extractability of P added to three soils of contrasting sorption properties. Borzsonyi and Fuleky (1978) added P to samples of nine soils varying in pH and texture. Regression functions based on an ordinary differential equation were used to describe the decline in ammonium lactate - and $NaHCO_3$ - extractable P over a two and a half year period.

Russell (1977), in presenting a mechanistic model of the behaviour of nutrients applied to soils, assumed that soil nutrients could be divided into two compartments, available and unavailable. Changes in these fractions were described by two differential equations which included three coefficients pertaining to fixation (K_1), loss (K_2) and release (K_3) of soil nutrient. Russell regarded the model as particularly suitable for soil P because the loss coefficient (K_2) is often close to zero and residual effects are large. The model predicts an exponential rate of decline in available P, with the decline curve asymptoting to the value $K_3/K_1 + K_3$ if K_2 is assumed to be zero.

A dynamic model of P utilization in grazed, temperate pastures, including soil, plant and animal components, was recently developed by Blair et al (1976). They regarded soil solution P and exchangeable P as together constituting the "available" soil P pool. Contributions to this pool came mainly from fertilizer application and organic matter mineralization, whereas plant uptake and "fixation" depleted the available pool. The net fixation of available P was predicted from a generalization of the empirical rate equation used by Barrow and Shaw (1975a). The model indicated an initial rapid drop in the available soil P level upon cessation of fertilizer application which then declined more slowly being sustained by mineralisation of the organic matter pool.

To summarize, it is apparent that kinetic studies of the reactions between added P and soil or soil components have involved widely differing experimental conditions, and have also varied in terms of the soil parameters monitored and the time scale involved. There has also been a wide variety of mathematical functions used; some assume first-order kinetics, others are more complex.

There appear to have been few attempts made, however, to extend the results of kinetic experiments carried out in the laboratory or glasshouse to the field situation. Where "field" models have been developed, it has been usual to consider changes in an "available" or "labile" soil P fraction (Larsen and Probert, 1968; Blair et al, 1976; Russell, 1977) rather than in a more specific soil P phase such as P in solution. With few exceptions (Blair et al, 1976; Russell, 1977), the models include no capacity to translate changes in available or extractable soil P into increased or reduced plant growth in field situations.

There is a need to develop simple models capable of simulating both changes in the availability of fertilizer P applied to field soils, and the consequent effects of these changes upon crop or pasture production. These models could be particularly useful as an aid in the assessment of optimum rates and frequencies of fertilizer application. Such an approach has been used very recently (Peaslee, 1978) to calibrate extractable soil P levels (Bray No 1 method) in terms of fertilizer requirements for specific crop-soil-climate situations.

CHAPTER 3

GLASSHOUSE STUDY WITH INTACT SOIL CORES

3.1 INTRODUCTION

The relationship between pasture yield and extractable soil P should preferably be defined under field conditions, possibly for different seasons of the year. This would necessitate pasture yield measurements on plots which vary only in terms of the level of extractable soil P. Several years measurements would probably be required because of the variability typically inherent in field data. For this reason, and because suitable field plots varying only in extractable P level were not available within a suitable distance of the University, it was decided that investigation of yield-extractable soil P relationships within the time available for this study was only feasible in the glasshouse.

The objectives of the glasshouse study were to define the relationship between relative "pasture" yield and extractable soil P and to investigate the extent to which this relationship varied between two different soils. Two soil P extraction procedures were selected, the bicarbonate extraction method of Olsen et al (1954a) and the water extraction method of Ryden et al (1976). The Olsen method was selected because it is currently the standard method used in New Zealand by the Ministry of Agriculture and Fisheries' soil testing service. The water extraction procedure was selected because it was considered to be independent of soil type which implies that the relationship between relative yield and water-extractable P would be the same for all soils.

To create conditions as realistic as possible, it was decided to collect intact soil cores from the field for the glasshouse study. It was considered that the use of intact cores would not only permit pasture growth measurements to be made on reasonably typical "swards" but that the soil profile within the cores would be representative of that which occurs in the field.

Small-plot field trials, previously treated with different rates of P fertilizer, provided an ideal source of intact cores varying in soil P status but relatively uniform in terms of other soil properties and sward composition. A number of such trials, located on different soils but all having received the same fertilizer treatments, were available in the Wairarapa district.

3.2 MATERIALS AND METHODS

3.2.1 Preliminary assessment of field trials as a source of intact cores.

In December 1977 preliminary soil samples (0-8 cm) were collected from several plots of five field trials in the Wairarapa hill country and analysed for Olsen P and water-extractable P (section 3.2.5). Treatments applied to the trials in 1973 and 1974 included all factorial combinations of four rates of mono-calcium phosphate (0, 25, 50 and 100 kg P/ha/an) and four sulphur treatments (0, 30, 60 kg S/ha as gypsum, 30 + 30 kg S/ha as gypsum + elemental sulphur). Consequently, the plots within each trial varied in terms of soil P status which was reflected by the analyses carried out. Irrespective of the soil P status, however, the ratio Olsen P: water-extractable P was relatively constant within each trial (or soil) but varied between soils from about 1.0 to 4.0.

One of the five trial sites was found to be unsuitable because of an overall high P status (Olsen P 35-60 μg/g soil, water-extractable P 30-50 μg/g). A further two sites were rejected because the swards contained negligible ryegrass or clover. The remaining two sites were selected as being the most suitable from which to collect intact cores. The soils at these two sites were Konini*, a very strongly leached soil formed from loess over greywacke, and Kumeroa*, a strongly leached soil from silty sandstone. Other pedological and chemical information relevant to these soils is shown in Appendix 1.

3.2.2 Selection of field plots and collection of cores.

Intact cores were collected from plots which had received the gypsum plus elemental sulphur treatments, as the clovers in these plots were less likely to have suffered from sulphur deficiency than the clovers in plots which had received only gypsum in 1973 and 1974. There were two replicate plots for each rate of applied P, both of which were sampled. The plot numbers and previous P fertilizer treatment for each pair were as follows:

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* The soil names are taken from the Interim Report on Soils of Wairarapa Valley, New Zealand (NZ Soil Bureau Record 40), by J.C.Heine, H.S.Gibbs and J.D.Cowie (1975), and the soil names are provisional only.

Konini soil: plots 7 and 26 (nil P), 10 and 18 (low P), 14 and 20 (medium P), 6 and 30 (high P).

Kumeroa soil: plots 12 and 19 (nil P), 6 and 27 (low P), 8 and 32 (medium P), 13 and 17 (high P).

Three cores, identified as A, B and C, were obtained from each plot. As well as the plots listed above, additional plots were sampled as follows:

Konini soil: Three extra cores (D, E and F) were taken from the high P plots (6 and 30), to which P would be added during the glasshouse experiment to achieve maximum yield. Also, two cores (A and B) of "very high" P status were collected from each of three plots (LP3, LP22, LP25) of an adjacent rates of lime x P trial which had received fertilizer P (50 kg/ha) each autumn from 1973 to 1978.

Kumeroa soil: Three cores, to which P would be added to achieve maximum yield, were collected from each of plots 4 and 28 (high P plus 60 kg S/ha as gypsum). Since the plot size was smaller at this site, it was not possible to obtain three additional cores from the high P plots which had also received elemental sulphur.

In total, 36 intact cores of the Konini soil and 30 of the Kumeroa soil were collected, covering a range of soil P status. The cores were collected in the following manner. Open-ended containers 18 cm in depth were made from 15 cm diameter, 24 gauge, galvanized iron downpipe. These were placed upon the ground surface, an attempt being made to select areas within and between plots where the sward composition appeared to be similar. The containers were hammered into the soil until the soil surface was within 1-2 cm of the top, then removed, labelled and transported back to the glasshouse.

The levels of extractable soil P within the intact cores could not be determined without disturbing the cores. Therefore, soil P levels within the cores were estimated by analysing soil samples (0-4 cm and 0-8 cm depth) collected from around the outer perimeter of the containers prior to their removal.

3.2.3 Initial preparation of cores in glasshouse.

When returned to the glasshouse the base of the intact cores was trimmed level with the bottom of the containers using a knife. Each core was placed upright upon a clean plastic lid and watered frequently until apparently saturated. After removing excess water from the lids, the cores were allowed to drain overnight and were then weighed. At these weights, which varied from 4.31-5.09 kg for the Konini soil and from 4.54-5.18 kg for the Kumeroa soil (container and lid included), the cores were assumed to be at or near field capacity. During the subsequent glasshouse study each core was watered to field capacity at least once weekly.

About a week after collecting the cores, the herbage growth present was trimmed off at about 2 cm above the soil surface. Diazinon 5 G granules were applied to the surface of each core to control any grassgrub which may have been present.

3.2.4 Design and conduct of glasshouse experiments.

The intact cores were placed on two separate trolleys, one for each soil, in a completely randomized design. Watering of the cores with nutrient solutions applied to the surface was carried out every two or three days, at which times the cores were shifted to new positions on the trolleys according to a predetermined plan. When applying the nutrient solutions, the core with the least weight loss due to evapotranspiration determined the amount of nutrient solution applied to all cores of that soil. The two soils were treated independently while different rates of moisture loss between cores of the same soil were made up once a week with distilled water.

Nutrient solutions with and without P, modified from Middleton and Toxopeus (1973), were prepared as detailed in Appendix 2. Initially no nitrogen was included in the solutions but for reasons discussed later, nitrogen was included prior to the third and fourth harvests. The nutrient solution without P was added to all cores except 6D, 6E, 6F, 30D, 30E and 30F (Konini soil) and 4A, 4B, 4C, 28A, 28B and 28C (Kumeroa soil). The latter "high P status" cores received the +P nutrient solution and will be collectively referred to as the +P cores. They were intended to give an estimate of maximum yield with P non-limiting. All cores of the same soil received equal amounts of nutrient solution at all times.

Herbage growth above 1-2 cm was harvested on four occasions at about 25 day intervals. The date of each yield harvest and the amounts of nutrient solution applied per core are shown in Table 3.1. Harvested herbage was weighed after oven drying overnight at 75°C. When the fourth harvest was made, the herbage from each core was assessed for species composition by dissecting a subsample into ryegrass, other grasses and other species (weeds and clovers). Each species component was also weighed after oven drying overnight at 75°C, and expressed as a percentage of the total weight of herbage dissected.

After the fourth harvest each core was removed from its container and cut into three sections, viz: 0-4, 4-8 and 8-18 cm, the latter section being discarded. The upper sections were air-dried, sieved and subsampled to give 0-4 cm and 0-8 cm subsamples for chemical analysis.

3.2.5 Analytical procedures.

Bicarbonate-extractable soil P, referred to in this thesis as Olsen P (Olsen et al, 1954a), was determined after shaking 1 g air-dry soil for 30 minutes in 20 ml of 0.5 M $NaHCO_3$ solution adjusted to pH 8.5 with NaOH, followed by centrifugation and filtration of the supernatant solution.

Water-extractable soil P (Ryden et al, 1976) was determined after shaking 1 g air-dry soil for 1 hour in 40 ml of distilled water, followed by centrifugation and filtration of the supernatant solution, then addition of another 40 ml of distilled water, shaking for 1 hour and again followed by centrifugation and filtration of the supernatant solution. Equal volumes of the first and second filtered extracts were combined prior to analysis. Both water-extractable P and Olsen P are expressed as μg P/g of air-dry soil (<2 mm).

Retention of P (Saunders, 1965) was determined after shaking 5 g of air-dry soil for 16 hours in 25 ml of 0.2 M sodium acetate solution containing 1000 μg P/ml (ie 0.032 M with respect to KH_2PO_4) and adjusted to pH 4.65 with glacial acetic acid. P retention was calculated as the amount of P removed from solution by the soil expressed as a percentage of the amount originally in solution.

For all P determinations samples were shaken in 50 ml polycarbonate centrifuge tubes in an end-over-end shaker at 18 rpm. A thermostat inside the shaker was set at 20°C though in winter the actual air temperature was usually slightly below 20°C and in summer slightly above 20°C. At the completion of shaking, the samples were centrifuged at 13000 rpm for 2-3 minutes in a Sorvall RC2-B refrigerated centrifuge and the solution extracts filtered. Inorganic P in an aliquot of the solution extract was determined by Watanabe and Olsen's (1965) modification of Murphy and Riley's (1962) method, except that Olsen extracts were not neutralized prior to colour development (see below). Absorbance was measured at 712 nm using a Pye Unicam SP 1800B spectrophotometer.

To check that neutralization of Olsen extracts was unnecessary, the inorganic P in 2 ml, 4 ml and 8 ml aliquots of an Olsen extract from a sample of Tokomaru soil (Appendix 1) was determined both with and without neutralization of the aliquots prior to colour development. The results, shown as means of duplicate determinations in Table 3.2, indicated that although the amount of P extracted increased with increasing aliquot size, there was no difference between aliquots neutralized and not neutralized. Throughout this study, therefore, 4 ml aliquots of Olsen extracts were always used and they were not neutralized prior to colour development.

Soil inorganic nitrogen (nitrate and ammonium) in the soil samples collected from around the soil cores was determined following reduction of nitrate to ammonium, steam distillation of ammonia, and titration with standard acid (Bremner and Keeney, 1965).

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

3.2.6 Statistical treatment of data.

A bivariate linear regression equation of the form

$$y = a + bx_1 + cx_2$$

was fitted to the data for the first two harvests to determine the separate effects of inorganic soil nitrogen (x_2) and extractable soil P (x_1) on dry matter yield (y). Linear correlation coefficients between yield and extractable soil P were calculated because of the lack of any curvilinear relationship in the data.

For the third and fourth harvests an exponential regression equation of the form

$$y = A - Be^{-cx}$$

was fitted to the yield (y)-extractable soil P (x) data for each soil

TABLE 3.1: Harvest dates, growth intervals and amounts of nutrient solution (ml) applied per core prior to each harvest.

	Konini soil	Kumeroa soil
Date of collecting cores from field plots:	12.5.78	23.5.78
Date of commencing glasshouse experiment (cores trimmed):	18.5.78	29.5.78
First harvest:		
Date of harvest:	11.6.78	21.6.78
Days of growth:	24	23
Total nutrient solution applied:	600	600
Second harvest:		
Date of harvest:	6.7.78	17.7.78
Days of growth:	25	26
Total nutrient solution applied:	860	755
Third harvest:		
Date of harvest:	30.7.78	11.8.78
Days of growth:	24	25
Total nutrient solution applied:	540	560
Fourth harvest:		
Date of harvest:	24.8.78	4.9.78
Days of growth:	25	24
Total nutrient solution applied:	400	400

TABLE 3.2: Effects of aliquot size and neutralization of Olsen extract prior to colour development on the apparent Olsen P level (µg P/g soil) of a sample of Tokomaru soil.

Aliquot size (ml)	Not neutralized	Neutralized	Mean
2	13.80	13.92	13.86
4	15.11	15.05	15.08
8	16.10	15.80	15.95
Mean	15.00	14.92	

separately. The value of parameter A (maximum yield when x = infinity) in the fitted regression equation was used to convert all yield data to relative yields where

$$\text{relative yield} = \frac{\text{actual yield} \times 100}{\text{maximum yield (A)}}$$

Corresponding data for the two soils could then be directly compared by plotting relative yields against extractable soil P levels. Correlation coefficients for the curvilinear relationships between yield and extractable soil P were calculated.

All correlations and regressions were calculated using programs available on the DSIR computer PDP 11/45. An exponential function was used to relate yield to extractable soil P, in preference to other mathematical expressions, because firstly, immobile soil nutrients such as P tend to be related to plant yield in an exponential manner (Melsted and Peck, 1977) and secondly, the coefficients in the exponential equation have some meaning.

3.3 RESULTS

3.3.1 First and second harvests.

Olsen P levels in the soil samples collected from around the outside of the intact cores, as determined in June 1978, are shown in Appendix 3. No samples were collected from around the +P cores since the extractable P levels initially present in these cores would have been irrelevant once P had been applied to the cores.

For the Konini soil, Olsen P ranged from 7 to 32 μg/g soil in the 0-8 cm depth and from 9 to 50 μg/g in the 0-4 cm depth. The range was smaller for the Kumeroa soil since no lime x P trial plots had been sampled. Variation in Olsen P level between cores from the same plot was generally small for the "nil P" and "low P" cores but was greater for the "medium" and "high P" cores. Except for the "low P" treatment, the fertilizer P applied to the field plots in 1973 and 1974 had raised the level of Olsen P in both sampling depths, relative to the "nil P" treatment (Appendix 3).

Water-extractable P levels in the same soil samples were not determined until June 1979 and were then found to be 50-100% greater than expected based on the Olsen P: water-extractable P ratios for these soils and the water-extractable P levels in the preliminary field samples (section 3.2.1). Despite the apparent increases in water-extractable P levels during storage of the air-dry samples, Olsen P levels determined again in June 1979 were found to be within ±1 μg/g of the original figures (Appendix 3). No attempt was made to correlate the "inflated" water-extractable soil P values with dry matter yields.

Yields of dry matter per core for the first and second harvests are listed in Appendix 4. The cores of Konini soil yielded on average 25% more dry matter than the Kumeroa cores in the first harvest, though this difference was reduced to less than 15% in the second harvest. For both harvests there was considerable variation in yield between cores of similar soil P status and even between cores taken from the same field plot. These differences were particularly large for cores 10A, B and C of the Konini soil (Plate 3.1 and Appendix 4) and for cores 4A, B and C of the Kumeroa soil (Plate 3.2 and Appendix 4).

Although yields were more than 30% higher on average in the second harvest than in the first, there appeared to be little if any reduction in yield variability in the second harvest. In both harvests considerable differences between cores in terms of species composition were apparent, though most cores contained negligible clover.

Dry matter yields for the first and second harvests were combined as both gave essentially the same results. Combined yields were plotted against Olsen P levels in the 0-8 cm and 0-4 cm sampling depths. Attempts to fit an exponential equation to the data were unsuccessful in the case of the Konini cores, even when core 10A was excluded, while for the Kumeroa soil the fitted curves conflicted with the law of diminishing returns.

Linear regressions were then fitted to each set of data as illustrated in Figures 3.1 and 3.2 for the Konini and Kumeroa soils respectively. The intercepts and regression coefficients for the lines of best fit and the linear correlation coefficients are shown in Table 3.3. For the Konini cores, about one quarter of the variation in yield was accounted for by differences in the level of Olsen P in both sampling depths. However, core 10A was excluded from the analysis on the basis that it was considered to be an outlier (see below), which undoubtedly increased the correlation coefficients. For the Kumeroa cores, only 10-12% of the yield variation could be accounted for by differences in Olsen P (Table 3.3).

The levels of inorganic nitrogen in the 0-8 cm soil samples, most of which was in the ammonium form, are shown in Appendix 3. Much higher levels were present in the Konini samples (mainly 20-40 μg N/g soil)

PLATE 3.1: "Pasture" growth at the second harvest showing variation between cores from plot 10 on the Konini soil.

PLATE 3.2: "Pasture" growth at the second harvest showing variation between cores from plot 4 on the Kumeroa soil.

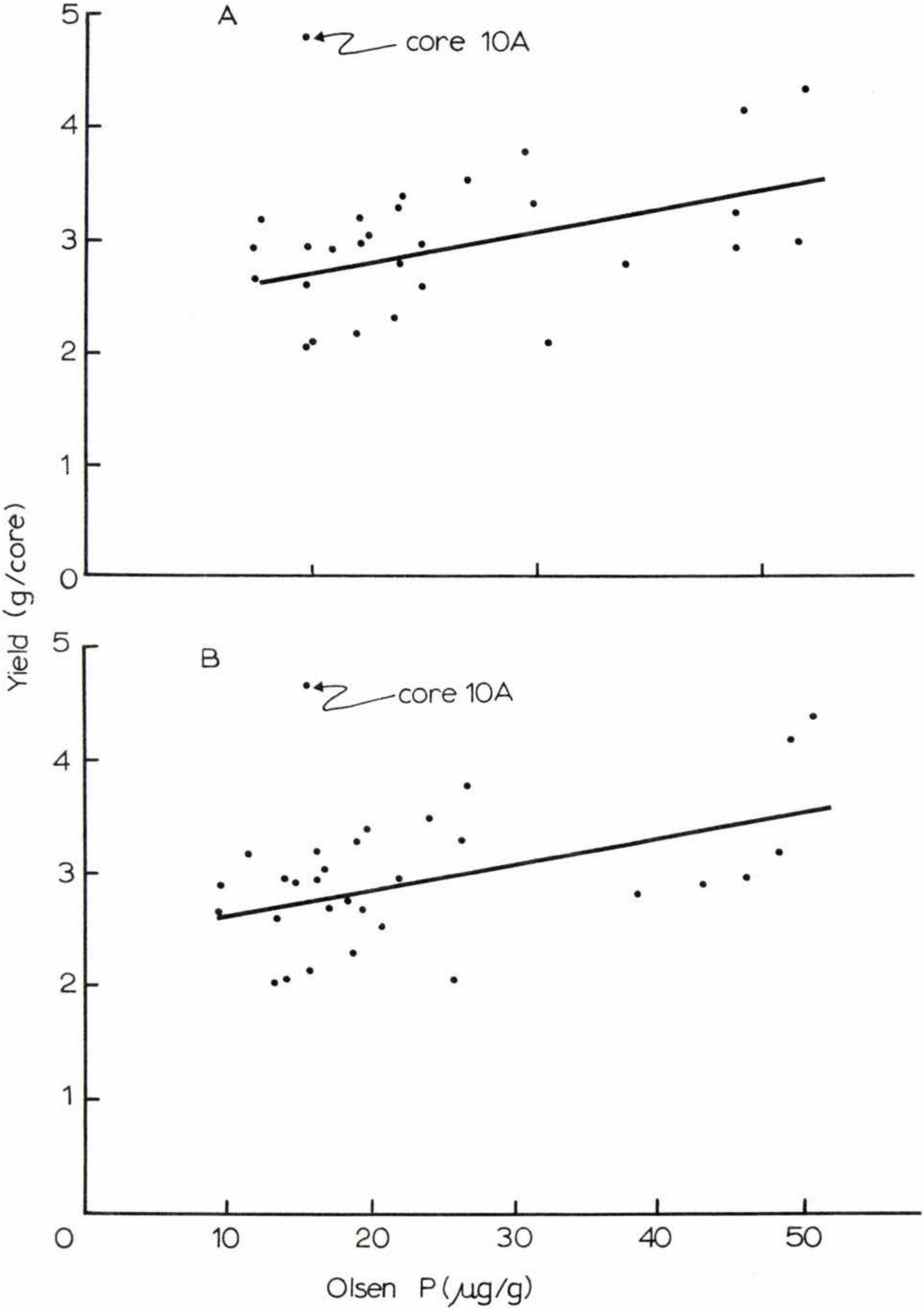

FIGURE 3.1: Dry matter yield per core in harvests 1 + 2 as a function of the level of Olsen P in 0-8 cm (A) and 0-4 cm (B) samples of Konini soil taken from around the cores.

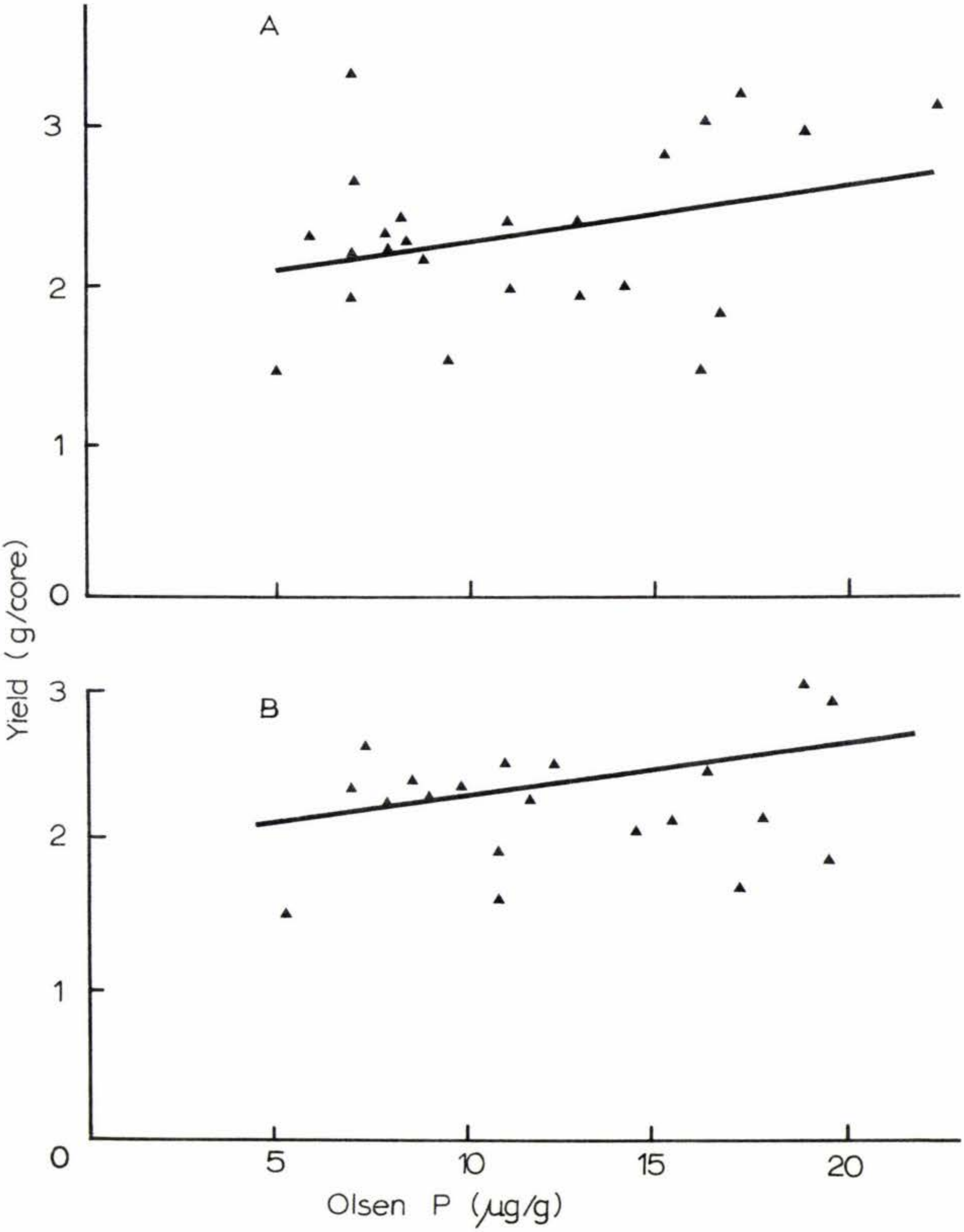

FIGURE 3.2: Dry matter yield per core in harvests 1 + 2 as a function of the level of Olsen P in 0-8 cm (A) and 0-4 cm (B) samples of Kumeroa soil taken from around the cores.

TABLE 3.3: Values of the intercept a (g), the regression coefficient b ($g^2/\mu g$), and the correlation coefficient r, for the fitted linear regressions.

	a	b	r
Konini soil:			
0-8 cm depth	2.38	0.036	0.49**
0-4 cm depth	2.40	0.023	0.52**
Kumeroa soil:			
0-8 cm depth	1.94	0.038	0.34 ns
0-8 cm (adjusted yields)	1.17	0.047	0.49*
0-4 cm depth	1.92	0.032	0.32 ns

ns not significant
* significant at 5% level
** significant at 1% level

than in the Kumeroa samples (mainly 8-15 μg/g). Core 10A of the Konini soil contained an abnormally high level of inorganic nitrogen (106 μg/g) which suggests this was the reason for the high yield of this core in harvests 1 and 2 (Figure 3.1 and Appendix 4).

When core 10A was excluded, a bivariate regression fitted to the data for the Konini soil indicated that inorganic soil nitrogen had had no significant effect on yield. The equation was:

$$y = 2.25 + 0.036 \text{ (Olsen P)} + 0.0035 \text{ (Inorganic N)}$$

with t-values of 2.83 ($P < 0.01$) and 0.20 (not significant) for the Olsen P and inorganic nitrogen coefficients respectively.

For the Kumeroa soil a bivariate regression fitted to the data indicated that inorganic soil nitrogen had significantly influenced yield. The equation was:

$$y = 1.17 + 0.047 \text{ (Olsen P)} + 0.054 \text{ (Inorganic N)}$$

with t-values of 2.55 ($P < 0.05$) and 3.51 ($P < 0.01$) for the Olsen P and inorganic nitrogen coefficients respectively.

Dry matter yields for the Kumeroa cores were adjusted to remove the effect of nitrogen: ie

$$\text{adjusted yield} = \text{actual yield} - 0.054 \text{ (Inorganic N)}$$

Adjusted yields are listed in Appendix 4. When a linear regression was fitted to a plot of the adjusted yields against Olsen P (0-8 cm), as illustrated in Figure 3.3, about one quarter of the variation in yield was accounted for (Table 3.3).

3.3.2 Third and fourth harvests.

Olsen P levels in the soil samples collected from within the intact cores after the experiments are listed in Appendix 5. These values, on average, were slightly less than the Olsen P levels in the samples collected from around the cores before the experiments (Figures 3.4 and 3.5). The difference between the two sets of figures tended to be greatest for the 0-4 cm samples (Figure 3.5) and at the higher levels of Olsen P where yield would be expected to be least affected. It was

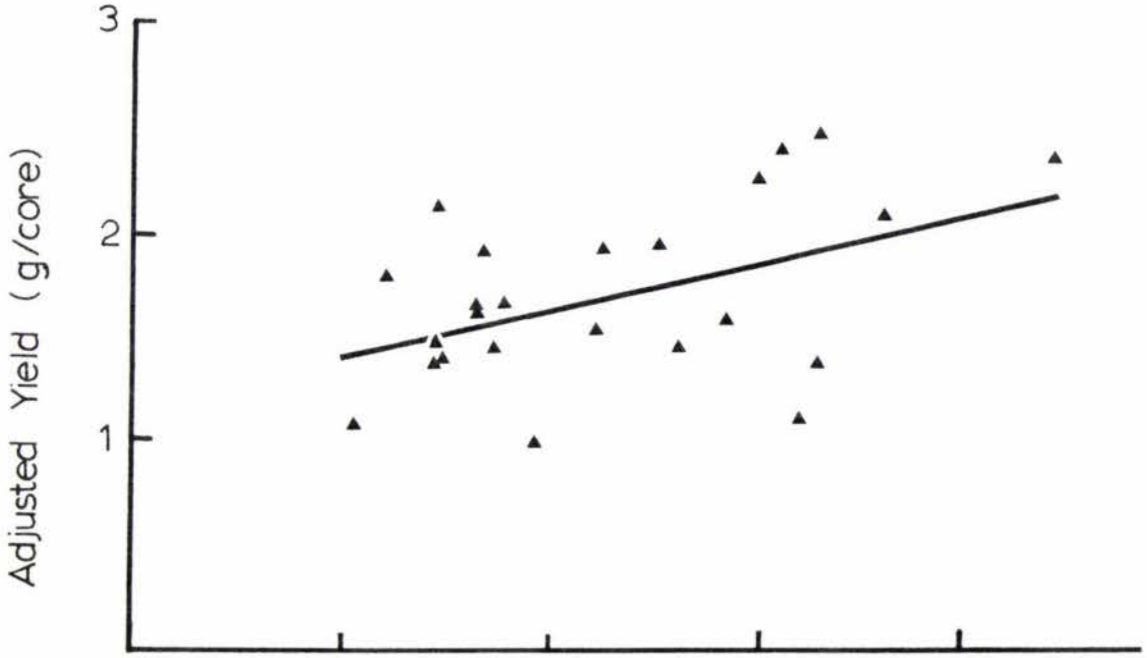

FIGURE 3.3: Dry matter yield per core in harvests 1 + 2, adjusted for the effect of inorganic soil nitrogen, as a function of the level of Olsen P in 0-8 cm samples of Kumeroa soil taken from around the cores.

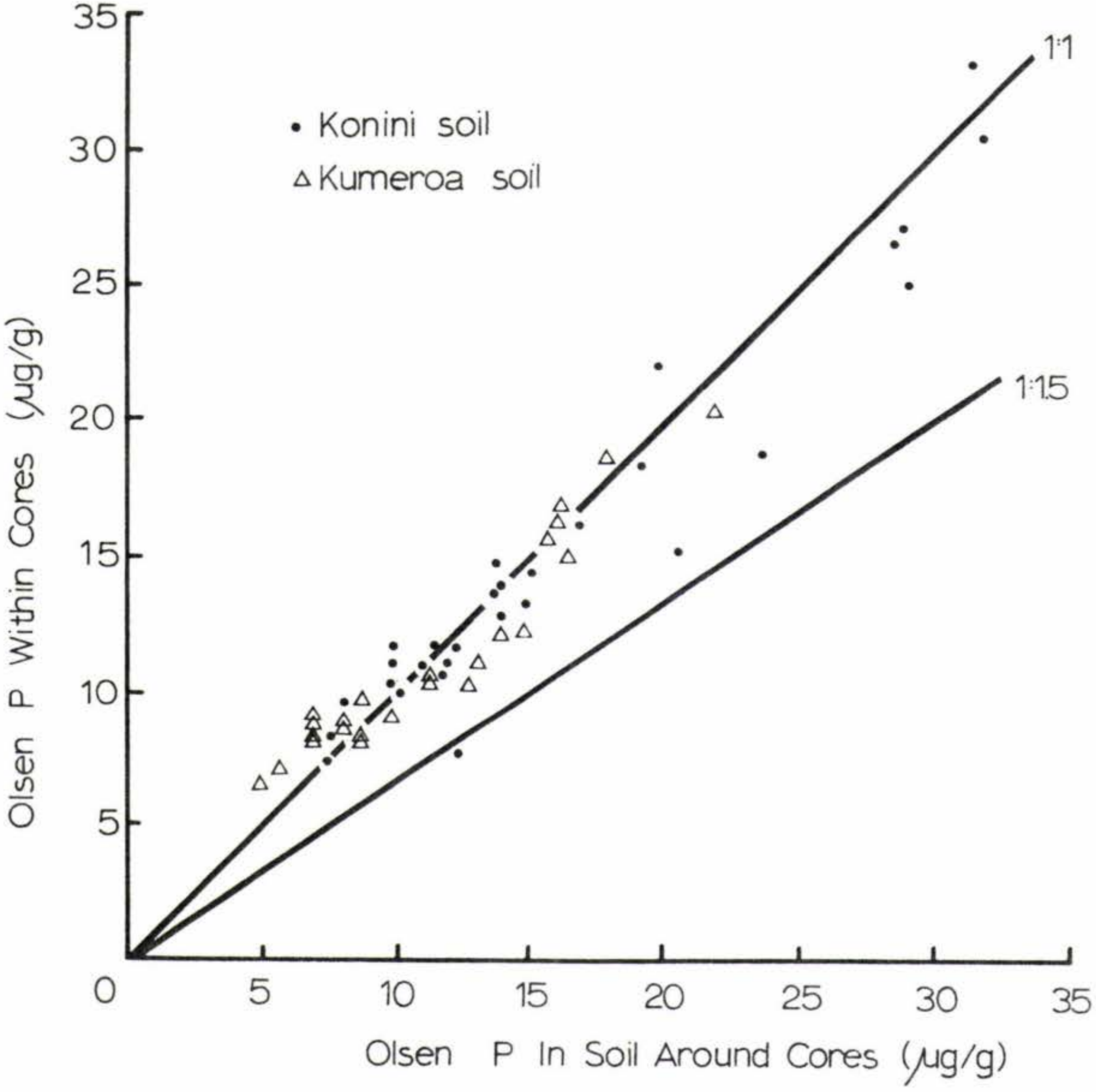

FIGURE 3.4: Relationship between Olsen P levels within cores at the end of the glasshouse study and Olsen P levels in soil from around the cores (0-8 cm depth).

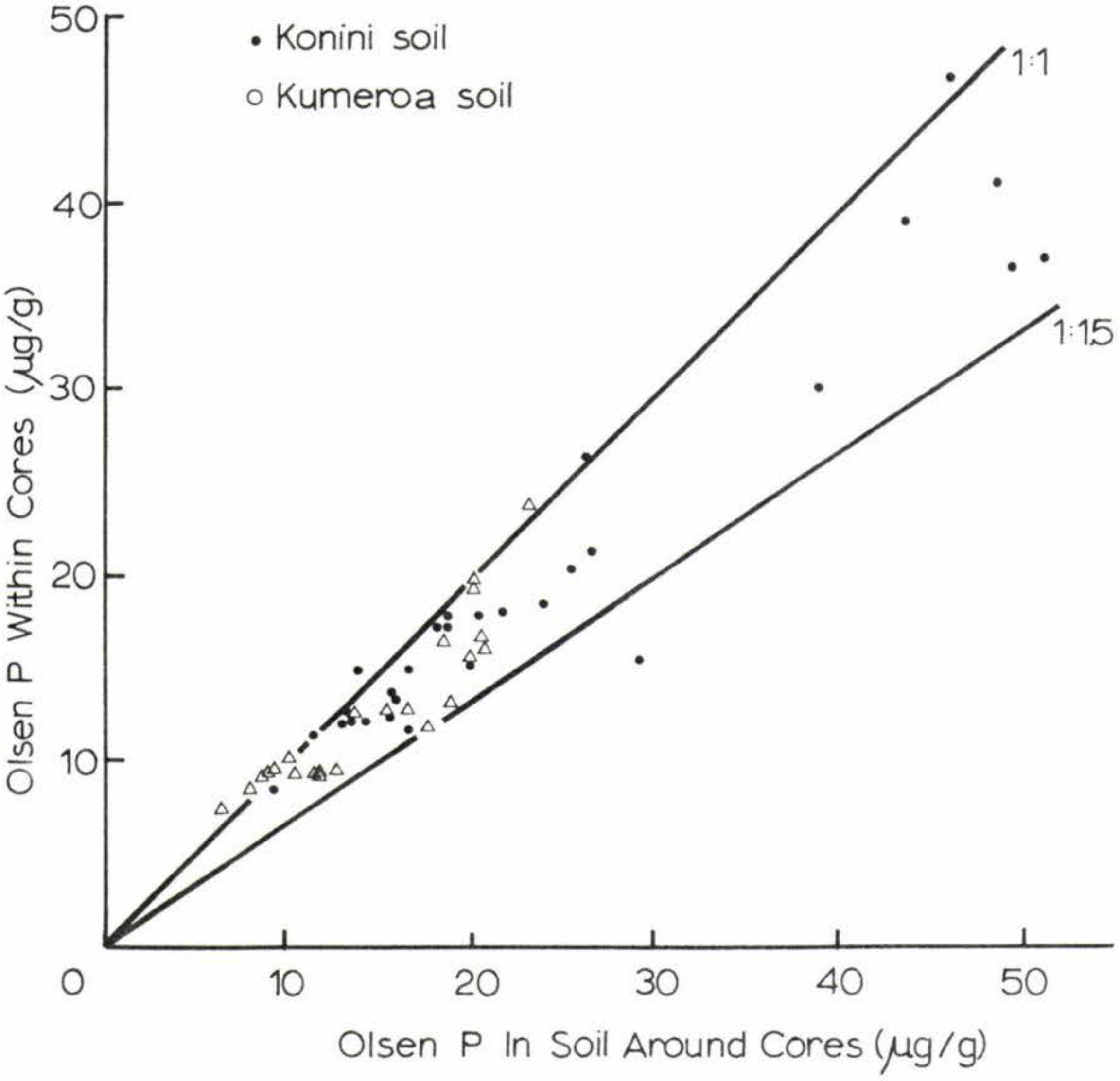

FIGURE 3.5: Relationship between Olsen P levels within cores at the end of the glasshouse study and Olsen P levels in soil from around the cores (0-4 cm depth).

therefore considered that relating within-core soils data to yields for the third and fourth harvests would not significantly alter the relationship between yield and Olsen P. This allowed the yield and extractable soil P data for the +P cores to be included.

Water-extractable P levels within the intact cores, determined in June 1979 after storing the soil samples in the glasshouse since September 1978, are also listed in Appendix 5. They ranged from 1 to 18 μg/g for the Konini soil and from 4 to 21 μg/g for the Kumeroa soil. It was assumed that water-extractable P levels within the cores, like Olsen P, had not changed sufficiently during the experiments to significantly alter the relationship between yield and water-extractable P.

Compared to water-extractable P levels within the intact cores, those in soil samples from around the intact cores (section 3.3.1) were 50-100+% greater when determined in June 1979 (Figure 3.6). This was taken to indicate that water-extractable P levels had increased during storage of these soil samples in the laboratory. However, since these samples had not previously been analysed following their collection in May 1978, it is not possible to say with absolute certainty that water-extractable P levels had increased during storage. Increases in the water-extractable P content of stored soil samples will be discussed further in Chapter 5.

Dry matter yields per core for the third and fourth harvests are listed in Appendix 6. The Kumeroa soil cores outyielded the Konini cores, particularly in the third harvest, in contrast to the first two harvests. In both the third harvest and the fourth harvest, yields were about 45% higher than in the preceding harvest, undoubtedly due in part to the nitrogen applied. Yields were still rather variable in harvests 3 and 4 though less so than in the earlier harvests. Thus prior to the fourth harvest an increasing yield trend among "average" cores representing each of the previous field treatments was readily discernable (Plates 3.3 and 3.4).

Considerable species differences between cores were apparent in harvests 3 and 4, as in the earlier harvests. The species composition of individual cores appeared not to change much during the experiments. The proportion of yield attributable to ryegrass and to other grass species in the fourth harvest is shown in Appendix 6; the balance unaccounted for (generally less than 10%) was made up of weeds and

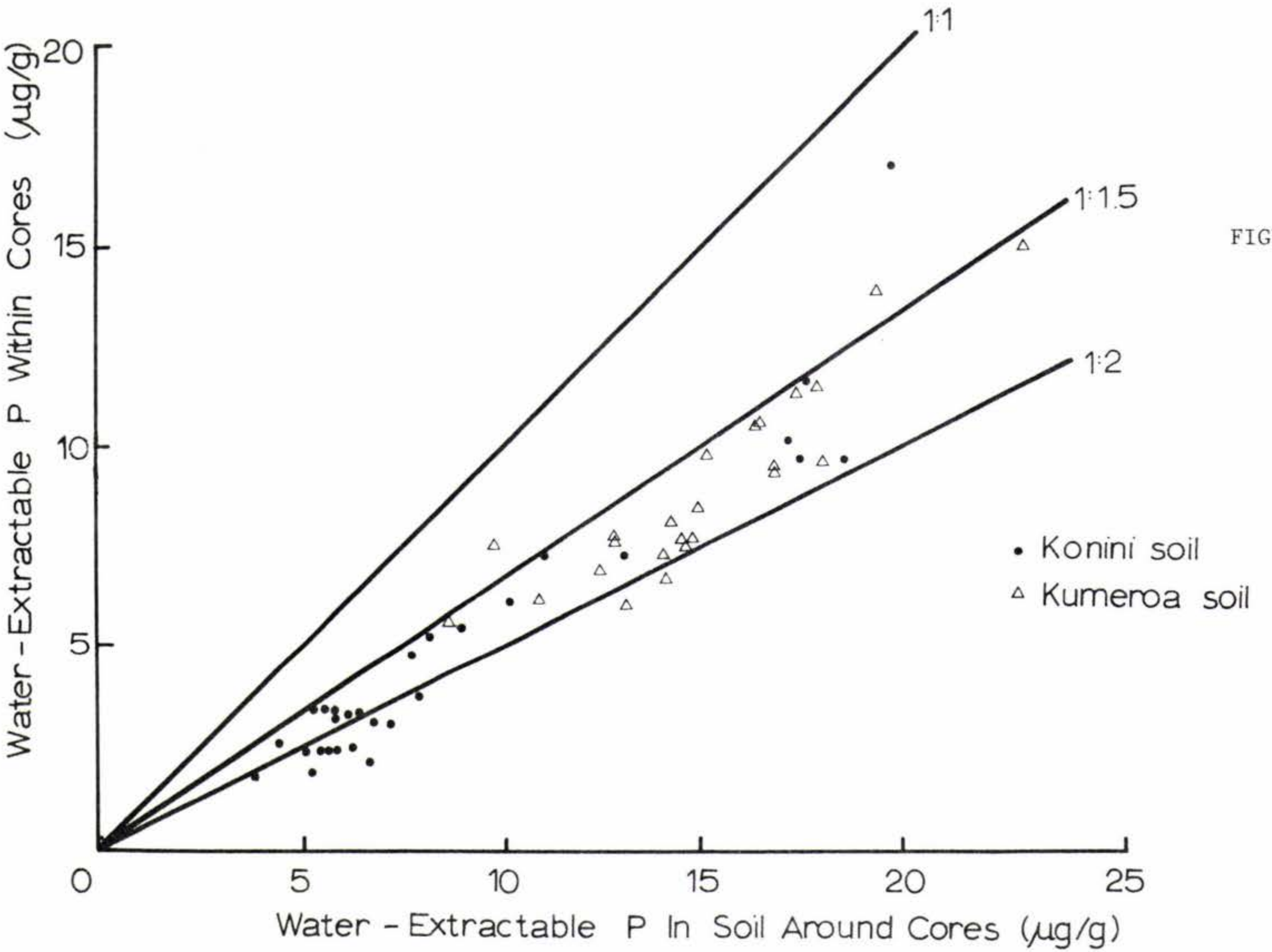

FIGURE 3.6: Relationship between water-extractable P levels within cores at the end of the glasshouse study and water-extractable P levels in soil from around the cores (0-4 cm depth).

PLATE 3.3: "Pasture" growth at the fourth harvest on average cores of Konini soil arranged in order of increasing extractable P level (L to R).

PLATE 3.4: "Pasture" growth at the fourth harvest on average cores of Kumeroa soil arranged in order of increasing extractable P level (L to R).

clovers. The Kumeroa cores and the Konini cores from the Lime x P trial contained more ryegrass than most of the other Konini cores. The proportion of ryegrass varied widely between coras (from 4 to 50+%). Poa species made up the largest component of "other grasses" on the Konini cores while other species on both soils included browntop, Yorkshire fog, crested dogstail, sweet vernal, goose grass and timothy.

Yields for the third and fourth harvests were combined as both gave similar results. The mean yield of the six +P cores was 6.03 g and 7.50 g for the Konini and Kumeroa soils respectively. Combined yields were plotted against Olsen P and water-extractable P levels within the cores for the two soils separately.

It was found that exponential curves of a diminishing returns nature could be fitted to all plots of yield versus extractable soil P. Most of the exponential curves did not give a significantly better fit than a straight line, the only exception being for water-extractable P in the Konini soil ($P < 0.01$). For these data, however, the fitted curves intercepted the y axes (ie where extractable soil P is zero) at yields approaching half of the maximum values predicted by the curves (Table 3.4). For the Kumeroa soil the y intercepts varied from 16 to 30% of the predicted maximum yield (Table 3.4).

Exponential curves constrained to pass through the origin were also fitted to the data. Table 3.5 shows the values of parameter A (maximum yield), parameter c (curvature coefficient) and of the correlation coefficient for both constrained and unconstrained curves. Constraining the curves through the origin improved agreement between predicted maximum yield and the mean yield of the +P cores, but decreased the proportion of variation accounted for (r^2). Differences between the soils in terms of the magnitude of the c coefficient were large for the water-extractable P curves but much smaller for the Olsen P curves, particularly when constrained through the origin (Table 3.5, Figures 3.7, 3.8, 3.9 and 3.10).

Extractable soil P levels at 90% of the predicted maximum yields, which will be referred to as "critical" levels, were calculated for both constrained and unconstrained curves and are shown in Table 3.6. For the constrained curves, the critical levels of Olsen P were almost identical for both soils while the critical water-extractable P levels were much higher for the Kumeroa soil than for the Konini soil. Critical

TABLE 3.4: Values of parameter B (g) for unconstrained exponential curves, and of the y intercept (ie A-B) expressed as a proportion (%) of maximum yield (parameter A).

	Konini soil		Kumeroa soil	
Yield of cuts 3 + 4 versus:	B	y intercept	B	y intercept
Olsen P (0-8 cm)	5.05	39	6.22	28
Olsen P (0-4 cm)	4.16	43	6.23	30
Water-extractable P (0-8 cm)	3.45	46	7.92	22
Water-extractable P (0-4 cm)	3.27	47	7.51	16

TABLE 3.5: Values of parameters A (g) and c (g/μg), and of the correlation coefficient r, for constrained and unconstrained exponential curves.*

Yield of cuts 3 + 4 versus:	Konini soil	Kumeroa soil
	Parameter A	
Olsen P (0-8 cm)	6.20 (8.27)	7.73 (8.64)
Olsen P (0-4 cm)	6.13 (7.31)	7.80 (8.91)
Water-extractable P (0-8 cm)	5.97 (6.37)	8.29 (10.15)
Water-extractable P (0-4 cm)	5.92 (6.21)	8.32 (8.93)
Mean yield of +P cores:	6.03 g	7.50 g
	Parameter c	
Olsen P (0-8 cm)	0.129 (0.031)	0.130 (0.070)
Olsen P (0-4 cm)	0.106 (0.033)	0.112 (0.054)
Water-extractable P (0-8 cm)	0.874 (0.390)	0.181 (0.088)
Water-extractable P (0-4 cm)	0.576 (0.269)	0.136 (0.098)
	r[Δ]	
Olsen P (0-8 cm)	0.732 (0.768)	0.821 (0.831)
Olsen P (0-4 cm)	0.735 (0.769)	0.855 (0.871)
Water-extractable P (0-8 cm)	0.747 (0.794)	0.813 (0.822)
Water-extractable P (0-4 cm)	0.739 (0.773)	0 851 (0.853)

* Figures within brackets relate to unconstrained curves.

[Δ] All values of the correlation coefficient are significant at the 0.1% level.

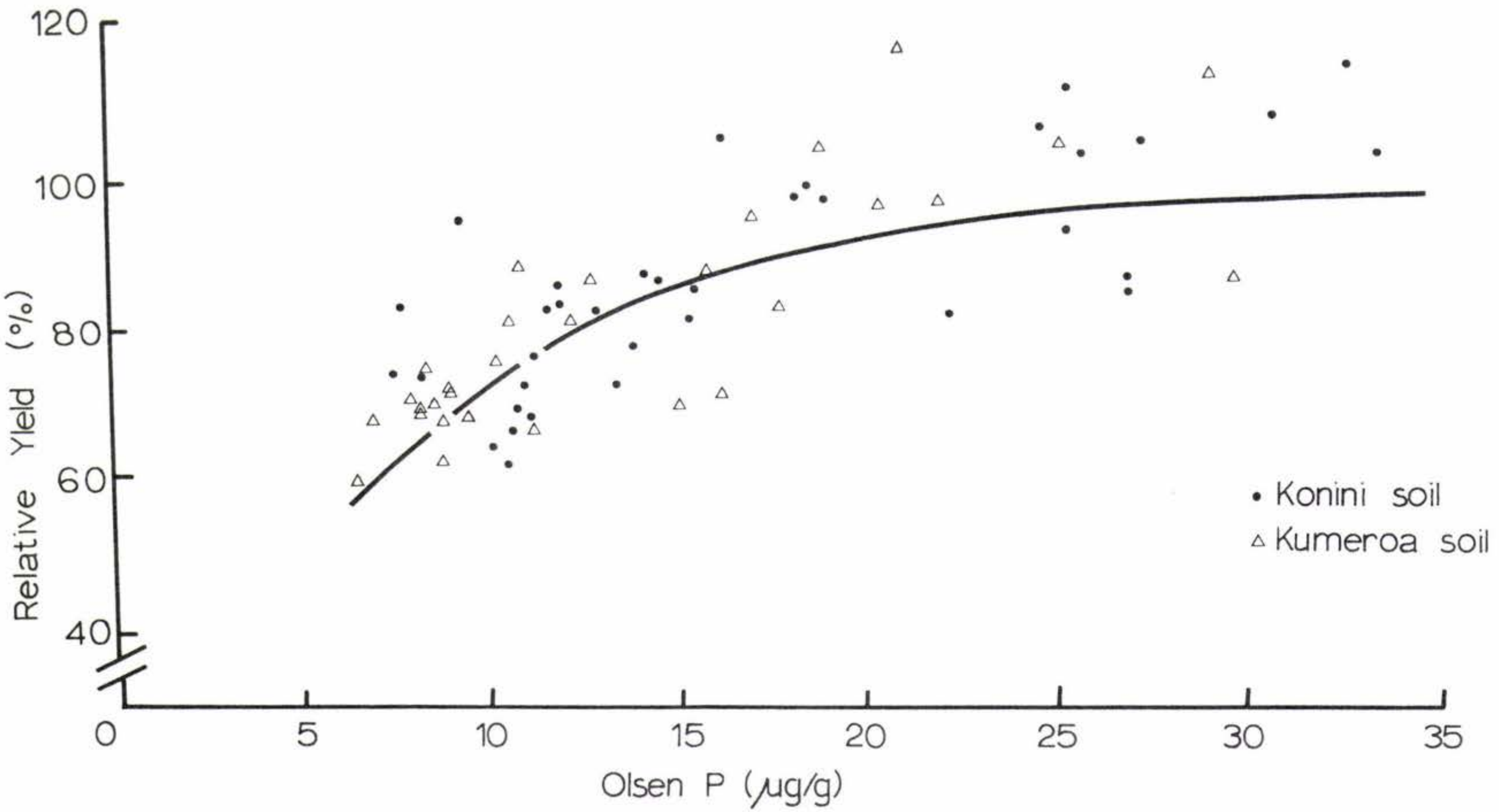

FIGURE 3.7: Relative dry matter yield per core in harvests 3 + 4 as a function of the level of Olsen P (0-8 cm depth) within the cores.

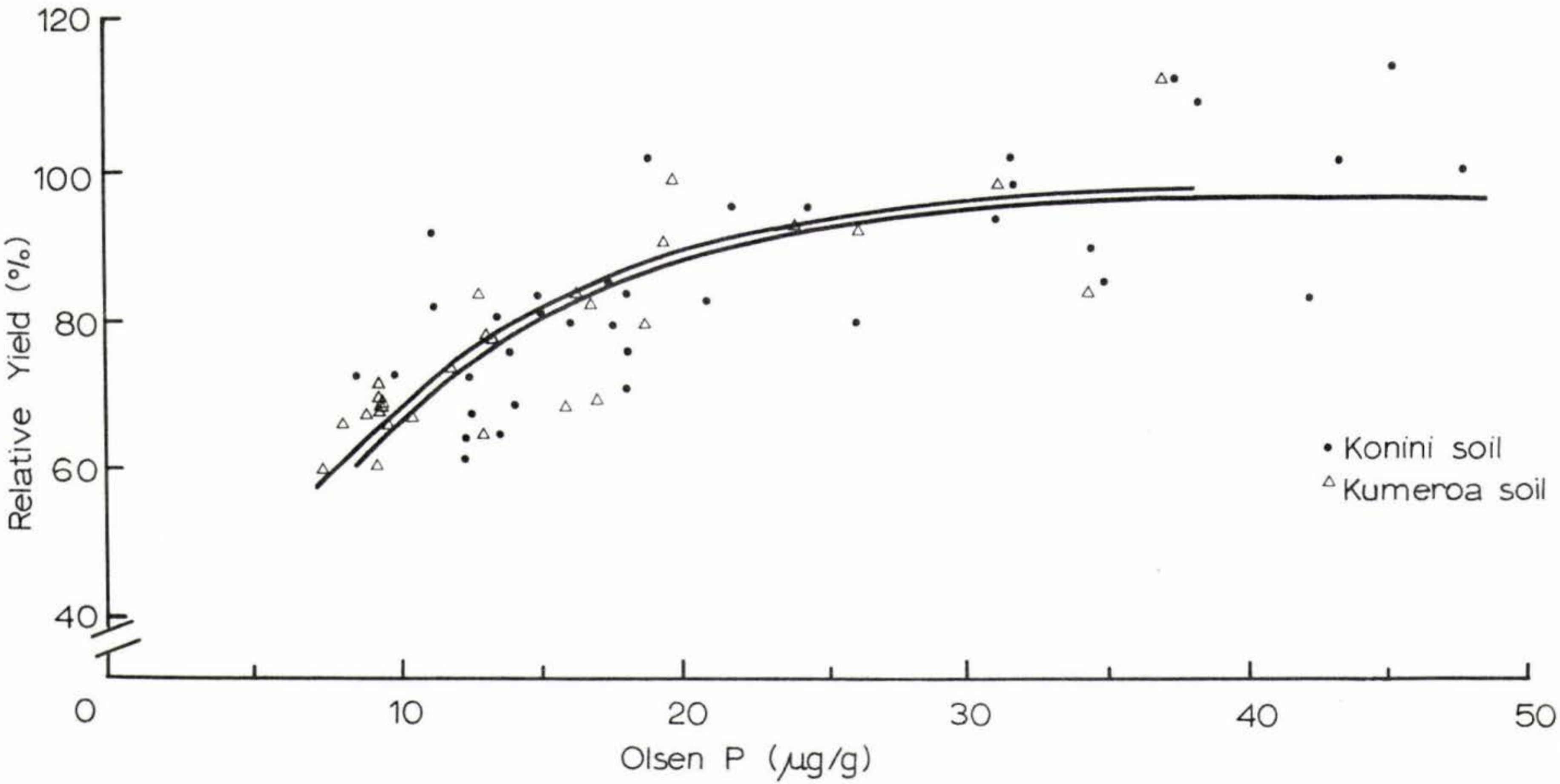

FIGURE 3.8: Relative dry matter yield per core in harvests 3 + 4 as a function of the level of Olsen P (0-4 cm depth) within the cores.

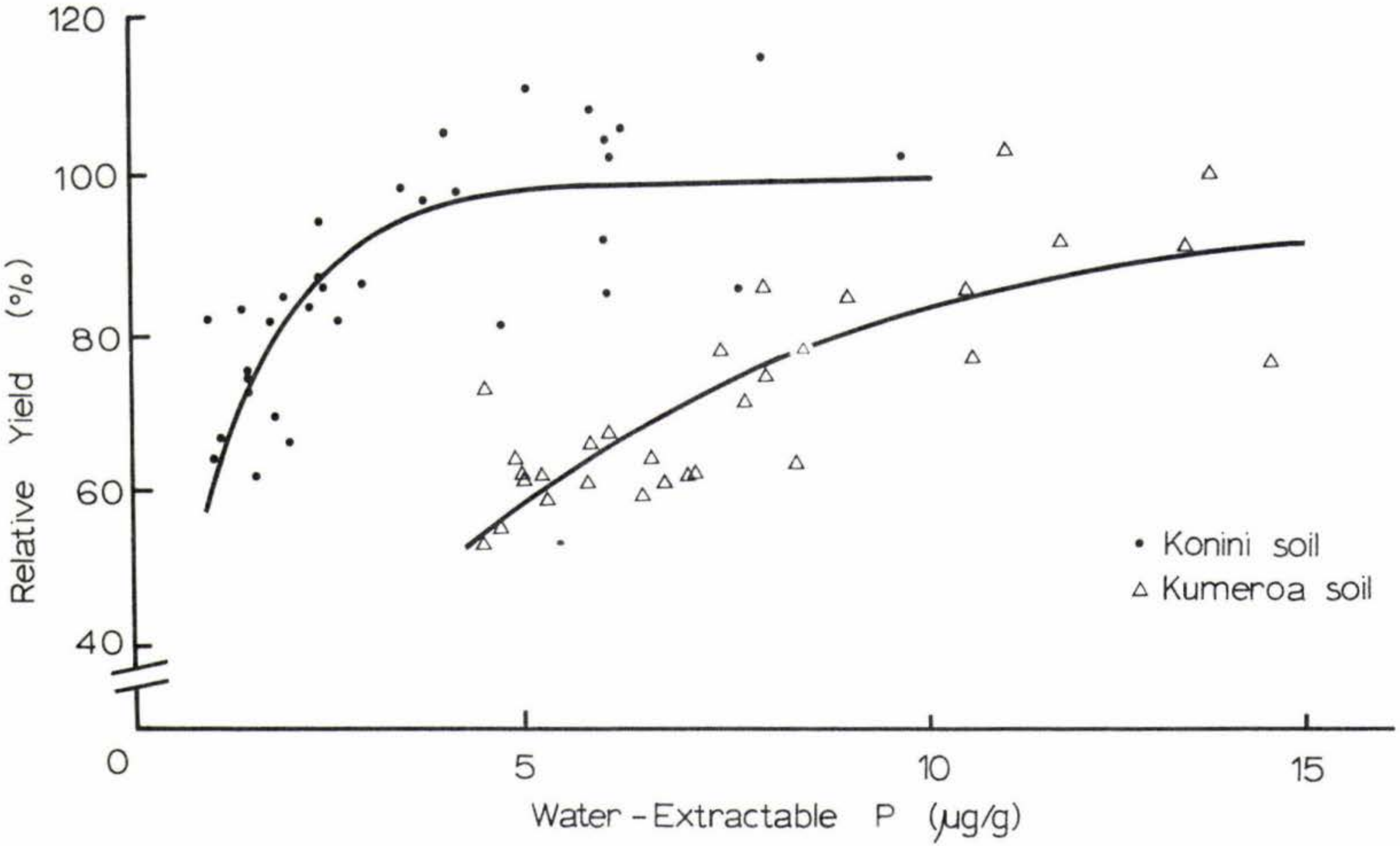

FIGURE 3.9: Relative dry matter yield per core in harvests 3 + 4 as a function of the level of water-extractable P (0-8 cm depth) within the cores.

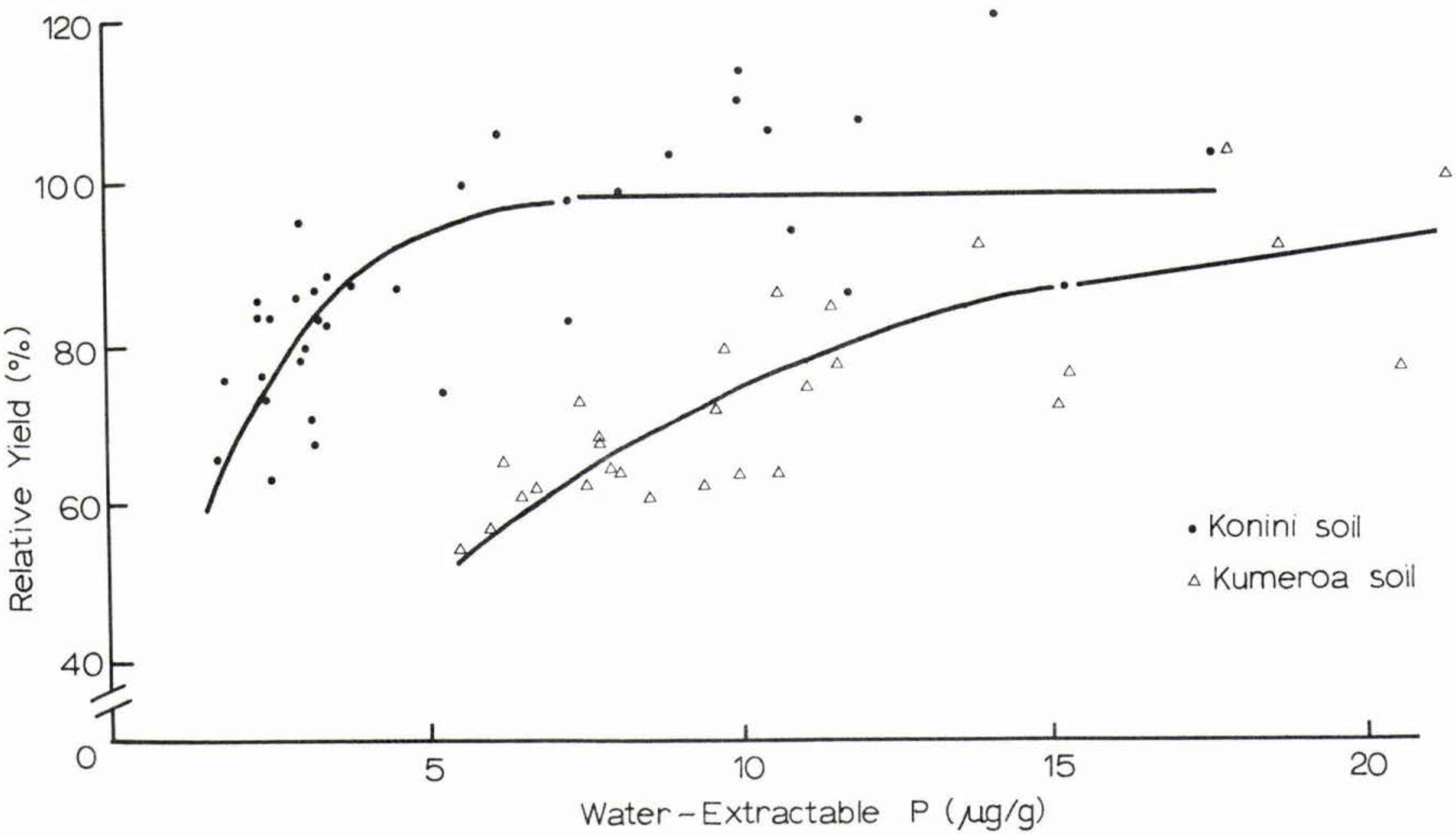

FIGURE 3.10: Relative dry matter yield per core in harvests 3 + 4 as a function of the level of water-extractable P (0-4 cm depth) within the cores.

TABLE 3.6: Critical values of extractable soil P ($\mu g/g$) for which yield given by the fitted curves equals 90% of the maximum yield (parameter A) for constrained and unconstrained exponential curves.*

Yield of cuts 3 + 4 versus:	Konini soil	Kumeroa soil
Olsen P (0-8 cm)	17.8 (57.8)	17.7 (28.1)
Olsen P (0-4 cm)	21.7 (52.2)	20.6 (36.0)
Water-extractable P (0-8 cm)	2.6 (4.3)	12.7 (23.4)
Water-extractable P (0-4 cm)	4.0 (6.2)	16.9 (21.7)

* Figures within brackets relate to unconstrained curves.

levels were higher for the unconstrained curves than for the constrained curves, particularly for Olsen P in the Konini soil (Table 3.6).

3.4 DISCUSSION

The first two harvests from the intact soil cores were characterized by considerable yield variability. Inorganic nitrogen levels in the soil appeared to be one factor causing, or at least related to, some of this variation, particularly for the Kumeroa soil. The soil samples in which inorganic nitrogen levels were determined had been air-dried and stored at room temperature for several weeks, hence the actual levels may not have accurately reflected the inorganic nitrogen status of the soil cores at the start of the experiments. However, the inorganic nitrogen levels measured would have reflected the initial nitrogen status of the cores in a relative sense, since any changes which occurred during air-drying and storage of the soil samples prior to analysis should have affected all samples similarly.

The contrast between the soils in terms of the effect of inorganic soil nitrogen on yield in the first two harvests appeared to reflect the contrasting management of the two trial sites just prior to collecting the cores. Pasture growth on both sites had been spelled from grazing for several weeks to permit assessment of pasture responses to fertilizer treatments in adjacent field trials. The Konini site, normally grazed mainly by sheep, was sampled during this spelling period which enabled most urine patches to be avoided. The Kumeroa site, on the other hand, had been hard grazed by cattle immediately preceding collection of the intact cores, some of which are sure to have been influenced by freshly deposited urine. In addition to this, the average level of inorganic nitrogen in the Kumeroa soil (11 μg/g) was lower than in the Konini soil (28 μg/g) which suggests that the pasture growing on the Kumeroa soil would probably have been more responsive to any nitrogen added to the soil in the form of urine.

The difference between the soils in terms of their inorganic nitrogen content may have partly accounted for the 25% higher mean yield from the Konini cores in the first harvest, particularly since the Kumeroa cores were higher yielding than the Konini cores in the third and fourth harvests after nitrogen had been applied in the nutrient solutions. However, the lower yields of the Kumeroa cores in the earlier harvests may also have been partly the result of treading damage to the sward caused by the hard grazing immediately before the cores were collected from the field trial.

For both soils, approximately three quarters of the variation in yield between cores in harvests 1 + 2 was due to factors other than inorganic soil nitrogen and Olsen P (Table 3.3). These other factors may include previous grazing effects, carry-over of previous differences in fertility and variation in plant density or in species composition. Thus, at least for the Kumeroa soil, cores with a low ryegrass content tended to yield less in harvests 3 + 4 than predicted by the fitted curves and vice versa. Another factor which may have helped to reduce the correlations between yield in harvests 1 + 2 and Olsen P level was the use of "estimated" Olsen P levels instead of actual levels within the intact cores. Figures 3.4 and 3.5 give some indication of the errors involved in estimating the Olsen P status of the cores from samples taken around the cores, although some allowance must be made for differences due to the different sampling dates.

Yields of dry matter from the intact cores were less variable in the third and fourth harvests; at least 50% of the variation was accounted for by differences in extractable soil P (Table 3.5). The extent to which variability was reduced by applying nitrogen to the cores is difficult to judge. Since inorganic nitrogen in the Konini soil was found not to have significantly affected yields in harvests 1 + 2, applying nitrogen would not have been expected to significantly reduce yield variability for the Konini cores in harvests 3 + 4. It therefore appears that at least some of the reduction in variability between the two sets of yield data would have occurred even without applying any nitrogen to the cores. This may have been partly due to, firstly, the use of "within core" extractable P levels and, secondly, the inclusion of data for the +P cores. These latter cores provided more data points in the "high P" range where previously there were relatively few points.

Although extractable soil P accounted for more than half of the variation in yield in harvests 3 + 4, most of the exponential curves fitted to the data without any constraints did not give a significantly improved fit over a straight line. This can be attributed to the yield variability and to the lack of data in the low to medium yield range; almost all cores yielded between 65% and 110% of the mean yield of the

+P cores. As a result of the lack of data with which to define the lower ends of the curves, those fitted to the Konini data intercepted the y axes at yields of 40-50% of the maximum yield (Table 3.4). Though nil extractable soil P may not necessarily imply zero yield, it would be expected that yield would be low relative to that attainable with a non-limiting P supply. This suggests that the curves are likely to be more realistic when constrained to pass through the origin.

Better agreement between predicted maximum yield (parameter A) and measured maximum yield (mean yield of the +P cores) was achieved when the curves were constrained through the origin (Table 3.5). For the Konini soil, parameter A expressed as a proportion of the mean yield of the +P cores varied from 103 to 137% for the unconstrained curves and from 98 to 103% for the constrained curves. Similarly for the Kumeroa soil, parameter A varied from 115 to 136% for the unconstrained curves and from 103 to 111% for the constrained curves. On this basis also the constrained curves appear preferable to the unconstrained curves.

It is important that the magnitude of the c coefficient be determined as accurately as possible since exponential relative yield curves (ie where A = 100) constrained through the origin differ only in terms of the c coefficient. Unconstrained curves may differ also in terms of parameter B. For any given set of yield-extractable soil P data, the choice therefore is essentially between constrained and unconstrained curves. These differ markedly in terms of the magnitude of the c coefficient as shown in Table 3.5.

For Olsen P in the Konini soil and water-extractable P in the Kumeroa soil, the c coefficent for the 0-4 cm depth was larger than that for the 0-8 cm depth when the curves were not constrained through the origin (Table 3.5). This was reflected in higher critical extractable P levels for the 0-8 cm depth than for the 0-4 cm depth (Table 3.6) which is illogical since extractable P levels were in all cases higher in the 0-4 cm depth than in the 0-8 cm depth (Appendices 3 and 5). On the other hand, when all curves were constrained through the origin, c coefficients were consistently greater and critical levels consistently smaller for the 0-8 cm depth than for the 0-4 cm depth. This is further evidence that the constrained curves (Figures 3.7, 3.8, 3.9, and 3.10) are more realistic and therefore to be preferred to the curves fitted without any constraints. Consequently, only the constrained curves will be considered in the General Discussion (section 4.5) covering both the intact core experiments (Chapter 3) and the pot experiments (Chapter 4).

The intact core technique adopted for this glasshouse study appears to have provided reasonably realistic "pasture growth" data otherwise obtainable only under field conditions. Initially the major problem encountered was one of variability which is not surprising in view of the very small surface area of the cores in relation to the size of normal field plots. Consequently, yield data from the initial harvests was of little value. As the number of harvests increased, so also did the proportion of yield variation which could be accounted for. Even so, differences in the level of extractable soil P explained little more than half of the yield variation in the third and fourth harvests.

There would appear to be relatively little scope for reducing this variability other than by selecting cores which appear to be of similar sward composition and vigour, by avoiding cores which have obviously been contaminated by animal excreta, and possibly by increasing the size (surface area) of the cores. Given that variability will be high, it would be advisable to collect more cores than are required, so allowing outliers to be subsequently eliminated, and to subject the cores to a uniformity period before yield measurements are commenced.

CHAPTER 4

GLASSHOUSE STUDY WITH CONVENTIONAL POTS

4.1 INTRODUCTION

The intact core experiments (Chapter 3) suggested that the relationship between relative yield and Olsen-extractable soil P was similar for the two soils studied. When soil P was extracted with distilled water, however, the relationship between relative yield and extractable P appeared to differ between the two soils. The yield data for the intact cores, particularly in the first two harvests, were affected by factors other than soil P status which meant that the yield-extractable soil P relationships could not be defined accurately.

The purpose of this glasshouse study was therefore to define more accurately the yield-extractable soil P relationships for the Olsen and water extraction procedures. The Kumeroa soil included in the previous study was replaced by the Pirinoa* soil, a moderately leached soil from fine sandy siltstone with some admixed loess. The Pirinoa soil had lower P retention and a smaller ratio of Olsen P:water-extractable P (Appendix 1) than the Kumeroa soil, which increased the contrast between the two soils (Konini and Pirinoa) being compared.

4.2 MATERIALS AND METHODS

4.2.1 Collection of soil samples from field plots.

Two main requirements had to be met if the yield-extractable soil P relationships for each soil were to be defined as precisely as possible. Firstly, variation due to factors other than soil P status had to be reduced to a minimum and, secondly, as large a range as possible of extractable soil P values was required.

The first requirement was met by collecting approximately 30 small soil cores (2.5 cm diameter, 8 cm deep) from each field plot, instead of a small number of large cores as in the previous study. All the small cores from a plot were bulked to form one sample representing that plot. It was expected that for the same soil type these bulked soil samples would vary mainly in P status, with minimal variation due to other factors. Any variation due to other nutrients, in particular

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* See footnote on page 27.

nitrogen and sulphur, would be unimportant because it was intended to use nutrient solutions containing all nutrients except P.

To maximise the range of soil P values it was decided to restrict the number of glasshouse pots per field plot to one (ie no replication) and sample all available field plots at each site; ie 32 plots for each rates of P x sulphur trial numbered from 1 to 32. In addition, four bulked samples numbered 33 to 36 were collected from around the outside of both rates of P x sulphur trials to give extra "low" P samples, and eight bulked samples were collected from an adjacent rates of lime x P trial on each soil, which had received the same lime treatment as the corresponding rates of P x sulphur trial in 1973 (Appendix 1).

The eight plots of the rates of lime x P trials included four control (nil P) plots, and four plots which had received 50 kg P/ha each autumn from 1973 to 1978 (ie "very high" P status). These samples were identified by the prefix ML or PL before the plot number, the plots sampled being as follows:

Konini soil: plots ML 4, 16, 19, 29 (nil P) and ML 3, 15, 17, 28 (high P), all of which received 2500 kg lime/ha in June 1973;

Pirinoa soil: plots PL 7, 12, 24, 27 (nil P) and PL 8, 15, 22, 31 (high P), none of which received any lime in 1973.

In total 44 bulked soil samples were collected from both sites, covering as wide a range of soil P status as possible. Sampling was carried out on 12 September 1978.

4.2.2 Preparation and potting of soils.

Each bulked sample of soil was passed through a 6 mm sieve to remove most of the vegetation and was then air-dried. A 20-30 g subsample was taken for chemical analysis and 660 g of each sample was weighed into a labelled 10 cm x 10 cm plastic pot and firmed down. One extra pot of each of samples ML 3, 15, 17, 28 and PL 8, 15, 22 and 31 was prepared to which P would be added to give an estimate of maximum yield. These pots were labelled with +P after the appropriate number and will be collectively referred to as the +P pots.

A composite sample of each of the Konini and Pirinoa soils was saturated with water in the laboratory, then allowed to drain at 50 cm tension to provide a laboratory estimate of field capacity. The moisture content (oven-dry basis) at "field capacity" was 54% for the Konini soil and 50.4% for the Pirinoa soil. Hence the weights at "field capacity" of the 660 g air-dry samples in each pot were 985 g and 960 g for the Konini and Pirinoa soils respectively.

4.2.3 Design and conduct of glasshouse experiments.

On 25 September 1978, 45 Ruanui ryegrass seeds were surface-sown into each pot and gently pressed into the soil, after which distilled water was added. The young seedlings, once established, were thinned to 25 per pot and the pots were placed on two separate trolleys, one for each soil, in a completely randomized design. Watering of the pots with nutrient solutions was commenced a week after sowing the seed and was carried out every 2-3 days initially and daily during the latter stages of the experiments. Each time the pots were watered, their positions were changed by shifting each pot to the position previously occupied by the pot numbered one less than itself. The two trolleys were also interchanged and turned end-for-end regularly.

Nutrient solutions with and without P, but containing nitrogen, were prepared as detailed in Appendix 2. The nutrient solution without P was used for all pots except the +P pots, which received only the +P nutrient solution so as to provide an estimate of maximum yield with P non-limiting. Prior to the first harvest all pots were given the same amount of nutrient solution but because of the large growth differences and hence large differences in water use it became necessary to apply larger amounts of nutrient solution to the higher yielding pots. Throughout the experiments, however, the +P pots (eg ML 3 +P) received identical amounts of nutrient solution to the corresponding -P pots (eg ML 3).

The ryegrass growth was harvested on three occasions when the yield of the best pots was estimated to have reached 4-5 g of dry matter per pot. For the first two harvests the ryegrass was cut 1.5 cm above the soil surface but for the third harvest all herbage "above ground" was harvested. The weight of herbage removed from each pot was determined after oven-drying overnight at 75°C. The date of each harvest and the maximum amount of nutrient solution applied per core prior to each harvest are shown in Table 4.1.

TABLE 4.1: Harvest dates, growth intervals and maximum amounts of nutrient solution (ml) applied per pot prior to each harvest.

	Konini soil	Pirinoa soil
First harvest:		
Date of harvest:	9.11.78	8.11.78
Days of growth (since sowing):	45	44
Nutrient solution applied:	550	560
Second harvest:		
Date of harvest:	28.11.78	27.11.78
Days of growth:	19	19
Nutrient solution applied:	600	670
Third harvest:		
Date of harvest:	12.12.78	12.12.78
Days of growth:	14	15
Nutrient solution applied:	890	980

4.2.4 Analytical procedures.

Olsen P, water-extractable P, P retention and pH were determined on air-dry soil samples (<2 mm) by the methods described in section 3.2.5.

4.2.5 Statistical treatment of data.

Dry matter yields representing increasing periods of growth were calculated as follows: Harvest 1, harvests 1 + 2 and harvests 1 + 2 + 3. Exponential regressions were fitted to the yield-extractable soil P data for each soil, and correlation coefficients calculated, as described in section 3.2.6.

4.3 RESULTS

The levels of Olsen P and water-extractable P in the soil samples used for the pot experiments, as determined in mid-October 1978, are listed in Appendix 7. Olsen P ranged from 6 to 47 μg/g and from 5 to 57 μg/g in samples of the Konini and Pirinoa soils respectively. However the only samples of Konini soil with more than 22 μg/g were the four samples from the lime x P trial. Water-extractable P ranged from 1 to 12 μg/g and from 6 to 44 μg/g in samples of the Konini and Pirinoa soils respectively. All but four of the Konini samples contained less than 4 μg/g of water-extractable P.

Phosphate retention and pH for a selection of samples of both soils are shown in Table 4.2. The values indicate a certain amount of spatial variability within the field trial sites. Phosphate retention was higher for the Konini soil (52.5 to 64.5%) than for the Pirinoa soil (24.5 to 32%), whereas pH was higher for the Pirinoa soil (5.7 to 6.6) than for the Konini soil (5.3 to 5.8).

Dry matter yields per pot for each of the three harvests of ryegrass are shown in Appendix 8. The Pirinoa soil out-yielded the Konini soil in all three harvests. Differences in ryegrass growth between pots covering a range of extractable P levels are illustrated in Plates 4.1 and 4.2.

Exponential curves were fitted without any constraints to the yield-extractable P data for each soil separately. Table 4.3 shows the values of parameter A (maximum yield), parameter C (curvature coefficient) and the y intercept for the fitted curves. All curves gave a significantly ($P < 0.001$) better fit to the data than a straight line. Extractable P in the Pirinoa soil accounted for at least 94% of the yield variation. For the Konini soil a similar proportion of yield variation was accounted

TABLE 4.2: Phosphate retention (%) and pH of selected samples of Konini and Pirinoa soils used for the pot experiments.

Konini soil			Pirinoa soil		
Pot No	pH	P retention	Pot No	pH	P retention
1	5.60	55.0	1	6.45	25.5
8	5.70	53.5	8	6.60	25.0
25	5.60	64.5	25	6.35	24.5
32	5.80	57.5	32	6.50	28.5
33	5.30	58.0	33	6.25	31.5
34	5.60	52.5	34	6.00	28.0
35	5.35	62.5	35	6.25	25.5
36	5.60	53.0	36	5.70	27.0
ML 3	5.75	56.5	PL 7	6.15	29.5
ML 29	5.65	67.5	PL 31	6.05	32.0

PLATE 4.1: Ryegrass growth at the third harvest on selected pots of Konini soil arranged in order of increasing extractable P level (L to R).

PLATE 4.2: Ryegrass growth at the third harvest on selected pots of Pirinoa soil arranged in order of increasing extractable P level (L to R).

TABLE 4.3: Values of (i) parameter A expressed as a proportion (%) of the mean yield of the +P pots; (ii) the y intercept (A - B) expressed as a proportion (%) of maximum yield (parameter A); (iii) parameter c (g/μg); and (iv) the correlation coefficient (r); for exponential curves fitted without any constraints (data from the +P pots excluded).

	(i)	(ii)	(iii)	(iv)*
Yield versus Olsen P				
Konini soil:				
Harvest 1	131.7	5.4	0.028	0.946
Harvests 1 + 2	107.1	6.0	0.039	0.944
Harvests 1 + 2 + 3	98.5	8.1	0.046	0.948
Pirinoa soil:				
Harvest 1	99.3	17.2	0.058	0.972
Harvests 1 + 2	98.7	22.5	0.049	0.977
Harvests 1 + 2 + 3	96.9	24.7	0.047	0.982
Yield versus water-extractable P				
Konini soil:				
Harvest 1	97.3	8.5	0.287	0.966
Harvests 1 + 2	89.3	9.6	0.339	0.965
Harvests 1 + 2 + 3	86.3	13.8	0.363	0.960
Pirinoa soil:				
Harvest 1	97.4	-0.5	0.087	0.972
Harvests 1 + 2	96.8	10.2	0.072	0.972
Harvests 1 + 2 + 3	94.7	13.6	0.070	0.973

* All values of the correlation coefficient are significant at the 0.1% level.

for by water-extractable P, though Olsen P accounted for slightly less of the variation (Table 4.3).

The values of parameter A for cut 1 closely approximated the mean yields of the +P pots for all curves except yield versus Olsen P in the Konini soil. As the number of harvests increased parameter A decreased relative to the mean yields recorded for the +P pots. The y intercept was generally low for the first harvest but increased as the number of harvests increased. For the Konini soil the size of the c coefficient also increased as the number of harvests increased but the reverse occurred with the Pirinoa soil (Table 4.3).

Exponential curves were also fitted without any constraints to all the available data, including the +P pots, because of the large discrepancy between measured maximum yield in cut 1 and that predicted by the curve for yield versus Olsen P in the Konini soil (Table 4.3). On the assumption that growth of the +P pots was not limited by P, Olsen P in both soils and water-extractable P in the Pirinoa soil were arbitrarily set at 500 μg/g, while water-extractable P in the Konini soil was set at 100 μg/g. Table 4.4 shows the values of parameter A, parameter C and the y intercepts for curves fitted to both the -P and +P data.

Not surprisingly, there was very good agreement between parameter A and the mean yield of the +P pots for all curves, with negligible change as the number of harvests increased. The y intercept was generally small for harvest 1 but increased as the number of harvests increased. The size of the c coefficient declined in all cases as the number of harvests increased (Table 4.4).

Exponential curves, constrained to pass through the origin, were also fitted to the data (excluding the +P pots) because not all curves fitted without this constraint intercepted the y axis close to the origin (Table 4.3). Table 4.5 shows the values of parameter A and parameter C for the constrained curves. Almost without exception, constraining the curves through the origin decreased parameter A and increased the c coefficient. Also, the size of the c coefficient increased in all cases as the number of harvests increased (Table 4.5).

Attempts to fit curves to all the data (both -P and +P) and at the same time constrain the curves to pass through the origin were mostly unsuccessful and will therefore not be considered. For all other fitted curves (Tables 4.3, 4.4 and 4.5), "critical" extractable soil P levels at 90% of the predicted maximum yields were calculated

TABLE 4.4: Values of (i) parameter A expressed as a proportion (%) of the mean yield of the +P pots; (ii) the y intercept (A - B) expressed as a proportion (%) of maximum yield (parameter A); and (iii) parameter c (g/μg); for exponential curves fitted without any constraints (data from the +P pots included).

	(i)	(ii)	(iii)
Yield versus Olsen P			
Konini soil:			
Harvest 1	102.1	-2.3	0.048
Harvests 1 + 2	100.6	3.5	0.046
Harvests 1 + 2 + 3	99.9	8.7	0.044
Pirinoa soil:			
Harvest 1	99.8	17.6	0.057
Harvests 1 + 2	99.7	22.9	0.047
Harvests 1 + 2 + 3	99.5	25.8	0.043
Yield versus water-extractable P			
Konini soil:			
Harvest 1	99.3	9.5	0.270
Harvests 1 + 2	97.1	14.0	0.262
Harvests 1 + 2 + 3	96.5	19.8	0.248
Pirinoa soil:			
Harvest 1	99.3	3.1	0.081
Harvests 1 + 2	99.5	13.3	0.065
Harvests 1 + 2 + 3	99.3	18.2	0.059

TABLE 4.5: Values of (i) parameter A expressed as a proportion (%) of the mean yield of the +P pots; and (ii) parameter c (g/μg); for exponential curves constrained through the origin (data from the +P pots excluded).

	(i)	(ii)
Yield versus Olsen P		
Konini soil:		
Harvest 1	113.5	0.040
Harvests 1 + 2	98.8	0.050
Harvests 1 + 2 + 3	91.6	0.059
Pirinoa soil:		
Harvest 1	93.3	0.081
Harvests 1 + 2	89.1	0.082
Harvests 1 + 2 + 3	86.4	0.085
Yield versus water-extractable P		
Konini soil:		
Harvest 1	93.0	0.362
Harvests 1 + 2	86.2	0.423
Harvests 1 + 2 + 3	82.5	0.488
Pirinoa soil:		
Harvest 1	97.5	0.087
Harvests 1 + 2	93.1	0.087
Harvests 1 + 2 + 3	89.9	0.091

and are shown in Table 4.6. Critical levels of water-extractable P were consistently very much less for the Konini soil than for the Pirinoa soil. There was less difference between the soils in terms of critical Olsen P levels, which were invariably higher for the Konini soil than for the Pirinoa soil.

4.4 DISCUSSION

In contrast to the intact core experiments, the yield data obtained in the pot experiments included only a small amount of unexplained variation as indicated by the high correlation coefficients (Table 4.3). It is possible that some of the unexplained variation was caused by differences in P retention (Table 4.2) since, for both soils, pots with higher P retention tended to yield lower than predicted by the Olsen P curves (Table 4.3) and vice versa. However, there were insufficient data to draw any definite conclusions about the effect of P retention.

When exponential curves were fitted without any constraint to the data from the -P pots only, the curves tended either not to intercept the y axis close to the origin or not to accurately predict measured maximum yield. The curve for yield versus water-extractable P in the Pirinoa soil was a notable exception (Table 4.3). When the +P data were included to improve agreement between predicted and measured maximum yields (Table 4.4), or when the curves were constrained through the origin (Table 4.5), the magnitude of the c coefficient tended to change considerably. Since the y intercept (ie where extractable soil P is zero) might be expected to occur close to the origin, the relationship between relative yield and extractable soil P is essentially described by the c coefficient. It is therefore important to ascertain which values of the c coefficient given in Tables 4.3, 4.4 and 4.5 are most realistic for each set of yield-extractable P data.

Results for the Pirinoa soil will be considered first. Both the Olsen P and water-extractable P curves accurately predicted the maximum yield recorded in the first harvest (Table 4.3). Such close agreement was probably achieved because most of the pots were in the medium to high yielding range; ie between about 50% and 95% of the mean yield of the +P pots. This strongly suggests that the mean yield of the +P pots was in fact an accurate estimate of the maximum yield attainable under the conditions of the experiment.

TABLE 4.6: Critical values of extractable soil P (μg/g) for which yield given by the fitted curve equals 90% of the maximum yield (parameter A) for (i) curves fitted without constraint to -P data only; (ii) curves fitted without constraint to both -P and +P data; (iii) curves fitted to -P data only and constrained through origin.

	(i)	(ii)	(iii)
<u>Yield versus Olsen P</u>			
Konini soil:			
Harvest 1	79.7	48.4	57.9
Harvests 1 + 2	57.1	49.8	46.3
Harvests 1 + 2 + 3	48.2	49.8	38.8
Pirinoa soil:			
Harvest 1	36.7	37.2	28.5
Harvests 1 + 2	42.0	43.4	28.2
Harvests 1 + 2 + 3	42.8	46.5	27.1
<u>Yield versus water-extractable P</u>			
Konini soil:			
Harvest 1	7.7	8.1	6.3
Harvests 1 + 2	6.5	8.2	5.4
Harvests 1 + 2 + 3	5.9	8.4	4.7
Pirinoa soil:			
Harvest 1	26.5	28.1	26.6
Harvests 1 + 2	30.3	33.0	26.3
Harvests 1 + 2 + 3	30.6	35.5	25.2

The Olsen P curve, however, intercepted the y axis at 17.2% of the maximum yield which may simply have been a reflection of the lack of data with which to define the lower end of the curve; ie between 0 and 50% of the mean yield of the +P pots. Yet when the Olsen P curve was constrained through the origin, agreement between predicted and measured maximum yield declined (Table 4.5). It has already been concluded that the maximum yield as measured was accurate. This implies that even if data were available to define the lower end of the Olsen P curve, it may still not have intercepted the y axis any closer to the origin.

As the number of harvests increased, constraining the curves for the Pirinoa soil through the origin further reduced agreement between predicted and measured maximum yield and, particularly for Olsen P, increased the magnitude of the c coefficient (Table 4.5). On the other hand, when the +P data were included and the curves were left unconstrained the c coefficient decreased only slightly while agreement between predicted and measured maximum yield improved, particularly as the number of cuts increased (Table 4.4). This suggests that the curves should not be constrained to pass through the origin but that the +P data should be included.

Support for these conclusions is provided by the calculated results for critical extractable soil P levels shown in Table 4.6. The main effect of including the +P data for the Pirinoa soil was to increase the difference in critical level between harvests 1 + 2 and harvests 1 + 2 + 3. For both sets of data (ie with and without the +P pots), critical extractable P levels increased as the number of harvests increased. This indicates, as would be expected, that the level of extractable soil P required to achieve a given proportion of maximum yield increased as the period of growth increased. When the curves were constrained through the origin, on the other hand, critical levels were lower and tended to decline slightly as the number of harvests increased (Table 4.6). This contrasts with results obtained by Holford and Mattingly (1976) in pot experiments with ryegrass. They found that critical levels increased as the number of harvests increased, irrespective of whether the extraction procedure measured P intensity or quantity.

Results for the Konini soil differed in some respects from those of the Pirinoa soil. Only the water-extractable P curve accurately predicted the mean yield of the +P pots (Table 4.3). The maximum yield predicted by the Olsen P curve, on the other hand, was more than 30% higher than the mean yield of the +P pots. This indicates that at least one of the fitted curves was inaccurate. Since the P applied to the +P pots during the experiment could have been inadequate to achieve maximum yield, it is possible that either or both curves was inaccurate. The discrepancy between the Olsen P and water-extractable P curves can probably be attributed to the lack of data with which to accurately define the upper portion of the curves. In contrast to the Pirinoa soil, only four pots of Konini soil yielded more than 65% of the mean yield of the +P pots.

If the Olsen P curve for harvest 1 is assumed to be correct, then both the water-extractable P curve and the mean yield of the +P pots underestimated maximum attainable yield. This would imply that the P applied to these pots during the experiment was insufficient to achieve maximum yield. Of the two soils, this would be more likely to occur with the Konini soil because of it's higher P retention (Table 4.2). However, the critical Olsen P level was very high (80 μg/g) for the first harvest and declined markedly as the number of harvests increased (Table 4.6), in contrast to the results for the Pirinoa soil and also in marked contrast to the findings of Holford and Mattingly (1976). Also, it can be argued that logically the critical level must increase, rather than decrease, as the number of harvests increases. It is therefore concluded that the Olsen P curve for the Konini soil was anomalous, and the water-extractable P curve was accurate. The mean yield of the +P pots is therefore considered to provide an accurate estimate of maximum yield for the Konini soil also.

An increase in the c coefficient (Table 4.3) and a decrease in the critical level (Table 4.6) as the number of harvests increased occurred not only with Olsen P but also with water-extractable P in the Konini soil. The same trends were present when the curves were constrained to pass through the origin (Tables 4.5 and 4.6). However, when the +P data were included these trends were completely reversed (Tables 4.4 and 4.6), in line with the findings of Holford and Mattingly (1976) discussed earlier.

It is therefore concluded that the curves for the Konini soil, as for the Pirinoa soil, should not be constrained through the origin but that the data for the +P pots should be included. Curves fitted to the data in this way (Table 4.4) are shown in Figures 4.1 and 4.2 for Olsen P and

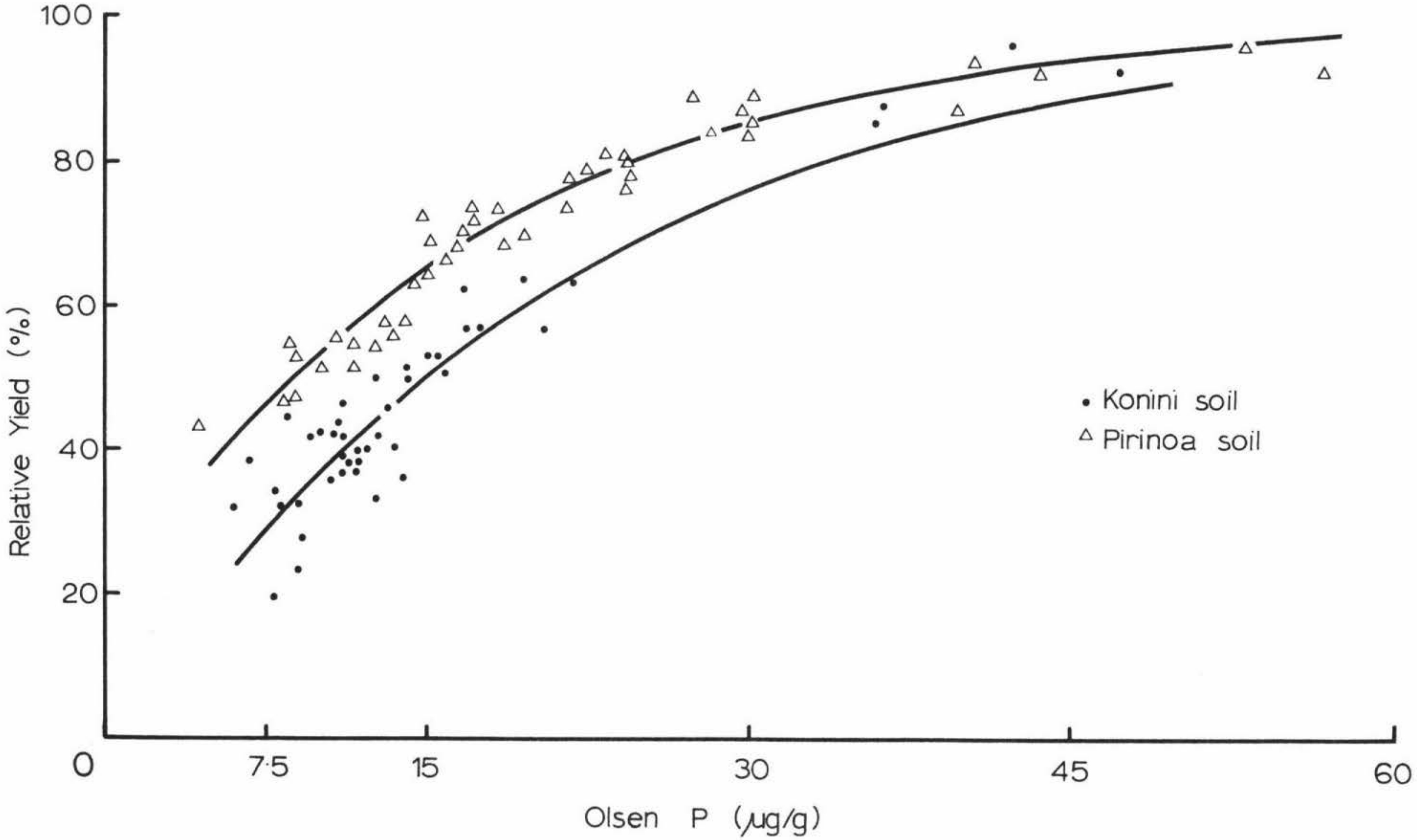

FIGURE 4.1: Relative dry matter yield per pot in the first harvest as a function of the level of Olsen P.

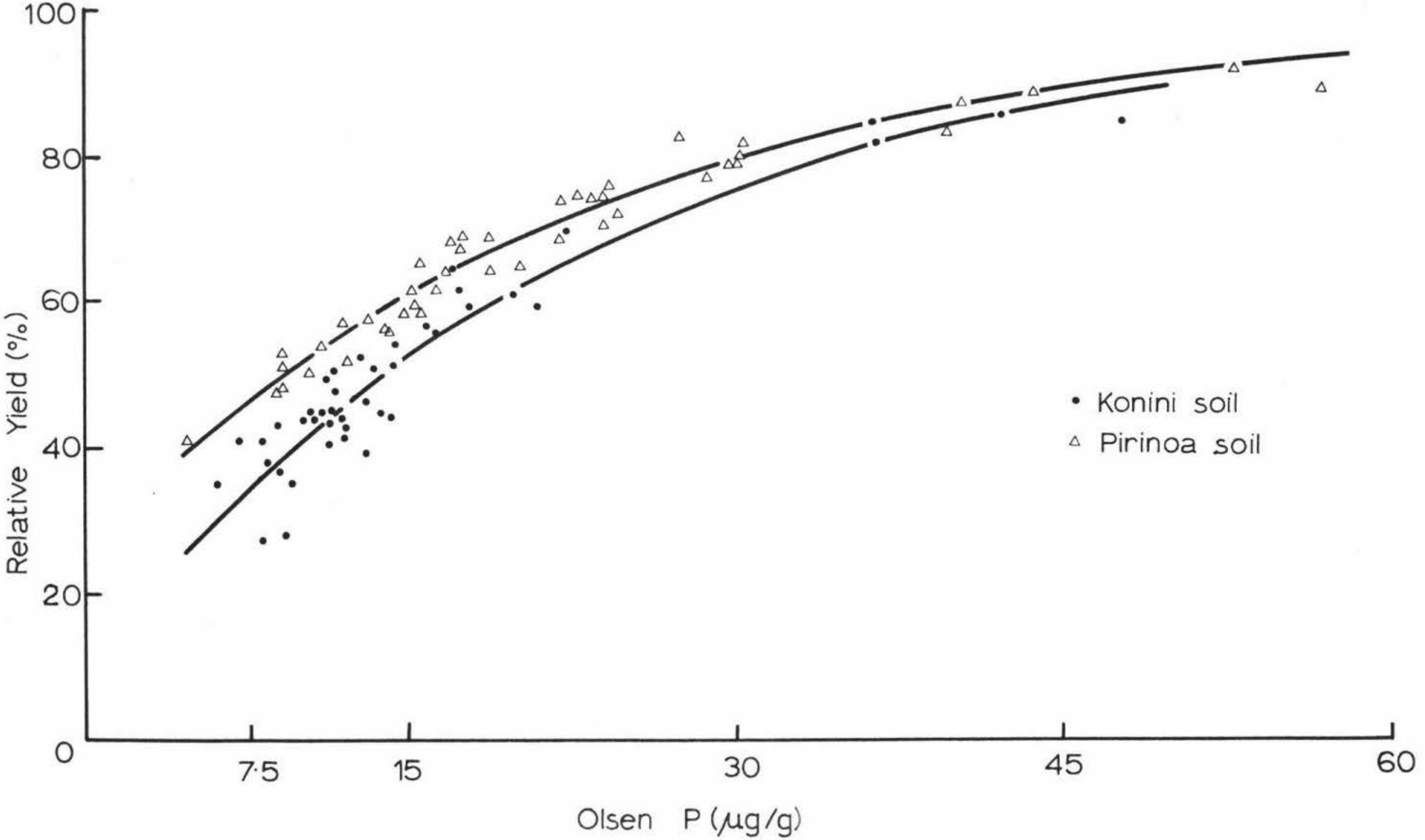

FIGURE 4.2: Relative dry matter yield per pot in three harvests as a function of the level of Olsen P.

and in Figures 4.3 and 4.4 for water-extractable P. Only the curves for harvest 1 and harvests 1 + 2 + 3 are shown to illustrate the effect of different periods of growth.

4.5 GENERAL DISCUSSION OF POT EXPERIMENTS AND INTACT CORE EXPERIMENTS

The pot experiments clearly showed that a curvilinear relationship existed between yield of dry matter and the amount of soil P extracted by either water or sodium bicarbonate. This curvilinear relationship was defined much more accurately in the pot experiments than in the intact core experiments for two main reasons. Firstly, variation in yield between pots caused by factors other than extractable soil P was greatly reduced and, secondly, the pot trial data covered a greater range of relative yields. As a result the difference between soils could be more accurately assessed in the pot trials than in the intact core experiments. Against this, however, is the disadvantage that the results of the pot trials are not directly applicable to the field situation.

The Konini soil was common to both the pot experiments and the intact core experiments which permits results obtained by the two techniques to be compared. For Olsen P (0-8 cm depth), the c coefficient (as g soil/μg P) decreased from 0.13 in the intact core experiment to about 0.05 in the pot experiment, while the corresponding critical level of Olsen P rose from 18 to 48 μg/g. For water-extractable soil P (0-8 cm) the c coefficient decreased from 0.87 in the intact core experiment to 0.27 in the pot experiment, resulting in an increase in the critical level from 2.6 to 8 μg/g. Thus there was an approximately three-fold difference between the techniques in terms of the magnitude of both the c coefficients and the critical levels of extractable soil P. This difference is a reflection of the lower relative yields recorded in the pot experiment compared with those recorded in the intact core experiment at the same levels of extractable soil P. This would be expected since it is invariably found that responses to applied P in pot experiments are much greater in relative terms than those obtained on the same soil in the field (Sherrell and Saunders, 1974).

The intact core experiments were essentially a compromise between much more demanding field trials on the one hand and much quicker, less variable but less applicable pot experiments on the other. Although the intact core technique appears not to have been investigated previously for soil test correlation purposes, it was hoped that results from such experiments would be more applicable to the field situation than are

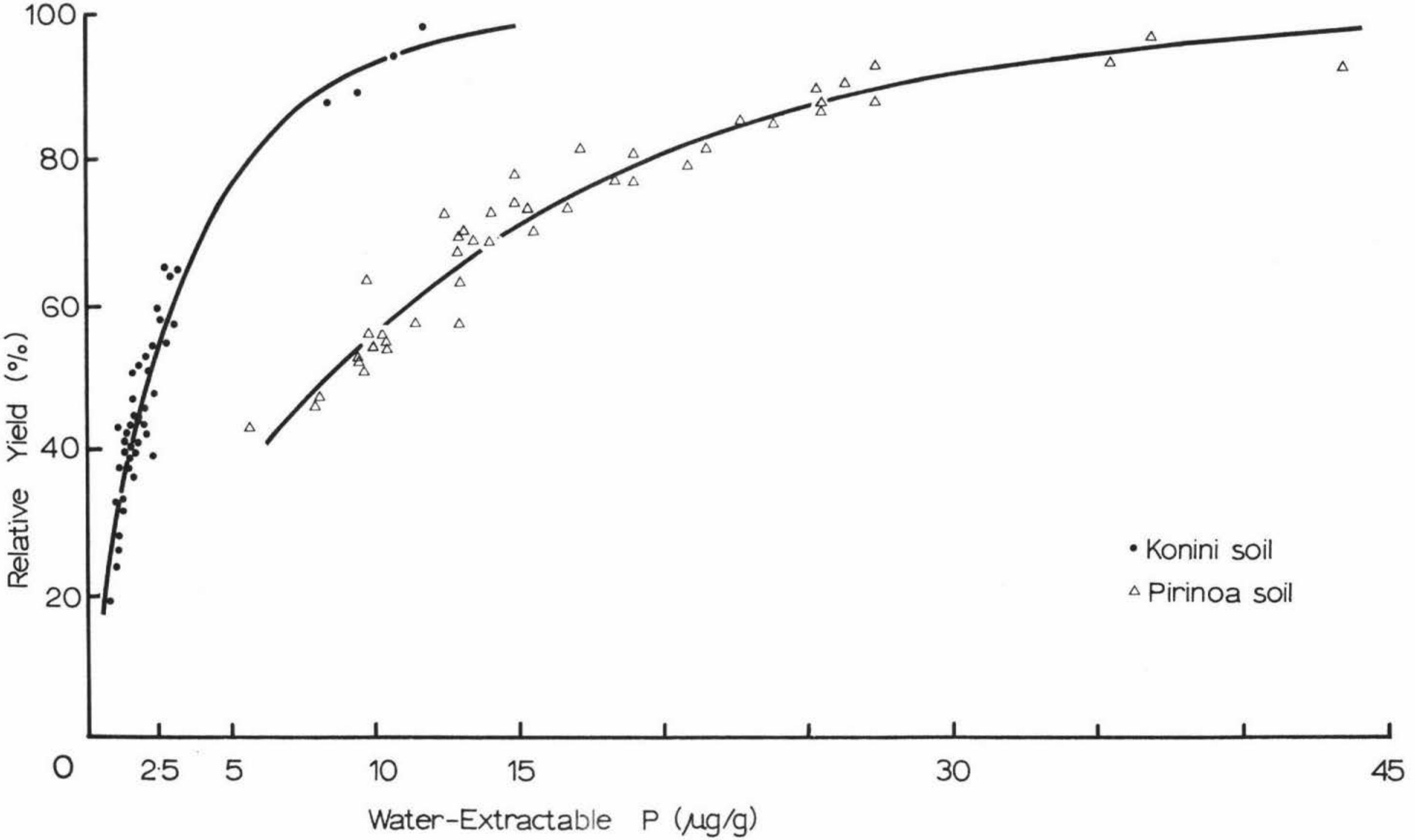

FIGURE 4.3: Relative dry matter yield per pot in the first harvest as a function of the level of water-extractable soil P.

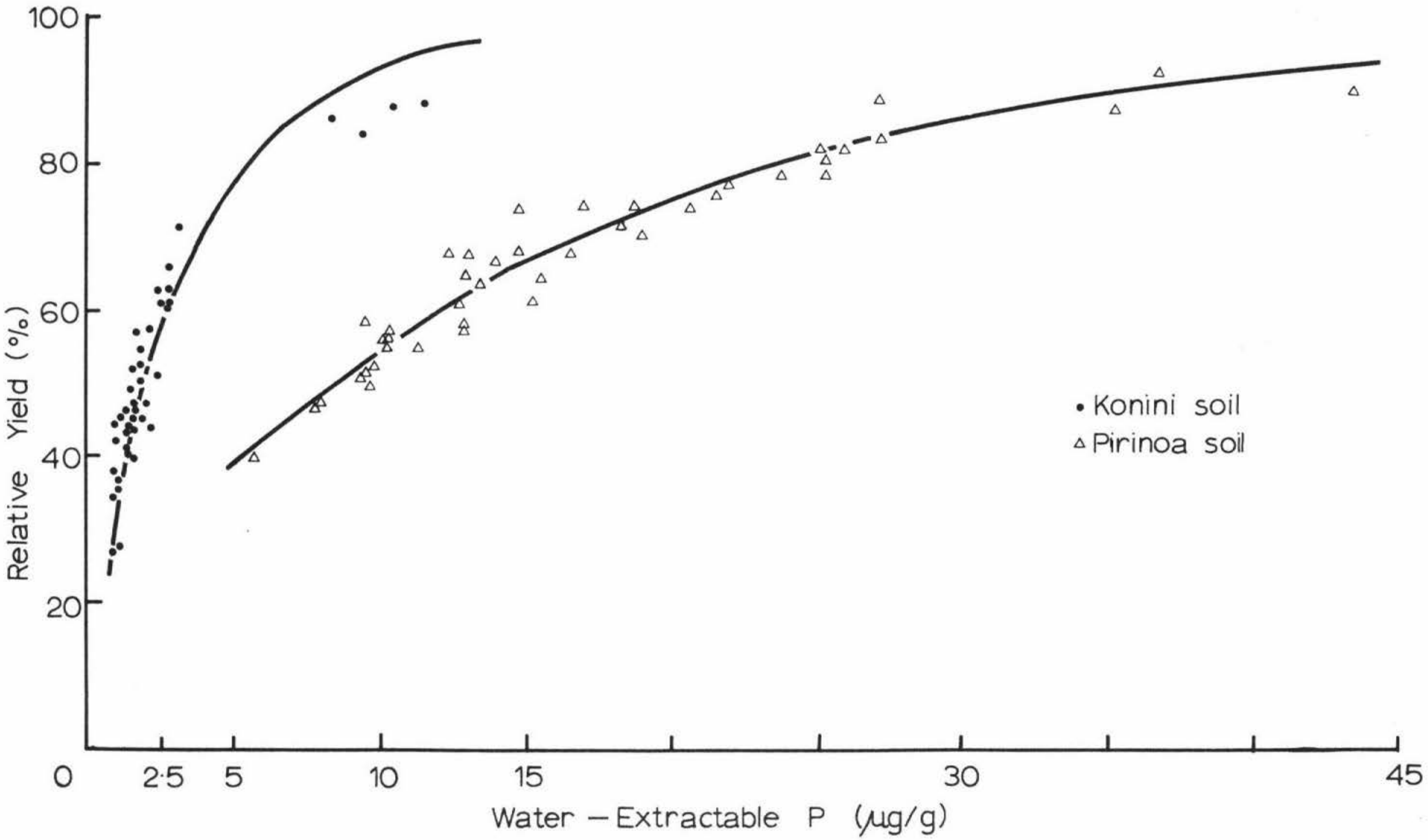

FIGURE 4.4: Relative dry matter yield per pot in three harvests as a function of the level of water-extractable soil P.

pot experiments. The results of Grigg (1972) tend to confirm this. He found that an Olsen P level (0-7·5 cm depth) of 20 μg P/g soil best distinguished responsive and non-responsive pasture trials on a range on zonal soils in New Zealand. These trials were assessed for response to applied P in spring. If it is assumed that pastures become responsive to applied P when yield in the absence of applied P falls below 90% of that obtained in the presence of applied P, then Grigg's (1972) "critical" Olsen P level of 20 μg/g is very similar to the critical levels of about 18 μg/g found for both soils in the intact core experiments. Further, had Olsen P been determined for the 0-7.5 cm depth, instead of the 0-8 cm depth, the critical levels found in the intact core experiments would have tended to be slightly greater.

The results of the two glasshouse techniques appear to differ more when the Olsen P curves are compared than when the water-extractable P curves are compared. It was not possible to distinguish between the Konini and Kumeroa soils on the basis of the relationship between yield and Olsen P in the intact core experiments (Figures 3.7 and 3.8). In the pot experiments, on the other hand, a difference between the soils studied was plainly evident in the first harvest, the less-buffered Pirinoa soil yielding more than the more-buffered Konini soil at equal levels of Olsen P (Figure 4.1). This may have been partly because the Pirinoa soil was used in place of the Kumeroa soil in the pot experiments, however.

Barrow (1967) obtained similar results to those obtained in the pot experiments in a glasshouse study in which soft brome grass was grown in 42 different surface soils and harvested on several occasions. In the first harvest, P uptake from soils of equal bicarbonate-extractable P (Colwell's method) decreased with increasing buffering capacity, suggesting that Colwell's bicarbonate extraction overestimates the availability of P in soils of high buffering capacity and vice versa. This would appear to be true of any soil P extraction method which measures quantity, as opposed to intensity, because the higher the buffering capacity the lower will be the P concentration in solution and hence plant uptake will be lower (Holford and Mattingly, 1976). Olsen's extraction method, which provides less of a P quantity measurement than Colwell's method, was found to overestimate soil P availability in soils of high buffering capacity to a lesser extent than Colwell's method in pot trials with both clover and grass (Barrow and Shaw, 1976b).

Because extraction methods which measure P quantity underestimate the effects of buffering capacity on soil P availability, the critical level (for say 90% of maximum yield) is higher for soils of high buffering capacity than for soils of low buffering capacity. This has been demonstrated in pot trials with ryegrass in which soil P quantity was measured as adsorbed P plus isotopically-exchangeable P (Holford and Mattingly, 1976) and also in field trials on subterranean and white clover pastures in which P quantity was measured by Colwell's bicarbonate extraction procedure (Helyar and Spencer, 1977). Likewise in the present pot experiments, the critical Olsen P level was higher for the more-buffered Konini soil than for the less-buffered Pirinoa soil in the first harvest (Table 4.6), suggesting that Olsen extraction also at least partially reflects P quantity.

The difference in critical Olsen P level between the soils decreased from 9.2 to 3.3 μg/g as the number of cuts increased from one to three (Table 4.6), indicating that the effect of the different buffering properties of the two soils on the critical level had declined. Both Barrow (1967) and Holford and Mattingly (1976) also found that in pot trials the effects of buffering capacity became smaller with time. Barrow attributed this to more rapid depletion of soil P reserves in soils of low buffering capacity as a result of greater P uptake, and also to more extensive root exploration with time in soils of high buffering capacity. On this basis it would be expected that the effects of buffering capacity differences on yield-Olsen P relationships and on critical Olsen P levels would be at a minimum in undisturbed soils supporting permanent pasture and at a maximum shortly after plant establishment in pots.

It is not surprising, therefore, that no difference in the critical Olsen P level was found between the Konini and Kumeroa soils in the intact core experiments. This does not imply that a difference would not have been found between soils of more contrasting P retention properties. In Australia, Helyar and Spencer (1977) found that the critical level of bicarbonate-extractable P varied by up to three-fold for pasture soils of widely different buffering capacities. However, since these workers used Colwell's method to extract soil P, the variation in critical level between soils of different buffering capacity was probably greater than it would have been for soil P extracted by Olsen' method.

In the present study quite different relationships between yield of dry matter and water-extractable P were found to exist for different soils, not only in the pot experiments but also in the intact core experiments. At equal levels of water-extractable P, the more-buffered Konini soil was much higher yielding than the less-buffered Kumeroa and Pirinoa soils (Figures 3.9, 3.10, 4.3 and 4.4), suggesting that water extraction underestimates the availability of P in soils of high buffering capacity and vice versa. This indicates that the water extraction method measures predominantly P intensity, as opposed to quantity, since the higher the buffering capacity of soils of equal intensity, the more P is desorbed as intensity is lowered by root uptake, and hence plant uptake and yield will be higher (Holford and Mattingly, 1976).

As a result of very different relationships between yield and the amount of soil P extracted by water, the critical levels of water-extractable P were much higher for the less-buffered soils than for the more-buffered Konini soil (Tables 3.6 and 4.6). This result is in general agreement with the findings of Holford and Mattingly (1976) who showed that for extraction methods which measure intensity, critical levels decrease as the buffer capacities of soils increase. Consequently, even greater differences between soils than those found in the intact core experiments seem likely to exist between soils of more contrasting P retention properties.

The difference in critical water-extractable P level between the Konini and Pirinoa soils increased from 20 to 27 µg/g as the number of harvests increased from one to three (Table 4.6). Holford and Mattingly (1976) similarly showed that with intensity measurements the effects of buffering capacity became greater as the period of growth, and hence the time since sowing, increased. Since this trend is the opposite of that for Olsen P discussed earlier, it might be expected that the effects of buffering capacity on yield-water-extractable P relationships and on critical levels of water-extractable P would be greatest in long-term pot trials and in undisturbed soils in the field supporting permanent pasture.

The effects of buffering capacity on critical levels led Holford and Mattingly (1976) to conclude that it is impossible to set a universal critical level for either quantity or intensity of soil P in a group of soils, unless the buffering capacity and time of cropping are uniform. While critical levels for quantity increase, those for intensity decrease, as the buffer capacities of soils increase. However, the extent to which critical levels for quantity increase with increasing buffering capacity, must decline as the emphasis of soil P extraction gradually shifts away from quantity measurement towards intensity measurement. Conversely, the extent to which critical levels for intensity decrease with increasing buffering capacity, must decline as the emphasis of extraction shifts away from intensity measurement towards quantity measurement. This suggests that for a soil P extraction procedure to be independent of soil type (ie the critical level is the same for all soils) it should provide a composite measure of both intensity and quantity. The Olsen extraction procedure, according to Williams (1967), falls within this category.

When the Olsen extraction method replaced the Truog method in New Zealand in 1976, interpretation of the Olsen soil test was based on the division of North Island soils into low rainfall (yellow-grey earths, some recent alluvial soils, some yellow-brown sands) and high rainfall (yellow-brown earths, yellow-brown pumice soils, red and brown loams) categories (W.M.H. Saunders, pers. comm.). However, no published information is available to indicate the extent to which critical Olsen P levels vary between different soils within New Zealand. The present glasshouse studies provide some information in this respect. The results of the intact core experiments indicate a critical Olsen P level (0-8 cm depth) of about 18 μg/g in both the Konini and Kumeroa soils. Further information is required for New Zealand soils of more contrasting sorption properties.

Critical levels of water-extractable P, in contrast to Olsen P, varied between the soils studied. The results of the intact core experiments indicate critical water-extractable P levels (0-8 cm depth) of 2.6 and 12.7 μg/g for the Konini and Kumeroa soils respectively. These findings conflict with the suggestions of Ryden et al (1976), which appeared to be confirmed by Luscombe (1976), that the water extraction method should be essentially independent of soil type. The glasshouse study of Luscombe (1976) included five soils, comprising three soil types of widely varying P retention. The response of ryegrass to applied P was better correlated with water-extractable P than with Olsen P in the five soils. There is no obvious reason for the discrepancy between Luscombe's results and those of the present experiments, except perhaps that the number of soils included in Luscombe's study was insufficient to provide a reliable comparision of the different extraction procedures.

The Olsen procedure would provide a more suitable index of plant-available soil P for any simulation model intended to predict pasture production from soil P extraction data. The relationship between yield and Olsen-extractable P, and hence the c coefficient, would not need to be determined for each different soil type. The magnitude of the c coefficient, at least for soils of low to medium P retention (20 - 60%), appears to be of the order of 0.13 g/μg P. This compares with values of 0.03 (more-buffered soils) to 0.08 (less-buffered soils) found by Helyar and Spencer (1977) for constrained exponential curves fitted to data from pasture trials in Australia. The smaller values of the c coefficient obtained by these workers can be attributed to the greater amounts of soil P extracted by the Colwell method as compared with the Olsen method.

In addition to the need for information on possible variation in the c coefficient between New Zealand soils of more contrasting soil properties, information is also required on the extent to which the c coefficient varies between different seasons of the year. In spring the P status of pastures is generally higher than in autumn and responses to applied P occur less frequently within a given range of soil test values (Saunders and Metson, 1971). This seasonal variation in the availability of soil P for pasture growth prompted the soil testing service of the Ministry of Agriculture and Fisheries to have different soil test interpretations for spring and autumn when the Olsen procedure was introduced in 1976. These observations suggest that the magnitude of the c coefficient may vary between seasons, possibly to a greater extent than the variation between contrasting soils. This could only really be determined under field conditions although it may be possible to investigate variation in the c coefficient between simulated seasons through the use of controlled climate facilities.

CHAPTER 5

FIELD STUDIES

5.1 INTRODUCTION

The field studies had two main aims. Firstly to determine whether the level of extractable soil P in a typical New Zealand pasture soil changed seasonally in the absence of any fertilizer P applications to the soil. The second main aim of the field studies was to measure increases in extractable soil P at various time intervals after the application of fertilizer P at normal rates of usage. A secondary aim was to determine whether changes in extractable soil P following the application of fertilizer P differed according to the time of year when the fertilizer was applied.

Seasonal variation in extractable soil P was studied in detail at one site over a full year. The effects of fertilizer P applications on extractable soil P levels were studied at the same site as above and at a second site. The two experimental sites were located on soils of contrasting P retention properties. The soil P extraction procedures used in the glasshouse studies were also used in the field studies.

5.2 MATERIALS AND METHODS

5.2.1 Selection of soils and trial sites.

The trial site selected for the major part of the field studies was located on Tokomaru silt loam, a weakly leached, moderately to strongly gleyed soil formed on thick loess deposits (Cowie, 1978). The Tokomaru soil is characterized by a fine textured B horizon and a fragipan which together impede drainage through the profile.

The site selected for the trial was on the Agronomy Research Area (paddock 13), having previously been part of a University sheep farm prior to 1970. The area was used as a dairy beef unit between 1970 and 1976, and was taken over by the Agronomy Department in January 1977 who grazed the pastures with sheep. The paddock in which the trial was located was topdressed with 250 kg/ha of 50% potassic superphosphate in May 1977 and was closed for a hay crop later in the year. The hay was cut and baled in mid-January 1978. The dominant pasture species present included ryegrass, white clover and *Poa* species.

The second trial site was located on Ramiha silt loam, a strongly leached soil formed on loess, solifluction material and slope deposits

(Cowie, 1978). The Ramiha soil is free-draining because of a very friable, weakly structured B horizon, typical of soils with high amounts of allophane. Other chemical and pedological information relevant to the soils at both trial sites is given in Appendix 1.

The trial located on the Ramiha soil was on a sloping site adjacent to the Pahiatua Track road between Palmerston North and Pahiatua. The site had been initially cultivated, sown to pasture and topdressed regularly with fertilizer for many years, although receiving less fertilizer in total than the site on the Tokomaru soil. The pasture sward included a large component of low fertility species such as browntop and lotus in addition to some ryegrass, cocksfoot and white clover. The site was previously grazed by both cattle and sheep.

5.2.2 Preliminary assessment of spatial variability of extractable soil P.

A preliminary sampling of the trial site on the Tokomaru soil was carried out in December 1977, some weeks after the paddock had been closed for a hay crop. Three plots, each of about 6 m^2, were selected within the trial area, one towards each end (plots A and C) and the third (plot B) midway between the first two. A distance of about 20 m separated adjacent plots. Within each plot twelve soil cores (three across x four along the plot) to 4 cm depth were collected at 1 m intervals.

A further three soil cores were collected at points about 2 m on either side of plots A, B and C and at points midway between adjacent plots; each set of three cores was bulked together. After air-drying and sieving (section 5.2.4), the soil samples from within plots were analysed for Olsen P and water-extractable P (section 3.2.5), while the bulked samples were analysed only for Olsen P.

The levels of Olsen P and water-extractable P recorded are listed in Appendices 9 and 10 respectively, which show the spatial distribution of individual plots relative to an adjacent fenceline, and of cores within each plot, as they occurred in the field. The lowest, highest and mean extractable P levels for each plot, and the overall mean and standard error associated with individual cores, are shown in Table 5.1. The mean and standard error for water-extractable P were approximately half those for Olsen P. For individual cores within plots both Olsen P and water-extractable P varied more than two-fold, the variation being three-fold for Olsen P in plot B.

TABLE 5.1: Mean levels of Olsen P (μg/g) and water-extractable P (μg/g) in 0-4 cm cores of Tokomaru soil.

	OLSEN P		
	Plot A	Plot B	Plot C
Lowest value	21.4	13.1	22.7
Highest value	49.0	39.9	47.6
Plot mean	35.7	26.0	36.8
Overall mean (plots A + B + C)		32.8	
Standard error of overall mean		8.1	

	WATER-EXTRACTABLE P		
	Plot A	Plot B	Plot C
Lowest value	9.2	10.6	9.9
Highest value	24.2	23.4	22.6
Plot mean	17.5	16.4	17.5
Overall mean (plots A + B + C)		17.1	
Standard error of overall mean		4.1	

The spatial variability of extractable soil P in the Ramiha soil was not measured since the Ramiha soil contained lower levels of extractable soil P than the Tokomaru soil. Spatial variability was therefore expected to be less in the Ramiha soil because spatial variation and the overall level of extractable soil P appear to be directly related (During and Mountier, 1967).

5.2.3 Fertilizer treatments and trial designs.

For the experiment on the Tokomaru soil, five treatments covering normal rates and times of superphosphate application were selected:

Treatment 1: Control (nil fertilizer)
Treatment 2: Superphosphate 250 kg/ha in autumn
Treatment 3: Superphosphate 500 kg/ha in autumn
Treatment 4: Superphosphate 250 kg/ha in spring
Treatment 5: Superphosphate 500 kg/ha in spring

The superphosphate used was the 0.5 to 2.0 mm fraction sieved from a bag of commercial "Flowmaster Super" with a total P content (O'Connor and Syers, 1975) of 8.0% and a water-soluble P content (Fertilizer Regulations, 1969) of 2.0%. The autumn treatments (2 and 3) were applied on 26.3.78 and the spring treatments (4 and 5) on 29.8.78.

The five treatments were replicated six times giving a total of 30 plots which were arranged in a randomized complete block design. The results of the initial variability study indicated that a fertility gradient existed in the direction at right angles to the fenceline, with low extractable P levels close to the fence and higher levels away from the fence (Appendix 9). Individual plots measuring 1.5 x 5.25 m were therefore aligned at right angles to the fence in one long block running parallel to the fence so as to minimise differences between plots.

For the experiment located on the Ramiha soil, four treatments were selected:

Treatment 1: Control (nil fertilizer)
Treatment 2: Superphosphate 250 kg/ha in autumn
Treatment 3: Superphosphate 500 kg/ha in autumn
Treatment 4: Superphosphate 1000 kg/ha in autumn

The highest rate of superphosphate (treatment 4) was included because the treatments were expected to increase extractable soil P (especially water-extractable P) levels in the high P retention Ramiha soil to a smaller extent than in the low P retention Tokomaru soil.

The four treatments were replicated six times in a randomized complete block design. The individual plots measuring 1 m x 4 m were aligned to run down the slope and were arranged in three blocks of eight plots running across the slope.

A fifth treatment was subsequently included in the experiment on the Ramiha soil when it appeared that the comparison between autumn-applied and spring-applied treatments on the Tokomaru soil would be inconclusive. This extra treatment (ie superphosphate 1000 kg/ha in spring) was intended to provide additional information as to whether time of application affects subsequent changes in extractable soil P. Since the six extra plots could not be included in the original trial design, one plot was added on to the end of the first and second blocks and a fourth block of four plots was located below the existing three blocks. The original control plots were retained for comparison with the spring-treated plots, which were sampled at only one depth. The autumn-treated plots were soil sampled at two depths (see section 5.2.4).

The autumn and spring treatments were applied to the Ramiha soil on 3.4.78 and 5.9.78 respectively. Both field trials were fenced to reduce variability resulting from contamination of soil samples by animal excreta. Pasture growth on the trial plots was trimmed off with a rotary mower as necessary and the clippings discarded.

5.2.4 Field sampling, drying and sieving of soils.

In view of the large spatial variability of extractable soil P in the Tokomaru soil, it was apparent that as many cores per plot as possible should be taken at each sampling in attempting to measure small changes in extractable soil P over time. A sampling intensity of 20 cores per plot at each sampling was selected. This number was based on consideration of the area available per plot, the number of samplings likely to be made and the time likely to be involved in the collection and preparation of samples for chemical analysis.

Each plot on the Tokomaru soil was subdivided into 20 subplots (two across x ten along the plot) to ensure good coverage during soil sampling. Within each subplot were 30 potential core sampling sites (ie 600 sites per plot) evenly distributed on a 10 cm x 10 cm grid. A large metal frame subdivided with appropriately spaced strings running across and along the plot was used to define subplot boundaries and to locate individual sampling sites within each subplot. In this way it was possible to avoid resampling sites which had previously been sampled.

A systematic sampling procedure was used. The 30 sampling sites within each subplot were identified numerically in a clockwise sequence. For the first sampling (8.2.78), one core was taken at random from one of the 30 possible sites within each subplot. At each subsequent sampling the next core in sequence was taken so that over time there was no net shift in any direction of the positions from which samples were collected.

A similar sampling procedure was used on the Ramiha soil except that the number of cores per sampling taken from each plot was reduced from 20 to 16. However, sampling intensity was greater than on the Tokomaru soil because of the smaller plot size on the Ramiha soil.

Two depths of sampling were carried out on both soils. The 0-8 cm depth was selected as being close to the conventional depth (three inches) of sampling pasture soils in New Zealand for soil testing purposes. The second sampling depth was 0-4 cm which it was thought may show up seasonal changes and fertilizer effects on extractable P levels more clearly than the deeper depth. To minimise variations in sampling depth as soil moisture content varied throughout the year, the method of sampling adopted involved taking cores to a depth of about 9 cm. A sharp knife was then used to cut each core precisely into 0-4 cm and 4-8 cm sections. The double lots of 20 (or 16) cores per plot were bulked together according to depth. A standard 2.5 cm diameter tubular corer was used for all soil sampling in both field trials.

If the soil cores were too moist to sieve immediately, they were spread out on paper in the glasshouse for a period. Each bulk sample was then passed through a 4 mm sieve to remove most of the plant material and allow thorough mixing of the whole sample. A 20 to 30 g subsample was taken, passed through a 2 mm sieve and air-dried. Further subsamples were taken from both the 0-4 cm and 4-8 cm bulk samples from each plot, in proportion to their respective weights, and combined to give a 0-8 cm subsample. This 20-30 g combined subsample was also passed through a 2 mm sieve and air-dried. The subsamples were then transferred to labelled polythene bags and stored unsealed in cardboard cartons in the laboratory.

5.2.5 Estimation of initial effects of fertilizer P on extractable soil P.

To estimate the initial (time-zero) increases in extractable P level as a result of applying superphosphate to the field plots, soil samples were analysed after adding finely ground fertilizer to air-dry soil in the laboratory. To reduce variability, it was necessary to grind the superphosphate to a smaller particle size than the 0.5 to 2.0 mm fraction applied in the field.

When mixing superphosphate with soil in the laboratory an attempt was made to achieve the same ratio of fertilizer: soil as in the field. For one particular sampling of each soil type the whole sample from each plot was air-dried and weighed. The mean weights (± SE) of 20 cores of Tokomaru soil were 360 ± 11.6 g and 807 ± 17.6 g for the 0-4 cm and 0-8 cm sampling depths respectively; the mean weights (± SE) of 16 cores of Ramiha soil were 205 ± 10.4 g and 462 ± 16.7 g for the 0-4 cm and 0-8 cm sampling depths respectively. The surface area sampled was 100 cm^2 for 20 cores and 80 cm^2 for 16 cores.

Based on these measurements and the amounts of fertilizer applied per unit surface area in the field, the ratios of fertilizer: soil for the two depths of sampling on both soil types were calculated. The following soil-fertilizer combinations were analysed:

Tokomaru soil: Superphosphate equivalent to 250 and 500 kg/ha was mixed with samples of both "low" and "high" extractable soil P levels from both depths of sampling. Superphosphate equivalent to 750 kg/ha was similarly mixed with soil samples from the 0-8 cm sampling depth.

Ramiha soil: Superphosphate equivalent to 500 kg/ha was mixed with one "average" sample from both sampling depths. Only one rate of superphosphate was used because the results obtained for the Tokomaru soil confirmed the findings of other workers that extractable P is increased in proportion to the amount of P added (see Results and Discussion).

After thorough mixing of the fertilizer and soil, Olsen P and water-extractable P levels in each sample were immediately determined in quadruplicate. The same soil samples without superphosphate added were similarly analysed and the net fertilizer effect calculated by difference.

5.2.6 Analytical procedures.

Olsen P, water-extractable P, P retention and pH were determined for samples of air-dry soil (<2 mm) by the methods described in section 3.2.5. The mean level of extractable P in some "standard" soil samples was found to fluctuate by several μg/g when determined on a number of occasions during the early stages of this study. Two factors possibly causing some of this variation were considered to be temperature and pH of the extracting solution.

Simple experiments were carried out to evaluate the effects of varying temperature or pH on the amount of soil P extracted by the Olsen bicarbonate solution from samples of Tokomaru soil. The results, shown in Table 5.2, indicated that the amount of Olsen P extracted was sensitive to both temperature and pH. The temperature of the extracting solution was recorded immediately before adding the solution to the sample of soil in the centrifuge tube, so was not the temperature of extraction. The shaker temperature was set at 20°C; consequently there was little difference in temperature between the "high" and "low" temperature solutions at the end of the 30 minute extraction period.

Colwell (1963) similarly noted that temperature was a critical factor in the Olsen extraction and concluded that extraction in a constant temperature room was essential. Since it was desired to measure accurately changes in extractable soil P over time, care was taken in the present study to ensure that the temperature of the extracting solution (bicarbonate and water) was always at 20.0 ± 0.5°C before being added to the soil samples. Standard buffer solutions were also prepared with which to calibrate the pH meter prior to adjusting the pH of the Olsen solution to 8.5.

A constant temperature room in which to carry out soil P extractions was not available. Actual air temperatures within the laboratory varied from less than 10°C in winter to more than 25°C in summer. It was therefore decided to store soil samples collected on different dates, then analyse them all together to further reduce variations resulting from

TABLE 5.2: Effect of initial temperature (^{o}C) and pH of the bicarbonate solution on the level of Olsen-extractable P (μg/g).

Initial temperature of extracting solution	Sample A*	Sample B*
16.5	13.4	20.5
28.0	15.7	24.9

pH of extracting solution	Sample B†
8.1	19.2
8.3	20.4
8.5	22.2
8.7	25.5
8.9	28.1

* Means of triplicate determinations.

† Means of duplicate determinations.

differences in the conditions of extraction. It was considered that changes in the extractable P content of stored, air-dry soil samples were very unlikely to occur, particularly for periods of up to one year.

5.2.7 Other measurements.

The moisture content of the Tokomaru soil was determined weekly. Composite samples representing the 0-4 cm depth (10 cores) and the 0-8 cm depth (6 cores) were collected from the trial area and oven-dried overnight at 105°C. Soil moisture content was calculated as the weight loss upon drying expressed as a percentage of the oven-dry weight. No soil moisture determinations were made for the Ramiha soil.

5.3 RESULTS

5.3.1 Changes in extractable P during storage of air-dry soil samples.

When the temperature and pH of the bicarbonate extracting solution were controlled, the levels of Olsen P in soil samples were found to be reasonably repeatable. As the field study progressed, however, it became apparent that the levels of water-extractable P in stored soil samples were changing. This is illustrated by the levels of extractable P in soil samples from the Tokomaru control plots collected in the summer (Table 5.3) and winter (Table 5.4) of 1978.

The mean level of Olsen P in the samples collected in summer did not change between April 1978 and February 1979 (Table 5.3A). Higher levels were recorded in February 1978, reflecting the lack of control over extraction temperature (and possibly pH) at that time. Water-extractable P, on the other hand, was apparently less affected than Olsen P by the higher temperatures in February 1978 but increased during the subsequent twelve months, the mean increases being 24% in the 0-4 cm samples and 35% in the 0-8 cm samples (Table 5.3B).

Similar results were obtained for soil samples collected in June 1978. Olsen P increased by 7% between July 1978 and February 1979 (Table 5.4A) probably caused by differences in ambient temperature. Mean levels of water-extractable P, on the other hand, increased by 42% in the 0-4 cm samples and by 53% in the 0-8 cm samples between July 1978 and May 1979 (Table 5.4B).

Water-extractable P levels in air-dry samples of Ramiha soil also increased during storage in the laboratory (Table 5.5). The levels of water-extractable P in samples collected from the Ramiha control plots and first analysed in April 1978 had more than doubled by March 1979.

TABLE 5.3A: Levels of Olsen P (μg/g) determined on various dates in soil samples collected from the Tokomaru control plots on 8 February 1978.

0-8 cm depth:

Plot No	Dates of Analysis		
	Feb 1978*	22.4.78	23.2.79
5	14.8	13.2	14.5
9	17.5	14.0	15.2
14	24.5	19.3	19.5
19	19.0	14.9	15.2
22	19.8	16.3	16.0
30	20.9	17.1	17.7
Mean	19.42	15.80	16.35

0-4 cm depth:

Plot No	Dates of Analysis				
	Feb 1978*	22.4.78	23.11.78	14.2.79	16.2.79
5	21.2	18.7	20.1	19.3	19.6
9	22.7	20.0	20.0	20.2	20.7
14	32.8	29.4	29.0	27.3	28.6
19	24.2	20.8	20.5	20.2	20.5
22	26.0	22.7	22.7	22.5	21.9
30	28.1	25.0	25.2	25.0	25.8
Mean	25.83	22.77	22.92	22.42	22.85

* Means of triplicate determinations.

TABLE 5.3B: Levels of water-extractable P (μg/g) determined on various dates in soil samples collected from the Tokomaru control plots on 8 February 1978.

0-8 cm depth:

Plot No	Dates of Analysis			
	14.2.78*	13.7.78	21.11.78	21.2.79
5	7.9	8.8	11.0	10.3
9	7.4	9.1	10.4	10.3
14	11.2	11.7	13.9	13.8
19	10.4	11.9	14.3	13.9
22	11.7	13.3	15.4	15.6
30	9.3	12.2	13.5	14.4
Mean	9.65	11.17	13.08	13.05

0-4 cm depth:

Plot No	Dates of Analysis		
	14.2.78*	11.7.78	19.2.79
5	11.5	14.0	15.6
9	11.8	13.0	14.5
14	15.7	17.7	20.0
19	14.0	15.9	17.0
22	15.7	18.2	19.0
30	15.0	16.3	17.6
Mean	13.95	15.85	17.28

* Means of duplicate determinations.

TABLE 5.4A: Levels of Olsen P (μg/g) determined on various dates in soil samples collected from the Tokomaru control plots on 16 June 1978.

0-8 cm depth:

Plot No	Dates of Analysis		
	5.7.78	24.10.78	23.2.79
5	14.4	14.6	15.7
9	13.6	13.8	15.0
14	19.6	20.2	21.7
19	17.1	18.3	17.9
22	15.6	16.4	15.7
30	19.0	20.0	19.9
Mean	16.55	17.22	17.65

0-4 cm depth:

Plot No	Dates of Analysis			
	5.7.78	26.10.78	23.11.78	15.2.79
5	19.9	21.4	21.7	22.7
9	19.6	20.8	21.1	21.8
14	26.8	27.6	28.5	26.8
19	23.0	22.7	23.6	24.3
22	19.9	21.5	21.4	21.4
30	25.4	26.8	27.5	26.4
Mean	22.43	23.47	23.97	23.90

TABLE 5.4B: Levels of water-extractable P (μg/g) determined on various dates in soil samples collected from the Tokomaru control plots on 16 June 1978.

0-8 cm depth:

Plot No	Dates of Analysis				
	8.7.78	15.11.78	21.11.78	11.12.78	30.5.79
5	7.2	9.7	10.2	10.4	11.1
9	5.9	7.4	8.4	7.0	8.4
14	10.0	13.7	14.0	13.3	15.4
19	10.2	13.3	14.7	14.2	14.7
22	9.5	11.6	13.4	12.3	15.3
30	8.6	12.0	13.0	12.5	13.9
Mean	8.57	11.28	12.28	11.62	13.13

0-4 cm depth:

Plot No	Dates of Analysis					
	9.7.78	30.10.78	17.11.78	5.12.78	11.12.78	19.5.79
5	10.7	15.8	12.9	15.3	15.0	18.0
9	9.5	12.6	11.2	13.9	15.3	14.1
14	14.6	19.0	17.3	19.0	19.1	19.7
19	14.1	19.0	17.4	18.4	17.9	18.9
22	12.8	17.9	17.0	17.3	16.6	17.4
30	13.7	17.9	15.4	17.9	17.9	19.3
Mean	12.57	17.03	15.20	16.97	16.97	17.90

TABLE 5.5: Levels of water-extractable P (μg/g) determined on various dates in 0-4 cm soil samples collected from the Ramiha control plots on 25 April 1978.

Plot No	Dates of Analysis				
	30.4.78	25.3.79	30.3.79 (am)	30.3.79 (pm)	2.4.79
2	1.7	3.8	3.2	2.8	2.7
8	1.4	3.4	2.8	2.8	2.2
12	1.9	4.1	3.2	3.4	2.9
13	1.5	3.6	3.2	2.9	2.7
18	1.2	3.2	2.6	2.7	2.5
23	1.5	3.9	3.7	3.3	2.9
Mean	1.53	3.67	3.12	2.98	2.65

Plot No	Dates of Analysis			
	3.4.79	13.4.79	15.4.79	19.5.79
2	2.5	3.7	2.9	2.5
8	2.0	3.4	2.5	2.0
12	2.7	4.3	3.0	2.5
13	2.6	3.9	2.9	2.2
18	1.7	3.3	2.3	1.9
23	2.5	4.5	3.0	2.5
Mean	2.33	3.85	2.77	2.27

In addition to an overall increase with time, water-extractable P levels were found to fluctuate over time in samples of both Tokomaru soil (Table 5.4B: 0-4 cm depth) and Ramiha soil (Table 5.5) while stored in the laboratory.

While investigating possible reasons for the fluctuations in water-extractable P, it was found that distilled water from two different stills in the laboratory differed in pH. The water-extractable P contents of two samples of soil were therefore determined using the two different sources of distilled water. The results, shown in Table 5.6, indicated that more soil P was extracted from both soils by the lower pH water than by the higher pH water.

5.3.2 Seasonal changes in extractable soil P in the Tokomaru soil.

The Tokomaru control plots were sampled on 22 occasions between February 1978 and February 1979 and again in late March 1979 when the final sampling of the fertilized plots was made. Olsen P levels in the control plots, determined at the completion of the sampling programme, are listed in Appendices 11A (0-8 cm depth) and 11B (0-4 cm depth). The variance associated with changes in Olsen P between consecutive sampling dates did not appear to change between seasons. Standard deviations were therefore calculated for pooled data from the whole year. Standard deviations of Olsen P changes of individual plots between consecutive samplings were 1.05 and 1.13 μg/g for the 0-8 cm and 0-4 cm depths respectively.

Mean Olsen P levels plotted over time are shown in Figures 5.1 (0-8 cm depth) and 5.2 (0-4 cm depth), as are weekly soil moisture measurements and mean weekly soil temperatures (10 cm depth). Daily (9 am) soil temperature measurements at Massey University, approximately 1 km from the trial site, were used to calculate the weekly means. The standard errors of mean Olsen P changes between consecutive samplings were 0.40 and 0.46 μg/g for the 0-8 cm and 0-4 cm depths respectively.

Olsen P in both sampling depths increased to a peak in late April-early May and then declined in June-July when soil temperatures were at a minimum and soil moisture levels were rapidly increasing. After levelling out slightly in August-September, Olsen P again declined between October 1978 and February 1979. Throughout this period soil temperatures gradually increased and soil moisture levels, while variable, gradually declined. Both the absolute levels of Olsen P and the magnitude of the changes over time were greater in the 0-4 cm depth

TABLE 5.6: Levels of water-extractable P (μg/g) in two soils determined in quadruplicate using distilled waters of pH 4.9 (low pH) and pH 6.1 (high pH).

Soil Name		Low pH water	High pH water
Tokomaru		15.1	14.2
(sample B)		16.9	14.7
		16.6	14.6
		15.5	14.2
	Mean	16.02	14.42
Pirinoa		33.1	30.1
		33.8	31.3
		33.4	31.0
		32.3	31.9
	Mean	33.15	31.07

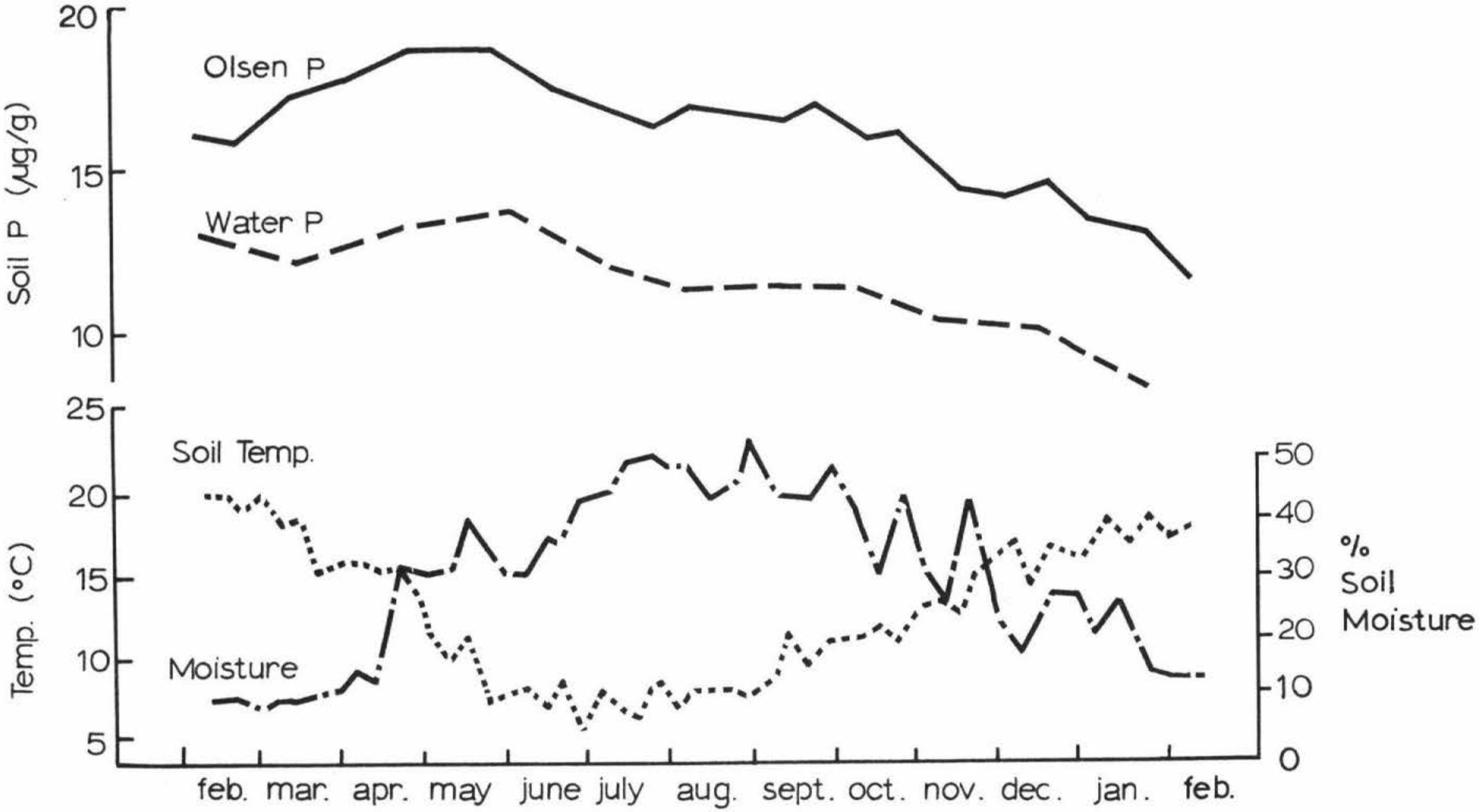

FIGURE 5.1: Mean levels of Olsen P, water-extractable P and soil moisture in the Tokomaru control plots (0-8 cm depth), and mean weekly soil temperature.

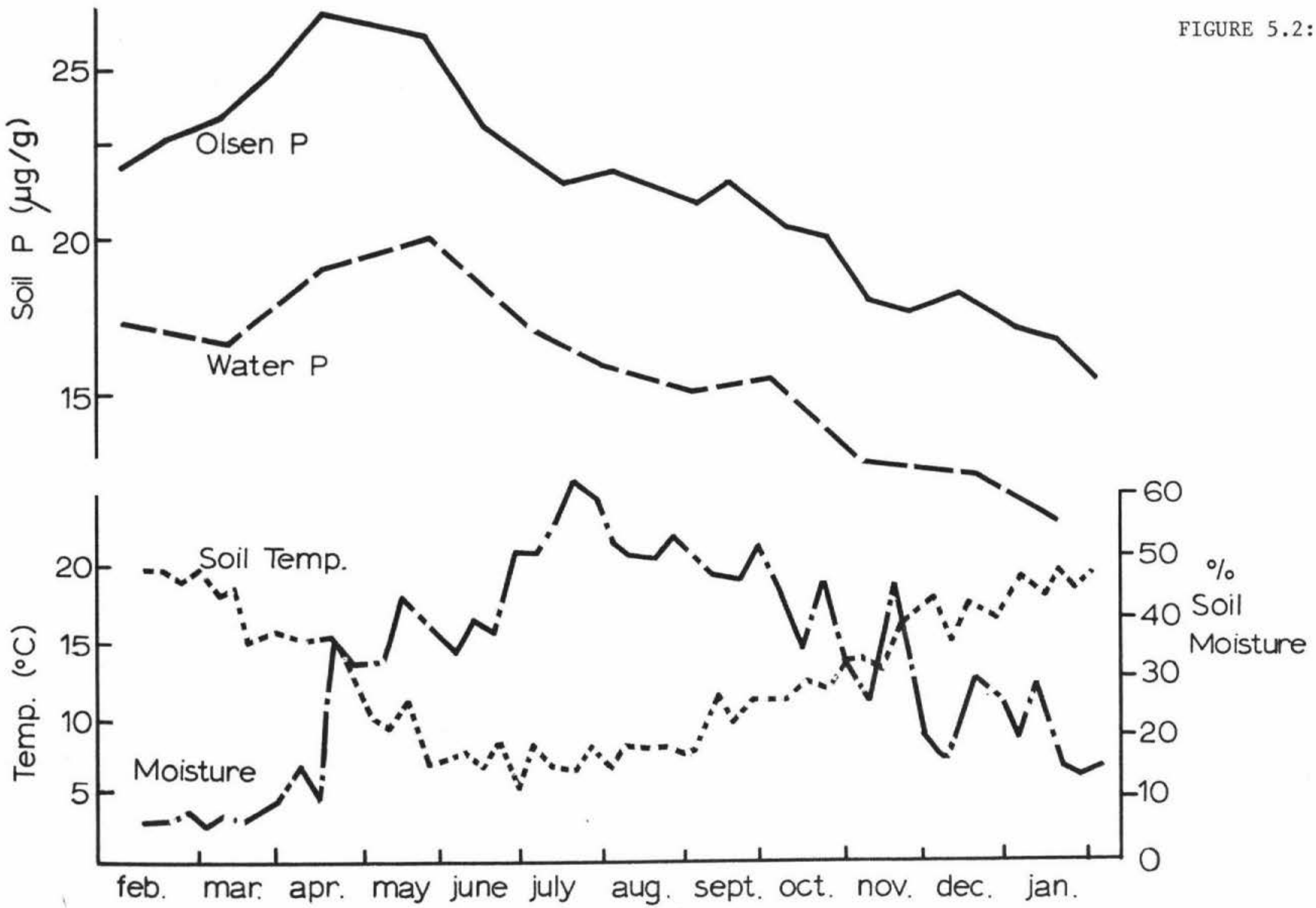

FIGURE 5.2: Mean levels of Olsen P, water-extractable P and soil moisture in the Tokomaru control plots (0-4 cm depth) and mean weekly soil temperature.

(Figure 5.2) than in the 0-8 cm depth (Figure 5.1)

Levels of water-extractable P in the Tokomaru control plots, determined for every second sampling date at the completion of the sampling programme, are listed in Appendix 12. Mean levels of water-extractable P plotted over time are shown in Figures 5.1 (0-8 cm depth) and 5.2 (0-4 cm depth). Seasonal changes in water-extractable P appeared to follow quite closely the changes in Olsen P, even though the levels of water-extractable P shown are inflated values.

5.3.3 Initial (time-zero) effects of fertilizer P on extractable soil P.

5.3.3.1 Tokomaru soil.

Increases in extractable soil P, determined after mixing appropriate rates of superphosphate with samples of Tokomaru soil in the laboratory are shown in Table 5.7. The initial level of extractable soil P had no consistent effect on the magnitude of the fertilizer effect, although the range of initial extractable P levels compared was rather restricted. The rate of superphosphate also had no consistent effect on the mean increase in extractable soil P per unit of added P. All data for the same extraction method and sampling depth were therefore averaged to give an overall mean increase per 250 kg/ha of superphosphate. This figure was doubled to obtain the mean increase per 500 kg/ha of superphosphate (Table 5.7).

Water-extractable P was increased more by superphosphate than was Olsen P in soil samples from both depths of sampling. This was in contrast to the greater amounts of P extracted by the Olsen method from unfertilized samples of Tokomaru soil. The recovery of a greater proportion of added fertilizer P by water extraction is presumably due to the greater volume of extracting solution and the much longer extraction time in comparison to the Olsen procedure.

The highest proportion of P recovered (ie from the 0-8 cm samples by water extraction) was equivalent to 24% of the total P added in superphosphate (Table 5.7). This equates very closely with the 25% water-solubility of the P applied as superphosphate to the field plots (section 5.2.3). However, the two figures are not directly comparable; firstly, the superphosphate mixed with the soil in the laboratory was finely ground, and secondly, the water extraction method (for soil P) involved a longer extraction time and a much wider fertilizer: water

TABLE 5.7: Mean increases (± SE) in extractable P (μg/g) after mixing finely ground superphosphate with air-dry Tokomaru soil at rates equivalent to field application rates.

Initial extractable P level (μg/g)	Superphosphate rate in field (kg/ha)		
	250	500	750
OLSEN P 0-8 cm depth:			
Low P (12.0)	4.9 ± 1.2	11.2 ± 3.6	10.9 ± 1.3
High P (17.8)	5.1 ± 1.4	9.7 ± 1.6	13.6 ± 1.3
Overall mean increase	4.8	9.6	
	(= 19% of total added P)		
OLSEN P 0-4 cm depth:			
Low P (18.0)	10.0 ± 1.0	19.1 ± 2.5	
High P (23.5)	8.9 ± 2.3	18.0 ± 1.3	
Overall mean increase	9.3	18.6	
	(= 16.5% of total added P)		
WATER-EXTRACTABLE P 0-8 cm depth:			
Low P (6.0)	6.7 ± 2.3	10.4 ± 2.3	18.9 ± 2.6
High P (8.9)	6.2 ± 1.7	11.1 ± 2.0	17.5 ± 2.6
Overall mean increase	6.1	12.2	
	(= 24% of total added P)		
WATER-EXTRACTABLE P 0-4 cm depth:			
low P (7.1)	11.5 ± 0.5	23.9 ± 3.1	
High P (10.3)	13.4 ± 3.5	26.4 ± 4.4	
Overall mean increase	12.5	25.0	
	(= 22% of total added P)		

ratio than the procedure used to determine the water-soluble P content of the fertilizer.

There appeared to be a slightly higher proportion of added P recovered from the 0-8 cm samples than from the 0-4 cm samples of Tokomaru soil (Table 5.7). For a given rate of superphosphate per hectare, the ratio of added fertilizer: soil was greater for 0-4 cm samples than for 0-8 cm samples. However, the proportion of added P recovered from a given sample was independent of the amount of P added suggesting that the greater recovery of added P from the 0-8 cm samples was possibly due to some other factor, such as a difference in soil properties between the two sampling depths.

5.3.3.2 Ramiha soil.

Initial increases in extractable P in the Ramiha soil, after adding superphosphate at rates equivalent to 500 kg/ha in the laboratory, are shown in Table 5.8. It was assumed that extractable P increases, as in the Tokomaru soil, would occur in proportion to the rate of added P. The results shown in Table 5.8 provide some evidence to support this assumption. When superphosphate was mixed with 0-8 cm samples at two different rates, the proportion of added P recovered was essentially constant. Initial increases in extractable P for the superphosphate rates 250 and 1000 kg/ha were therefore calculated by respectively halving and doubling the mean increases recorded for the 500 kg/ha rate.

Olsen P was increased more by superphosphate than was water-extractable P, in contrast to the results obtained for the Tokomaru soil. However the amounts of added P recovered by the two extraction procedures differed less than the amounts of soil P extracted from unfertilized Ramiha soil. The Olsen method removed about nine times more P from unfertilized soil (Appendix 1) but recovered less than twice as much added P from fertilized soil (Table 5.8) in comparison to water extraction. This difference was again presumably due to the greater volume of solution and the longer time involved in the water extraction method.

There appeared to be a higher proportion of added P recovered from the 0-4 cm samples than from the 0-8 cm samples (Table 5.8), again in contrast to the results obtained for the Tokomaru soil. The difference between the sampling depths was greater for water-extractable P than for Olsen P. It is assumed that the difference was probably due to variation in soil properties between the two sampling depths and not to the different ratios of fertilizer: soil.

TABLE 5.8: Mean increases (± SE) in extractable P (μg/g) after mixing finely ground superphosphate with air-dry Ramiha soil at rates equivalent to superphosphate 500 kg/ha in the field.

Sampling depth	Olsen P	Water-extractable P
0-8 cm	9.0 ± 1.1	5.8 ± 0.8
% of total added P	13	8
0-8 cm*	6.6 ± 1.1	3.4 ± 0.6
% of total added P	13	7
0-4 cm	23.8 ± 2.2	18.6 ± 0.9
% of total added P	15	12

* Same ratio of superphosphate: soil as for Tokomaru soil (0-8 cm).

Reference to Tables 5.7 and 5.8 permits a comparison of the Ramiha and Tokomaru soils. Increases in Olsen P were similar in both soils or greater in the Ramiha soil, although a greater proportion of added P tended to be recovered by Olsen extraction from the Tokomaru soil. Both the increases in water-extractable P and the proportion of added P recovered by water extraction were greater for the Tokomaru soil than for the Ramiha soil.

5.3.4 Effects of fertilizer P applied in the field on extractable soil P.

5.3.4.1 Tokomaru soil.

The levels of Olsen P (0-4 cm depth) in the autumn-fertilized Tokomaru plots on various sampling dates are listed in Appendix 13. The control and fertilizer treatment means plotted over time are shown in Figure 5.3. The "low P" and "high P" treatment means differed by less than 2 μg/g at all times, being higher initially for the low P treatment. Both rates of superphosphate increased Olsen P above the mean level of the "control" treatment by 4 to 6 μg/g.

Changes in the levels of water-extractable P in the autumn-fertilized Tokomaru plots appeared to be similar to those for Olsen P (Appendix 13), but are not presented because the levels of water-extractable P increased substantially during storage of the soil samples.

The levels of Olsen P in the spring-fertilized Tokomaru plots on various dates are listed in Appendices 14A (0-8 cm depth) and 14B (0-4 cm depth). The control and fertilizer treatment means plotted over time are shown in Figure 5.4. Changes in Olsen P with time followed a similar pattern in both sampling depths. The mean increases in Olsen P in the fertilized plots were approximately in proportion to the rate of superphosphate applied.

The levels of water-extractable P in the control and spring-fertilized plots on various sampling dates are listed in Appendices 15A (0-8 cm depth) and 15B (0-4 cm depth). The treatment means plotted over time are shown in Figure 5.5. The levels of water-extractable P had increased during storage but the changes over time followed a similar pattern to the changes in Olsen P. The magnitude of the increases in water-extractable P (ie the difference between control and fertilized plots) appeared to undergo relatively little change during storage, unlike the absolute levels of water-extractable P.

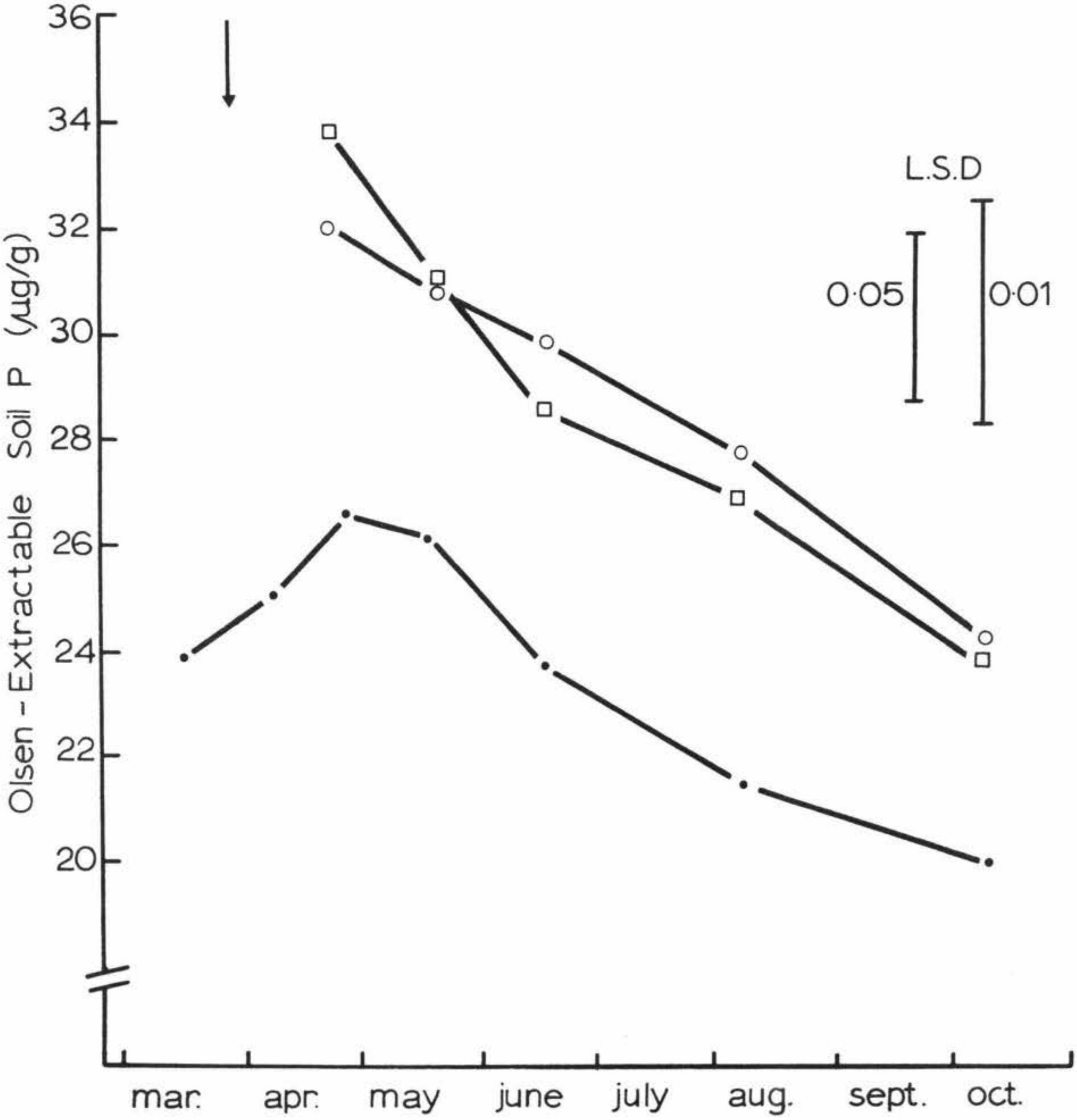

FIGURE 5.3: Mean levels of Olsen P in Tokomari soil (0-4 cm depth) following the application of nil (•), 250 (□) and 500 (○) kg/ha of superphosphate in March 1978.
The arrow (top left corner) in this and subsequent Figures indicates when superphosphate was applied.

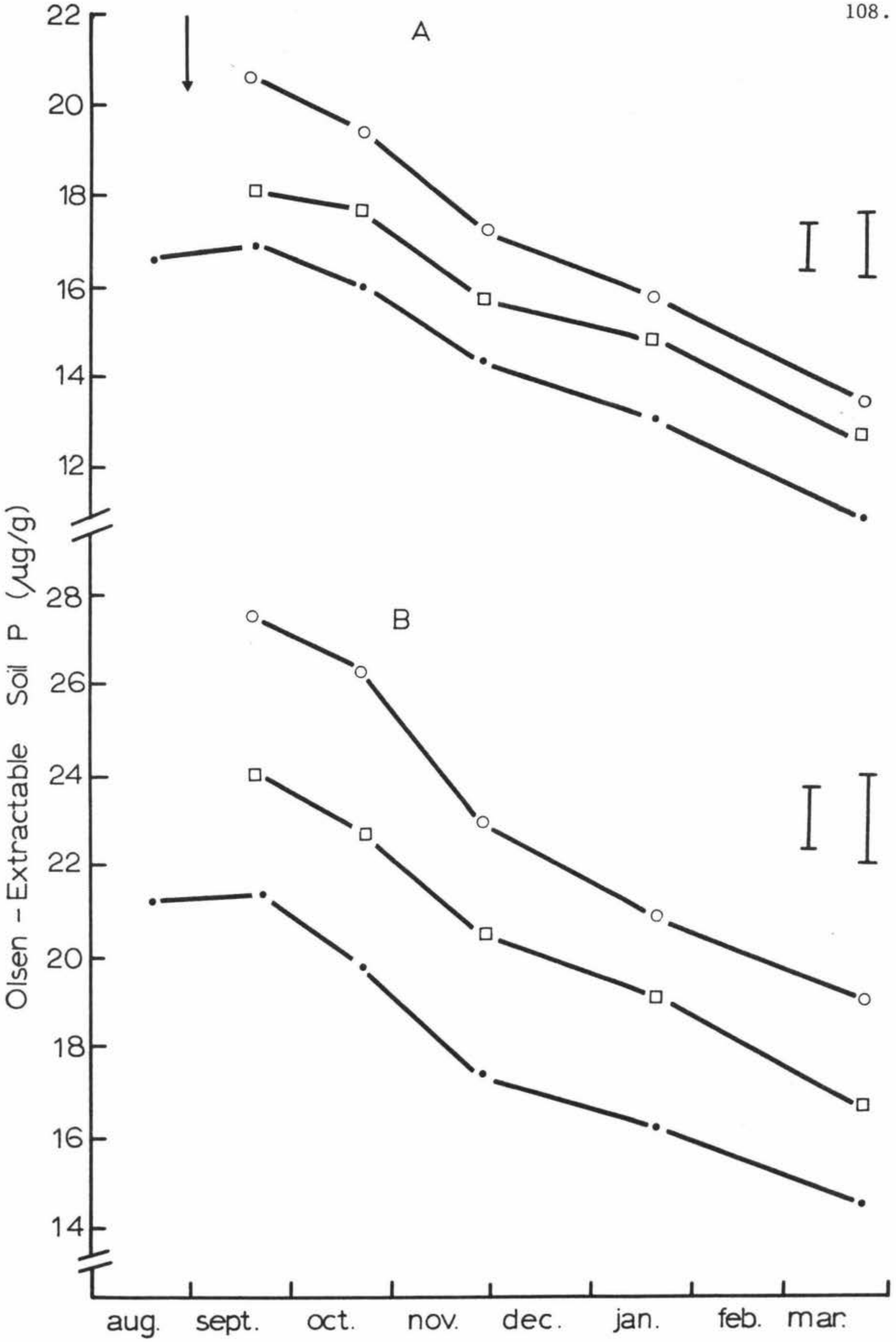

FIGURE 5.4: Mean levels of Olsen P in 0-8 cm (A) and 0-4 cm (B) depths of Tokomaru soil following the application of nil (•), 250 (□) and 500 (○) kg/ha of superphosphate in August 1978.

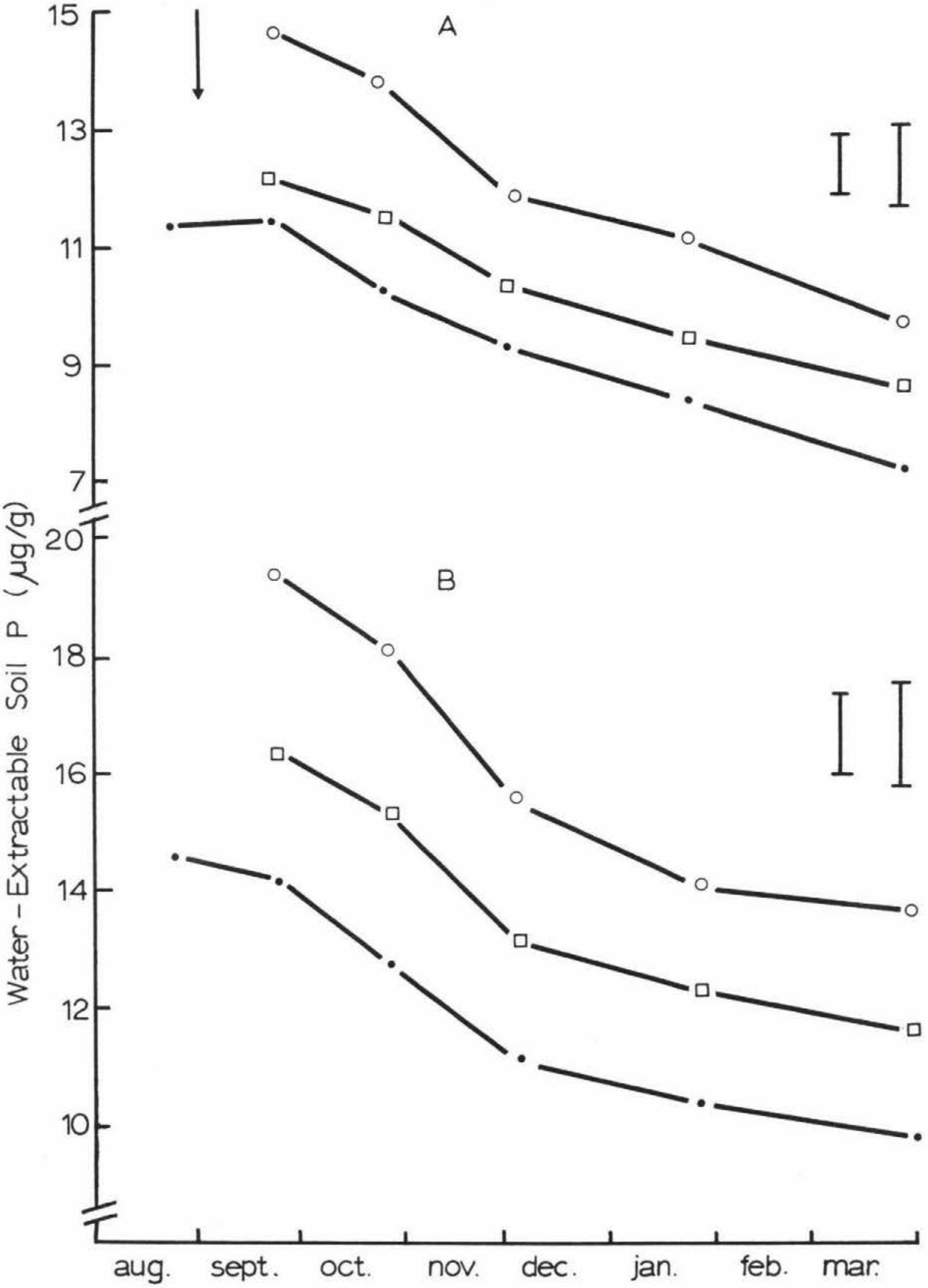

FIGURE 5.5: Mean levels of water-extractable P in 0-8 cm (A) and 0-4 cm (B) depths of Tokomaru soil following the application of nil (•), 250 (□) and 500 (○) kg/ha of superphosphate in August 1978.

Mean increases in extractable P due to superphosphate applied in both autumn and spring, and the mean increases expressed as a proportion of the initial (time-zero) increases in extractable P (Table 5.7), are shown in Tables 5.9 (Olsen P) and 5.10 (water-extractable P). These "proportional increases" in extractable soil P showed some variation between sampling dates but did not differ consistently between the two rates of superphosphate, except for the autumn treatments (Table 5.9). Since the proportional increases for the high P treatment were in general agreement with the results for the spring-applied treatments, it is assumed that the proportional increases for the low P treatment were abnormally high.

These apparently anomalous results imply that application of the autumn fertilizer treatments, or at least the low P treatment, was faulty. Consequently, no valid comparison between the two different times of application is possible, even though proportional increases at the high rate of superphosphate appeared not to differ between the spring and autumn applications.

There were no consistent differences in the proportional increases in extractable soil P between the two depths of sampling (Tables 5.9 and 5.10). Because of the absence of any consistent differences between the sampling depths, the rates of superphosphate and the times of application, all data were plotted together as shown in Figures 5.9 (Olsen P) and 5.10 (water-extractable P). "Proportional decline curves" were fitted by eye to the plotted data.

5.3.4.2 Ramiha soil.

The levels of Olsen P in the control and autumn-fertilized Ramiha plots on various dates are listed in Appendices 16A (0-8 cm depth) and 16B (0-4 cm depth). The control and fertilizer treatment means plotted over time are shown in Figure 5.6. Changes in Olsen P with time followed a similar pattern in both sampling depths. The mean increases in Olsen P in the fertilized plots were approximately in proportion to the rate of superphosphate applied.

The levels of water-extractable P (0-4 cm depth) in the control and autumn-fertilized plots on various sampling dates are listed in Appendix 17. The treatment means plotted over time are shown in Figure 5.7. The levels of water-extractable P had increased during storage of the soil samples which may account for the different patterns of change over time compared with changes in Olsen P (Figure 5.6). Water-extractable P

TABLE 5.9: Mean increases in Olsen P in Tokomaru soil due to superphosphate, as µg/g soil and expressed as a proportion (%) of the initial (time-zero) increase.

	AUTUMN FERTILIZER TREATMENTS					
0-4 cm depth						
Days since application	0	26	52	82	133	197
Super 250 kg/ha:						
Increase over control	9.3	7.10	4.91	4.75	5.24	3.68
Proportional increase	100	76	53	51	56	40
Super 500 kg/ha:						
Increase over control	18.6	5.37	4.70	6.05	6.15	4.08
Proportional increase	100	29	25	33	33	22

	SPRING FERTILIZER TREATMENTS					
0-8 cm depth						
Days since application	0	24	57	99	152	214
Super 250 kg/ha:						
Increase over control	4.8	1.13	1.60	1.40	1.79	1.64
Proportional increase	100	24	33	29	37	34
Super 500 kg/ha:						
Increase over control	9.6	3.68	3.40	2.93	2.70	2.55
Proportional increase	100	38	35	31	28	27
0-4 cm depth						
Super 250 kg/ha:						
Increase over control	9.3	2.66	3.14	3.17	2.87	2.10
Proportional increase	100	29	34	34	31	23
Super 500 kg/ha:						
Increase over control	18.6	6.13	6.62	5.69	4.65	4.48
Proportional increase	100	33	36	31	25	24

TABLE 5.10: Mean increases in water-extractable P in Tokomaru soil due to superphosphate, as μg/g soil and expressed as a proportion (%) of the initial (time-zero) increase.

	SPRING FERTILIZER TREATMENTS					
0-8 cm depth						
Days since application	0	24	57	99	152	214
Super 250 kg/ha:						
Increase over control	6.1	0.66	1.37	1.04	1.09	1.31
Proportional increase	100	11	22	17	18	21
Super 500 kg/ha:						
Increase over control	12.2	3.18	3.57	2.65	2.77	2.40
Proportional increase	100	26	29	22	23	20
0-4 cm depth						
Super 250 kg/ha:						
Increase over control	12.5	2.21	2.60	2.04	1.89	1.80
Proportional increase	100	18	21	16	15	14
Super 500 kg/ha:						
Increase over control	25.0	5.25	5.41	4.42	3.70	3.85
Proportional increase	100	21	22	18	15	15

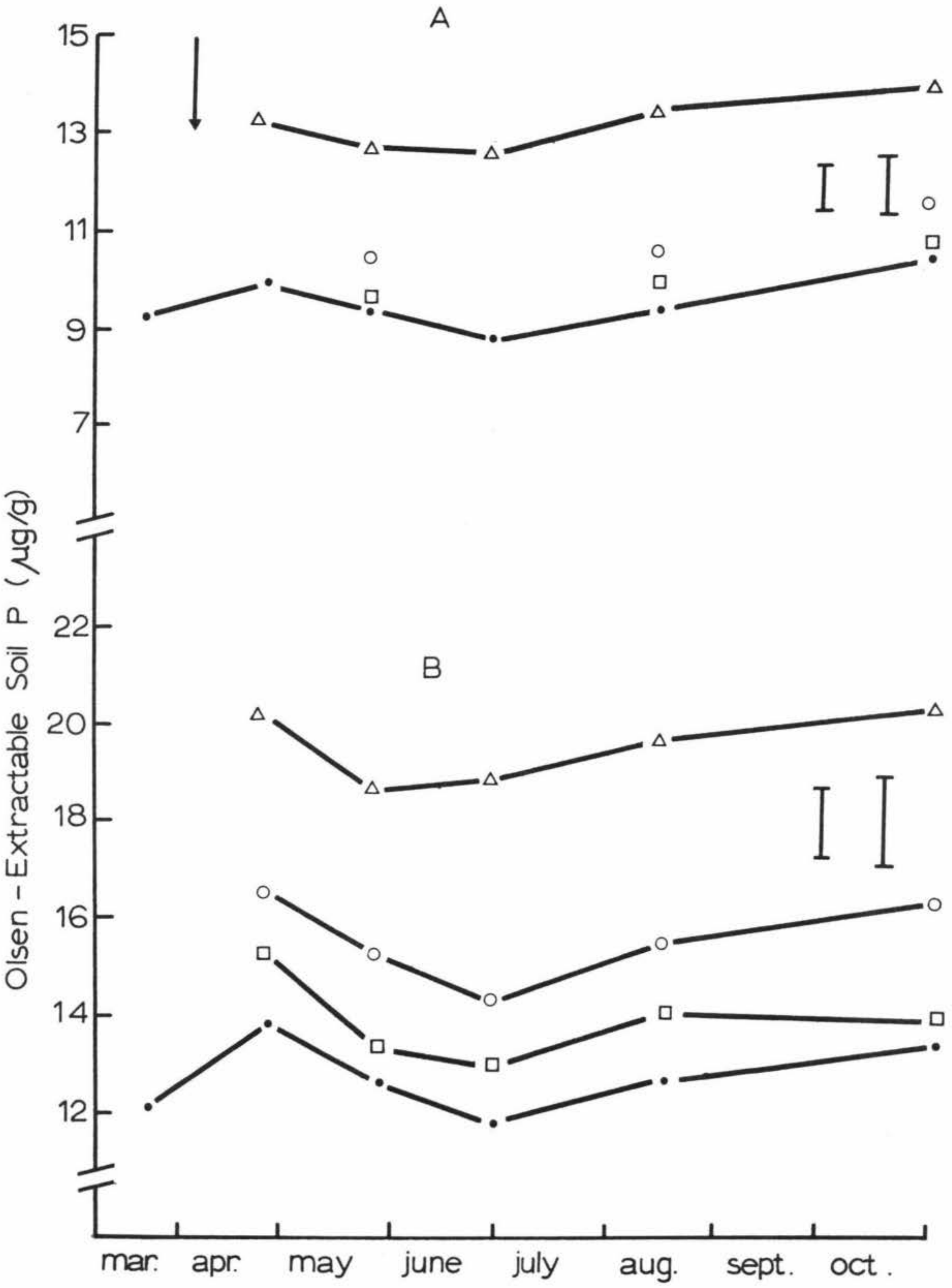

FIGURE 5.6: Mean levels of Olsen P in 0-8 cm (A) and 0-4 cm (B) depths of Ramiha soil following the application of nil (•), 250 (□), 500 (○) and 1000 (△) kg/ha of superphosphate in April 1978.

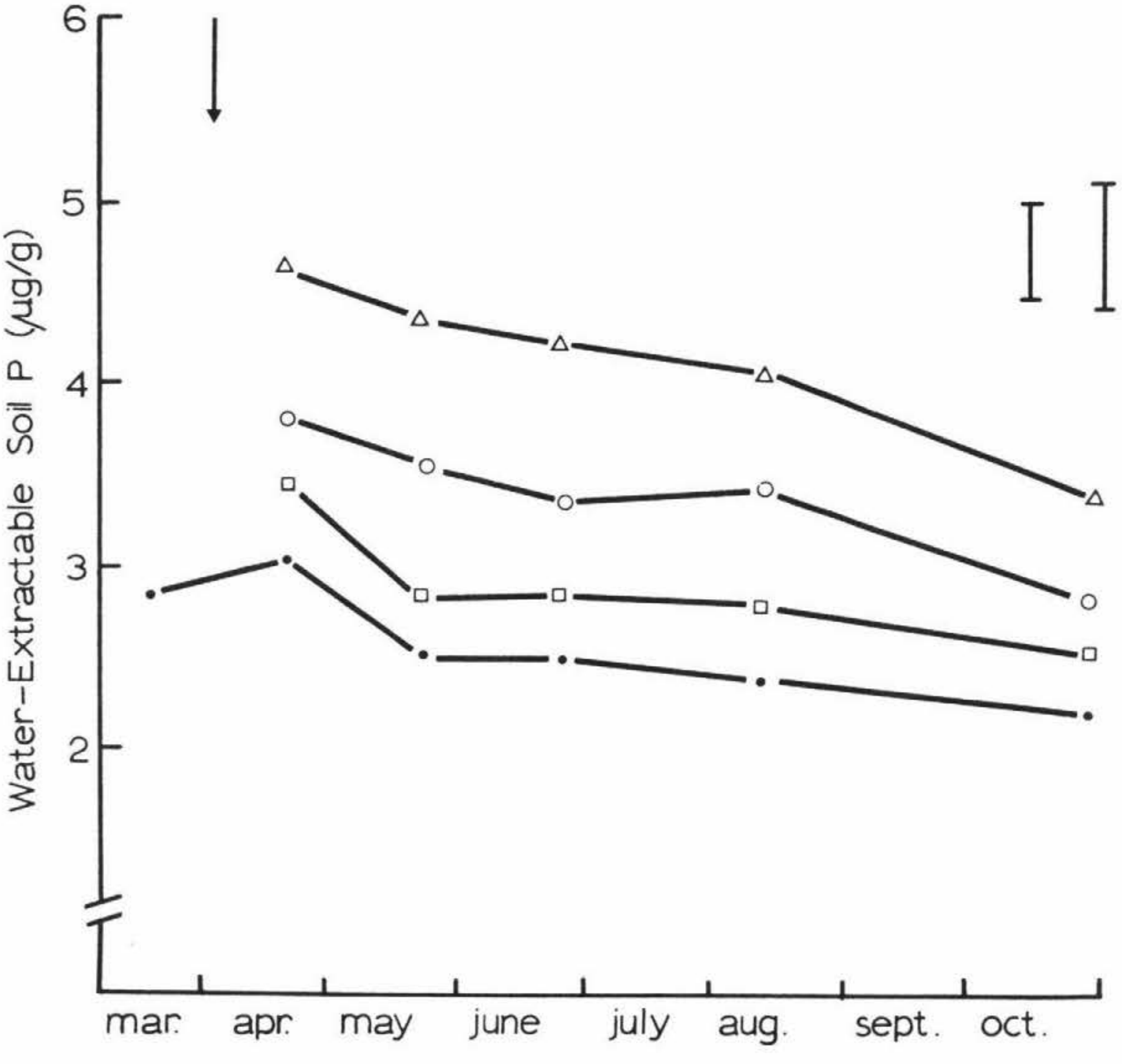

FIGURE 5.7: Mean levels of water-extractable P in Ramiha soil (0-4 cm depth) following the application of nil (•), 250 (□), 500 (○) and 1000 (△) kg/ha of superphosphate in April 1978.

levels did not increase at the August and November samplings, possibly because the levels of water-extractable P in soil from the earlier samplings had increased more during storage than had the levels in soil from the later samplings.

Despite the increases in water-extractable P levels during storage of soil samples, the magnitude of the fertilizer effects (ie the difference between control and fertilized plots) appeared to undergo relatively little change during storage. In general, these increases were approximately in proportion to the rate of superphosphate applied (Figure 5.7).

The levels of Olsen P and water-extractable P in the control and spring-fertilized plots (0-4 cm depth) on various dates are listed in Appendices 18 and 19 respectively. The treatment means plotted over time are shown in Figure 5.8. Different patterns of change over time between Olsen P and water-extractable P are apparent, particularly at the final sampling. The increases in water-extractable P in late-January seem unlikely to have occurred during storage as the soil samples collected in January 1979 had been stored for a much shorter time than those collected earlier.

Mean increases in extractable P due to superphosphate applied in both autumn and spring, and the mean increases expressed as a proportion of the initial (time-zero) increases in extractable P (Table 5.8), are shown in Tables 5.11 (Olsen P) and 5.12 (water-extractable P). There appeared to be a tendency for proportional increases in Olsen P to increase as the rate of superphosphate increased. This was more apparent in the 0-8 cm depth but was not very consistent in the 0-4 cm depth (Table 5.11). In view of the variation between samplings, however, the different proportional increases are more likely a reflection of the relatively large errors associated with attempting to measure the small increases in Olsen P at the lowest rate of superphosphate and in the 0-8 cm depth of this soil.

Proportional increases in Olsen P in the Ramiha soil at the highest rate of superphosphate appeared to be smaller for the spring application than for the autumn application (Table 5.11). The same effect was not apparent in the data for water-extractable P (Table 5.12) and since the spring plots were not part of the original trial design, the comparison between spring and autumn applications is again of doubtful validity.

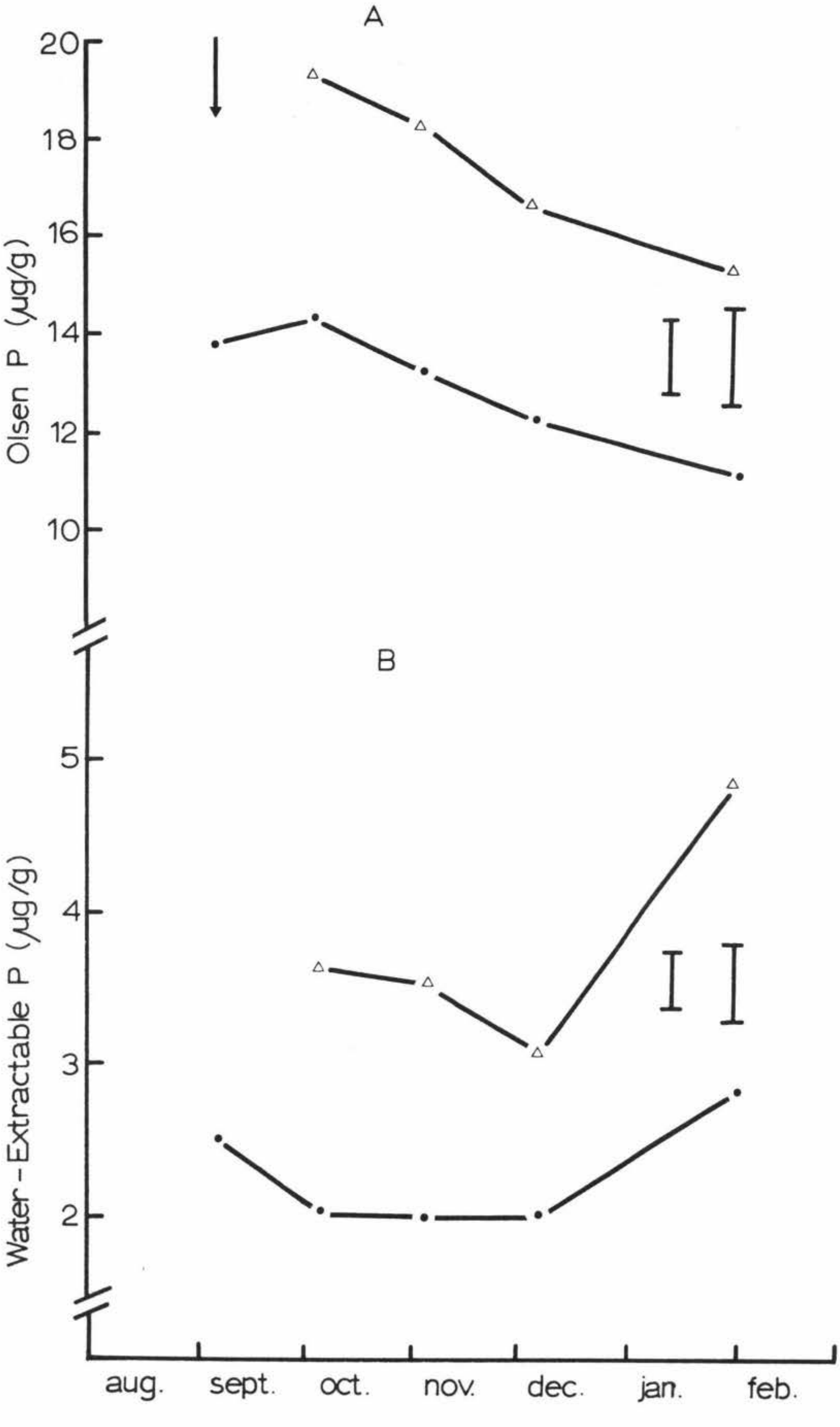

FIGURE 5.8: Mean levels of Olsen P (A) and water-extractable P (B) in Ramiha soil (0-4 cm depth) following the application of nil (•) and 1000 (△) kg/ha of superphosphate in September 1978.

TABLE 5.11: Mean increases in Olsen P in Ramiha soil due to superphosphate, as $\mu g/g$ soil and expressed as a proportion (%) of the initial (time-zero) increase.

	AUTUMN FERTILIZER TREATMENTS					
0-8 cm depth						
Days since application	0	22	53	82	131	209
Super 250 kg/ha:						
Increase over control	4.5	-	0.25	-	0.61	0.25
Proportional increase	100	-	5.6	-	14	6
Super 500 kg/ha:						
Increase over control	9.0	-	1.09	-	1.28	1.25
Proportional increase	100	-	12	-	14	14
Super 1000 kg/ha:						
Increase over control	18.0	3.35	3.39	3.89	4.16	3.56
Proportional increase	100	19	19	22	23	20
0-4 cm depth						
Super 250 kg/ha:						
Increase over control	11.9	1.39	0.78	1.20	1.40	0.45
Proportional increase	100	12	7	10	12	4
Super 500 kg/ha:						
Increase over control	23.8	2.75	2.70	2.50	2.86	2.90
Proportional increase	100	12	11	11	12	12
Super 1000 kg/ha:						
Increase over control	47.6	6.35	5.92	7.13	7.06	6.87
Proportional increase	100	13	12	15	15	14

	SPRING FERTILIZER TREATMENT				
0-4 cm depth					
Days since application	0	29	59	92	148
Super 1000 kg/ha:					
Increase over control	47.6	5.05	5.02	4.43	4.23
Proportional increase	100	11	10	9	9

TABLE 5.12: Mean increases in water-extractable P in Ramiha soil due to superphosphate, as μg/g soil and expressed as a proportion (%) of the initial (time-zero) increase.

	AUTUMN FERTILIZER TREATMENTS					
0-4 cm depth						
Days since application	0	22	53	82	131	209
Super 250 kg/ha:						
Increase over control	9.3	0.40	0.33	0.33	0.38	0.32
Proportional increase	100	4	4	4	4	3
Super 500 kg/ha:						
Increase over control	18.6	0.78	1.06	0.86	0.65	0.62
Proportional increase	100	4	6	5	3	3
Super 1000 kg/ha:						
Increase over control	37.2	1.61	1.90	1.75	1.70	1.24
Proportional increase	100	4	5	5	5	3

	SPRING FERTILIZER TREATMENTS				
0-4 cm depth					
Days since application	0	29	59	92	148
Super 1000 kg/ha:					
Increase over control	37.2	1.62	1.52	1.10	2.12
Proportional increase	100	4	4	3	6

Proportional increases in extractable soil P for both autumn and spring applications were plotted together as shown in Figures 5.9 (Olsen P) and 5.10 (water-extractable P). Proportional decline curves were fitted by eye to the plotted data. The proportional decline curves for the Ramiha soil are much lower than those for the Tokomaru soil, particularly for water-extractable soil P (Figure 5.10). In absolute terms, the overall "average" increases in extractable soil P six months after the application of 500 kg/ha of superphosphate (40 kg P/ha) were as shown in Table 5.13. Again the soils differed more in terms of water-extractable P increases than in terms of Olsen P increases.

5.4 DISCUSSION

5.4.1 Changes in extractable soil P during sample storage.

Throughout this study, analytical difficulties which appeared to be of two main types were encountered with the water extraction procedure. Firstly, short-term fluctuations in extractable P content occurred when analyses were repeated and, secondly, the levels of water-extractable P in air-dry soil samples increased during storage in the laboratory.

Short-term fluctuations were unlikely to be a reflection of real changes in extractable P levels within the soils but probably resulted instead from a change in the conditions of extraction. Changes in temperature can be eliminated since the temperature of extracting solutions was closely controlled for all analyses carried out after March 1978. This was reflected in reasonably repeatable Olsen P levels despite wide fluctuations in air temperature within the laboratory between winter and summer.

One factor which was shown to apparently influence the amount of water-extractable P removed was the pH of the distilled water. This is somwhat surprising in view of the totally unbuffered nature of distilled water. Consequently, it would be expected that the pH during the extraction would be controlled by the soil. It is not possible to determine, however, whether the pH difference per se caused different amounts of soil P to be extracted or whether a difference in some other unmeasured property of the distilled water was responsible.

The longer-term increases in water-extractable P occurred in all soil samples stored in the laboratory, irrespective of soil type. In samples of Tokomaru soil water-extractable P typically increased by 3 to 5 μg/g (or 25-50%). In samples of Ramiha soil, increases were typically from 1 to 2 μg/g (or about 100%). Similar large increases

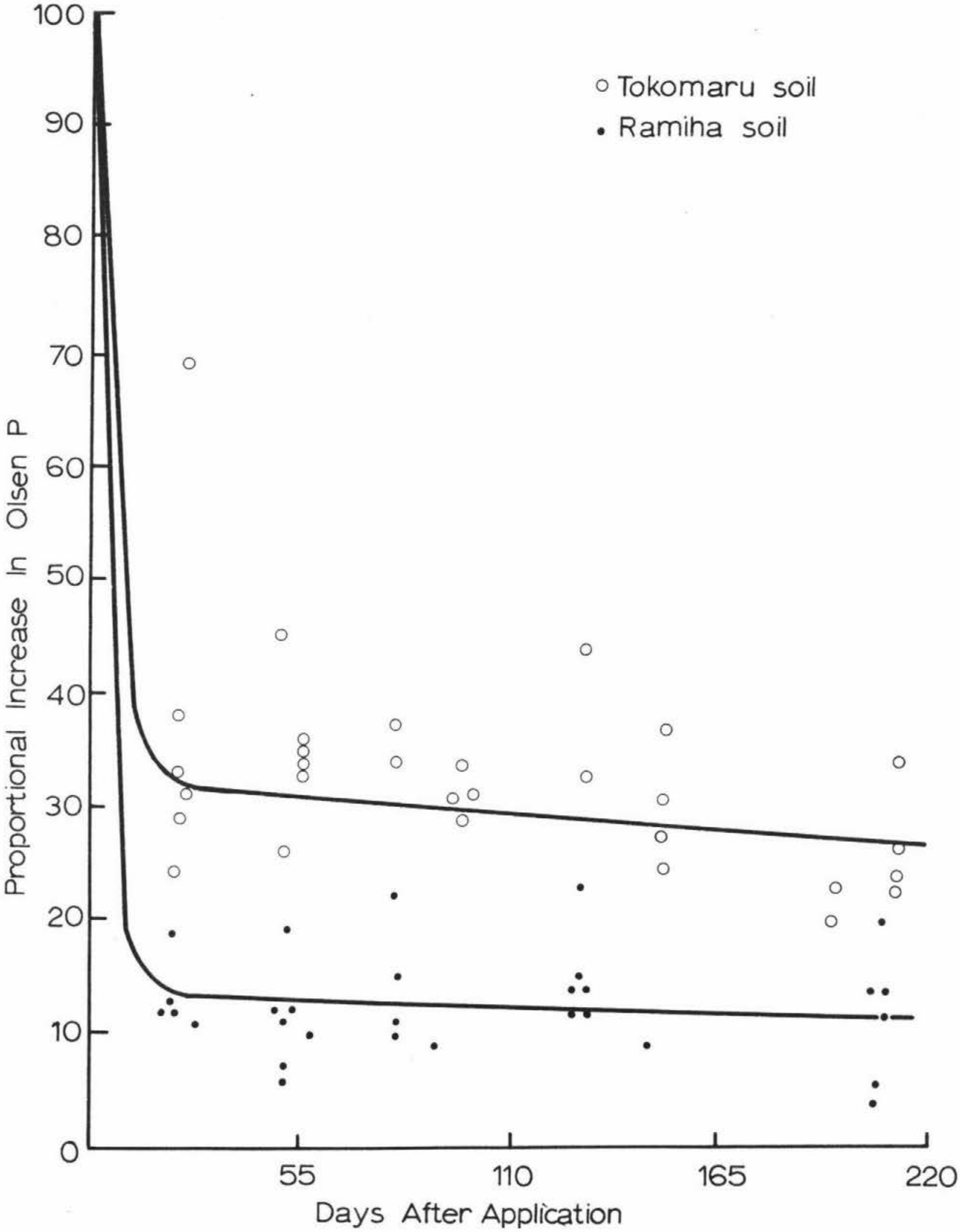

FIGURE 5.9: Mean proportional increases in Olsen P at various times after superphosphate application.

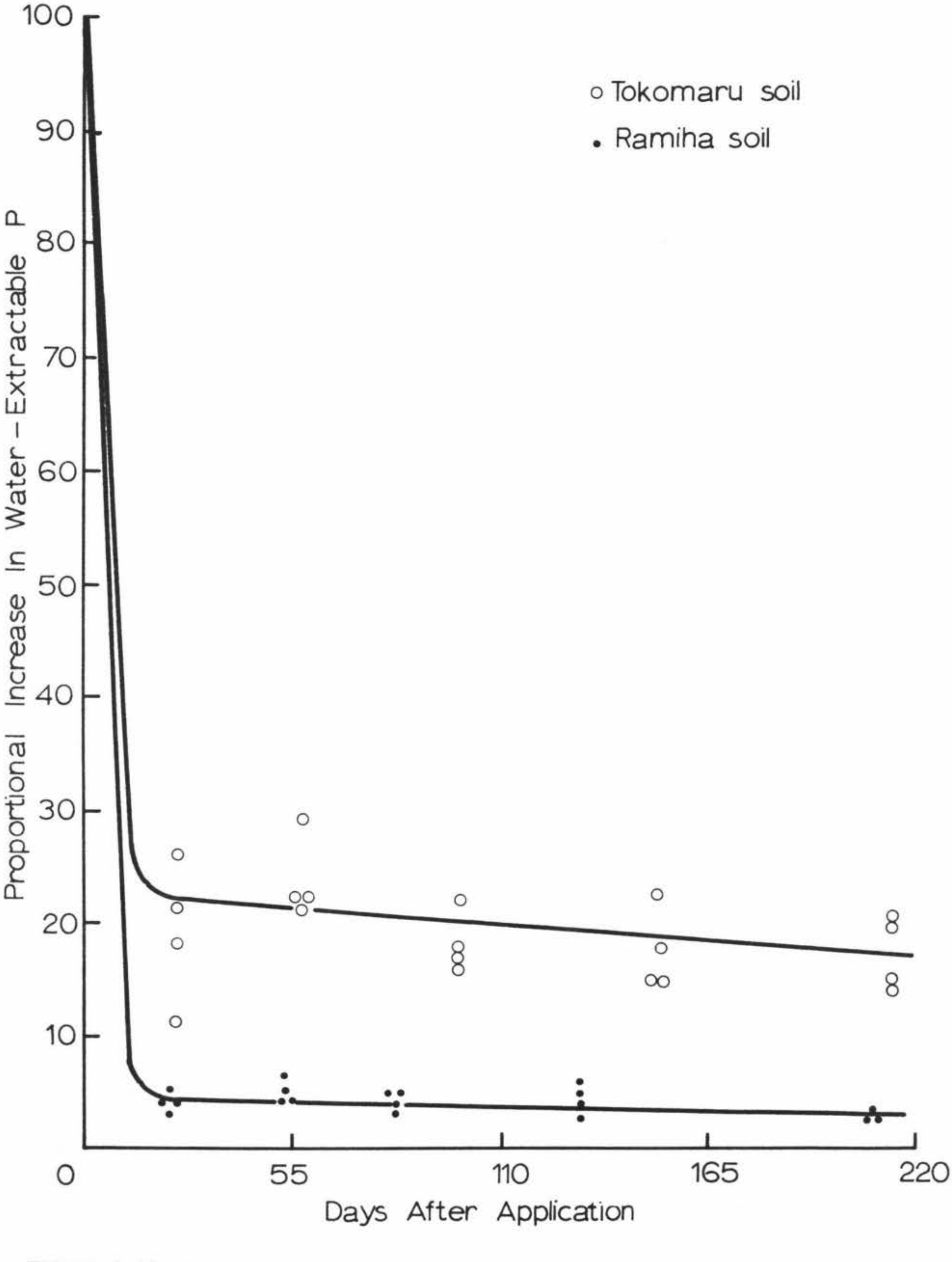

FIGURE 5.10: Mean proportional increases in water-extractable P at various times after superphosphate application.

TABLE 5.13: Overall average increases in extractable soil P (μg/g), six months after the application of 500 kg/ha of superphosphate (40 kg P/ha).

	Depth of sampling	
OLSEN P:	0-8 cm	0-4 cm
Tokomaru soil	2.7	5.2
Ramiha soil	1.1	2.9
WATER-EXTRACTABLE P:		
Tokomaru soil	2.3	4.7
Ramiha soil	0.2	0.6

in water-extractable P occurred in samples of Konini and Kumeroa soils during storage in the laboratory (section 3.3.1). On the other hand, in other samples of these soils, which had been stored in the glasshouse, water-extractable P levels appeared not to have changed (section 3.3.2). This suggests that some factor associated with the conditions of storage in the laboratory caused water-extractable P levels to increase. Contamination of the soil samples or of the analytical equipment can be ruled out as this would have been expected to similarly affect Olsen P levels.

Changes in the mineral nitrogen content of soils have been widely reported, indicating that microbiological activity continues during storage, even in air-dry soils (Gasser, 1961). In contrast, relatively few workers have investigated changes in the level of extractable soil P. Bajescu et al (1958) reported that acid-extractable P levels fluctuated during storage and increased at higher temperatures (28°C). Nowosielski and Sklodowski (1963) found that "available" P, determined by the *Aspergillus niger* method, may increase by 14% during storage.

More recently, Gupta and Rorison (1974) measured short-term changes in the level of soil P soluble in 0.01 M $CaCl_2$ solution in samples of three soils during storage. Over a six week period, soluble P levels in air-dry soil stored at 20°C, and in soil oven-dried and stored at 40°C, increased each week except for a marked decrease in the second week. The decline in the second week was apparently as a result of temporary immobilization of soluble soil P by the soil microflora. Increases after the second week, which were several times greater than the level of soluble P initially present, were attributed to mineralization of both dead microbes and easily mineralizable organic matter.

Drying the soils at 100°C markedly increased the levels of soluble P which then remained relatively constant when subsequently stored at room temperature. Soluble P levels in fresh soil stored at 5°C did not increase (Gupta and Rorison, 1974).

Batten (1978) recently reported long-term increases in acid-extractable soil P. The mean extractable P level of twenty soils increased by 3-5 ppm (about 20%) when stored in paper bags at room temperature for six years. Possible reasons for the increases were not discussed.

That the changes in water-extractable P in the present study occurred in the absence of any concomitant changes in Olsen P suggests that there was a change in the form of soil P. The implication is that part of the Olsen P fraction which was initially not water-extractable subsequently became water-extractable during storage. Similar conclusions were reached by Peverill et al (1975) with respect to changes in the level of extractable soil sulphur during storage. Oven-dried (40°C) soils stored at room temperature or 3°C for up to twelve months showed significant increases in sulphur extractable with calcium phosphate but not in sulphur extractable with charcoal plus calcium phosphate. The increases, while reduced, still occurred when toluene was applied to prevent bacterial activity, suggesting that the increases were caused by changes in the form of soil sulphur in addition to microbial release of inorganic sulphur. However, if the increases in water-extractable P in the present study resulted from changes in the form of soil P, it is not known why this occurred for samples stored in the laboratory but not for those stored in the glasshouse.

When it became obvious that the longer-term increases in water-extractable P in the present study were real, most soil samples had been collected and stored for some period of time. Few of the samples had been analysed immediately after collection, therefore the extent to which water-extractable P levels had increased during storage was not known for the majority of samples.

When soil samples collected throughout the year were analysed together at the end of the sampling programme, the samples had been stored for widely varying intervals of time. Consequently, it is likely that the extent to which water-extractable P had increased also varied, being greatest for the samples stored longest (eg Table 5.4B) and least for the most recently collected samples. As a result, discussion of the field trial results will be concentrated on changes in Olsen P, both between seasons and following the application of P fertilizer.

5.4.2 Seasonal changes in extractable soil P.

Seasonal changes in the levels of extractable P in the Tokomaru soil can be conveniently divided into four main phases. The changes included an initial increase to reach a peak in April-May, followed by a decrease in June-July, a levelling out in August-September and then a more or less steady decline through to February 1979.

An increase in extractable soil P during the "dry" season has previously been reported by a number of workers, including Robertson and Simpson (1954), Blakemore (1966), Childs and Jencks (1967) and Saunders and Metson (1971). In the present study, mean Olsen P levels in the Tokomaru soil initially increased by about 2.5 and 4.0 μg/g in the 0-8 cm and 0-4 cm depths respectively. Pasture growth was negligible before mid-April because of drought conditions as evidenced by the low soil moisture levels (Figures 5.1 and 5.2) Hence plant P uptake was likely to have been negligible during this time. This suggests that the late summer-autumn increases in Olsen P may have resulted from release of inorganic P by mineralization of organic residues, as postulated by Saunders and Metson (1971).

Such a conclusion implies that soil moisture levels which are inadequate for plant growth still permit microbial activity in the soil, though presumably at a reduced rate. This is consistent with the findings of Gasser (1961) and Gupta and Rorison (1974) discussed earlier (section 5.4.1).

In the study of Saunders and Metson (1971), covering a range of New Zealand soils, extractable P levels tended to reach a peak in February rather than in April-May as occurred in the present study. The different weather patterns experienced during the two studies possibly account for this difference. March was an abnormally wet month during the Saunders and Metson study whereas March and early April were exceptionally dry during the present study.

Mean Olsen P levels declined during June-July 1978 from the peak values recorded in the autumn. Similar observations have been made by other workers, including Childs and Jencks (1967), Williams (1968), Saunders and Metson (1971) and Sharpley et al (1977). Soil temperatures were at their lowest during the winter while soil moisture levels were rapidly increasing (Figures 5.1 and 5.2). Under these conditions microbial mineralization would be expected to be minimal (Dalal, 1977).

On the other hand, pasture growth in the late autumn-early winter period would have resulted in significant uptake of soil P which may have been partly responsible for the winter decline in Olsen P. It is also possible that the decline was initially assisted by microbial immobilization of inorganic soil P during breakdown of plant residues accumulated during the previous dry season. This is particularly likely when the plant residues have a high carbon: P ratio (Cosgrove, 1967).

The magnitude of the winter decrease in Olsen P in the 0-4 cm depth (5.3 μg/g) was more than twice that in the 0-8 cm depth (2.4 μg/g). When the difference in soil density between the two sampling depths (Appendix 1) is taken into account, it is apparent that most, if not all, of the Olsen P decrease in the 0-8 cm depth is attributable to the decrease in the 0-4 cm depth. It plant P uptake was largely responsible for the decline in Olsen P, the decrease might be expected to occur predominantly in the top 4 cm since most of the soil P taken up by pasture plants is obtained from the P-enriched surface layer of soil (Jackman and Mouat, 1972).

As a result of the more rapid rate of decline in the 0-4 cm depth, the mean level of Olsen P in this surface layer fell below the early February level in July 1978 (Figure 5.2). In contrast, this did not occur until three months later in the 0-8 cm depth. The tendency for extractable P to "level out" between July and September may have reflected low plant uptake caused by low soil temperatures and high soil moisture levels.

A further decline in mean Olsen P levels commenced in early October which coincided with soil temperatures rising above 10°C and therefore with a rapidly increasing rate of pasture growth. This suggests that the decline was a reflection of rapid plant uptake of soil P, implying that the rate of mineralization of organic residues was insufficient to satisfy plant P requirements during the spring flush of growth. Saunders and Metson (1971) found little or no change in extractable soil P during the spring flush. They concluded that the high rates of P uptake at that time of year were largely met by increased release of inorganic P as a result of microbial activity.

On the other hand, differences in trial technique could also account for the different results. The trials carried out by Saunders and Metson (1971) were occasionally mown with clippings returned to the plots. The trials were grazed between mowings. There was therefore, some return of nutrients in the form of both clippings and animal excreta. In the present study the trial plots were mown at regular intervals and the clippings were discarded. This continuous drain on soil nutrients, including P, was probably sufficient to cause extractable P levels to decline when plant uptake of soil P increased rapidly in the spring.

By late March 1979 the mean levels of Olsen P in the Tokomaru control plots were little more than 60% of the March 1978 levels. Also there was no indication of any increase in Olsen P as occurred in the previous late summer-early autumn period. The 40% decrease in mean Olsen P levels in only one year and the absence of any summer-autumn increase were probably due to a combination of the relatively wet summer in 1979 and loss of P in discarded clippings. The possible significance of discarded clippings is obvious when it is considered that the removal of 10 000 kg/ha of pasture dry matter containing 0.30% P would be equivalent to losing more than 35 μg P/g soil in the 0-8 cm depth, assuming that most of the P was taken up from this soil layer.

The Ramiha control plots were sampled less frequently than the Tokomaru plots and over a shorter period of time; certain seasonal changes in Olsen P were never-the-less apparent. Mean Olsen P levels declined in May-June, slightly earlier than in the Tokomaru soil, and again in the period November through to January 1979. These decreases also could reflect a loss of soil P through plant uptake and its subsequent removal in clippings. In the August-September period, however, Olsen P in the Ramiha soil increased while in the Tokomaru soil it remained relatively constant. These differences between the soils may be a reflection of differences in patterns of pasture growth, soil microbiological activity and climate.

If the loss of soil P in discarded clippings significantly influenced changes in extractable P, as suggested, then the changes over time recorded in this study were not true seasonal fluctuations. However, there was negligible pasture growth before April 1978 and relatively little growth during the winter. Prior to October 1978 therefore there was unlikely to have been sufficient P lost to have significantly influenced changes in extractable soil P. Consequently, the changes in Olsen P recorded prior to October 1978 are considered to represent genuine seasonal variation.

During the spring flush and subsequent moist summer, P lost in discarded clippings was more likely to have modified seasonal variation in extractable soil P. The recorded changes in Olsen P during this period may therefore have been largely a reflection of the management of the pasture. This problem might have been avoided by returning clippings to the plots though it could also be argued that the even return of P in clippings is a poor approximation of the uneven return of P by grazing animals in the form of dung.

Alternatively the study could have been conducted under normal grazing conditions. This may have created other problems such as pugging of the soil surface in winter leading to sampling depth errors and also the possible contamination of soil samples by dung, thus increasing variability. The selection of trial sites on free-draining soils under sheep grazing would be advisable to minimise such problems in any future work undertaken to assess seasonal variation in the level of extractable soil nutrients.

5.4.3 Changes in extractable soil P due to applied fertilizer P.

The results of the field studies are in agreement with the conclusion of Rennes (1978) that proportional decline curves for water-extractable P differ between soils of contrasting P sorption properties. The present study has shown this to be also true of proportional decline curves for Olsen P. Thus, both the water-extractability and Olsen-extractability of applied fertilizer P, relative to the initial increase in extractable P, decline more rapidly in soils of high P retention than in soils of low P retention. For a given soil, however, common proportional decline curves appear to apply to different depths of sampling and different rates of P application. The latter finding is consistent with the conclusions of Ryden et al (1977) and Rennes (1978).

The proportional decline curves derived in the present study indicate a much larger initial decline in the relative water-extractability of applied P than was found in a recent field study by Rennes (1978). The reason for this is at least partly attributable to different methods of expressing results. Rennes (1978) based his proportional decline curves on actual levels of extractable P, not on increases in extractable P above the control level.

In the present study, fluctuations over time in the level of extractable P in the control plots were of comparable magnitude to the increases resulting from applied fertilizer. It was therefore essential to base the proportional decline curves on increases in extractable P due to fertilizer instead of on actual levels of extractable P in the fertilized soil.

The proportional decline curves of Rennes (1978) also differed from those of the present study in another respect. Rennes (1978) estimated the initial increase in water-extractable P from soil samples collected in the field three days after superphosphate application. A preliminary investigation undertaken during the present study indicated that this method gave extremely variable results. It was found that initial increases in extractable P could be determined with greater accuracy after mixing finely-ground superphosphate with sieved, air-dry soil in the laboratory. Accuracy was considered important because of the comparisons that were to be made between different soils, rates of superphosphate and depths of sampling. However, the method used in the present study would tend to overestimate the initial effects of the applied fertilizer, thus reducing the relative extractability of applied P when subsequently measured in the field. The initial extractable P increases reported here are therefore essentially potential maximum increases.

The initial recovery of P added as superphosphate to soil in the laboratory was greatest (up to 24%) from the low P retention Tokomaru soil. Rennes (1978) similarly recovered up to 20% of the P added to a low P retention Pahiatua soil. Although other workers have usually not made time-zero measurements, they have sometimes recovered a much greater proportion of the P added to soils. Fuleky (1978) measured increases in Olsen P one week after commencing incubation which accounted for 33-40% and up to 80% of the P applied to noncalcareous and calcareous soils respectively. These high recovery rates suggest that the superphosphate P used by Fuleky (1978) was totally water-soluble. Kafkafi et al (1968), for example, added P in a water-soluble form (monocalcium phosphate) to six calcareous soils and recovered up to 70% by Olsen extraction after two days incubation.

The difference in recovery of added P between the two soils included in the present study can be attributed to their contrasting P retention properties. Superphosphate P dissolved during the extraction would be partially retained by the soil, particularly by the high P retention soil. Consequently, less of the added P was recovered from the Ramiha soil than from the Tokomaru soil. Rennes (1978) similarly recovered a smaller proportion of the P added to a high P retention Egmont soil than he recovered from a low P retention Pahiatua soil.

Differences between soils in terms of the recovery of added P have also been attributed to other soil properties. Kafkafi et al (1968) concluded that soil texture was important, the recovery of added P from coarse textured soils being greater than from fine textured soils. Fuleky (1978) confirmed the importance of soil texture and also showed that recovery of added P from calcareous soils, using both alkaline and acidic extractants. However, the effect of texture and pH differences on the Olsen-extractability of added P, while important initially, subsequently became insignificant.

The initial recovery of added P by water extraction differed more between the soils in the present study than did recovery by Olsen extraction. For example, the proportions of added P recovered from 0-8 cm samples of Tokomaru and Ramiha soils were 19% and 13% respectively by Olsen extraction, and 24% and 8% respectively by water extraction. These percentage recoveries suggest that probably about 70% of the P dissolved from the superphosphate was subsequently sorbed by the Ramiha soil during extraction with water. In contrast, probably less than half as much was sorbed by the same soil during Olsen extraction. Hydroxide and bicarbonate ions compete with phosphate ions for sorption sites (Barrow and Shaw, 1976b), resulting in less sorption of dissolved superphosphate P by soils of high P retention during Olsen extraction relative to that which occurs during water extraction.

The proportion of added P recovered from the Tokomaru soil, both initially in the laboratory and subsequently in the field, appeared to be independent of the amount of superphosphate added. This result is in general agreement with the findings of other workers. Power et al (1964) found that the relationship between fertilizer P added and the change in Olsen P after 50 days was linear. Rennes (1978) recently showed that water-extractable P values immediately after mixing superphosphate with Pahiatua soil, and for up to 18 days after commencing incubation, similarly increased in proportion to the rate of added P .

Fuleky (1978), on the other hand, observed that the relationship between added P and the change in extractable P, while linear at rates up to 120 ppm of added P, deviated from linearity in some soils with the addition of 1200 ppm P. This was possibly caused by secondary adsorption during extraction, resulting in a curvilinear relationship between the amount of P added and the amount extracted, as found by Barrow and Shaw (1976a). However, the relationship was essentially linear at rates of less than 200 ppm P, such as were used in the present study. This supports an earlier suggestion that the lack of a linear relationship between added P and increases in Olsen P in the Ramiha soil was a reflection of the errors associated with measuring small increases in Olsen P in the field.

In the Ramiha soil, proportional increases in Olsen P at the highest rate of superphosphate appeared to be smaller following the spring application than following the autumn application. Higher soil temperatures in the six months after the spring application may account for this apparent difference since the rate at which added P is immobilized in soils is positively related to temperature (Barrow and Shaw, 1975a). The Olsen- and water-extractability of added P were both reduced at higher temperatures in an incubation study by Power et al (1964).

In the present study, however, the apparent difference between spring and autumn applications was not apparent in terms of the water-extractability of added P. Since the spring plots on the Ramiha soil were not part of the original trial design, the comparison between spring and autumn applications is of doubtful validity. Further work would be required to determine whether real differences exist in terms of the rate of decline in extractability of applied P between spring and autumn applications.

It is therefore apparent that the major factor influencing the rate of decline in extractability of added P in this study was the difference between soils. Both proportional increases and actual increases in extractable P in the field were higher in the Tokomaru soil than in the Ramiha soil. These differences were apparent in the first sampling of the field plots and were maintained with relatively little change throughout the period of measurement. Rennes (1978) observed similar between-soils differences for water-extractable P in an incubation study comparing two contrasting soils. However, the Olsen-extractability of added P was much higher than that recorded in the present study. No obvious reason could be found to explain these conflicting results.

It is never-the-less apparent that more superphosphate must be applied to soils of high P retention than to soils of low P retention to achieve the same increase in extractable soil P. This is particularly so for water-extractable P, although the levels of water-extractable P required for near-maximum pasture growth are also much higher in soils of low P retention (Chapters 3 and 4). Further work of a long term nature would be required to determine whether similar differences between soils exist in terms of the fertilizer rate required to maintain extractable soil P at a given level, once this level has been achieved.

CHAPTER 6

SUMMARY AND CONCLUSIONS

The purpose of the study was to obtain experimental data which could be used to quantify the relationships within a simple P submodel. The information required concerned the relationship between relative pasture yield and the level of extractable soil P, and changes in the level of extractable soil P both over time and as a function of applied fertilizer P. A review of the literature revealed that there was a distinct lack of this information, particularly for New Zealand conditions.

The relationship between yield and extractable soil P level was studied using two different glasshouse techniques. Changes in extractable soil P over time and as a function of applied fertilizer P were investigated in two field trials.

In the first glasshouse study, "pasture" yield on intact soil cores, collected from field plots of varying soil P status on two soil types, was related to the level of soil P extracted by either sodium bicarbonate solution (Olsen P) or distilled water. Differences in the level of extractable soil P accounted for 25% or less of the yield variation between cores in harvests 1 + 2, and for 50-75% of the yield variation between cores in harvests 3 + 4. The improved relationships in harvests 3 + 4 were the result of changes in both trial technique and methods of calculation.

The relationship between yield in harvests 3 + 4 and the level of Olsen P was very similar in the two soils studied. In contrast, the relationship between yield and the level of water-extractable P differed between the two soils. At the same level of water-extractable soil P, relative yield was higher for the higher-P retention soil (Konini) than for the lower-P retention soil (Kumeroa). As a result, critical levels of water-extractable P (ie those required for 90% of maximum yield) were four to five times greater in the Kumeroa soil than in the Konini soil, in contrast to the almost identical critical Olsen P levels in the two soils.

The second glasshouse study involved conventional pot experiments. Ryegrass yield was related to the level of Olsen P and water-extractable P in samples of two soils. A high proportion (89-97%) of the yield variation in all harvests was explained by differences in the level of extractable soil P. For the Konini soil, relative yield was lower in the pot experiment than in the intact core experiment at the same level of extractable soil P. However, the results of the intact core experiments were considered to be more directly applicable to the field situation than the pot trial results.

The relationship between ryegrass yield and the level of Olsen P in the pot experiments differed between the two soils studied, although the difference became less as the number of harvests increased. At the same level of Olsen P, relative yield was slightly lower in the higher-P retention soil (Konini) than in the lower-P retention soil (Pirinoa). The relationship between ryegrass yield and the level of water-extractable P also differed between the two soils, but the difference was of much greater magnitude than, and in the opposite direction to, that found for Olsen P.

The results of both glasshouse techniques showed that in terms of the relationship between relative yield and extractable soil P, the Olsen procedure is less affected, than the water extraction procedure, by differences in P retention and thus is nearer to soil type independence. It is concluded that the Olsen extraction procedure would therefore provide a more suitable index of plant-available soil P from which to predict pasture production on different soils. The extent to which the relationship between relative pasture yield and Olsen P varies between more contrasting soils than those studied, and between different seasons of the year, requires investigation.

The field studies were conducted on two pasture soils of contrasting P retention properties. Seasonal variations in the level of extractable soil P were investigated in a low P retention Tokomaru soil and changes in the level of extractable soil P as a function of applied fertilizer P were studied in the same soil and in a high P retention Ramiha soil. Seasonal changes in extractable P in the Tokomaru soil included an increase during the dry season to reach a peak in late autumn, followed by a decline in winter. These changes in extractable soil P were considered to reflect the net effect of opposing processes within the soil, particularly plant uptake of soil P and microbial release of inorganic P from organic residues. Extractable P levels in the Tokomaru soil also declined gradually during the spring and second summer which was relatively moist in comparison to the first summer. The spring-summer decline was attributed largely to plant uptake of soil P and its subsequent loss in discarded clippings. Changes in extractable soil P during this period were therefore considered not to reflect true seasonal fluctuations.

The magnitude of increases in extractable soil P following the application of superphosphate was found to differ between the two soils studied. The increases per unit of applied fertilizer P, in both absolute terms and relative to an initial (time-zero) increase, were greater in the soil of low P retention (Tokomaru) than in the soil of high P retention (Ramiha). Increases in water-extractable P differed between the two soils more than did increases in Olsen P following superphosphate application. Hence it is concluded that, in this respect also, the Olsen procedure is nearer to being independent of soil type than is the water extraction procedure.

The magnitude of the increase in extractable soil P was proportional to the amount of fertilizer P applied. Thus, although different proportional decline curves were obtained for different soils, a common proportional decline curve was found to apply to different rates of fertilizer P application to the same soil. A common proportional decline curve was similarly found to apply to the two different depths of sampling. Further work is required to determine whether this also applies to different times of fertilizer application.

The level of water-extractable soil P was found to increase considerably when soil samples were stored for several months in the laboratory, though there was no concomitant increase in Olsen P. Short-term fluctuations in water-extractable P content also occurred. It is concluded that short-term fluctuations reflected changes in the conditions of extraction, such as pH of the distilled water. Longer-term increases, although of unknown cause, apparently reflected real changes in the level of water-extractable P within the soil samples.

This study has shown how the relationship between relative "pasture" yield and the level of extractable soil P can be expected to vary between soils of different P retention. The range of soils within which this relationship remains essentially constant is likely to be much greater for Olsen P than for water-extractable P. This study has also indicated the approximate magnitude of increases in extractable soil P in contrasting soils resulting from the application of superphosphate fertilizer. These data, although somewhat limited in scope, will enable a preliminary evaluation of the P submodel.

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APPENDIX 1: Some pedological and chemical information relevant to the soils included in the glasshouse and field studies.

GLASSHOUSE STUDIES

Soil name	Konini	Kumeroa	Pirinoa
Soil Group *	central YBE	YGE-YBE intergrade	YGE-YBE intergrade
Topsoil texture	fine sandy loam	silt loam	silty clay loam
Phosphate retention (%)	55-60	35-40	25-30
Approximate ratio of Olsen P: water-extractable P	4.0	2.0	1.2
pH range (winter 1978)	5.5-6.0	5.5-6.0	6.0-6.5
Lime applied in 1973 (kg/ha)	2500	2500	nil

FIELD STUDIES

Soil type	Tokomaru silt loam	Ramiha silt loam
Soil Group *	YGE	YBE
Bulk density of 0-8 cm depth (g/cc)	1.01	0.72
Phosphate retention (%)	20-25	85-90
Approximate ratio of Olsen P: water-extractable P	1.5-2	8-10
pH range (autumn 1978)	5.9-6.3	6.0-6.4

* YGE = Yellow-grey earth
YBE = Yellow-grown earth

APPENDIX 2: Composition of stock solutions and amounts of each used to make up nutrient solutions* for use in the glasshouse studies.

Stock solution	Salt	Elements (me/l) in the stock solution							Grams of salt per 4.5 l of stock solution
		P	S	Cl	K	Na	Mg	Ca	
+P	KH_2PO_4	66			22				13.5
	K_2HPO_4	56			38				14.7
	K_2SO_4		20		20				7.8
-P	$KHCO_3$				60				27.0
	K_2SO_4		20		20				7.8
Other major elements	$MgCl_2.6H_2O$			10			10		4.6
	$CaCO_3$							10	2.3
	HCl (N)			10					45 ml
	Na_2SO_4		22			22			7.0
Trace elements									mg/4.5 l
	$CoCl_2.6H_2O$								1.8
	$CuCl_2.2H_2O$								4.5
	$MnCl_2.H_2O$								90.0
	$(NH_4)_6Mo_7O_{24}.4H_2O$								1.8
	$ZnCl_2$								6.8
	H_3BO_3								13.5

Amount of each stock solution per 4.5 l of nutrient solution	+P Nutrient solution	-P Nutrient solution
+P	250 ml	-
-P	-	250 ml
Other major elements	250 ml	250 ml
Trace elements	100 ml	100 ml
Ferric citrate solution (58.5 mg/l)	10 ml	10 ml

* Nutrient solutions containing nitrogen were prepared after adding 97.2 g of NH_4NO_3 per 4.5 l of the -P and +P stock solutions.

APPENDIX 3: Levels of Olsen P (μg/g) and inorganic nitrogen (μg/g) in soil samples collected from around the intact cores.

KONINI SOIL					KUMEROA SOIL			
	Olsen P			Inorganic Nitrogen		Olsen P		Inorganic Nitrogen
Intact Core No	0-8 cm*	0-4 cm*	0-4 cm†	0-8 cm	Intact Core No	0-8 cm*	0-4 cm*	0-8 cm
7A	7.4	9.5	10.1	25.1	12A	7.1	8.8	14.0
7B	7.3	9.4	10.0	25.1	12B	5.8	8.0	10.8
7C	7.7	11.2	11.5	21.9	12C	7.1	9.2	35.5
26A	12.3	16.3	15.7	42.8	19A	5.1	6.5	8.2
26B	12.0	16.1	16.0	24.4	19B	7.1	8.3	8.7
26C	10.8	14.4	15.2	25.4	19C	7.0	11.8	10.8
10A	9.8	15.4	15.5	106.1	6A	9.5	11.9	11.1
10B	9.9	13.9	13.6	26.2	6B	8.3	11.9	11.1
10C	11.8	15.6	15.6	21.7	6C	8.5	10.8	17.1
18A	9.7	13.2	12.7	28.9	27A	7.9	9.4	14.2
18B	9.9	13.9	14.2	37.1	27B	8.8	10.1	11.0
18C	9.8	13.0	12.7	28.9	27C	7.9	12.7	12.1
14A	13.6	18.5	-	40.6	8A	11.2	16.4	10.8
14B	13.8	18.7	-	29.1	8B	12.6	17.4	9.2
14C	11.5	16.7	-	39.3	8C	12.9	15.5	10.5
20A	20.5	25.7	25.8	22.8	32A	16.4	20.0	12.7
20B	12.1	16.0	15.4	25.1	32B	21.9	23.1	12.4
20C	13.8	18.1	18.6	23.5	32C	15.4	20.7	11.7
6A	14.8	21.9	-	20.9	13A	16.2	18.3	9.2
6B	16.9	24.0	-	24.4	13B	16.4	20.0	9.2
6C	19.4	26.5	-	28.0	13C	14.0	18.8	9.8
30A	14.0	19.2	18.9	30.0	17A	14.8	20.5	10.8
30B	19.9	26.1	27.9	27.6	17B	18.0	20.0	16.5
30C	14.8	20.7	21.1	26.2	17C	11.1	13.3	10.1
LP 3A	31.9	50.5	49.2	31.6				
LP 3B	31.5	45.8	46.4	28.9				
LP 22A	28.8	43.1	43.5	33.9				
LP 22B	28.9	48.3	-	26.0				
LP 25A	23.8	38.5	-	27.9				
LP 25B	29.2	49.0	-	31.6				

* Analysed June 1978

† Analysed June 1979

APPENDIX 4: Yields of dry matter (g/core) in the first and second harvests from the intact cores.

	KONINI SOIL			KUMEROA SOIL			
		Dry Matter Yield			Dry Matter Yield		
Previous Fertilizer Treatment	Core No	Cut 1	Cut 2	Core No	Cut 1	Cut 2	Cut 1 + 2*
Nil P	7A	0.85	1.78	12A	0.91	1.32	1.47
	7B	1.30	1.60	12B	0.91	1.47	1.80
	7C	1.43	1.73	12C	1.66	1.63	1.37
	26A	1.48	1.52	19A	0.55	0.96	1.07
	26B	1.38	1.79	19B	1.05	1.56	2.14
	26C	1.16	1.74	19C	0.77	1.17	1.36
Low P	10A	2.52	2.20	6A	0.60	0.98	0.98
	10B	0.86	1.20	6B	1.10	1.40	1.90
	10C	0.97	1.14	6C	1.02	1.33	1.43
	18A	1.20	1.38	27A	0.99	1.40	1.62
	18B	1.36	1.55	27B	0.81	1.42	1.64
	18C	0.76	1.27	27C	0.91	1.32	1.58
Medium P	14A	0.92	1.36	8A	0.94	1.14	1.50
	14B	1.47	1.79	8B	1.10	1.31	1.91
	14C	1.14	1.52	8C	0.85	1.18	1.46
	20A	0.73	1.31	32A	1.30	1.87	2.48
	20B	1.23	1.70	32B	1.31	1.79	2.43
	20C	1.15	1.62	32C	1.17	1.86	2.40
High P	6A	1.38	1.55	13A	0.60	1.02	1.12
	6B	1.62	1.86	13B	0.82	1.05	1.37
	6C	1.72	2.04	13C	0.72	1.36	1.55
	30A	1.76	1.61	17A	1.16	1.69	2.27
	30B	1.29	2.00	17B	1.35	1.65	2.11
	30C	1.12	1.44	17C	0.98	1.49	1.92
Lime x P	LP 3A	1.76	2.57				
	LP 3B	1.30	1.63				
	LP 22A	1.10	1.79				
	LP 22B	1.40	1.78				
	LP 25A	1.25	1.53				
	LP 25B	1.85	2.27				

APPENDIX 4: continued ...

Previous Fertilizer Treatment	KONINI SOIL			KUMEROA SOIL			
		Dry Matter Yield			Dry Matter Yield		
	Core No	Cut 1	Cut 2	Core No	Cut 1	Cut 2	Cut 1 + 2*
High P + P added during the experiment	6D	1.26	1.87	4A	1.74	2.80	-
	6E	1.92	2.39	4B	0.99	1.38	-
	6F	1.55	1.69	4C	0.92	1.04	-
	30D	0.98	1.83	28A	1.77	2.22	-
	30E	1.52	1.68	28B	1.20	1.78	-
	30F	1.33	1.73	28C	1.03	1.28	-

* Combined yields adjusted for effect of soil inorganic nitrogen.

APPENDIX 5: Levels of Olsen P (μg/g) and water-extractable P (μg/g) within the intact cores at the completion of the experiments.

KONINI SOIL					KUMEROA SOIL				
	Olsen P		Water-extractable P			Olsen P		Water-extractable P	
Core No	0-8 cm	0-4 cm	0-8 cm	0-4 cm	Core No	0-8 cm	0-4 cm	0-8 cm	0-4 cm
7A	8.2	9.7	1.5	2.3	12A	8.1	9.3	4.9	7.5
7B	7.4	8.6	1.5	1.8	12B	7.0	8.2	5.0	6.7
7C	9.0	11.1	2.4	2.9	12C	8.5	9.4	6.8	9.5
26A	7.6	11.3	1.0	2.3	19A	6.5	7.4	4.4	5.6
26B	11.1	13.8	1.7	3.0	19B	8.1	9.0	5.2	6.9
26C	10.8	12.5	1.5	2.3	19C	8.8	9.4	4.9	6.2
10A	11.0	12.6	1.2	2.0	6A	8.9	9.5	6.7	7.9
10B	10.4	13.5	2.0	3.4	6B	8.3	9.3	5.9	7.7
10C	10.6	13.9	1.8	3.4	6C	7.9	9.5	7.2	8.1
18A	10.2	12.4	1.7	2.5	27A	8.6	9.5	6.5	8.4
18B	11.7	15.1	1.5	2.3	27B	9.4	10.1	5.8	7.7
18C	9.9	12.3	1.1	1.7	27C	8.7	9.4	4.7	6.0
14A	13.7	18.0	2.0	3.0	8A	10.4	13.0	4.6	7.4
14B	13.9	17.6	2.4	3.4	8B	10.1	11.5	6.2	7.7
14C	11.7	15.4	2.0	3.2	8C	11.1	13.0	5.3	7.2
20A	15.2	20.7	3.1	4.6	32A	16.7	19.3	9.1	11.4
20B	11.3	13.7	1.8	2.5	32B	20.1	23.7	8.0	10.6
20C	15.1	17.6	2.6	3.3	32C	15.6	16.5	7.5	9.7
6A	14.4	18.2	2.4	3.7	13A	16.1	16.7	8.6	10.5
6B	16.0	18.8	3.9	6.0	13B	14.9	15.8	7.1	9.9
6C	18.2	21.7	3.4	5.5	13C	12.1	13.3	7.9	9.6
30A	12.7	16.1	2.2	3.4	17A	12.4	17.1	10.7	15.2
30B	22.0	26.7	4.7	7.2	17B	18.6	19.8	11.8	13.7
30C	13.2	18.1	2.6	5.2	17C	10.7	12.9	8.6	11.5
LP 3A	30.4	37.5	5.8	9.7	4A	28.8	36.8	13.6	21.1
LP 3B	33.3	47.0	9.8	17.3	4B	29.3	33.7	14.7	20.4
LP 22A	26.7	39.3	6.0	11.6	4C	17.4	18.6	8.1	11.0
LP 22B	27.0	41.7	6.0	10.2	28A	20.5	28.1	11.2	17.5
LP 25A	18.8	30.7	3.7	7.2	28B	24.9	31.3	13.4	18.5
LP 25B	25.0	37.0	5.0	9.6	28C	21.8	25.8	10.6	15.0

APPENDIX 5: continued ...

KONINI SOIL					KUMEROA SOIL				
	Olsen P		Water-extractable P			Olsen P		Water-extractable P	
Core No	0-8 cm	0-4 cm	0-8 cm	0-4 cm	Core No	0-8 cm	0-4 cm	0-8 cm	0-4 cm
6D	32.3	44.2	8.0	13.3					
6E	25.5	32.0	6.0	8.8					
6F	24.4	31.9	6.2	11.7					
30D	26.7	34.3	7.7	15.2					
30E	25.2	33.8	6.0	10.7					
30F	18.0	24.5	4.1	7.9					

APPENDIX 6: Yields of dry matter (g/core) in the third and fourth harvests, and the proportion of yield in the fourth harvest due to ryegrass and other grasses.

KONINI SOIL					KUMEROA SOIL				
	DM Yield (g/core)					DM Yield (g/core)			
Core No	Cut 3	Cut 4	% Ryegrass	% Other Grasses	Core No	Cut 3	Cut 4	% Ryegrass	% Other Grasses
7A	1.80	2.66	12	86	12A	2.51	2.65	43	49
7B	1.93	2.49	6	92	12B	2.26	2.87	26	71
7C	2.23	3.40	11	88	12C	2.45	2.74	32	64
26A	1.73	3.22	4	94	19A	1.94	2.54	24	61
26B	1.80	2.81	15	82	19B	2.23	2.97	31	59
26C	1.62	2.72	13	84	19C	2.32	3.06	36	57
10A	1.64	2.41	11	88	6A	2.23	3.10	52	42
10B	1.53	2.42	4	95	6B	2.33	3.23	53	42
10C	1.70	2.46	4	93	6C	2.23	3.05	5	82
18A	1.50	2.19	10	85	27A	2.39	2.65	22	74
18B	1.93	3.08	10	87	27B	2.24	2.86	22	72
18C	1.40	2.43	10	88	27C	2.18	2.50	15	77
14A	1.81	2.86	11	88	8A	2.56	3.48	44	51
14B	1.78	3.46	15	82	8B	2.27	3.36	31	66
14C	1.82	3.31	23	72	8C	2.13	2.86	15	81
20A	1.75	3.38	17	82	32A	3.07	4.05	39	59
20B	1.90	3.04	19	80	32B	3.01	4.22	34	64
20C	1.70	3.16	8	91	32C	3.08	3.50	20	78
6A	1.88	3.31	27	69	13A	1.94	3.39	36	53
6B	2.37	3.95	17	83	13B	2.17	3.08	35	62
6C	2.13	3.78	51	46	13C	2.52	3.52	51	39
30A	1.77	3.18	30	66	17A	2.79	3.67	35	60
30B	1.90	3.00	15	81	17B	3.22	4.53	45	55
30C	1.65	2.70	17	83	17C	2.87	3.68	28	69
LP 3A	2.61	3.92	13	86	4A	3.94	4.59	23	71
LP 3B	2.37	3.85	22	76	4B	2.43	4.07	23	73
LP 22A	2.02	3.11	4	95	4C	2.45	3.77	49	50
LP 22B	2.40	3.91	21	78	28A	3.57	5.17	37	61
LP 25A	2.24	3.57	17	78	28B	3.24	4.50	24	64
LP 25B	2.47	4.24	11	89	28C	3.14	4.12	14	74

APPENDIX 6: continued ...

KONINI SOIL					KUMEROA SOIL				
	DM Yield (g/core)					DM Yield (g/core)			
Core No	Cut 3	Cut 4	% Ryegrass	% Other Grasses	Core No	Cut 3	Cut 4	% Ryegrass	% Other Grasses
6D	2.73	4.21	39	60					
6E	2.46	3.74	37	60					
6F	2.59	3.78	32	65					
30D	2.16	3 04	44	51					
30E	1.97	3.61	31	65					
30F	2.15	3.74	46	51					

APPENDIX 7: Levels of Olsen P (μg/g) and water-extractable P (μg/g) in samples of Konini and Pirinoa soils (0-8 cm depth) used in the pot experiments.

	KONINI SOIL		PIRINOA SOIL	
Pot No*	Olsen P	Water-extractable P	Olsen P	Water-extractable P
1	12.6	2.2	22.6	20.8
2	10.1	1.5	40.2	35.5
3	16.8	2.9	30.1	25.5
4	8.0	1.4	28.3	22.1
5	11.0	1.9	29.5	25.5
6	15.1	2.8	27.1	26.2
7	6.9	1.5	23.9	21.6
8	11.1	2.4	15.1	13.0
9	11.1	1.4	15.0	15.3
10	11.2	1.5	13.2	13.0
11	13.1	1.7	10.2	9.7
12	10.7	1.4	17.0	14.1
13	21.8	3.3	8.9	8.1
14	11.3	1.6	16.8	13.1
15	15.4	2.3	8.6	7.9
16	8.2	1.0	21.7	14.9
17	14.0	1.6	18.5	14.9
18	11.7	1.2	8.9	9.4
19	20.6	2.7	10.7	9.7
20	14.0	1.8	21.7	16.7
21	19.6	2.8	11.7	10.3
22	8.9	1.2	12.7	10.4
23	11.1	1.2	11.7	9.5
24	9.2	1.1	17.1	12.5
25	12.7	1.6	29.9	23.9
26	11.9	1.4	30.1	25.3
27	15.8	1.8	23.7	19.2
28	10.5	1.1	24.3	18.4
29	14.0	1.9	13.9	11.5
30	17.0	2.7	19.8	15.6

APPENDIX 7: continued ...

KONINI SOIL			PIRINOA SOIL		
Pot No*	Olsen P	Water-extractable P	Pot No*	Olsen P	Water-extractable P
31	12.1	1.7	31	18.5	13.5
32	17.5	3.0	32	16.0	12.8
33	9.2	1.0	33	23.7	19.1
34	6.0	1.0	34	14.5	13.0
35	7.9	0.8	35	8.8	9.8
36	8.6	1.7	36	4.6	5.7
ML 3	42.3	11.7	PL 7	16.4	14.0
ML 4	11.8	2.3	PL 8	56.8	43.7
ML 15	36.1	8.5	PL 12	23.3	17.2
ML 16	10.1	2.0	PL 15	53.0	36.9
ML 17	36.3	9.5	PL 22	43.3	27.3
ML 19	12.7	2.1	PL 24	13.6	10.2
ML 28	47.4	10.7	PL 27	15.0	9.7
ML 29	13.6	1.5	PL 31	39.5	27.3

* Pot numbers correspond with field plot numbers except for pots 33 to 36.

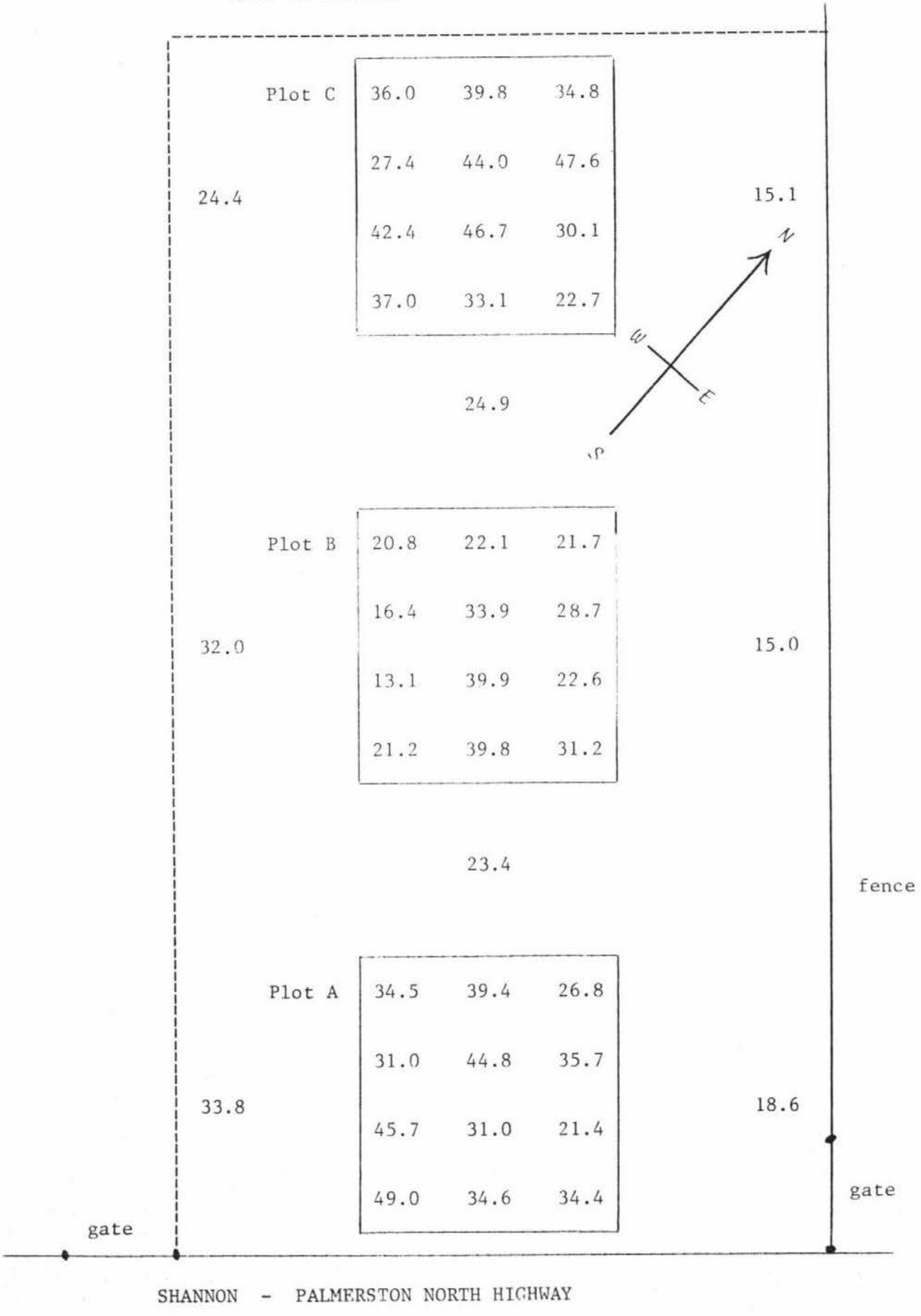
APPENDIX 8A: Yields of dry matter (g/pot) in three harvests of ryegrass grown in Konini soil.

	Dry Matter Yield		
Pot No	Cut 1	Cut 2	Cut 3
1	1.62	2.29	2.59
2	1.38	1.94	2.29
3	2.03	2.97	3.07
4	1.11	1.83	2.09
5	1.43	2.20	2.53
6	1.73	2.66	2.95
7	1.25	1.77	2.06
8	1.52	2.32	2.41
9	1.27	1.74	1.97
10	1.19	1.76	2.43
11	1.50	2.25	2.58
12	1.37	1.99	2.19
13	2.06	3.32	3.32
14	1.25	2.16	2.54
15	1.73	2.54	2.80
16	1.05	1.77	1.83
17	1.18	1.91	2.40
18	1.19	1.71	2.27
19	1.85	2.70	2.85
20	1.63	2.11	2.65
21	2.06	2.67	2.93
22	1.06	1.59	1.92
23	1.37	2.06	2.13
24	0.92	1.59	1.85
25	1.08	1.65	2.14
26	1.29	1.86	2.15
27	1.63	2.52	2.86
28	1.16	1.72	2.67
29	1.67	2.34	2.70
30	1.85	2.73	3.10
31	1.30	2.14	2.34
32	1.84	2.60	2.98
33	0.77	1.22	1.44
34	1.04	1.54	1.75
35	0.63	1.20	1.53
36	1.46	1.86	2.04
ML 3	3.13	3.80	3.85
ML 4	1.24	1.90	2.24
ML 15	2.80	3.92	3.81
ML 16	1.38	1.96	2.19
ML 17	2.86	3.71	3.67
ML 19	1.36	2.08	2.32
ML 28	3.02	3.70	3.99
ML 29	1.31	1.96	2.29
ML 3 + P	3.34	4.63	4.80
ML 15 + P	3.30	4.59	4.76
ML 17 + P	3.15	4.73	4.69
ML 28 + P	3.07	4.39	4.80
Mean of + P pots	3.22	4.58	4.76

APPENDIX 8B: Yields of dry matter (g/pot) in three harvests of ryegrass grown in Pirinoa soil.

	Dry Matter Yield		
Pot No	Cut 1	Cut 2	Cut 3
1	3.22	3.77	3.69
2	3.83	4.00	4.73
3	3.52	3.66	4.32
4	3.44	3.56	4.11
5	3.57	3.83	3.87
6	3.66	4.16	3.98
7	3.30	3.78	3.79
8	2.84	2.99	3.49
9	2.99	2.73	3.11
10	2.36	2.77	3.32
11	2.12	2.45	2.62
12	2.97	2.96	3.69
13	1.93	2.35	2.59
14	2.86	3.23	3.63
15	1.92	2.13	2.74
16	3.18	3.44	3.99
17	3.03	3.20	3.54
18	2.18	2.32	2.80
19	2.29	2.72	2.63
20	3.03	3.45	3.34
21	2.25	2.80	3.04
22	2.23	2.72	3.25
23	2.14	2.63	2.62
24	2.93	3.04	3.82
25	3.45	3.90	3.94
26	3.67	3.91	4.13
27	3.28	3.63	3.73
28	3.18	3.47	3.67
29	2.36	2.60	3.00
30	2.87	3.16	3.26
31	2.82	2.97	3.39
32	2.75	2.68	3.41
33	3.12	3.16	3.80
34	2.61	2.57	3.18
35	2.22	2.57	2.77
36	1.77	2.08	1.94
PL 7	2.81	3.00	3.39
PL 8	3.78	4.35	4.79
PL 12	3.30	3.54	3.84
PL 15	3.97	4.49	4.86
PL 22	3.80	4.23	4.73
PL 24	2.31	2.72	2.98
PL 27	2.64	2.73	3.09
PL 31	3.56	4.16	4.23
PL 8 + P	4.07	4.86	5.44
PL 15 + P	4.12	4.84	5.59
PL 22 + P	4.23	4.67	5.26
PL 31 + P	4.07	5.17	5.41
Mean of + P pots	4.12	4.88	5.42

APPENDIX 9: Levels of Olsen P (μg/g) in individual cores of Tokomaru soil, according to their spatial distribution in the field (not to scale).



Plot C

36.0	39.8	34.8
27.4	44.0	47.6
42.4	46.7	30.1
37.0	33.1	22.7

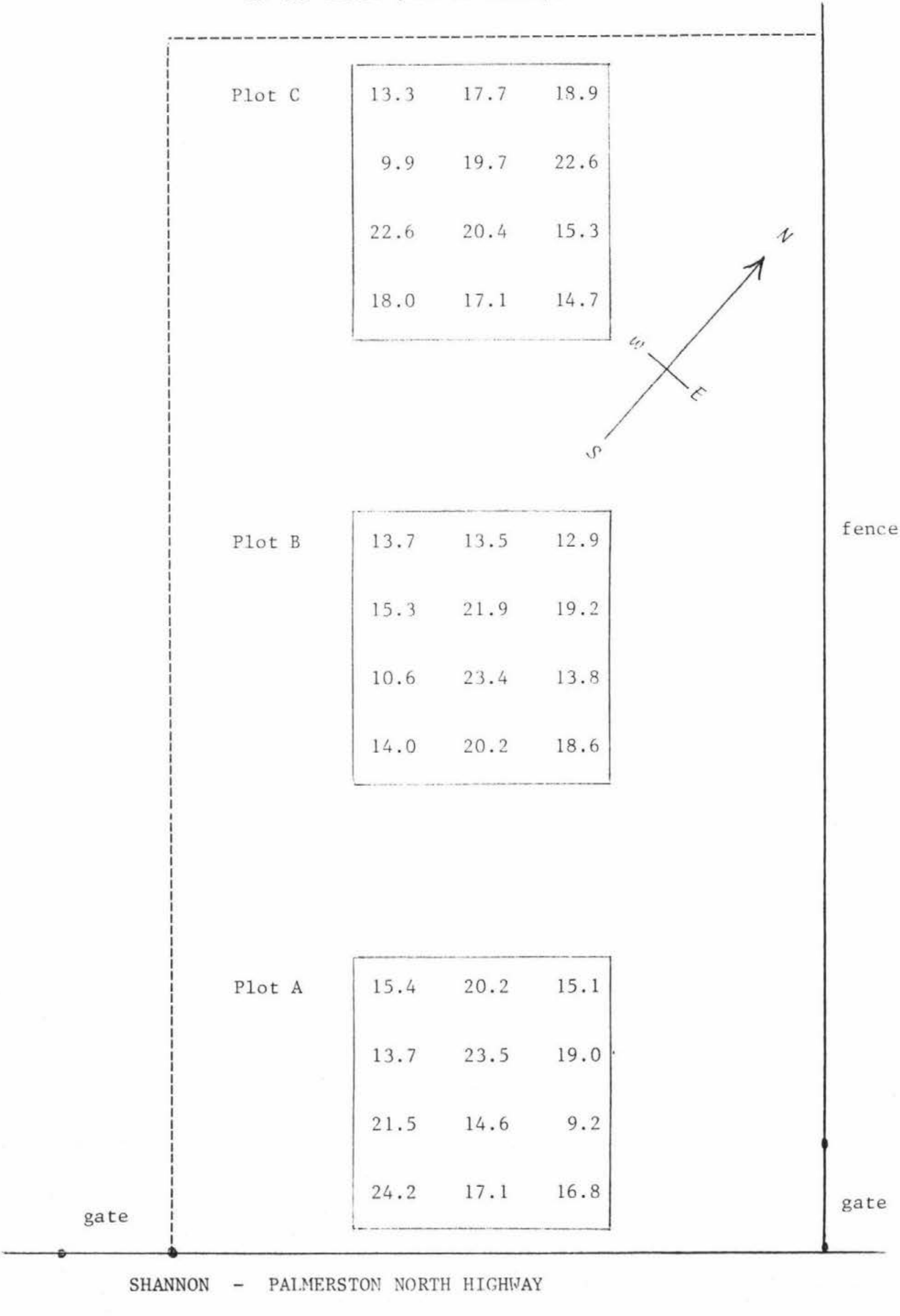
Plot B

20.8	22.1	21.7
16.4	33.9	28.7
13.1	39.9	22.6
21.2	39.8	31.2

Plot A

34.5	39.4	26.8
31.0	44.8	35.7
45.7	31.0	21.4
49.0	34.6	34.4

APPENDIX 10: Levels of water-extractable P (μg/g) in individual cores of Tokomaru soil, according to their spatial distribution in the field (not to scale).



Plot C

13.3	17.7	18.9
9.9	19.7	22.6
22.6	20.4	15.3
18.0	17.1	14.7

Plot B

13.7	13.5	12.9
15.3	21.9	19.2
10.6	23.4	13.8
14.0	20.2	18.6

Plot A

15.4	20.2	15.1
13.7	23.5	19.0
21.5	14.6	9.2
24.2	17.1	16.8

APPENDIX 11A: Levels of Olsen P (μg/g) in the Tokomaru control plots (0-8 cm depth) on various sampling dates.

Plot	Dates of Sampling							
No	8.2.78	22.2.78	15.3.78	5.4.78	26.4.78	17.5.78	31.5.78	16.6.78
5	13.5	13.2	15.4	14.0	15.8	16.3	15.7	14.9
9	14.3	14.3	15.1	15.8	16.1	16.8	15.7	14.2
14	19.0	18.9	20.4	21.3	21.1	21.7	21.2	20.6
19	15.1	16.0	16.1	18.7	19.6	21.0	18.3	18.1
22	16.2	14.9	16.5	17.1	17.4	15.1	17.4	16.2
30	17.5	17.1	19.0	18.5	20.4	20.2	22.0	20.0
Mean	15.93	15.73	17.08	17.57	18.40	18.52	18.38	17.33
	8.7.78	24.7.78	6.8.78	23.8.78	9.9.78	22.9.78	9.10.78	25.10.78
5	13.3	15.0	14.2	14.6	15.0	14.4	13.3	14.8
9	14.9	14.0	16.4	14.9	14.8	13.8	13.5	13.1
14	20.5	19.3	19.2	20.5	20.0	21.7	20.6	20.4
19	17.1	16.1	16.2	15.0	15.0	15.2	14.2	14.9
22	16.0	15.0	14.6	14.2	14.8	14.3	14.2	13.7
30	18.9	17.5	19.4	20.4	18.8	21.8	19.4	19.0
Mean	16.78	16.15	16.67	16.60	16.40	16.87	15.87	15.98
	10.11.78	1.12.78	20.12.78	5.1.79	23.1.79	8.2.79		26.3.79
5	13.8	13.5	12.7	12.3	11.7	11.1		9.3
9	13.1	13.5	13.3	12.4	12.4	11.1		10.0
14	17.3	16.1	16.0	16.5	15.8	13.5		13.5
19	14.0	13.7	13.8	12.6	12.6	10.6		9.3
22	12.7	11.9	12.5	11.9	11.4	10.1		9.2
30	16.1	16.5	17.7	14.6	13.7	12.9		13.7
Mean	14.50	14.20	14.33	13.38	12.93	11.55		10.83

APPENDIX 11B: Levels of Olsen P (μg/g) in the Tokomaru control plots (0-4 cm depth) on various sampling dates.

Plot	Dates of Sampling							
No	8.2.78	22.2.78	15.3.78	5.4.78	26.4.78	17.5.78	31.5.78	16.6.78
5	19.0	20.3	22.9	20.4	24.3	24.3	23.2	21.9
9	20.2	21.2	21.5	22.5	24.3	23.8	23.7	21.3
14	28.8	28.4	28.6	29.7	29.6	30.0	30.2	27.4
19	20.5	22.4	22.0	25.5	27.0	26.9	26.9	24.3
22	22.1	22.1	22.1	25.0	25.1	22.5	23.7	21.3
30	25.2	25.7	26.7	27.5	29.5	30.1	29.2	26.5
Mean	22.63	23.35	23.97	25.10	26.63	26.27	26.15	23.78
	8.7.78	24.7.78	6.8.78	23.8.78	9.9.78	22.9.78	9.10.78	25.10.78
5	19.8	20.4	19.6	19.8	18.9	18.9	17.9	18.2
9	21.2	20.7	22.4	20.7	19.5	19.5	18.5	17.5
14	25.5	23.8	23.8	25.0	24.8	25.5	25.4	24.6
19	21.2	20.7	19.8	18.8	17.5	18.6	17.3	17.7
22	20.8	18.9	19.1	17.5	18.5	18.1	17.0	16.8
30	25.9	23.3	24.8	25.6	24.0	27.3	24.3	23.0
Mean	22.40	21.30	21.58	21.23	20.53	21.32	20.07	19.63
	10.11.78	1.12.78	20.12.78	5.1.79	23.1.79	8.2.79		26.3.79
5	16.4	15.6	16.4	15.5	14.0	13.7		12.6
9	16.7	17.0	16.5	15.9	15.7	14.3		14.6
14	20.6	20.1	19.4	20.4	19.8	17.3		17.0
19	16.5	15.6	17.6	15.0	16.1	13.6		12.5
22	15.8	15.1	15.7	13.9	14.3	12.6		12.4
30	20.0	20.0	20.7	18.6	16.9	16.3		17.6
Mean	17.67	17.23	17.72	16.55	16.13	14.63		14.45

APPENDIX 12: Levels of water-extractable P in the Tokomaru control plots on various sampling dates.

Plot No	Dates of Sampling							
	0-8 cm depth				0-4 cm depth			
	8.2.78	15.3.78	26.4.78	31.5.78	8.2.78	15.3.78	26.4.78	31.5.78
5	10.2	11.3	11.0	11.3	15.6	15.5	16.6	17.0
9	10.2	9.0	10.0	8.7	14.5	13.0	15.8	15.8
14	13.7	13.2	14.2	14.8	20.0	18.0	20.5	20.4
19	13.8	13.2	15.7	17.1	17.0	15.9	20.8	23.1
22	15.5	13.7	14.2	15.1	19.0	16.1	19.2	20.5
30	14.3	11.7	13.6	15.2	17.6	19.6	20.6	21.1
Mean	12.95	12.02	13.12	13.70	17.28	16.35	18.92	19.65
	8.7.78	6.8.78	9.9.78	9.10.78	8.7.78	6.8.78	9.9.78	9.10.78
5	9.6	8.6	9.7	9.3	14.9	14.5	14.2	12.2
9	8.8	9.0	8.5	8.2	14.4	14.1	11.9	13.1
14	14.0	13.0	12.7	14.2	17.8	16.4	16.6	18.2
19	13.3	12.8	13.8	12.2	18.1	15.7	15.0	15.0
22	13.0	12.6	12.7	12.7	16.8	15.9	15.6	16.0
30	12.7	11.7	11.3	11.5	18.7	16.4	14.6	15.4
Mean	11.90	11.28	11.45	11.35	16.78	15.50	14.65	14.98
	10.11.78	20.12.78	23.1.79	26.3.79	10.11.78	20.12.78	23.1.79	26.3.79
5	9.0	9.1	6.8	6.0	10.7	10.5	8.4	8.4
9	7.5	7.4	6.2	5.8	10.1	9.6	8.3	8.1
14	12.5	10.0	10.3	8.6	14.3	12.4	13.2	11.5
19	12.0	11.7	9.7	8.1	13.0	13.9	12.0	10.7
22	10.9	11.0	9.3	7.5	12.8	12.4	10.7	9.1
30	9.9	10.1	7.6	7.6	12.9	13.2	9.7	10.6
Mean	10.30	9.88	8.32	7.27	12.30	12.00	10.38	9.73

APPENDIX 13: Levels of Olsen P (μg/g) in the autumn-fertilized Tokomaru plots (0-4 cm depth) on various sampling dates.

Plot No	Dates of Sampling					
	15.3.78	21.4.78	17.5.78	16.6.78	6.8.78	9.10.78
Superphosphate 250 kg/ha:						
4	21.2	30.0	25.5	22.7	23.1	17.1
10	27.9	34.0	27.5	26.7	25.1	21.7
13	25.7	31.2	30.0	26.4	25.6	24.5
17	25.4	37.7	35.6	35.4	31.9	28.7
25	25.7	35.7	35.0	30.8	27.6	26.2
27	25.4	33.8	33.5	29.2	27.6	24.3
Mean	25.22	33.73	31.18	28.53	26.82	23.75
Superphosphate 500 kg/ha:						
1	26.9	34.5	27.3	32.9	30.6	27.0
8	22.6	32.1	33.8	25.8	26.7	21.9
12	24.0	32.7	27.4	30.4	26.4	23.9
20	21.1	30.6	30.5	29.3	25.7	23.3
21	25.1	28.7	29.8	28.0	28.2	24.0
28	23.5	33.4	37.0	32.6	28.8	24.8
Mean	23.87	32.00	30.97	29.83	27.73	24.15

APPENDIX 14A: Levels of Olsen P (μg/g) in the spring-fertilized Tokomaru plots (0-8 cm depth) on various sampling dates.

Plot	Dates of Sampling					
No	23.8.78	22.9.78	25.10.78	1.12.78	23.1.79	26.3.79
Superphosphate 250 kg/ha:						
2	14.5	16.1	15.6	13.2	13.0	10.2
6	15.7	16.1	15.8	14.3	13.3	12.0
11	15.5	17.9	18.6	17.3	16.0	13.5
16	19.5	21.4	21.2	20.5	18.3	15.7
24	15.0	17.9	16.8	12.9	12.9	11.1
29	17.7	18.6	17.5	15.4	14.8	12.3
Mean	16.32	18.00	17.58	15.60	14.72	12.47
Superphosphate 500 kg/ha:						
3	14.2	18.2	16.5	14.3	12.8	10.6
7	15.0	18.2	17.6	16.0	14.7	11.4
15	19.2	22.7	21.9	19.6	17.6	16.2
18	18.7	21.9	20.6	18.8	17.6	15.7
23	14.5	18.6	16.8	15.2	13.8	11.8
26	18.9	23.7	22.9	18.9	17.3	14.6
Mean	16.75	20.55	19.38	17.13	15.63	13.38

APPENDIX 14B: Levels of Olsen P (μg/g) in the spring-fertilized Tokomaru plots (0-4 cm depth) on various sampling dates.

Plot No	Dates of Sampling					
	23.8.78	22.9.78	25.10.78	1.12.78	23.1.79	26.3.79
Superphosphate 250 kg/ha:						
2	19.2	21.3	21.0	17.6	16.6	13.6
6	21.1	23.0	20.7	19.2	17.4	15.5
11	21.0	23.5	24.9	22.6	20.9	19.5
16	24.9	26.7	26.0	24.9	23.3	20.0
24	19.4	24.2	20.8	17.5	16.3	14.3
29	22.5	25.2	23.2	20.6	19.5	16.4
Mean	21.35	23.98	22.77	20.40	19.00	16.55
Superphosphate 500 kg/ha:						
3	18.7	23.7	23.1	19.8	18.0	15.6
7	19.5	26.8	27.0	21.7	20.0	17.5
15	24.0	28.9	27.7	24.8	22.9	21.1
18	22.3	28.7	26.7	24.3	22.4	22.0
23	19.2	25.2	23.0	21.2	18.7	16.1
26	24.5	31.4	30.0	25.7	22.7	21.3
Mean	21.37	27.45	26.25	22.92	20.78	18.93

APPENDIX 15A: Levels of water-extractable P (μg/g) in the control and spring-fertilized Tokomaru plots (0-8 cm depth) on various sampling dates.

Plot No	Dates of Sampling					
	23.8.78	22.9.78	25.10.78	1.12.78	23.1.79	26.3.79
Nil Superphosphate:						
5	10.3	9.2	8.2	8.0	6.9	6.0
9	9.9	8.3	6.7	7.5	6.0	5.8
14	13.3	14.6	13.4	10.4	10.3	8.6
19	11.7	12.9	11.2	10.1	9.6	8.1
22	11.3	11.5	11.1	10.3	9.4	7.5
30	12.1	12.9	11.1	9.4	7.8	7.6
Mean	11.43	11.57	10.28	9.28	8.33	7.27
Superphosphate 250 kg/ha:						
2	11.3	11.9	11.8	10.2	8.9	8.1
6	10.6	10.6	10.1	8.9	8.7	8.0
11	8.9	9.2	9.6	9.1	8.4	7.7
16	14.1	14.5	14.1	12.1	11.3	10.1
24	12.1	14.9	12.9	10.3	9.7	9.2
29	12.0	12.3	11.4	11.3	9.5	8.4
Mean	11.50	12.23	11.65	10.32	9.42	8.58
Superphosphate 500 kg/ha:						
3	11.5	12.2	11.7	10.4	8.3	8.0
7	10.6	13.4	11.9	10.6	9.9	7.9
15	12.7	15.7	14.9	11.7	11.3	10.1
18	13.5	15.5	14.6	12.5	12.3	11.4
23	11.7	14.8	12.8	11.8	10.9	9.5
26	13.9	16.9	17.2	14.6	13.9	11.1
Mean	12.32	14.75	13.85	11.93	11.10	9.67

APPENDIX 15B: Levels of water-extractable P (µg/g) in the control and spring-fertilized Tokomaru plots (0-4 cm depth) on various sampling dates.

Plot	Dates of Sampling					
No	23.8.78	22.9.78	25.10.78	1.12.78	23.1.79	26.3.79
Nil Superphosphate:						
5	14.0	12.2	10.9	9.4	8.4	8.4
9	12.7	12.6	9.3	9.5	8.3	8.1
14	17.7	17.2	16.5	12.8	13.2	11.5
19	14.3	13.7	12.9	11.7	12.0	10.7
22	13.1	13.3	13.3	11.8	10.7	9.1
30	16.0	16.3	13.7	11.6	9.7	10.6
Mean	14.63	14.22	12.77	11.13	10.38	9.73
Superphosphate 250 kg/ha:						
2	14.7	15.7	14.4	12.9	10.9	10.8
6	13.9	15.6	13.0	11.9	11.5	10.9
11	13.2	13.5	13.8	12.5	12.1	11.9
16	18.2	18.9	19.7	15.7	14.3	13.5
24	14.5	18.0	16.2	12.8	12.5	11.2
29	15.1	16.9	15.1	13.2	12.3	10.9
Mean	14.93	16.43	15.37	13.17	12.27	11.53
Superphosphate 500 kg/ha:						
3	14.1	17.2	15.5	13.6	12.2	11.8
7	13.2	19.2	16.3	14.5	12.3	11.7
15	17.5	19.6	19.1	16.0	15.4	14.8
18	15.8	21.1	18.6	16.0	15.4	15.0
23	14.7	18.4	17.7	15.0	13.6	12.8
26	16.5	21.3	21.9	18.2	15.6	15.4
Mean	15.30	19.47	18.18	15.55	14.08	13.58

APPENDIX 16A: Levels of Olsen P (μg/g) in the control and autumn-fertilized Ramiha plots (0-8 cm depth) on various sampling dates.

Plot No	Dates of Sampling					
	23.3.78	25.4.78	26.5.78	28.6.78	16.8.78	3.11.78
Nil Superphosphate:						
2	9.4	10.6	9.5	9.5	9.3	11.0
8	8.0	9.0	9.0	7.7	8.2	9.0
12	11.8	11.3	10.5	9.5	10.8	11.6
13	9.6	10.2	9.2	9.0	10.0	10.6
18	7.6	8.5	7.9	7.4	8.1	8.9
23	9.3	10.1	10.5	9.3	10.1	11.1
Mean	9.28	9.95	9.43	8.73	9.42	10.37
Superphosphate 250 kg/ha:						
1	9.5		10.1		10.7	11.0
6	8.6		9.3		10.6	10.6
9	10.2		10.7		9.5	11.8
14	10.2		9.6		10.4	11.1
19	7.9		8.5		9.0	9.2
24	9.0		9.9		10.0	10.0
Mean	9.23		9.68		10.03	10.62
Superphosphate 500 kg/ha:						
4	9.4		9.9		10.6	11.3
7	8.0		9.6		9.6	9.4
10	11.7		12.0		11.9	13.7
16	9.3		10.5		11.0	12.4
17	8.0		10.0		10.5	11.2
21	9.3		11.1		10.6	11.7
Mean	9.28		10.52		10.70	11.62

APPENDIX 16A: continued...

Plot No	Dates of Sampling					
	23.3.78	25.4.78	26.5.78	28.6.78	16.8.78	3.11.78
Superphosphate 1000 kg/ha:						
3	8.8	11.6	11.1	12.0	11.7	14.0
5	7.9	13.0	12.9	11.5	13.3	12.5
11	10.4	14.9	14.9	13.5	14.8	16.8
15	8.5	12.5	11.9	10.6	14.9	13.5
20	9.2	14.9	13.0	13.8	13.1	13.1
22	9.0	12.9	13.1	14.3	13.7	13.7
Mean	8.97	13.30	12.82	12.62	13.58	13.93

APPENDIX 16B: Levels of Olsen P (µg/g) in the control and autumn-fertilized Ramiha plots (0-4 cm depth) on various sampling dates.

Plot No	Dates of Sampling					
	23.3.78	25.4.78	26.5.78	28.6.78	16.8.78	3.11.78
Nil Superphosphate:						
2	12.6	15.2	13.1	12.5	12.5	13.8
8	10.4	12.4	11.4	11.2	11.1	12.0
12	13.9	15.5	13.7	12.7	13.6	14.6
13	12.4	14.6	13.1	12.1	13.2	13.2
18	9.9	11.4	10.0	9.2	10.7	11.5
23	13.6	13.9	13.9	12.3	14.3	14.9
Mean	12.13	13.83	12.53	11.67	12.57	13.33
Superphosphate 250 kg/ha:						
1	13.7	16.2	15.9	14.0	16.8	14.8
6	11.1	15.2	12.8	11.9	14.3	13.6
9	14.5	16.4	14.8	14.4	14.0	16.0
14	11.8	15.8	12.8	12.6	14.2	14.6
19	10.4	13.4	11.1	11.8	11.4	12.1
24	11.7	14.3	12.5	12.5	13.1	13.7
Mean	12.20	15.22	13.31	12.87	13.97	13.78
Superphosphate 500 kg/ha:						
4	11.7	15.5	13.7	11.9	14.9	14.4
7	11.5	14.8	13.7	13.0	15.1	12.9
10	16.8	19.3	17.0	17.5	19.0	20.4
16	12.4	15.9	16.8	15.6	15.4	17.3
17	11.0	17.1	14.2	12.6	13.9	16.2
21	11.8	16.9	16.0	14.4	14.3	16.2
Mean	12.53	16.58	15.23	14.17	15.43	16.23

APPENDIX 16B: continued...

Plot	Dates of Sampling					
No	23.3.78	25.4.78	26.5.78	28.6.78	16.8.78	3.11.78
Superphosphate 1000 kg/ha:						
3	11.7	17.2	15.5	16.1	16.4	18.3
5	10.8	21.3	19.7	17.3	17.4	19.4
11	13.2	23.7	22.3	21.4	23.2	23.1
15	11.3	17.5	17.2	18.6	19.3	19.3
20	12.6	21.2	17.7	20.4	21.0	20.4
22	11.9	20.2	18.3	19.0	20.5	20.7
Mean	11.92	20.18	18.45	18.80	19.63	20.20

APPENDIX 17: Levels of water-extractable P (µg/g) in the control and autumn-fertilized Ramiha plots (0-4 cm depth) on various sampling dates.

Plot No	Dates of Sampling					
	23.3.78	25.4.78	26.5.78	28.6.78	16.8.78	3.11.78
Nil Superphosphate:						
2	3.1	3.2	2.4	2.8	2.5	2.5
8	2.2	2.7	2.0	2.3	1.9	2.0
12	3.3	3.4	2.7	2.5	2.5	2.3
13	3.4	3.0	2.6	2.5	2.3	2.0
18	2.3	2.5	2.2	2.2	2.0	1.7
23	2.7	3.3	2.9	2.5	2.9	2.3
Mean	2.83	3.02	2.47	2.47	2.35	2.13
Superphosphate 250 kg/ha:						
1	3.0	3.8	3.2	3.0	2.7	2.3
6	2.6	3.0	2.9	2.7	3.0	2.3
9	3.4	2.9	2.8	2.7	2.5	2.4
14	2.9	4.1	3.0	2.8	3.4	3.1
19	2.6	3.4	2.4	2.8	2.4	2.0
24	2.7	3.3	2.5	2.8	2.4	2.6
Mean	2.87	3.42	2.80	2.80	2.73	2.45
Superphosphate 500 kg/ha:						
4	2.9	3.5	3.0	3.0	2.7	2.8
7	2.3	3.6	3.7	3.1	2.7	2.0
10	3.5	4.3	3.8	3.7	3.8	3.3
16	2.8	3.4	3.8	3.6	3.2	3.7
17	2.9	3.7	3.2	3.1	3.0	2.3
21	2.7	4.3	3.7	3.5	3.9	2.4
Mean	2.85	3.80	3.53	3.33	3.38	2.75

APPENDIX 17: continued...

Plot No	Dates of Sampling					
	23.3.78	25.4.78	26.5.78	28.6.78	16.8.78	3.11.78
Superphosphate 1000 kg/ha:						
3	2.7	5.0	3.5	4.0	3.4	2.8
5	2.3	4.9	6.5	4.3	3.9	3.5
11	3.0	4.6	5.0	4.4	4.3	4.0
15	2.7	4.0	3.7	4.2	3.8	3.9
20	3.1	5.0	3.6	4.4	4.4	2.8
22	2.6	4.3	3.9	4.0	4.5	3.2
Mean	2.73	4.63	4.37	4.22	4.05	3.37

APPENDIX 18: Levels of Olsen P (μg/g) in the control and spring-fertilized Ramiha plots (0-4 cm depth) on various sampling dates.

Plot No	Dates of Sampling				
	5.9.78	4.10.78	3.11.78	6.12.78	31.1.79
Nil Superphosphate:					
2	15.8	15.5	13.9	13.1	11.3
8	12.5	13.2	12.0	11.0	9.8
12	14.8	15.8	14.9	13.1	12.5
13	14.0	14.0	13.1	12.1	11.7
18	11.4	11.8	11.1	10.2	9.4
23	14.2	14.9	14.2	13.1	11.3
Mean	13.78	14.20	13.20	12.10	11.00
Superphosphate 1000 kg/ha:					
25	13.5	18.8	20.4	17.2	15.0
26	13.3	23.8	19.3	18.5	17.3
27	13.3	18.7	17.5	15.8	15.2
28	11.3	17.7	16.4	14.5	12.4
29	11.1	17.0	16.3	15.8	15.1
30	12.1	19.5	19.4	17.4	16.4
Mean	12.43	19.25	18.22	16.53	15.23

APPDENIX 19: Levels of water-extractable P (μg/g) in the control and spring-fertilized Ramiha plots (0-4 cm depth) on various sampling dates.

Plot No	Dates of Sampling				
	5.9.78	4.10.78	3.11.78	6.12.78	31.1.79
Nil Superphosphate:					
2	2.1	1.7	2.0	2.0	2.0
8	2.0	1.5	1.5	1.5	2.5
12	2.8	2.3	2.1	2.2	3.4
13	2.9	2.2	2.1	2.0	2.9
18	2.0	1.9	1.7	1.7	2.3
23	3.0	2.3	2.3	2.3	3.0
Mean	2.47	1.98	1.95	1.95	2.68
Superphosphate 1000 kg/ha:					
25	2.3	3.6	3.0	2.9	4.5
26	2.2	3.1	3.0	3.6	5.1
27	2.9	3.9	4.9	2.6	5.0
28	2.5	4.0	3.2	2.9	4.1
29	2.2	3.6	2.9	2.9	5.0
30	2.7	3.4	3.8	3.4	5.1
Mean	2.47	3.60	3.47	3.05	4.80