DISTRIBUTION OF PHOSPHORUS IN SANDY SOILS OF COASTAL FYNBOS.

A Thesis presented for the degree of
Master of Science
at the University of Cape Town.

by
Gary James Brown.
B.A. (Biological Sciences.) .
Dip. Applied Science.(Agriculture.) .

Department of Botany
University of Cape Town
November 1982.

1. Abstract.

The levels of soil phosphorus (both total and plant available) were investigated at the Pella intensive study site and were found to be low. Resin extractable phosphorus fluctuated seasonally, peaking at the soil surface during summer and declining to a minimum in the winter months. Rates of microbial mineralisation were thought to be the major influencing factor. The profile distribution of all forms of phosphorus were similar to those predicted by Smeck (1973) and were thought to result from the removal of phosphorus by plant roots in the mid-zone (20-70 cm) and its subsequent deposition at the soil surface as litter. The majority of insoluble phosphorus (60%) was organic and the remaining insoluble inorganic compounds were mainly iron bound. The input from precipitation to the site was 194 g ha^{-1} yr^{-1} occurring chiefly during the winter months.

The different soil forms present at the site contained similar total phosphorus levels and underwent an increase in the size of the resin extractable phosphorus pool with progression from less to more weathered soils. This progressive change was linked directly to the decrease in total iron content in the soils. With decreasing iron content the number of binding sites within the soil declined.

Fire returned a large amount of readily available phosphorus to the soil which had the effect of immediately elevating the soil resin extractable phosphorus levels. This effect was a transient one. After twelve months the levels of resin extractable phosphorus had declined to values only slightly above those found in the prefire soil.

2. Acknowledgements.

I am grateful to the following people and institutions for their help and support during the course of this project:

Professor D.T.Mitchell under whose supervision the project was conducted, without his considerable help and encouragement the work could not have been completed.

Professor O.A.M.Lewis for providing laboratory space and equipment during the course of this work.

The CSIR for financial support for the duration of this project.

My colleagues, particularly Dr S.M.Jongens-Roberts, Mr P.G.F.Coley Miss J.Sommerville and Mr A.Quickfall for their advice, support and humour .

Mrs M.L.Jarman for her timely assistance and for proofreading the manuscript.

Mr W.D.Stock for constructing the rainwater collecting vessels and supplying the rainwater samples.

Dr S.Smith for his assistance during the CNH analyses.

Dr R.Bally for his help and advice during the creation of the 3D maps and drawings.

Mr M.Fry for the use of his soil maps.

Mr J.J.N.Lambrechts who provided the pedological history of the Pella site.

Mr Long of Metal Box for supplying jar lids for some of the apparatus.

Lastly, I would like to thank my wife Janelle and our two children Katie and Cameron who gave me sufficient reason to finish this thing. I dedicate this thesis to them.

> "Better a meal of vegetables where there is love
> Than a fattened calf with hatred." Prov.15:17.

Table of contents. Page.

Table of contents. Page.

Table of contents. Page.

Index of Figures.

Index of Figures.

List of Tables.

1. Introduction.

The fynbos biome is the major heathland of South Africa and occurs mainly in a mediterranean climate region. The climate is characterised by dry summers and cool wet winters with an annual rainfall in excess of 150 mm. The average rainfall may exceed 500 mm yr^{-1} (Wicht 1971) and frosts are infrequent. The mediterranean climate can be defined as the Köppen climatic types Csa, Csb and Bsk (Schulze 1947), the characteristics of which are given in Table 1.1.

Table 1.1 A description of the mediterranean climate according to the Köppen's Climatic Types.

KOPPEN TYPE	CLIMATE	WINTER	SUMMER
Csb	Warm	Mild Humid (At least one month below 18°C.)	Dry and Mild (Hottest month below 22°C.)
Csa	Warm	Mild Humid (At least one month below 18°C.)	Dry and hot (Hottest month below 22°C.)
Bsk	Semi arid	Mild sub humid (At least one month below 18°C.)	Dry and hot (Hottest month above 22°C.)

The biome consists of five vegetation categories, strandveld, coastal and inland renosterveld and coastal and mountain fynbos

(Kruger 1979). This study concentrates on fynbos, particularly the coastal form. The distinguishing features of coastal fynbos are a predominance of sclerophyllous shrubs, a scarcity of trees and a relatively minor occurrence of grasses and succulent shrubs (Kruger 1979). Taylor (1978) defines fynbos floristically by means of two salient features: a lack of single species dominance and a conspicuous presence of members of the Restionaceae. Fynbos vegetation can be divided into three physiognomic groups, proteoid, restioid and ericoid (Taylor 1978). Coastal fynbos has a proteoid upper stratum and a lower one consisting of ericoids and restioids.

Although fynbos occupies only 0,04% of the total area of the world's floral kingdoms it has the world's highest species concentration of approximately 1 300 species per 10 000 km^2 (Hall 1978). Fynbos ecosystems are thus of considerable scientific and aesthetic interest. As well as having a rich flora, fynbos is economically important in providing catchment areas as a water and recreation resource.

Present research into the fynbos biome is being conducted and organised as one of the National Scientific Programs for Environmental Sciences administered by the CSIR. This research has been designed to meet local needs and forms South Africa's contribution to the international program of SCOPE (Scientific Commitee on Problems of the Environment); the body set up by the International Council of Scientific Unions during 1970. The SCOPE programs focus on non-governmental international scientific effort in the environmental field.

Most of the research efforts in the fynbos biome have been centred on one intensive study site at Pella, near Atlantis in the Western Cape Foreland (See chapter 2 for a comprehensive site description). The Pella site is situated in coastal fynbos in which the vegetation is growing in sands of aeolian origin. The other subdivision of coastal fynbos is found in the Southern Cape Foreland between Hermanus and Mossel Bay and the soils are limestone derived but may be overlain by deposits of acid sands (Lambrechts 1979). Coastal fynbos soils of the Western Cape Foreland are mainly recent drift sands overlying clayey fluvial deposits or residually weathered materials (Lambrechts 1979). At the coast the sands can be highly calcareous but inland the lime content decreases. The soils at Pella, being an inland site are acidic, strongly leached sands similar to the quartzite weathering products of the folded ranges (Lambrechts 1979). The most common soil forms at Pella are Hutton, Clovelly, Constantia and Lamotte. One of the striking features of fynbos ecosystems is that the vegetation occurs on acid soils of low nutrient status and the soils are especially low in phosphorus (Mitchell 1980).

Studies on phosphorus cycling in the fynbos biome have not been extensive. In ecosystems generally the phosphorus cycle is known to be a 'closed' one and the inputs from bedrock weathering and precipitation are assumed to be negligible (Groves 1982). The total phosphorus content of the earth has been estimated to be about 10^{19} tonnes of which 10^{15} tonnes is in the crust (Van Wazer 1958) in concentrations of between 0,12%-0,23% phosphorus (Poldervaart 1955). The phosphorus status of sedimentary rocks is usually lower than that of igneous rocks and soils derived from sedimentary rocks are usually of lower phosphorus status than those of igneous parent material. Marchant and Moore (1978) reported a total phosphorus concentration in the Table Mountain Group sandstones (from which the soils at Pella are derived) of 0,03%. Beadle (1962) quoted values of 0,006% in Hawkesbury

Sandstones of Australia.

Phosphorus is one of the three macronutrients involved in plant growth (Larsen 1967, Russell 1973, Gauch 1972). It is a constituent of nucleic acids eg. Ribonucleic acid (RNA) Deoxyribonucleic acid (DNA), phospholipids, lecithin and sugar phosphates (Gauch 1972, Godwin and Wilson 1976). Energy is stored within the cells as high energy phosphate bonds in adenosine triphosphate (ATP) and the co-enzymes nicotinamide adenine dinucleotide (NAD) and nicotinamide adenine dinucleotide phosphate (NADP) also contain phosphorus. These compounds also contain the energy for the synthesis of sugars, starches and proteins (Street and Lowe 1950).

Phosphorus is obviously vital to the plant for respiration and photosynthesis and therefore its acquisition and retention in plants growing on soils of low nutrient status is of great importance. Phosphorus is transported within the plant as inorganic orthophosphate and is one of the most mobile of plant nutrients (Bieleski 1976). The natural "sinks" for phosphorus in the plant are the meristematic tissues as well as the flowering and fruiting regions. Mature and senescing organs may be regarded as "sources." As leaves senesce there is a net loss of phosphorus with as much as 85% of the leaf phosphorus being removed (Specht 1953). Robertson and Davies (1965) reported phosphorus content ratios for leaf:stem of 3:1 in young organs of Calluna heath dropping to 4:5,5 in older branches indicating a substantial withdrawal of phosphorus from the organ prior to senescence.

Bieleski (1976) indicated that only 2% of the plant tissue requirements of phosphorus are taken up passively ie. during normal water uptake and transport. The remaining 98% must be taken up by some selective process and the plant can then concentrate phosphorus within itself by a factor of 2 000 to 5 000 times above soil levels (Bieleski 1976). Most fynbos vegetation appears to have specialised and highly efficient root systems which have adapted to take up phosphorus under low nutrient and moisture conditions (Low 1980). One of the simplest and most effective root strategies is the proliferation of root hairs on rootlets. These occur in root clusters in the Proteaceae known as proteoid roots and a similar structure occurs in the Restionaceae known as capillaroid roots (Lamont 1982). Proteoid roots consist of dense clusters of determinate rootlets in longitudinal rows (Lamont 1982) and are concentrated in the uppermost 10 cm of the soil particularly in the region of decomposing litter (Jongens-Roberts et al 1980). Their function is the rapid absorption and uptake of nutrients from soils of low nutrient and moisture regimes. This process is verified by the fact that the uptake of phosphorus by proteoid roots is two to thirteen times that of non-proteoid regions on a dry mass basis (Lamont 1982).

Other strategies for maximising plant phosphorus uptake in strongly leached soils are the fungal associations known as mycorrhizas which are either general (vesicular-arbuscular) or host specific (ericoid, orchidaceous and sheathing). Mycorrhizas have been demonstrated to utilize a wide range of organic phosphorus compounds which are present in the soil (Mitchell and Read 1981) and have active phosphatase enzymes (Bartlett and Lewis 1973). They obtain inorganic phosphates from insoluble salts by taking it up at concentrations below the salts solubility product. They also present a larger surface area for adsorption and explore a greater volume of soil than do roots (Bieleski 1976).

Joubert (1965) found that the granite derived soils of the mountain fynbos had a total phosphorus concentration of 3-40 μg P

g^{-1} dry soil and the plant available phosphorus (using a Bray#2 extraction method) ranged from 1-4 µg P g^{-1} dry soil. No work has been carried out on the phosphorus status of soils of coastal fynbos although the total phosphorus levels are assumed to be extremely low. It has been speculated that only one to five percent of total phosphorus within the soil of South African fynbos and Australian heath is available for plant uptake (Groves 1982). This has not been verified experimentally for soils of coastal fynbos of the Western Cape Foreland. Nothing is known of the temporal and spatial distribution of the various forms of phosphorus in these soils of the fynbos biome. The factors controlling seasonal variation within the forms of soil phosphorus have not been investigated nor has the relationship been established between seasonal fluctuations in phosphorus availability.

Fire is thought to return phosphorus to the soil from burnt vegetation. Possible losses from the system during burning occur when ash and smoke are blown from the site and the volatilization of phosphorus as a result of the high temperatures generated by the fire. Working on chaparral vegetation in California, Rundel and Parsons (1979) found that luxury consumpton of phosphorus by the vegetation occurred after fire and concluded that this ability to store nutrients beyond immediate metabolic requirements may be an important adaptation in fire adapted plants growing on soils low in nutrients.

The quantity of phosphorus released annually as a result of weathering of parent material is small and the magnitude of losses and inputs from Australian heath and South African fynbos are assumed to be negligible (Groves 1982). There has been no work undertaken on the magnitude and importance of these movements within the whole coastal fynbos ecosystem and no conclusions can be drawn about their fluxes.

The size of the various fractions of inorganic and organic phosphorus have been investigated through a chronosequence of sandy soils for stabilized dunes in New Zealand (Syers and Walker 1969 a,b). These sandy soils which are aeolian in origin ranged from coastal dunes of very recent deposition to soils greater than 10 000 years of age. The relationship of the size of various phosphorus pools to leaching stage and soil age was examined (Syers and Walker 1969a,b). It was found that over time total phosphorus levels declined, organic phosphorus fraction increased in importance and a greater amount of inorganic phosphorus became bound up in stable nonreactive iron and aluminium complexes. No work of similar detail has been carried out on similar soils of coastal fynbos.

These studies undertaken at the fynbos biome Intensive Study Site at Pella are an attempt to provide more information on phosphorus cycling processes in coastal fynbos growing on soils of a low nutrient status. Despite the limitations of only one study site (See site description), the results contained in this thesis should be applicable to coastal and mountain fynbos of the South-Western Cape. Fynbos develops on strongly leached soil which is in contrast to the mediterranean shrublands (eg. renosterveld) which occur on moderately leached soils (Specht et al.1982).

Although there have been a number of references to these soils being strongly leached (Lambrechts 1979, Specht et al.1982), none of these have actually measured the movement of nutrients down the profile. It has been shown that nitrate losses from undisturbed ecosystems are very small (Vitousek et al. 1979).

2. Materials and Methods.

2.1. Site Description.

The Pella research site lies on Portion 2 of Burgherspost Farm number 754 in Groenkloof East in District number 4 of the Malmesbury Division. The site is located at Grid Reference number 3318 DA near the Moravian Mission Village of Pella and is marked by the survey beacon CF 7.3. This site is the intensive study area of Fynbos Biome Research Program and is 269 ha. The vegetation consists of coastal fynbos with small patches of renosterveld and strandveld. Vegetation (Boucher and Shepherd unpublished) and soil surveys (Fry unpublished MSc thesis) have already been performed at the site. The oldest patches of vegetation are approximately 20 years old, and the dominant shrubs are *Protea repens* L. and *Protea burchellii* Stapf. The site was partially burnt during December 1975 and again in November 1980 and consists of small shrubs and restioid elements. The vegetation is extremely heterogeneous and the major species are represented by the following:

proteoid	*P.repens*, *P.burchellii* *Leucospermum parile* L.
restioid	*Thamnochortus punctatus* Pillans. *Staberhoa distachya* (Rottb.) Kunth (Spelling after Adamson and Salter 1950).
ericoid	*Phylica cephalantha* Sond. *Erica mammosa* L..

In this investigation a major emphasis has been placed on studying variations in phosphorus levels (both temporal and spatial) in the Clovelly soil form but a general soil survey was also undertaken. The soil forms present at the Pella site are aeolian in origin overlying pre-existing laterite beds. These beds had been cut level by marine action during either the Miocene or Pleistocene eras and the sands were introduced approximately 10 000 years ago (Lambrechts pers.comm.). The red Hutton form probably covered the entire site. Riverine erosion caused changes in the topography resulting in alteration to the moisture regimes of the soils present in the various parts of the site. Those in lower lying areas remained moist while those with greater elevation drained more freely. The moister soils were more susceptible to the soil ageing process of chemical weathering and leaching than the drier soils. This has resulted in the creation of a genetic series of soils from Hutton, Griffin, Clovelly, Constantia, Lamotte, Westleigh and Longlands; the last two being somewhat displaced in that they are not considered to be freely draining (Lambrechts 1979 and pers.comm. and Fry unpublished).

A map of the soil forms found at the Pella site is shown in Fig.2.1.

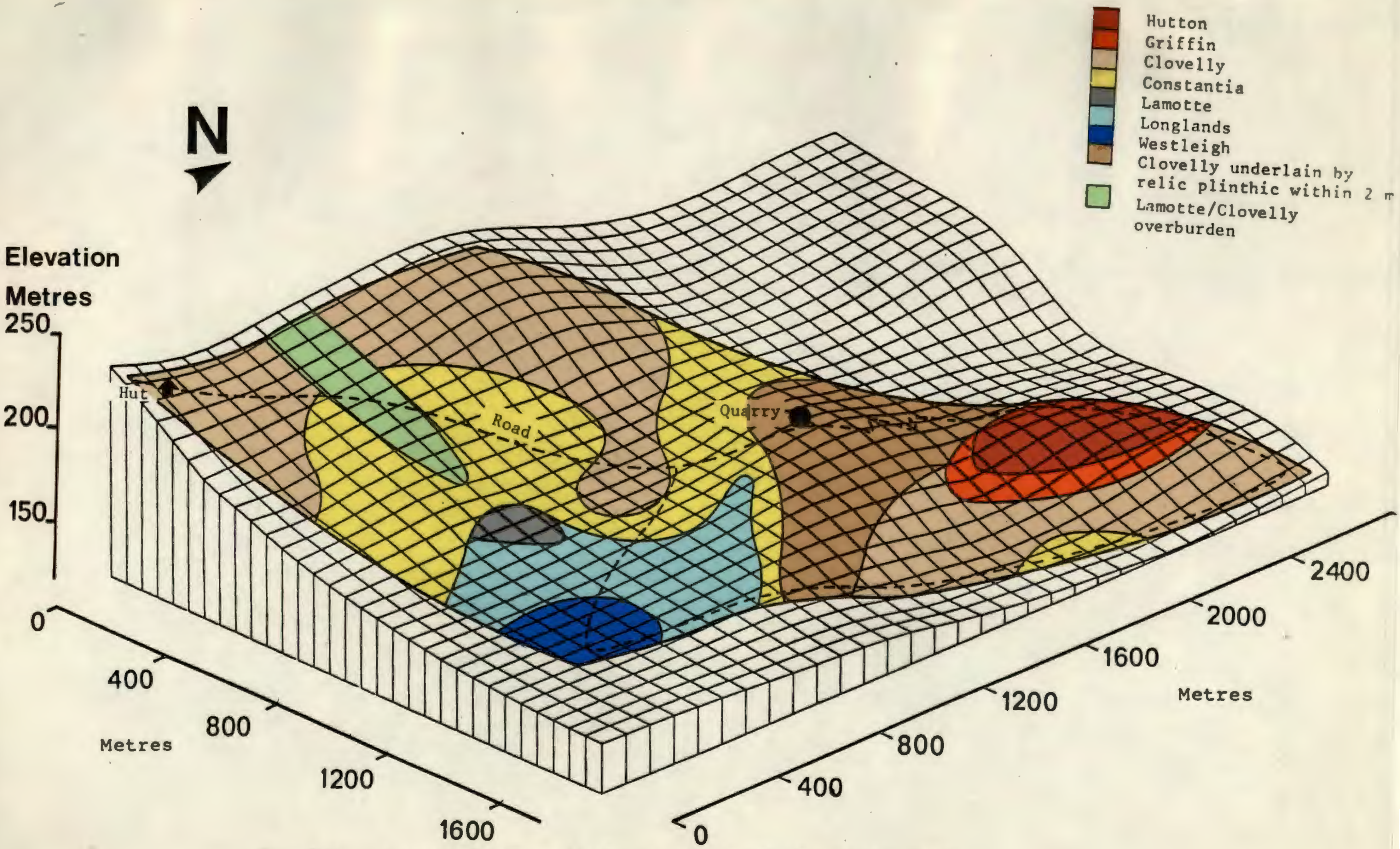


Fig.2:1. A map of the soil forms found at the Pella site.

2.2. Soil Sample Collection.

The sites were selected in open areas free from any disturbance eg. mole hills, erosion, termitaria etc. During April 1979 to March 1980, pits were dug at two monthly intervals to a depth of 110 cm. Samples were taken from the four sides of the pit at 0, 5, 10, 15, 20, 30, 40, 70 and 100 cm depths. This method however proved to be exceedingly destructive and a brass corer was designed and built to allow intact cores to be taken with little soil compaction. The corer was able to take samples to a depth of 120 cm and sampling continued at two monthly intervals from May 1980 to October 1980.

In the general soil survey three sites were selected in each soil form. Five cores of 10 cm depth were taken at each site. In both of these trials samples were analysed for pH, moisture content, organic matter levels, total iron levels, bulk density and total, Bray#2 extractable and resin extractable phosphorus. Immediately after the fire in November 1980 an intensive study of the effects of the burn on the distribution of phosphorus in the Clovelly soil form was carried out. An initial collection of surface samples of charcoal and ash was taken on the day of the fire. Thereafter at fortnightly intervals for 5 months and at monthly intervals for a further 7 months, three pits were dug and samples taken at 0-2,5; 2,5-7,5; 7,5-12,5; 12,5-17,5 and 17,5-22,5 cm depths.

2.3. Collection of soil within the rhizosphere.

An investigation of phosphorus levels within the root zones of four major fynbos species growing on the Clovelly soil form was undertaken at Pella during November 1979. Soil samples consisting of six replicates of cores of 6,7 cm diameter and 10 cm in length were collected under the canopies of <u>P.repens</u>, <u>L.parile</u>, <u>S.distachya</u>, <u>P.cephalantha</u> and in the open. The samples were analysed for total, Bray#2 and resin extractable phosphorus as well as pH,organic matter and moisture content. An area was considered to be open if there was no vegetation cover within 60 cm of the point of collection.

2.4. Rainwater Collection.

The rainwater collecting vessels consisted of a polyethylene funnel of 213 cm^2 collecting surface attached to a 2,5 litre brown glass bottle which was shaded with a plastic cover. A gauze cover and copper spikes were fitted to the surface of the funnel to prevent bird and insect contamination. The collecting vessels were mounted on tar poles 1,5 metres above the soil surface in order to minimise contamination from surrounding soil.

The jars were emptied at weekly intervals, the volume of water collected was noted and 100 cm^3 aliquots were taken for analysis. If no rain had fallen, the jars were thoroughly washed with 30 cm^3 of distilled water and this was used for analysis. The jars were washed once with distilled water, a second time with a mixture of distilled water and chloroform and finally with a pure chloroform rinse to remove any organic compounds which may have adhered to the inside of the jar.

2.5. Methods for Extracting Forms of Phosphorus.

All soil samples prior to analysis were sieved through a 2 mm sieve.

Total soil phosphorus.

The method used was similar to that of Hesse (1971) and has been previously described (Jongens-Roberts 1979). Soil samples were air-dried for one week and samples (2g) were heated in lidless crucibles at 240°C for 90 minutes in a muffle furnace. Samples were then transferred to thick-walled boiling tubes and after the addition of 10 cm^3 of concentrated hydrochloric acid they were heated at 110° C for 30 minutes in an aluminium digestion block. After cooling 20 cm^3 of distilled water was added to the solution and the samples were allowed to stand at 90°C for 30 minutes. The digest was then filtered into a 100 cm^3 volumetric flask and made up to volume with distilled water. An aliquot ($4cm^3$) was then assayed for phosphorus using the method of Murphy and Riley (1962). (Sect.2.11).

Bray#2 extractable phosphorus.

A Bray#2 extraction method was used to determine plant available phosphorus in the soil (Bray and Kurtz 1945). However as the soils under investigation were of a low nutrient status, the Bray#2 extraction may remove some of the bound phosphorus and may not provide a true measure of plant available phosphorus. The extraction procedure was used according to the method of FSSA Soil Analysis Methods (Anonymous 1974) without the addition of activated charcoal and flocculant solution. Soil (8g) was shaken for 45 seconds in 60 cm^3 of Bray#2 reagent (See Appendix). The suspension was filtered and 10 cm^3 aliquots were assayed for phosphorus using the method of Murphy and Riley (1962) (Sect.2.11).

Resin extractable phosphorus.

It has previously been pointed out that the Bray#2 extraction technique may not provide a true estimate of available phosphorus in typical fynbos soils. In order to compensate for this an anion exchange resin extraction procedure of greater sensitivity was used (Sibbesen 1977). Polyester bags of 300 micron mesh containing 8g of Biorad analytical grade anion exchange resins (Agl-X8 20-50 mesh chloride form) were washed in distilled water and were activated by stirring in 0,5M NaCl (200 cm^3 per bag) in a plastic beaker. Although this extraction technique may have been improved by priming the resins in the bicarbonate form instead of the chloride form (Sibbesen 1978), it was felt that other factors such as the shaking time of the soil suspension with the resins and the time elapsed between collection and analysis were of greater importance (Harrison 1975, Harrison and Helliwell 1979).

All extractions were carried out within three days of collection as no changes in levels of resin extractable phosphorus occurred in this time (Brown, unpublished data.) Soil samples (20g) were shaken with 100 cm^3 of distilled water and a resin bag in sealed jars on a rotary tumbler for sixteen hours. The adsorbed phosphate on the resins was then eluted into 75 cm^3 0,4 N HCl on a rotary tumbler for one hour. An aliquot of the eluate (10 cm^3) was then assayed for phosphorus using the method of Murphy and Riley (1962) (Sect 2.11.). This method of determining resin extractable phosphorus is identical to that used by Smith (1979).

2.6. Organic Phosphorus Determination.

The samples chosen for analysis were those collected in April and June 1979 and were of the Clovelly soil form. Three methods were employed to determine the levels of organic phosphorus in these samples. Two of these methods were extractions and the third was an ignition technique (Williams and Walker 1967).

Various methods of extraction have been used (Mehta et al. 1954). The modification of Legg and Black (1965) of the ignition method of Hesse (1971) was used as follows: 2g of 2 mm sieved air-dried soil was muffled for one hour in an electric muffle furnace at 240 °C while a second 2g sample was kept at room temperature. The samples were added to 100 cm^3 centrifuge tubes and mixed with 10 cm^3 of concentrated HCl and heated on a digestion block at 100 °C for ten minutes. A further 10 cm^3 of acid was added and the solution allowed to stand at room temperature for one hour. The solution was diluted with 50 cm^3 of water, centrifuged at 5000 g for 10 minutes and the supernatant was decanted into a 250 cm^3 volumetric flask and made up to volume. A suitable aliquot was taken and analysed for phosphorus content. The difference in levels between the ignited and non-ignited samples was estimated as total organic phosphorus.

The extraction methods used were a modification of the Mehta method altered by Anderson (1960) and the ultrasonic extraction of Steward and Oades (1972). The methods are similar in the way that they extract organic phosphorus. They consist of an initial acid extraction followed by one (Steward and Oades 1972) or a series (Anderson 1960) of alkaline extractions. The acid and alkaline extracts were then mixed and two aliquots were taken. One of the aliquots was digested with triacid mix (See Appendix) to destroy all organic matter and to yield a value for total phosphorus when analysed using the method of Murphy and Riley (1962) (Sect.2.11.). The other aliquot was analysed to yield a value for inorganic phosphorus. As in the ignition method the levels of organic phosphorus are derived by subtracting inorganic phosphorus levels from total phosphorus.

The major difference between the two methods is that the alkaline treatment in the Anderson (1960) method is a long procedure involving several extractions. The Steward and Oades (1972) method relies on ultrasonic vibrations to break up soil colloids and is faster requiring only one extraction. The two methods are represented in Fig 2:2 and 2:3. Unless otherwise stated all centrifugations were carried out at 5000xg for 15 minutes. The same method of determination of organic phosphorus is involved in both extractions. Both the acid (A) and the alkaline (B) supernatants were diluted to 500 cm^3 and mixed together. Duplicate 10 cm^3 aliquots were taken. One aliquot was analysed for inorganic phosphorus (Pi) in solution using the method of Murphy and Riley (1962). The second aliquot was evaporated to dryness and 0,75 cm^3 of triacid mix (See Appendix) was added. The mixture was heated to 90°C until fuming occurred, then diluted to 50 cm^3 and analysed for total phosphorus content (Pt) using the method of Murphy and Riley (1962). Organic phosphorus (Po) was determined by subtracting Pi from Pt.

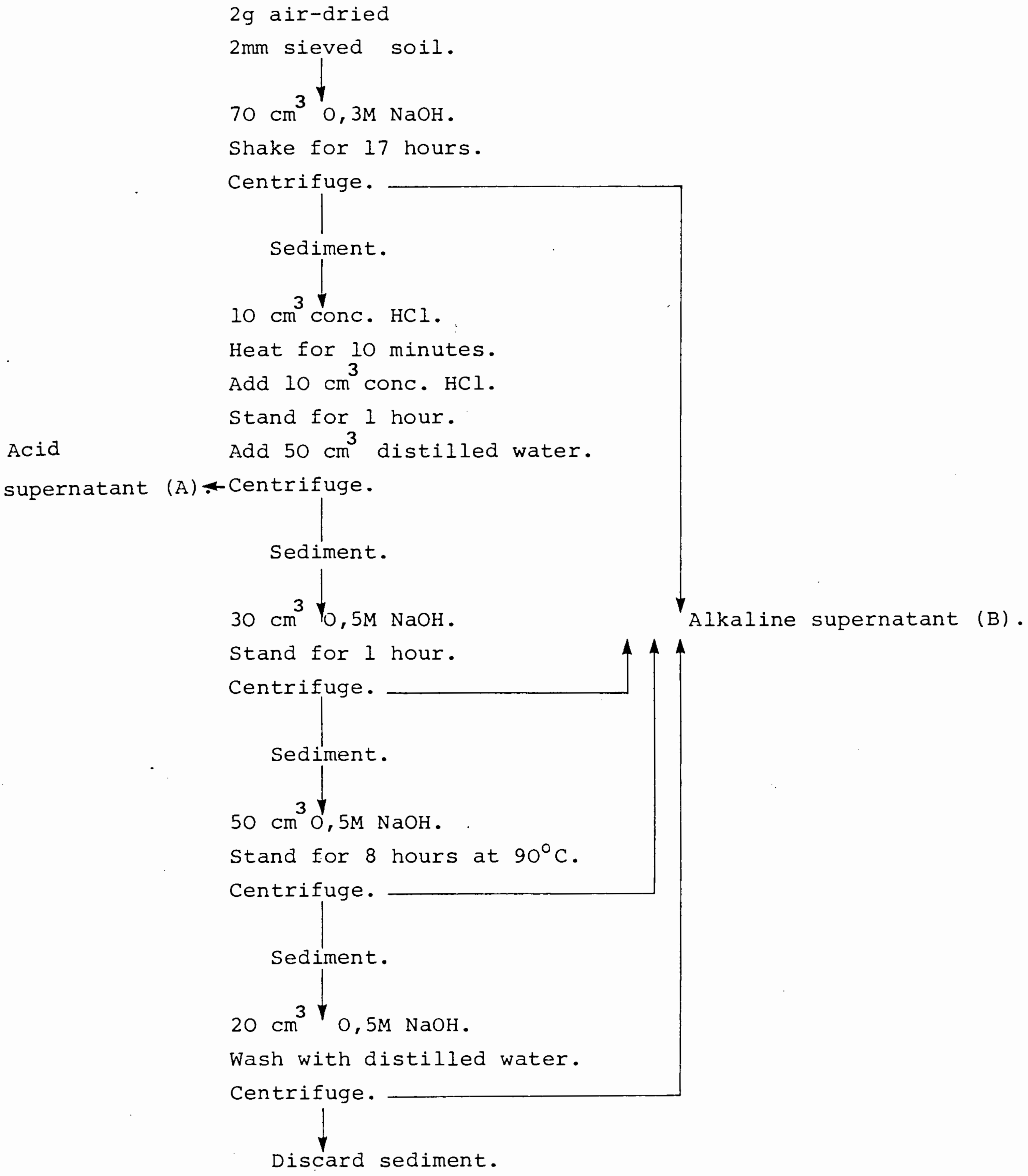
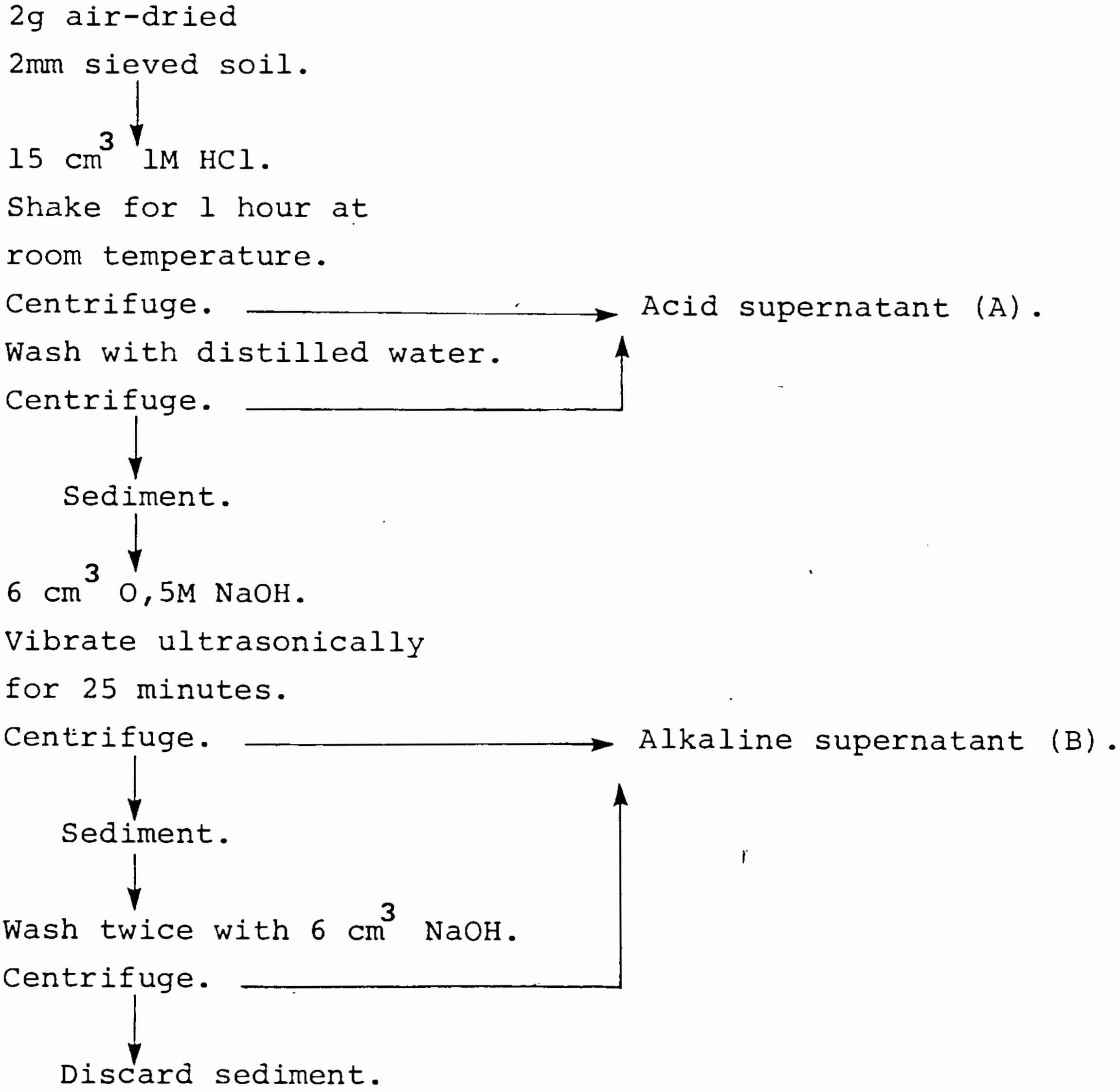


Fig.2:2. A flow diagram of the extraction method of Anderson (1960) employed to determine levels of organic phosphorus in the Clovelly soil form.



2g air-dried
2mm sieved soil.

15 cm^3 1M HCl.
Shake for 1 hour at
room temperature.
Centrifuge. → Acid supernatant (A).
Wash with distilled water.
Centrifuge.

Sediment.

6 cm^3 0,5M NaOH.
Vibrate ultrasonically
for 25 minutes.
Centrifuge. → Alkaline supernatant (B).

Sediment.

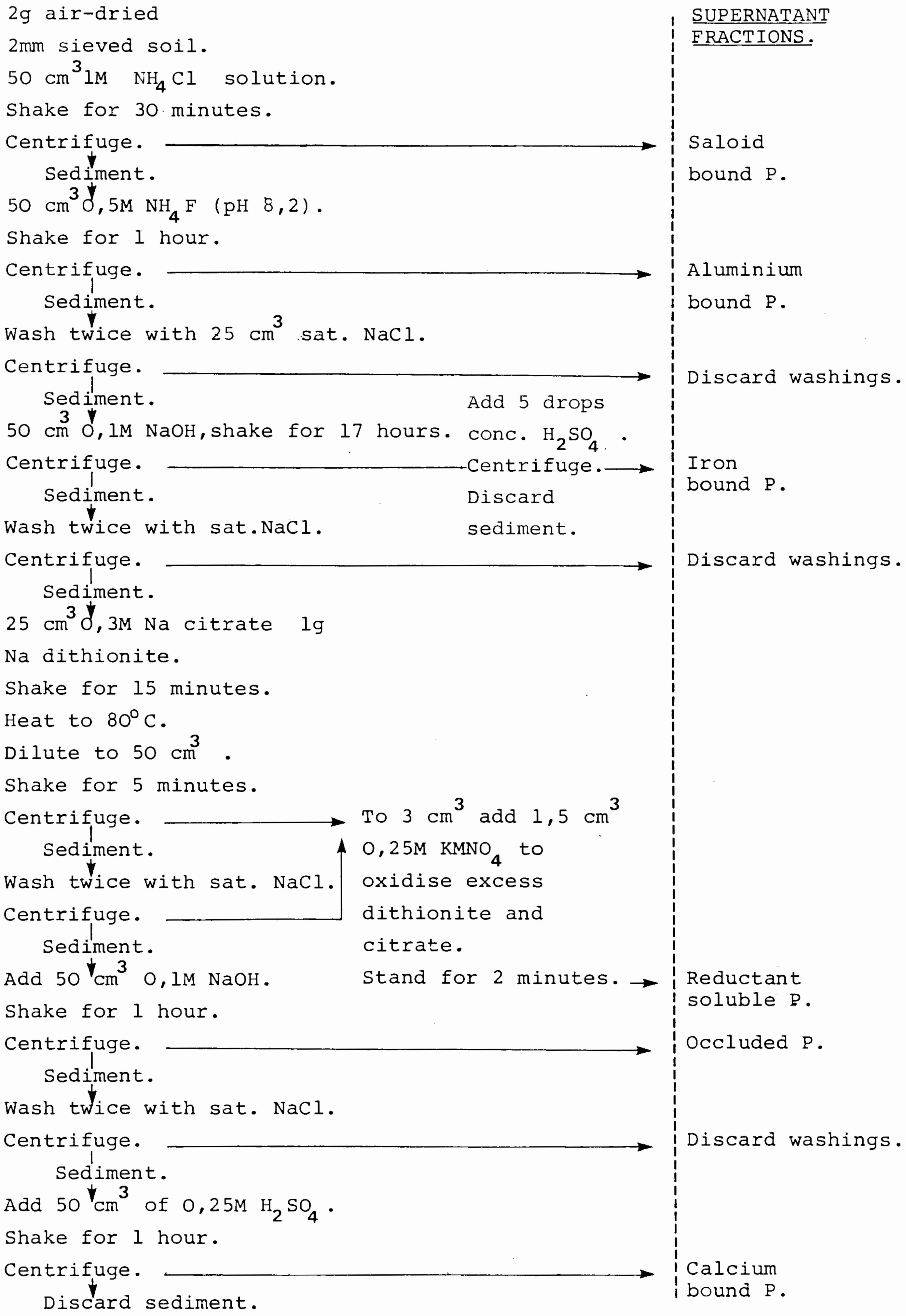
Wash twice with 6 cm^3 NaOH.
Centrifuge.

Discard sediment.

Fig.2:3. A flow diagram of the extraction method of Steward and Oades (1972) employed to determine levels of organic phosphorus in the Clovelly soil form.

2.7. Fractionation of Inorganic Phosphorus.

The method developed by Chang and Jackson (1958) has been modified by many workers (Khin and Leeper 1960, Saunders 1959, Smith 1965). The modification of Williams, Syers and Walker (1967) was employed in this trial. A flow diagram illustrating the steps involved in this extraction is given in Fig.2:4 The method of Murphy and Riley (1962) was used to analyse the levels of phosphorus in solution following the various extractions. The soil samples used for the organic phosphorus determinations were also analysed for inorganic phosphorus.



SUPERNATANT FRACTIONS.

2g air-dried
2mm sieved soil.
50 cm^3 1M NH_4Cl solution.
Shake for 30 minutes.
Centrifuge. → Saloid bound P.
Sediment.
50 cm^3 0,5M NH_4F (pH 8,2).
Shake for 1 hour.
Centrifuge. → Aluminium bound P.
Sediment.
Wash twice with 25 cm^3 sat. NaCl.
Centrifuge. → Discard washings.
Sediment.
50 cm^3 0,1M NaOH, shake for 17 hours.
Centrifuge. → Add 5 drops conc. H_2SO_4. Centrifuge. → Iron bound P.
Discard sediment.
Sediment.
Wash twice with sat. NaCl.
Centrifuge. → Discard washings.
Sediment.
25 cm^3 0,3M Na citrate 1g
Na dithionite.
Shake for 15 minutes.
Heat to 80°C.
Dilute to 50 cm^3.
Shake for 5 minutes.
Centrifuge. → To 3 cm^3 add 1,5 cm^3 0,25M $KMNO_4$ to oxidise excess dithionite and citrate.
Sediment.
Wash twice with sat. NaCl.
Centrifuge. →
Sediment.
Stand for 2 minutes. → Reductant soluble P.
Add 50 cm^3 0,1M NaOH.
Shake for 1 hour.
Centrifuge. → Occluded P.
Sediment.
Wash twice with sat. NaCl.
Centrifuge. → Discard washings.
Sediment.
Add 50 cm^3 of 0,25M H_2SO_4.
Shake for 1 hour.
Centrifuge. → Calcium bound P.
Discard sediment.

Fig.2:4. A flow diagram of the fractionation of soil inorganic phosphorus by the procedure of Chang and Jackson (1958)

2.8. Adsorption Trial.

The soils tested were representative samples of all the soil forms present at the Pella site (Hutton, Griffin, Clovelly, Constantia, Lamotte, Longlands and Westleigh) as well as samples of the Clovelly soil form collected at 0, 20 and 100 cm depth. Four replicates of each soil were analysed. The samples under test which were collected during the soil survey (Section 2.2.) were air-dried at 20° C for seven days and passed through a 2mm sieve. The method of Thompson (1971) was used to determine adsorption rates. For all equilibrations, 10g of sample was shaken with 50 cm^3 aliquots of solution containing graded amounts of KH_2PO_4 in the range of 0-150 x 10^{-3} M on a rotary shaker for one hour. After centrifuging at 4500 xg for 15 minutes, a 40 cm^3 aliquot was taken and immediately analysed for total inorganic phosphorus using the method of Murphy and Riley (1962). The amount of phosphorus adsorbed was calculated as M $x10^{-7}$ g^{-1} dry mass of soil.

2.9. Desorption Trial.

The stepwise extraction method for the removal of phosphorus from soil developed by Giskin and Larsen (1979) was used in a modified form to determine the desorption rates of the soils. To 10 g of soil was added 100 cm^3 of 200 $x10^{-7}$ M KH_2PO_4 and 0,01 M $CaCl_2$, mixed for four hours and the pH of the solutions were measured. Resin bag extractions (Section 2.5) were then carried out over a period of ten days and pH was recorded after each extraction. The rate of removal of phosphorus from the soil was calculated as µg phosphorus g^{-1} dry mass soil. Corrections were made to the final calculations for any removal of soil by the resin bags.

2.10. Physical Mineralisation Trials.

2.10.1. Fire Simulation Study.

A trial was carried out in order to evaluate the importance of physical mineralisation of soil phosphorus by high temperatures experienced by the soil for long periods during summer and the shorter more intense heating resulting from a fire. Fresh unburned Clovelly soil collected from the surface 2 mm of the soil was thoroughly mixed and divided into two equal parts . One was sieved through a 300 micron sieve to remove large particles of organic matter and the rest was untreated. Samples (100g each of both treatments) were exposed to temperatures beginning at 20 °C and in the range of 50-600° C increasing in 50° C increments. The soils were heated for 15 minutes at these temperatures. Following this treatment both soils were passed through a 2mm sieve and analysed for resin extractable phosphorus.

2.10.2. Simulation of Summer Soil Temperatures.

Soil similar to that used in Section 2.10.1. was divided into 12 samples of 100g following an additional mixing, and 6 placed in an oven at 55°C and the remainder stored at room temperature. Weekly resin extractable phosphorus analyses were carried out on soils of both treatments. It was assumed that the very dry nature of these soils (0,02% moisture content) would preclude any microbial activity.

2.11. Phosphorus Determinations.

The colorimetric method developed by Murphy and Riley (1962) was routinely used for the assay of phosphorus in solution. The reagent (see Appendix) reacts rapidly with free phosphate ions yielding a stable phosphomolybdate complex which obeys the Beer-Lambert Law at 0,02-2,0 µg phosphorus cm^{-3} (See Appendix). To an aliquot of the solution to be assayed, 10 cm^3 of distilled water and 8 cm^3 of Murphy and Riley (1962) solution were added to a 50 cm^3 volumetric flask. This was made up to volume with distilled water and allowed to stand for 40 minutes. The optical density of the solution was determined using a Spectronic 20 spectrophotometer at 882 nm. Corrections were made for variations in the absorbance of the colorimeter tubes. It was found that the method was less sensitive to assay solutions of greater than 1% acid. Thus a different calibration curve was used for each extraction technique. The standard method of Murphy and Riley (1962) is, however, not sensitive at concentrations of phosphorus below 0,02 µg phosphorus cm^{-3} and a modification of this method (Kempers 1975) was used to analyse phosphorus levels in rainwater. This method involves the partitioning of the blue antimony phosphomolybdenum complex from the aqueous phase into a small volume of isobutanol. This procedure entailed the addition of 40 cm^3 of rainwater and 4 cm^3 of Kempers (1975) reagent (See Appendix). The colour complex was allowed to develop by incubating the flasks at 5° C for 60 minutes. An 8 cm^3 aliquot of isobutanol was added, the contents thoroughly shaken and allowed to separate for 16 hours. The isobutanol layer was carefully removed using a Pasteur pipette and the optical density measured on a Spectronic 20 spectrophotometer at 698 nm.

2.12. pH Determination.

Soil pH was determined using the method developed by Schofield and Taylor (1955). 20g of fresh soil was mixed for 30 minutes with 50 cm^3 of 0,01 M $CaCl_2$ and the pH determined using a Radiometer pH Meter 29.

2.13. Gravimetric Moisture and Organic Matter Content.

8g of fresh soil was weighed and dried in a forced draught oven for 48 hours at 105°C, weighed again and heated for 16 hours at 450°C. The soil was reweighed after cooling and the moisture and organic matter content which was expressed as a percentage of dry mass, was calculated.

2.14. Bulk Density.

Cores of known volume (67 mm diameter x100 mm) were taken at the required depth and the bulk density calculated using the formula:

$$Y= \frac{w_1 - w_2}{v_1 - v_2}$$

where w_1 = mass before sieving

w_2 = mass after sieving through a 2 mm sieve.

v_1 = volume of soil before sieving.

v_2 = volume of stones removed in the sieving.

The bulk density was expressed as g cm^{-3} and results were means of three replicates.

2.15. Soil Temperatures.

Soil temperatures were measured using a Fluke 2175A digital thermometer using copper/constantin thermocouples.

2.16. Soil Iron Levels.

Total soil iron levels were determined by Scientific Services, Rondebosch, Cape Town, using an aqua regia leach to initially remove the iron compounds and Varian Techtron Atomic absorption spectrophotometer used to determine levels in solution.

2.17. CNH Analyses.

All CNH analyses were carried out on the Hewlett Packard 185B gas chromatograph analyser of the Geology Department, University of Cape Town, under the direction of Dr S.Smith.

2.18. Statistical Analyses and Presentation of Data.

All statistical analyses were carried out on an HP 67 calculator with a statistical pack option. The following programs were used;

: Curve fitting programs for one variable (program SD-03A).
: Multiple Linear Regression for two variables (program ST1-13A).
: One way analysis of variance (program ST1-06A).

The relevant values for r^2 and R were obtained from Table Y of Sokal and Rohlf (1969) and the relevant F values from Table D.11 of Zar (1974). The 3 dimensional graphs were drawn on a Univac 1100 at the University of Cape Town using a Saclant package.

3. Spatial and Temporal Variations in Soil Phosphorus.

The size of various phosphorus pools within the soil, particularly available phosphorus, is known to change seasonally (Larsen 1967). Its influence on plant growth is thought to be a major one in mediterranean-type ecosystems, especially if phosphorus is a limiting element for growth (Groves 1982). The time and location within the profile of active uptake of phosphorus by plant roots is often quite limited and for this reason patterns of spatial as well as temporal distribution of phosphorus within the Clovelly soil form are important. This chapter evaluates the seasonal variations in the size of various phosphorus pools within the soil as well as the allied factors of soil organic matter levels, temperature, and pH. The distribution of the various phosphorus pools through the Clovelly soil with depth is examined in detail.

3.1. Results.

Total phosphorus levels did not vary seasonally (Fig 3:1). Although large variations in levels were found between individual collections, these did not follow any seasonal pattern and there was no correlation between total phosphorus levels and either soil temperature or organic matter levels. Total soil phosphorus levels declined with depth from 39,7 $\mu g\ g^{-1}$ dry soil mass (52,8 kg ha^{-1} $10cm^{-1}$ depth) at the surface to 19,2 $\mu g\ g^{-1}$ dry soil mass at 20-40 cm depth and thereafter increased gradually to a depth of 200 cm (Fig 3:2).

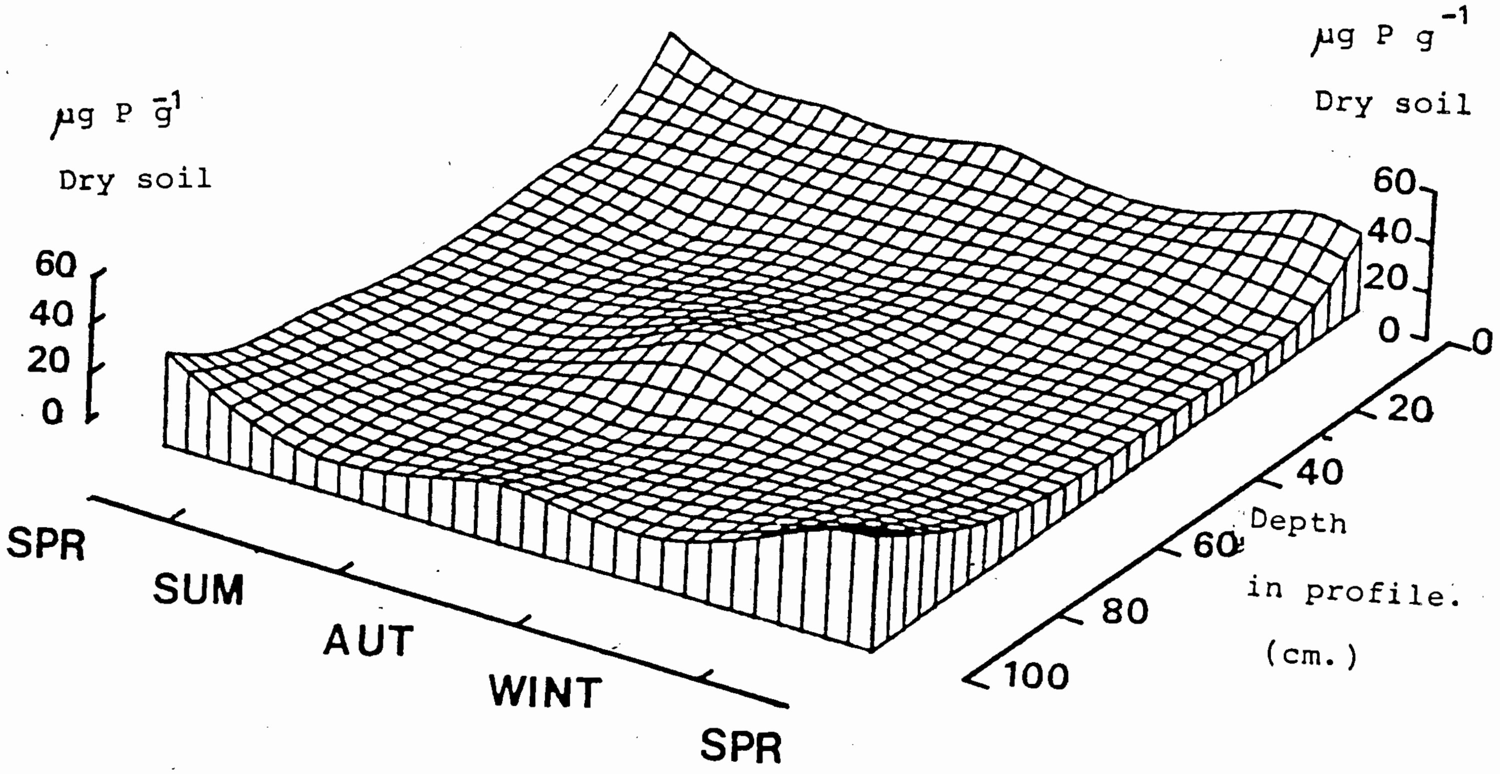


Fig.3:1. Seasonal variation in total soil phosphorus in a Clovelly soil form with depth. Data collected at 2 monthly intervals from April 1979 to October 1980 at 0, 5, 10, 15, 20, 30, 40, 70, and 100 cm depths and 4 replicates taken per depth per sampling.
SPR represents spring (September, October and November).
SUM represents summer (December, January and Feburary).
AUT represents autumn (March, April and May).
WINT represents winter (June, July and August).

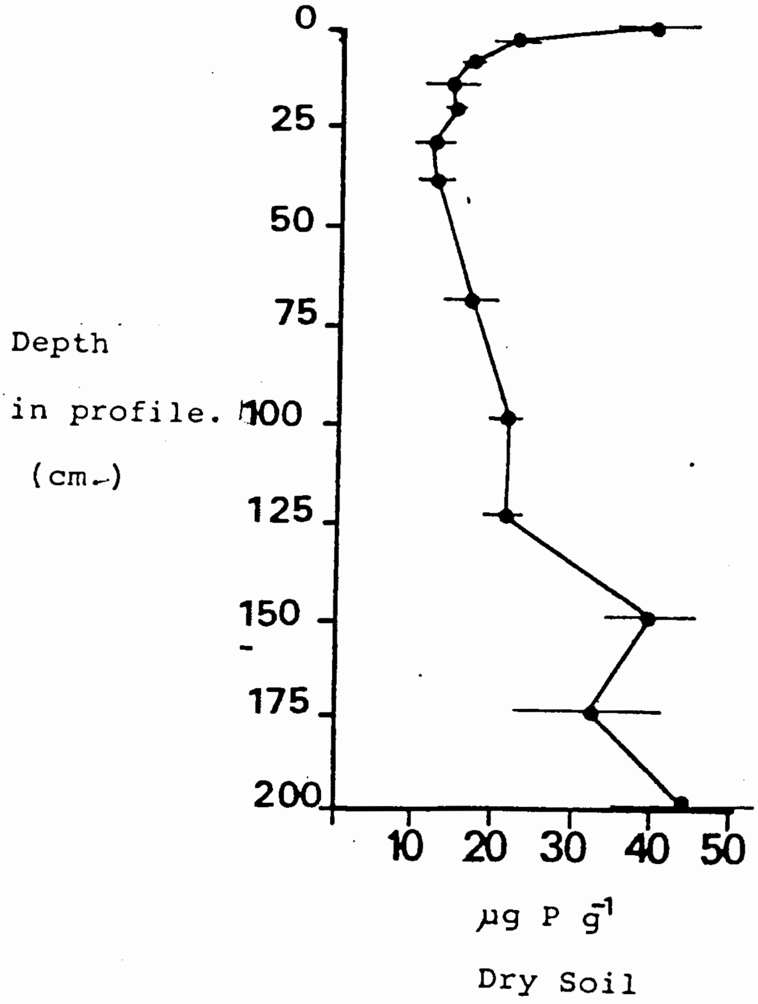


Fig.3:2.Soil profile distribution of total soil phosphorus in a Clovelly soil form to a depth of 200 cm. Results are means of 4 replicates and horizontal bars represent twice the standard error of the mean (SEM). From a sample collected in October 1980.

Resin extractable phosphorus levels varied significantly with season at the soil surface using one way analysis of variance (F=7,00; df= 3 , 29; $P<$ 0,001)(Fig.3:3). An increase in levels was determined in the surface layers of the soil during spring, reaching a maximum in summer and then declining in autumn and winter. The mean summer level of resin extractable phosphorus at the surface was 5,3 μg g^{-1} dry soil mass (7,1 kg ha^{-1} 10cm^{-1} depth as opposed to a winter mean of 1,0 μg g^{-1} dry soil mass (1,3 kg ha 10cm^{-1} depth). The overall mean was 3,2 μg P g^{-1} dry soil mass or 4,2 kg ha^{-1} 10cm^{-1} depth. As a result of these high summer surface values, there was a significant decline in resin extractable phosphorus values down the soil profile (0-100 cm) during summer (December-Feburary) using one way analysis of variance (F=4,54; df=6, 21; $P<$ 0,01). During each season with the exception of winter, lower levels of resin extractable phosphorus were recorded at the 10 cm depth than immediately above or below. A correlation was found to exist between soil temperature and resin extractable phosphorus levels at only 5 and 10 cm depths in the soil profile. This correlation did not exist at other depths. There was no significant increase in levels of resin extractable phosphorus down the profile between 40 and 200 cm in the October 1980 soil samples using one way analysis of variance (Fig.3:4.).

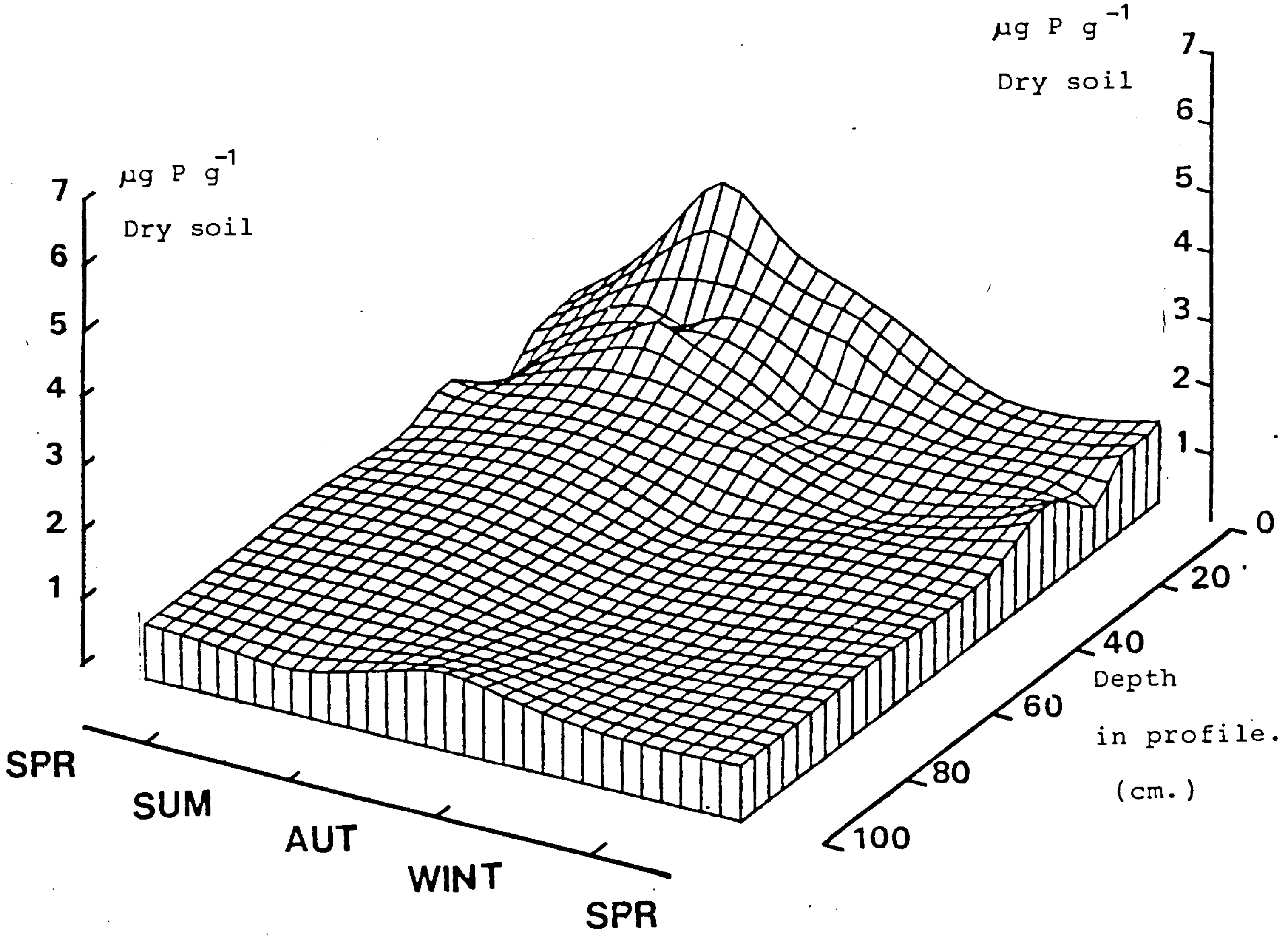


Fig.3:3. Seasonal variation in resin extractable phosphorus in a Clovelly soil form with depth. Data collected at 2 monthly intervals from April 1979 to October 1980 at 0, 5, 10, 15, 20, 30, 40, 70, and 100 cm depths and 4 replicates taken per depth per sampling.

SPR represents spring (September, October and November).

SUM represents summer (December, January and Feburary).

AUT represents autumn (March, April and May).

WINT represents winter (June, July and August).

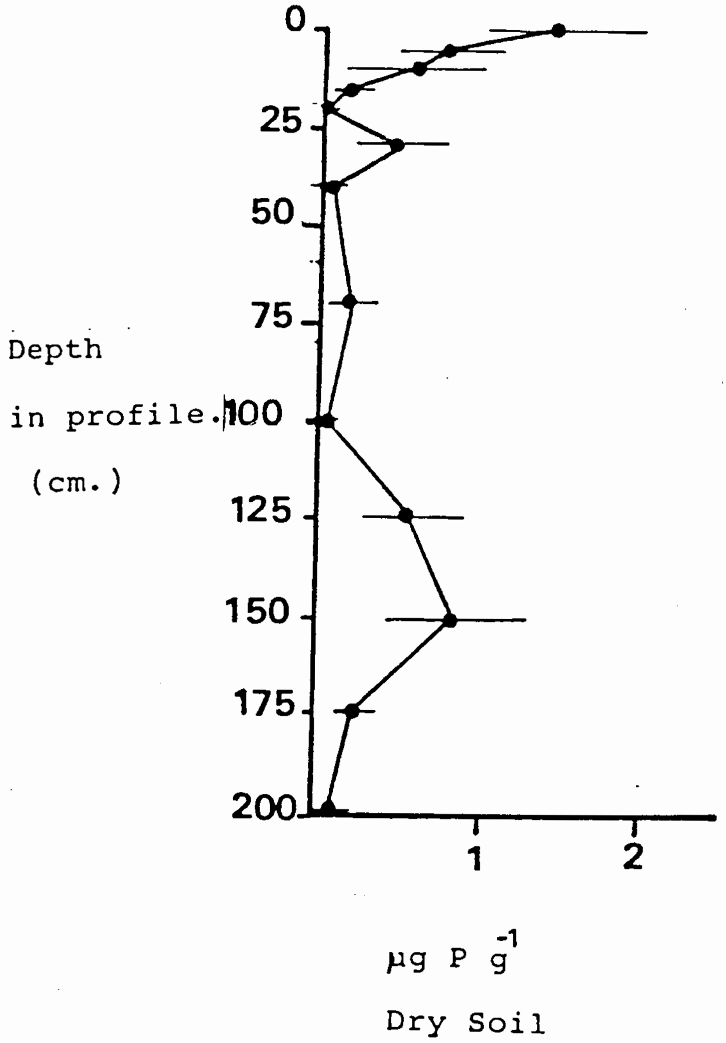


Fig.3:4.Soil profile distribution of resin extractable phosphorus in a Clovelly soil form to a depth of 200 cm. Results are means of 4 replicates and horizontal bars represent twice the standard error of the mean (SEM). From a sample collected in October 1980.

The Bray#2 values for available phosphorus were consistently higher than those obtained using the resin bag extraction technique. Bray#2 levels did not vary seasonally at any depth but there were significant changes in levels down the profile during spring, summer and autumn using one way analysis of variance ($F= 8{,}07$; $df=8{,}62$; $P<0{,}001$ for Spring; $F= 4{,}41$; $df=8{,}62$; $P<0{,}001$ for summer and $F= 21{,}00$; $df= 8{,}62$; $P<0{,}001$ for Autumn) (Fig.3:5). Levels were high at the surface with an autumn maximum of 5,3 µg phosphorus g^{-1} dry soil mass (7,1 kg 10 cm^{-1} ha^{-1}) declining to a minimum value at 30 cm and then rising to reach an autumn maximum of 7,30 µg g^{-1} dry soil mass at 100 cm (Fig 3:5). These levels continued to increase to 200 cm where a value of 18,70 µg g^{-1} dry soil mass occurred (Fig 3:6) which was higher than at the other depths. The implications of these increases down the profile are discussed in Chapter 10.

Seasonal fluctuations of soil organic matter content were not significant (Fig 3:7). Surface levels of organic matter reached a maximum of 2,14% in summer declining to a minimum of 1,71% in winter. Levels of organic matter declined down the profile to 40 cm where they stabilised at 0,5-0,7% and increased slightly to 1% at 200 cm (Fig 3:8).

Soil pH values did not vary seasonally throughout the soil profile (Fig.3:9). At the soil surface the pH was 3,7 during summer and then increased slightly to 4,3 during winter. Soil pH increased down the profile to 5,5 at 200 cm (Fig 3:10). Factors which may have caused these slight changes in pH were not examined.

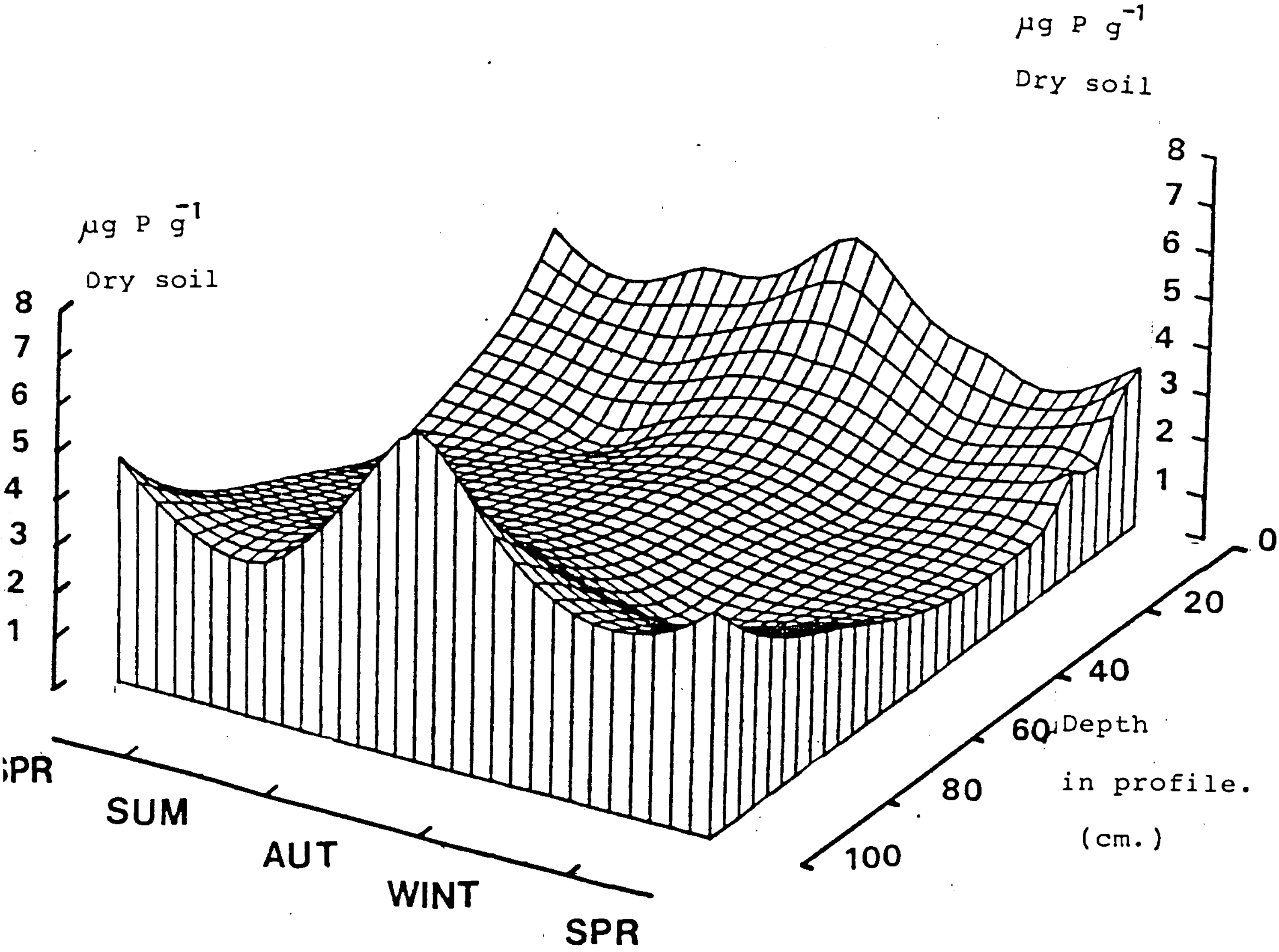


Fig.3:5. Seasonal variation in Bray#2 extractable phosphorus in a Clovelly soil form with depth. Data collected at 2 monthly intervals from April 1979 to October 1980 at 0, 5, 10, 15, 20, 30, 40, 70, and 100 cm depths and 4 replicates taken per depth per sampling.

SPR represents spring (September, October and November).

SUM represents summer (December, January and Feburary).

AUT represents autumn (March, April and May).

WINT represents winter (June, July and August).

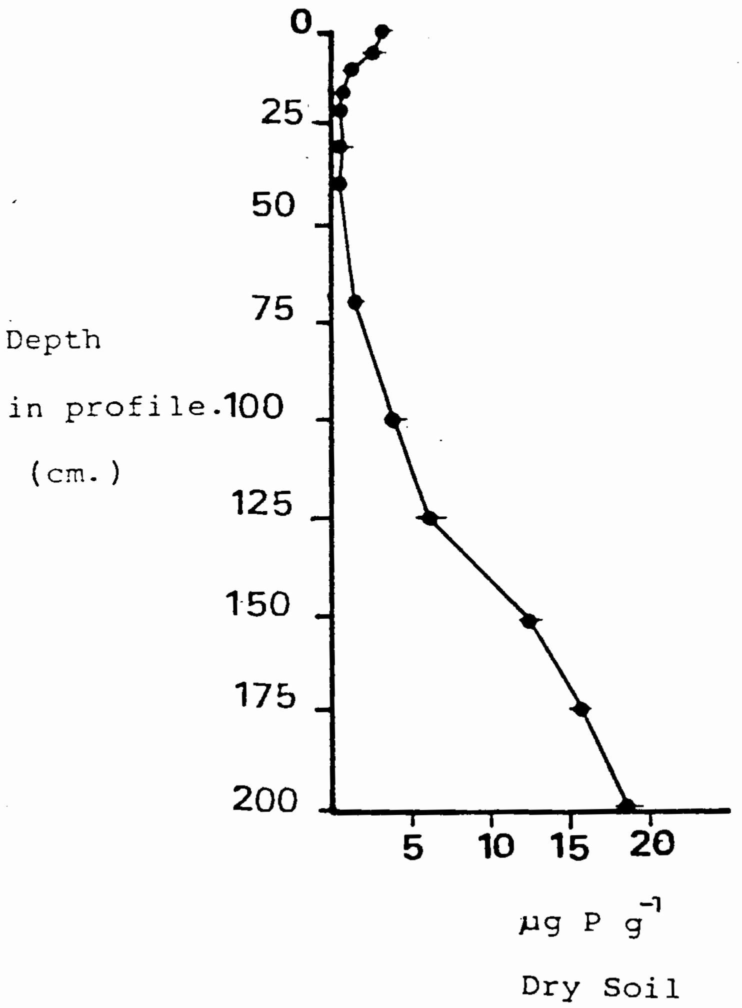


Fig.3:6. Soil profile distribution of Bray 2# extractable phosphorus in a Clovelly soil form to a depth of 200 cm. Results are a mean of 4 replicates and horizontal bars represent twice the standard error of the mean (SEM). From a sample collected in October 1980.

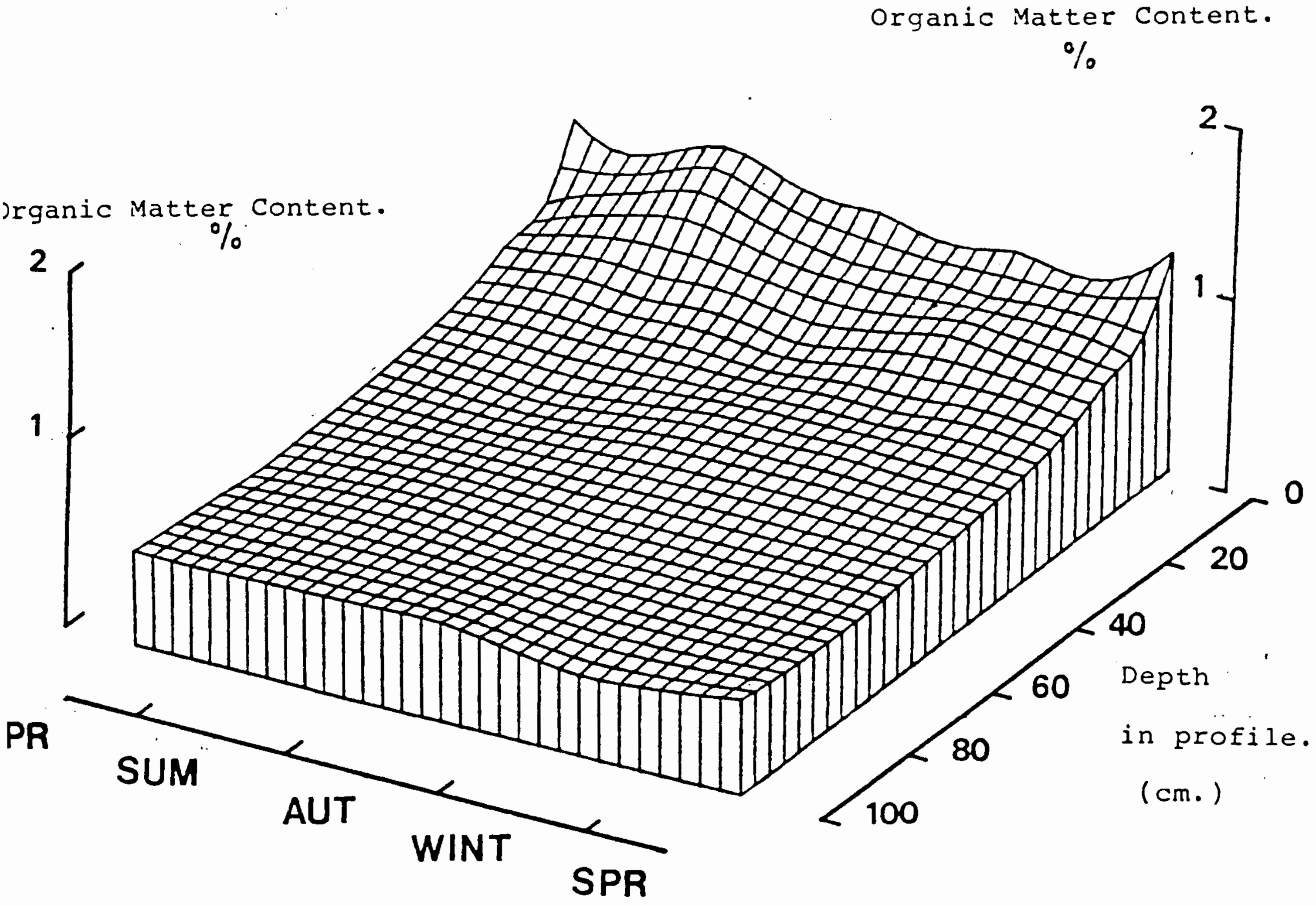


Fig.3:7. Seasonal variation in soil organic matter levels in a Clovelly soil form with depth. Data collected at 2 monthly intervals from April 1979 to October 1980 at 0, 5, 10, 15, 20, 30, 40, 70, and 100 cm depths and 4 replicates taken per depth per sampling.

SPR represents spring (September, October and November).

SUM represents summer (December, January and Feburary).

AUT represents autumn (March, April and May).

WINT represents winter (June, July and August).

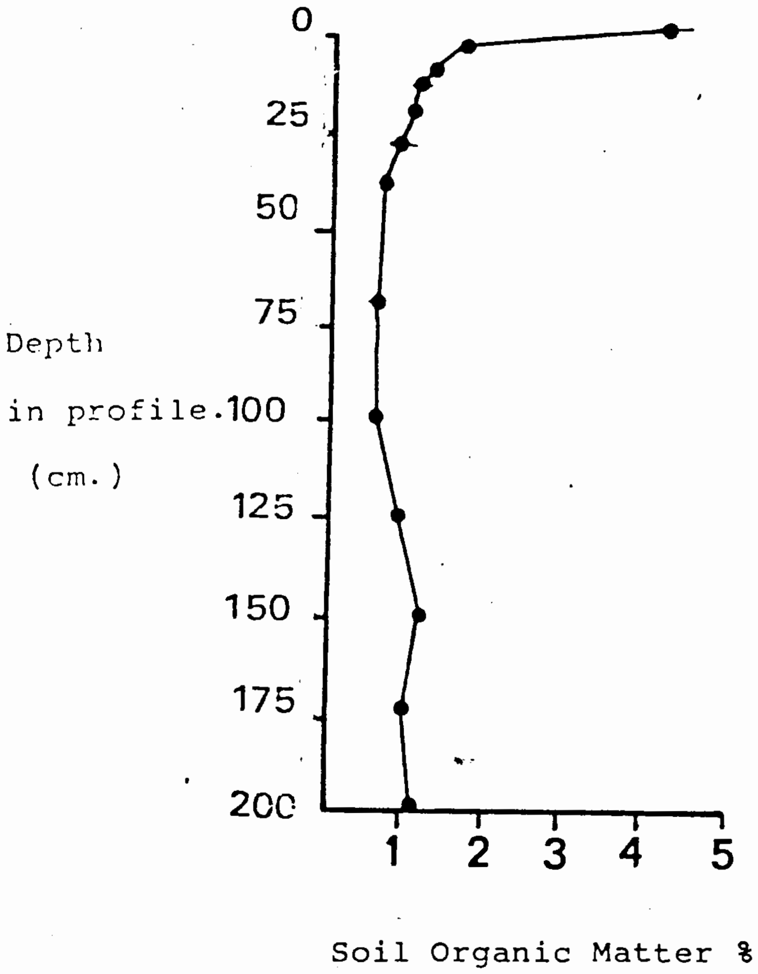


Fig.3:8.Soil profile distribution of soil organic matter in a Clovelly soil form to a depth of 200 cm. Results are means of 4 replicates and horizontal bars represent twice the standard error of the mean (SEM). From a sample collected in October 1980.

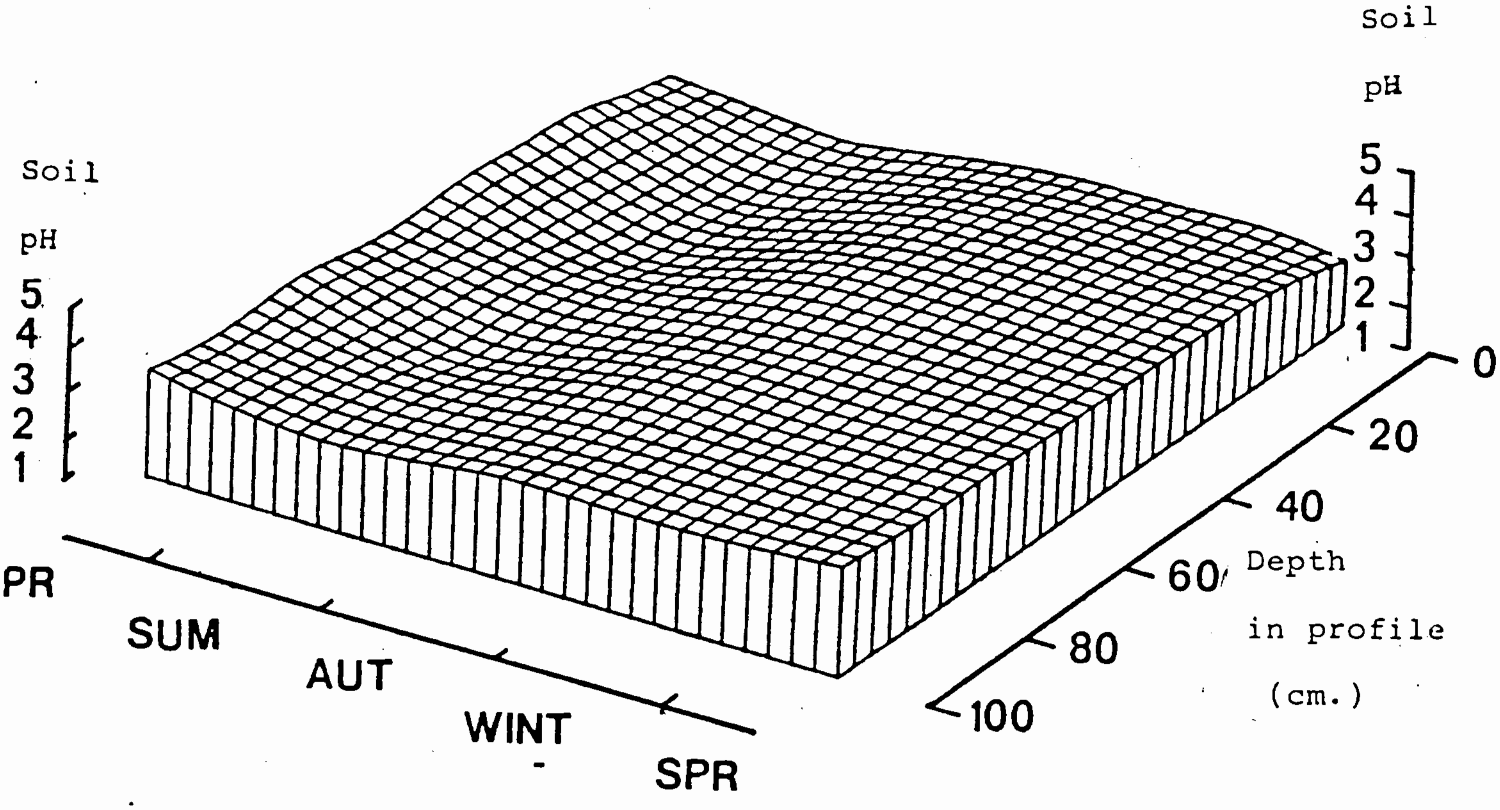


Fig.3:9. Seasonal variations in soil pH in a Clovelly soil form with depth. Data collected at 2 monthly intervals from April 1979 to October 1980 at 0, 5, 10, 15, 20, 30, 40, 70, and 100 cm depths and 4 replicates taken per depth per sampling.

SPR represents spring (September, October and November).

SUM represents summer (December, January and Feburary).

AUT represents autumn (March, April and May).

WINT represents winter (June, July and August).

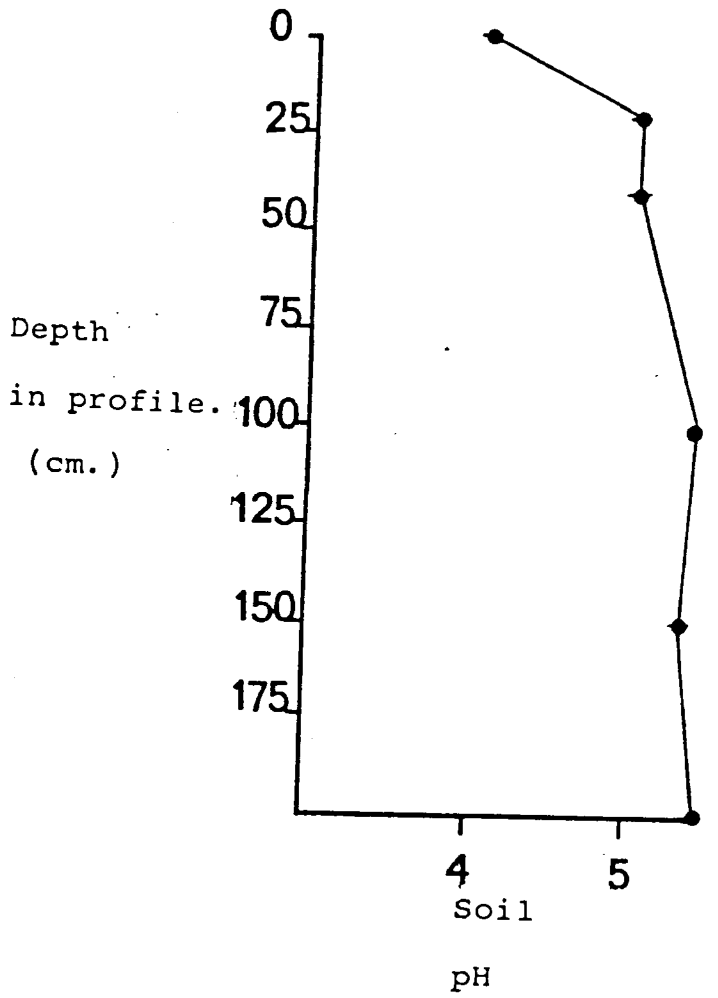


Fig.3:10.Soil profile variations in pH in a Clovelly soil form to a depth of 200 cm. Results are means of 4 replicates and horizontal bars represent twice the standard error of the mean (SEM). From a sample collected in October 1980.

Soil temperatures did not vary significantly throughout the year although a drop in temperature occurred during autumn and winter particularly at the soil surface (Fig 3:11) with a drop in mean temperatures from 38°C in summer to 22°C in winter. Below 40 cm, temperatures did not alter with depth and varied slightly seasonally with a mean summer temperature of 22° C and a winter mean of 16°C (Fig 3:11). In all seasons, temperatures declined with depth but this trend was more exaggerated in summer than in winter.

The results of a six week incubation trial are shown in Fig 3:12. There were no significant changes in resin extractable phosphorus during the incubation at room temperature and 55°C.

It was thus concluded that no physical mineralisation of organic phosphorus had taken place as a result of the elevated temperatures.

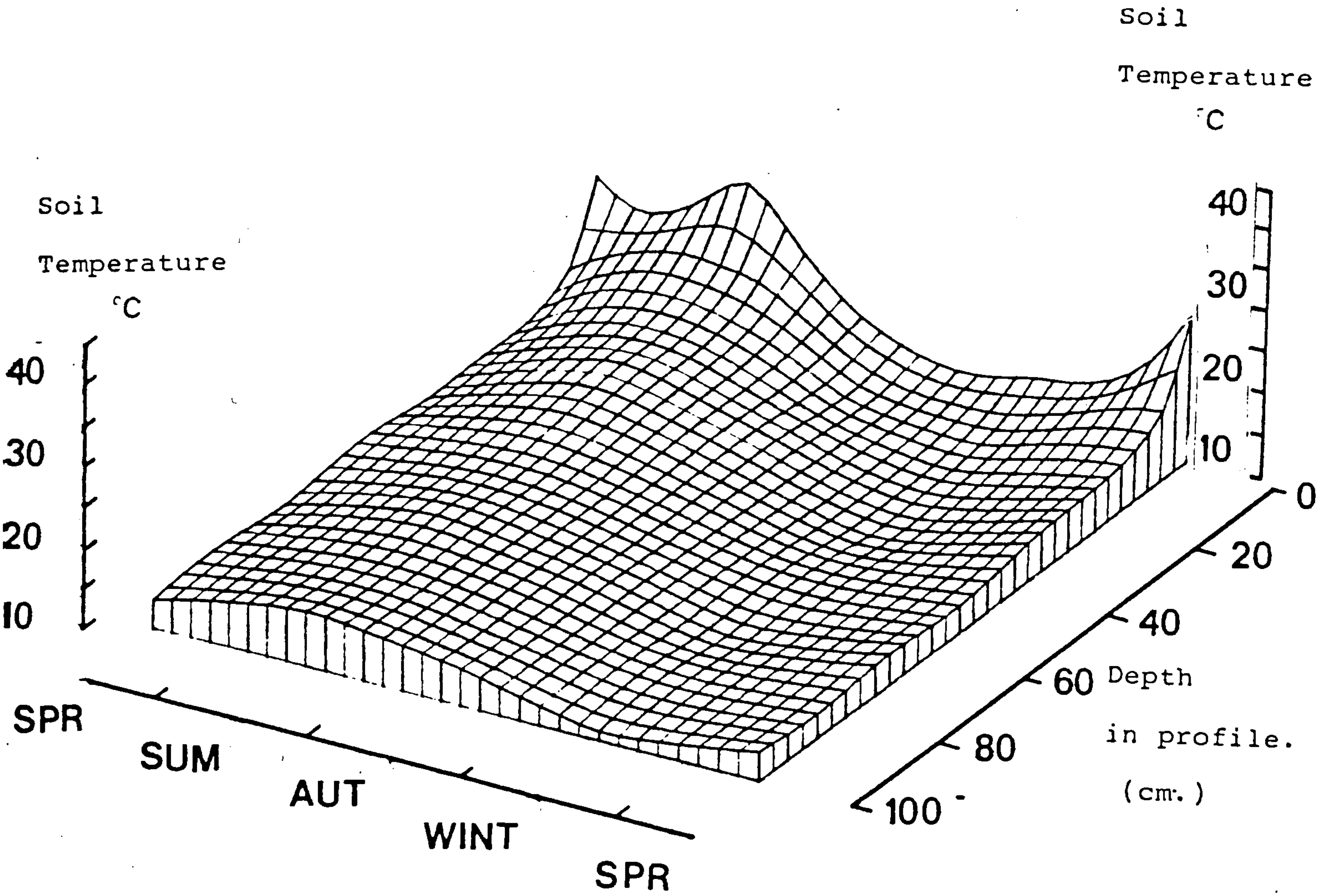


Fig.3:11. Seasonal variations in soil temperature in a Clovelly soil form with depth. Data collected at 2 monthly intervals from April 1979 to October 1980 at 0, 5, 10, 15, 20, 30, 40, 70, and 100 cm depths and 4 replicates taken per depth per sampling.

SPR represents spring (September, October and November).

SUM represents summer (December, January and Feburary).

AUT represents autumn (March, April and May).

WINT represents winter (June, July and August).

3.2. Discussion.

There were no seasonal variations in total phosphorus levels. The fluctuations between collections were not seasonally correlated and were probably a result of the patchy distribution of phosphorus within the soil. The high total phosphorus levels at the soil surface were a result of the return to the soil in litter and charcoal of phosphorus formerly bound within the plant. The root systems of the majority of shrubs eg. L.parile occur in a zone approximately 0-70 cm from the soil surface (Jongens-Roberts et al. 1981). Phosphorus would tend to be depleted in the middle soil layers (20-70 cm) while enriching the surface layers as a result of litter fall. Larsen (1967) reported similar results in a soil profile to 100 cm in base igneous till with a zone of depletion from 50-80 cm and a zone of enrichment in the topsoil.

There was a consistent pattern of resin extractable phosphorus in the surface layers of the soil particularly during the summer period. Smeck (1973) stated that soil available phosphorus levels were high near the soil surface decreasing to minimum values at 30-50 cm and then, in soils of moderate to high phosphorus values, increasing to levels characteristic of the parent material. In oligotrophic soils, he reported no increase below 100 cm. Smeck (1973) also reported that the high levels of plant available phosphorus found at the soil surface are primarily a result of rapid mineralisation of organic phosphorus compounds. This would appear to be the case in the Clovelly soil form. The lack of any physical mineralisation of insoluble phosphates during the simulation of summer temperatures within the soil (Fig 3:12) indicates that this process does not appear to contribute to the soil resin extractable phosphorus pool. The correlation between resin extractable phosphorus levels and temperature at the 5 and 10 cm zone in the soil supports the hypothesis that the chief source of available phosphorus at the soil surface comes from microbial mineralisation of soil organic phosphorus compounds. The lack of correlation directly at the surface (ie. 0 cm) is probably a result of the fact that temperature is subject to large diurnal fluctuations. Dalal (1977) stated that temperatures around 40 °C constituted the optimum conditions for microbial mineralisaton of organic phosphates within the soil. In another study, mineralisation did not occur at temperatures below 30 °C (Floate 1970). Alternate cycles of wetting and drying which can occur in the surface soils are ideal for mineralisation and good aeration also speeds up the process as does an increase in soil pH (Dalal 1977). It would appear that the warmer wetter periods of the year at Pella are correlated with higher levels of resin extractable phosphorus primarily as a result of the increase in rates of microbial mineralisation of organic phosphorus compounds in the surface layers of the soil. The implications of these increases down the profile are discussed in Chapter 10.

4. Fire and the Phosphorus Cycle.

Fire is known to be a major perturbation in mediterranean-type ecosystems (Gray and Schlesinger 1981). It destroys vegetation and organic matter in the upper soil and deposits soluble nutrients in the ash and charcoal layer laid down at the soil surface. While phosphorus is considered to be a major soil nutrient and one of the limiting factors for plant growth in mediterranean-type climatic regions of South Africa and Australia, the impact of fire on the phosphorus cycle has had very little attention (Rundel 1982). This chapter evaluates the effects of fire on the phosphorus status of oligotrophic soils of coastal fynbos. This study was initiated as a result of an accidental burn which occurred on the 3rd of November 1980 at the Pella site.

4.1. Results.

Total phosphorus levels did not vary significantly immediately after the fire but levels declined between 27 and 33 weeks (Fig 4:1). At the surface resin extractable phosphorus levels increased 8 to 10 fold (Fig 4:2) immediately after the fire and values of 11 μg phosphorus g^{-1} dry soil mass were attained. These surface levels fluctuated but remained high until the tenth week post-fire when they declined to values twice that recorded prior to the fire. Below the surface the increase and subsequent decline in resin extractable phosphorus levels was less marked with no immediate increase recorded below 5 cm. However, values of resin extractable phosphorus at the lower depths increased over time until the fourteenth week post-fire when they declined to pre-fire values. There was no correlation between either resin

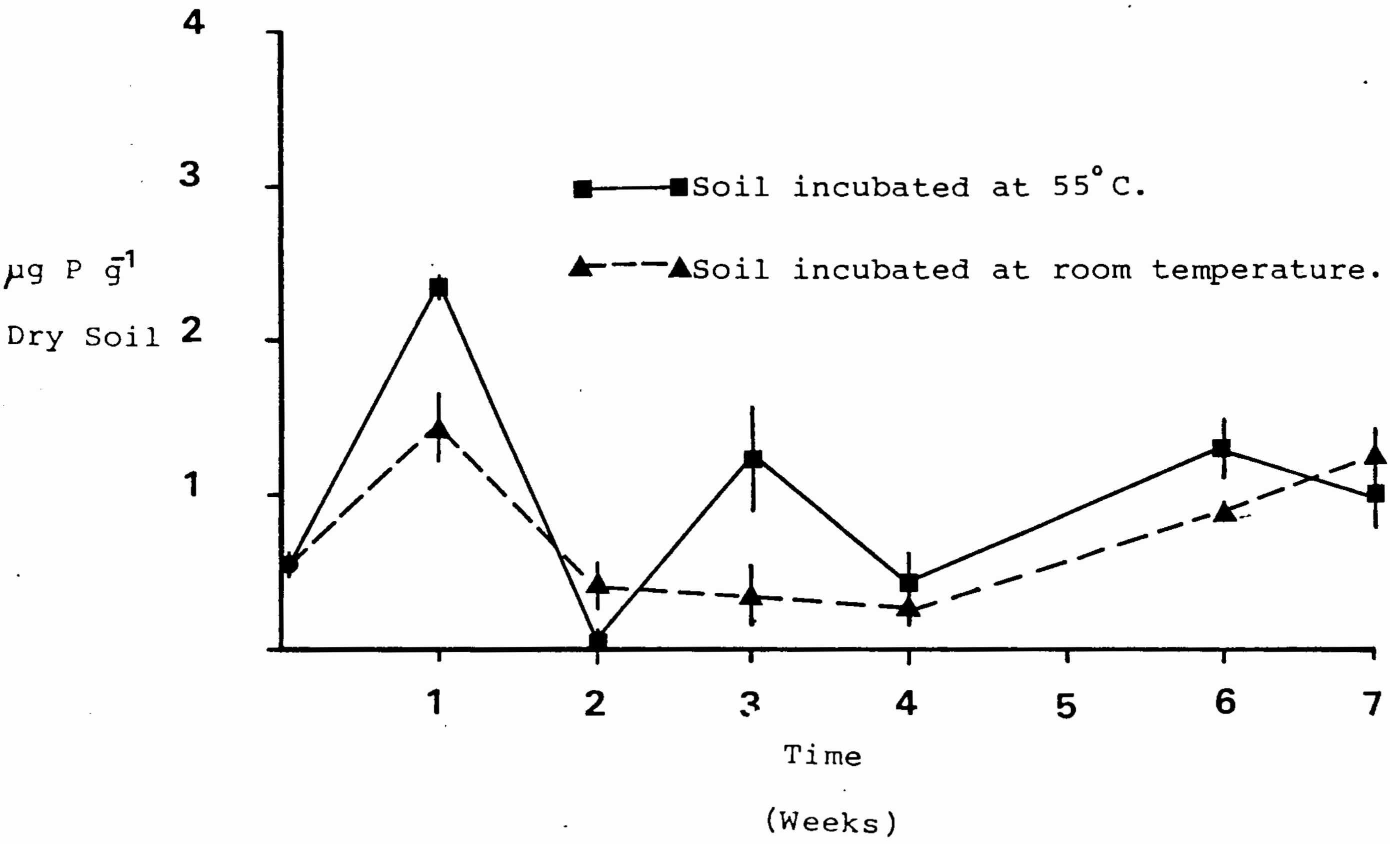


Fig.3:12. Change in levels of resin extractable phosphorus during an incubation trial carried out at two temperatures on Clovelly soil. Each point is a mean of 4 replicates, vertical bars representing twice the SEM.

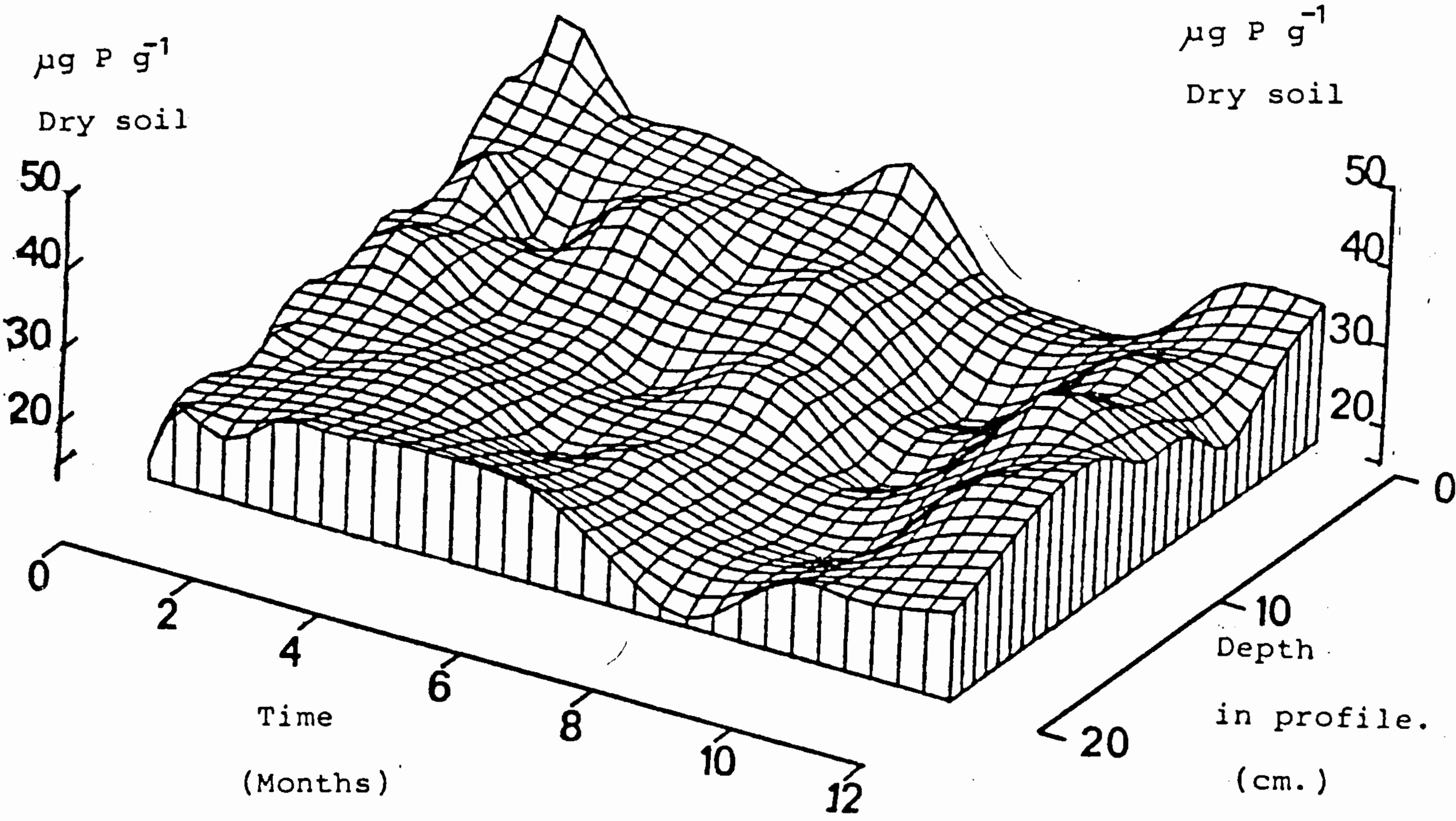


Fig.4:1. A representation of total soil phosphorus in a Clovelly soil profile to 20 cm for the post-fire period of 12 months. Collection begun on the 5th November 1980. Means of 12 replicates at soil surface and 5 cm and 8 replicates at 10,15 and 20 cm.

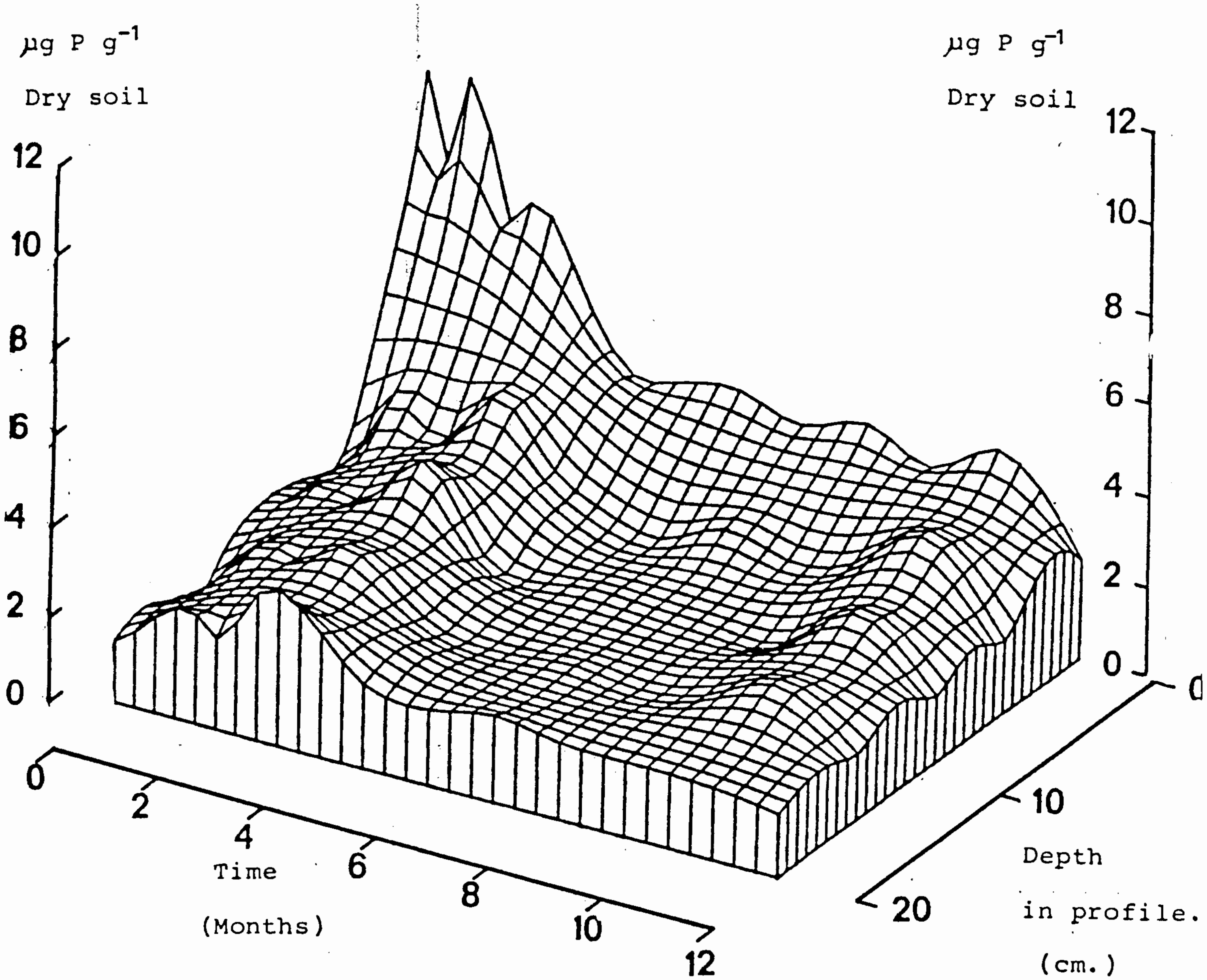


Fig.4:2. A representation of resin extractable phosphorus levels in a Clovelly soil profile to 20 cm for post-fire period of 12 months. Collection begun on the 5th November 1980. Values are means of 12 replicates at the soil surface and 5 cm and 8 replicates at 10, 15 and 20 cm.

extractable or total phosphorus levels with either organic matter or soil temperatures after the fire. The physical mineralisation trial carried out to determine the influence of fire on soil resin extractable phosphorus levels indicated that in the temperature range of 20-600° C there is no increase in resin extractable phosphorus levels either in the 300 micron sieved or the unsieved soils (Fig.4:3.). The short duration of these treatments may have been a contributing factor to the lack of response observed in this trial.

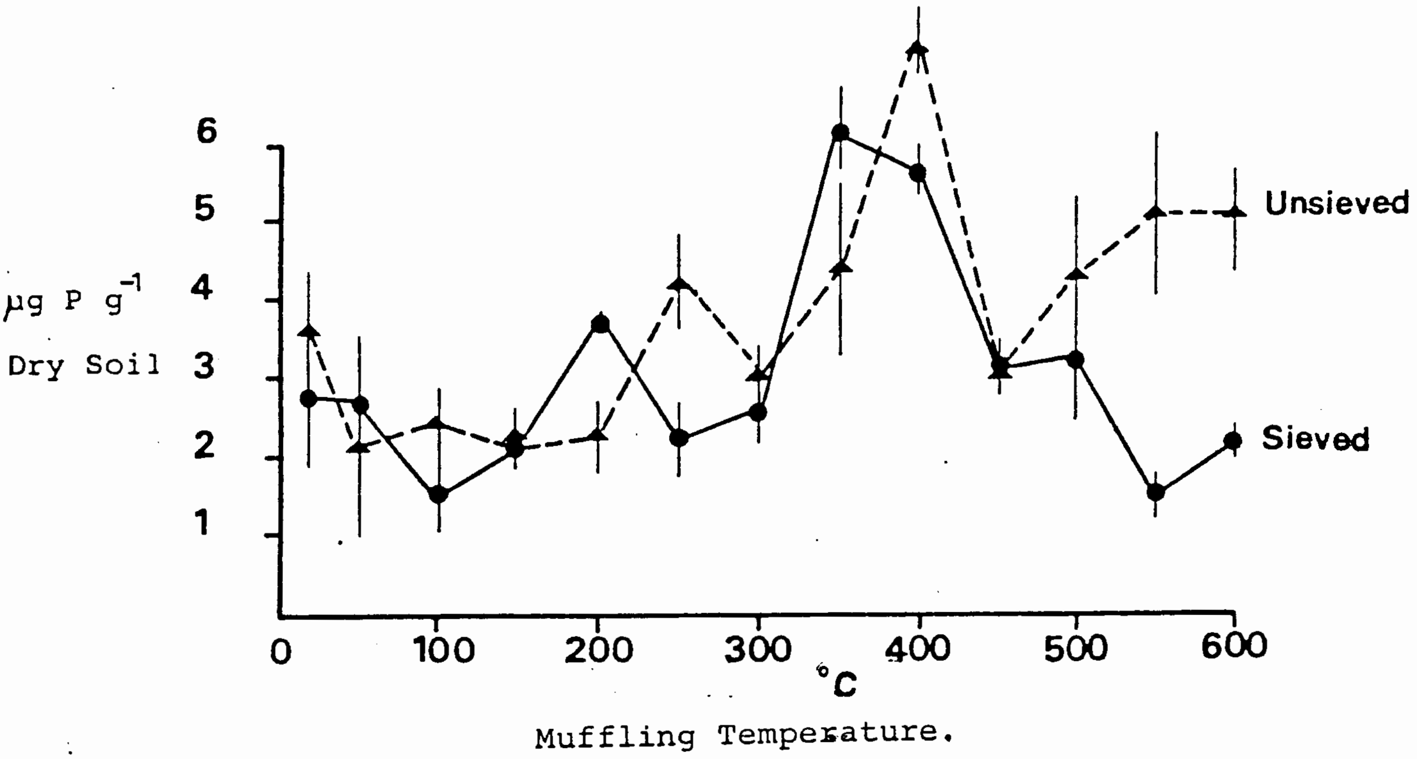


Fig 4:3 The effect of high soil temperatures on resin extractable phosphorus levels in 300 micron sieved and unsieved soils. Each point represents a mean of 4 replicates per treatment. Vertical bars represent twice the SEM.

Organic matter levels did not fluctuate significantly immediately after the fire or during the twelve month post-fire period (Fig 4:4). The slight increases in the organic matter content in the 0-4 cm zone of the Clovelly soil are given in Table 4:1 which also includes the changes in total and resin extractable phosphorus within the soil (<2 mm) and the charcoal (>2mm) fraction immediately after the fire. From these data it was possible to estimate the inputs of both total and resin extractable phosphorus from organic matter to the soil. In the 0-4 cm zone of the soil this increase was calculated to be in the range of 7-18 µg phosphorus g^{-1} dry soil mass resin extractable phosphorus and 23-32µg phosphorus g^{-1} dry soil mass total phosphorus. However only 18-25% of this increase is found in the <2 mm fraction, the rest being contained in the charcoal and litter fraction which was not included in the normal soil analyses.

Soil pH values increased after the fire reaching a maximum of 5,3 at the soil surface after 2 months and returning to prefire values after 7 months (Fig 4:5).

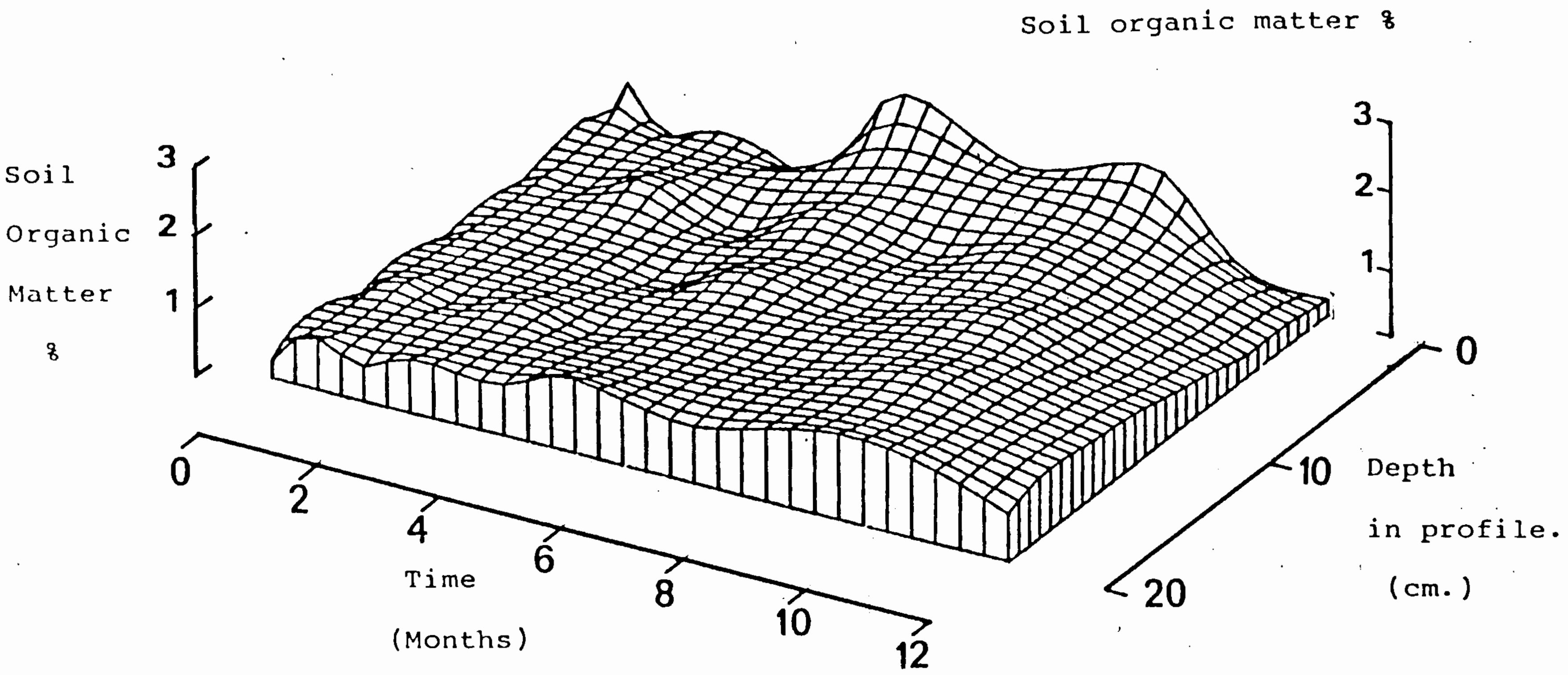


Fig.4:4 .A representation of soil organic matter in a Clovelly soil profile to 20 cm for the post-fire period of 12 months. Collection begun on the 5th November 1980. Means of 12 replicates at soil surface and 5 cm and 8 replicates at 10,15 and 20 cm.

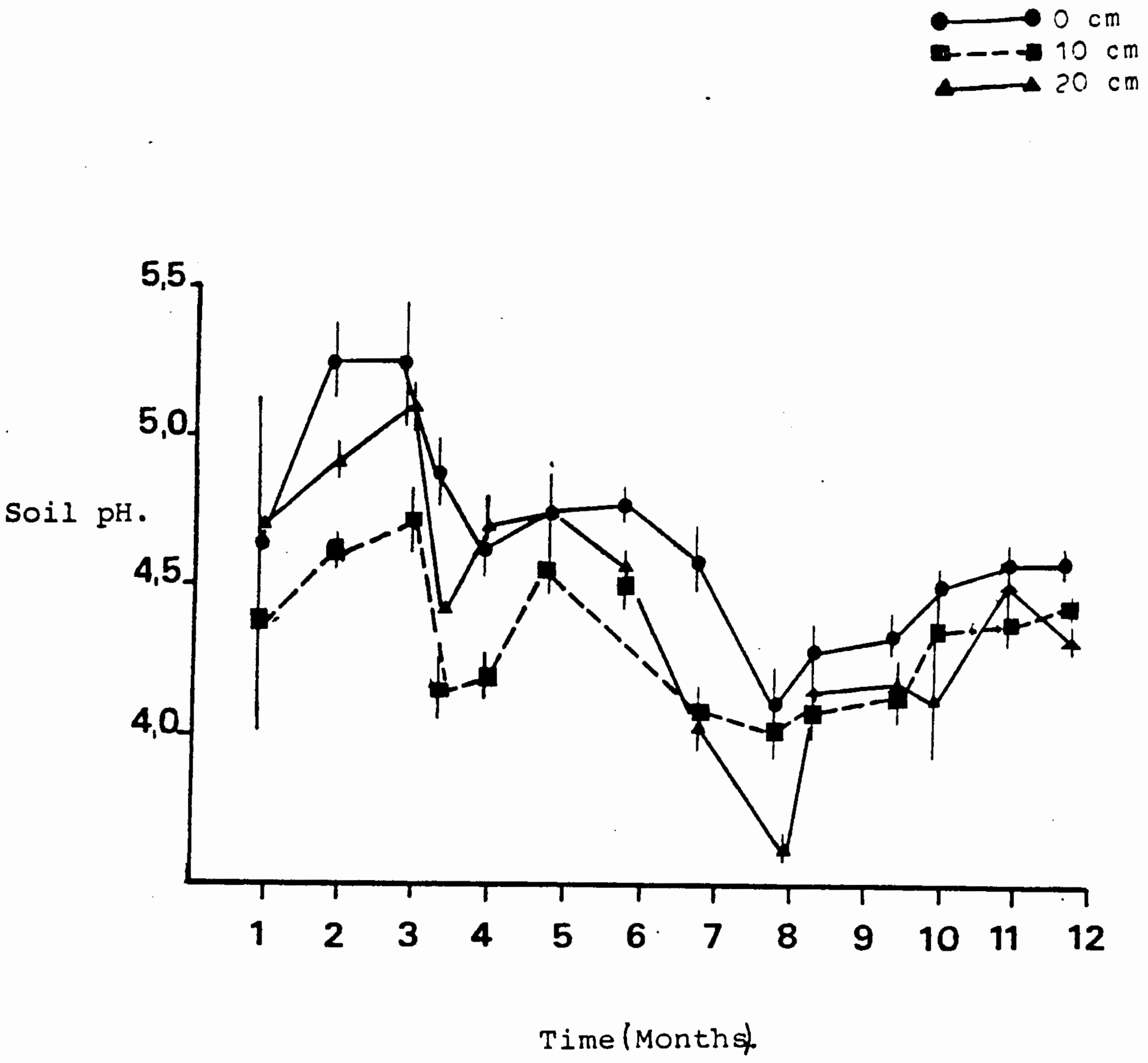


Fig.4:5. Levels of soil pH at 0, 10 and 20 cm depth in the soil profile for the post-fire period of twelve months. Values are means of 12 replicates at 0 cm and 8 replicates at 10 and 20 cm depth. Vertical bars represent twice the SEM.

Table 4:1. Organic matter, total and resin extractable phosphorus contents in the surface soil/litter component of the Clovelly soil form before and immediately after the fire.

	Organic matter(%)		Resin extractable P µg g^{-1} dry soil mass		Total P. µg g^{-1} dry soil mass	
	BEFORE	AFTER	BEFORE	AFTER	BEFORE	AFTER
Litter (>2mm)	7,3	13,3-51,2	1,4	7,1-9,4	150	170-175
Soil (<2mm)	4,32	8,9-15,3	1,4	2,9-11,9	40,3	42,0-66,2

The results are means of ten replicates.

4.2. Discussion.

Soil organic matter levels did not alter significantly after a fire either immediately or in the twelve months of the study. The destruction of the soil litter layer by fire and its consequent replacement with a layer of charcoal could not be detected by the gravimetric method of determination of soil organic matter. However this change may have had major effects on the soluble phosphorus status of the soils as levels of soluble phosphorus will be far higher in freshly deposited charcoal than in an old and possibly leached litter layer. The apparent lack of physical mineralisation of soil organic phosphorus within the range of soil temperatures reported by Taylor and Kruger (1978) for fynbos fires (150-380°C) indicates that this is not a contributing factor to the increase in resin extractable phosphorus after fire. Norton and McGarrity (1965) concluded that the soil temperatures of Australian native pastures measured in burns of pastures carrying normal cover suggested that fires of this type would be unlikely to have a direct effect on the chemical breakdown of soil compounds. This was extensively reviewed by Savage (1980).

Between 70-100% of phosphorus in above ground live biomass and litter mass in mountain fynbos at Jonkershoek Forest is returned to the soil following a burn accounting for an addition of between 0,59-6,47 kg phosphorus ha^{-1} (Van Wilgen and Le Maitre 1980). De Bano and Conrad (1978) found that fire in chaparral released disproportionately large amounts of nutrients from burnt plants. Destruction by fire of 66% of standing plant biomass and 46% of litter released 92% and 79% of stored phosphorus respectively. It appears that the soil's major source of available phosphorus immediately after a fire is organic matter added to the soil from burned vegetation and litter.

The increase in resin extractable phosphorus only occurs within the surface 2-3 cm of the soil and remains for a limited time. After 18 weeks the high levels had begun to decline and after 12 months of observation the levels had dropped to twice the pre-fire levels. The levels of resin extractable phosphorus found in Clovelly soil beneath vegetation burned five years previously were only slightly higher than those in pre-fire Clovelly soils (Brown, unpublished data). Wagle and Kitchen (1972) reported similar changes in available phosphorus levels after burning a stand of ponderosa pines, after three years the levels were still slightly higher than those of the unburnt plots.

The fluctuations observed in the first month of this study (See Fig 4:2) appear to be due to periodic rains. High rates of precipitation followed by warm days were associated with high levels of resin extractable phosphorus. This may be due to phosphorus released from plant material by pyrolysis and present in the soil in high concentrations after the fire undergoing microbial mineralisation. Fire causes the soil environment to become more favorable for mineralisation processes by micro-organisms as the pH increases, nutrients and organic matter become more plentiful and possible toxins are removed (Christensen and Muller 1975).

At Pella, Coley and Mitchell (1981) reported increases in the soil pH to 8,00 after the fire. These alkaline conditions stimulated bacterial growth which peaked after 2-3 weeks at the surface and then declined as the pH returned to its previous level. This increase in bacterial numbers could possibly have the effect of raising the rate of microbial mineralisation of organic phosphorus within the soil. Rundel (1982) stated that the degree to which pH is raised and the duration of time of these elevations is a function of a number of variables including the amount and chemical composition of ash produced by the fire, soil organic matter content and its buffering capacity, pH and precipitation. The pH shifts recorded in this study were slight (Fig.4:5.) when compared to those of Coley and Mitchell (1981) who worked in an adjacent area which was more heavily vegetated prior to the fire. The size of these shifts is probably due primarily to factors associated with the sparseness of the vegetation on the study site and the low soil organic matter content.

The total phosphorus levels within the soil would not be expected to increase to a large extent immediately after the fire, the majority (75-82%) of the total phosphorus input was in the >2mm fraction of the soil which are excluded from analysis (Table 4:1.). The lack of significant change in total phosphorus levels immediately post-fire observed in this study was also reported in soils beneath ponderosa pines destroyed by fire (De Bano and Conrad 1978). They reported a slight decrease in total phosphorus levels in the surface 2 cm of the soil immediately after fire. However they reported a significant increase in phosphorus in the ash/litter layer which compensated for this loss. They were not able to offer an explanation for this decrease but volatilization of phosphorus was not thought to be likely (Wells 1971).

The major influence of fire on phosphorus cycling in soils at Pella appears to be an elevation of the resin extractable phosphorus levels in the surface soils. This influence operates for only a short span of time and apparently only in the upper layers of the soil. The long term effects of fire on soil phosphorus levels and plant growth need to be examined closely in order to evaluate any permanent or semi-permanent changes that may be brought about in the soil by fire.

5. Fractionation of Soil Phosphorus.

It is necessary in any study on phosphorus cycling to determine the size of the various pools of phosphorus within the soil. Traditionally only the forms of inorganic phosphorus have been considered to be plant available. The role of organic phosphorus within the soil has often been overlooked chiefly because the greater part of total phosphorus in cultivated mineral soils is in the inorganic form (Dalal 1977). However organic phosphorus content of uncultivated soils varies considerably from as low as 4% of the total phosphorus content of podsolic soils to 85-90% under pasture species (Williams 1980).

The availability of organic phosphorus compounds for plant uptake has been demonstrated in various soils (Abbott 1978, Dalal 1977 and Jeffrey 1964). In a soil of low nutrient status such as the Clovelly soil form at Pella, the organic phosphate pool may be significant. The distribution of phosphorus within the organic and various inorganic pools is indicative of the weathering stage of the soil and can be used to determine its approximate age (Smeck 1973).

5.1. Organic Phosphorus.

Organic phosphorus was extracted from the Clovelly soil form using the method of Anderson (1960) and Steward and Oades (1972) and the ignition method of Legg and Black (1965). Organic phosphorus was expressed as a percentage of dry soil mass and total phosphorus levels (Fig. 5:1 and 5:2) The levels of carbon, nitrogen, organic matter, pH and total phosphorus levels are shown in Table 5:1. There was no correlation between organic phosphorus

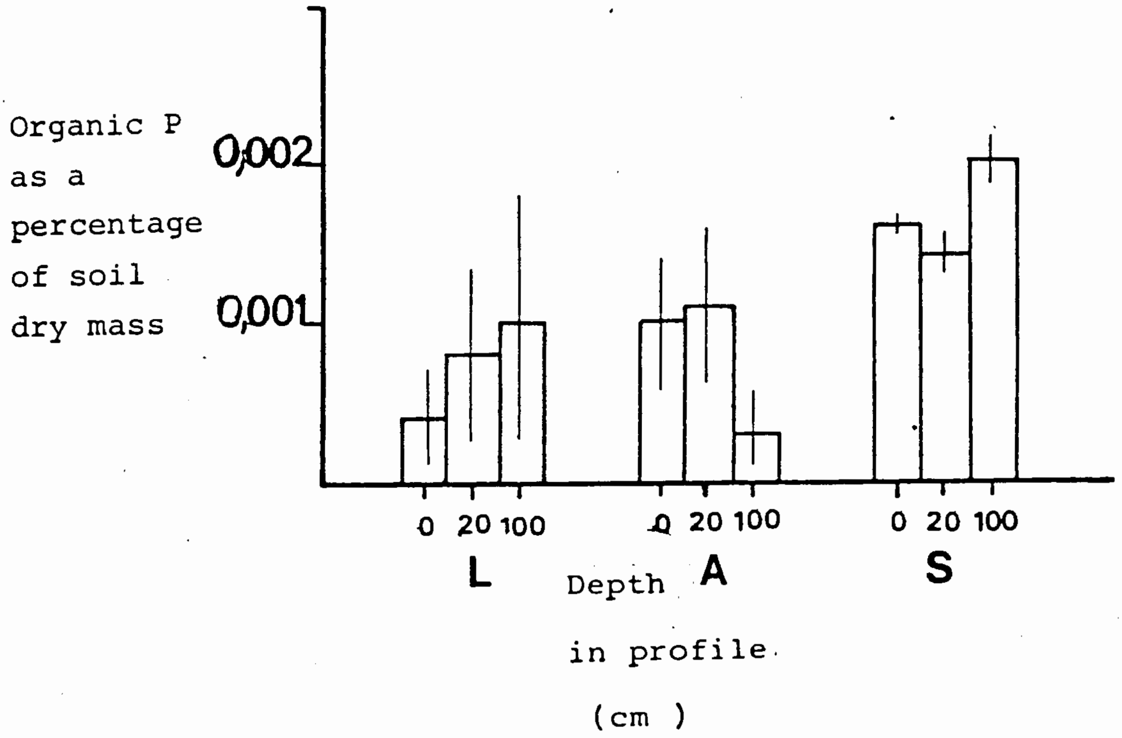


Fig.5.1. Organic phosphorus levels as a percentage of dry soil mass of Clovelly soil collected at 0, 20 and 100 cm depths in profile. Each value is a mean of 7 replicates. From soil samples collected in June 1979. Vertical bars represent twice the SEM.

L Legg and Black (1965)

Ignition Method.

A Anderson (1960)

Extraction Method.

S Steward and Oades (1972)

Extraction Method.

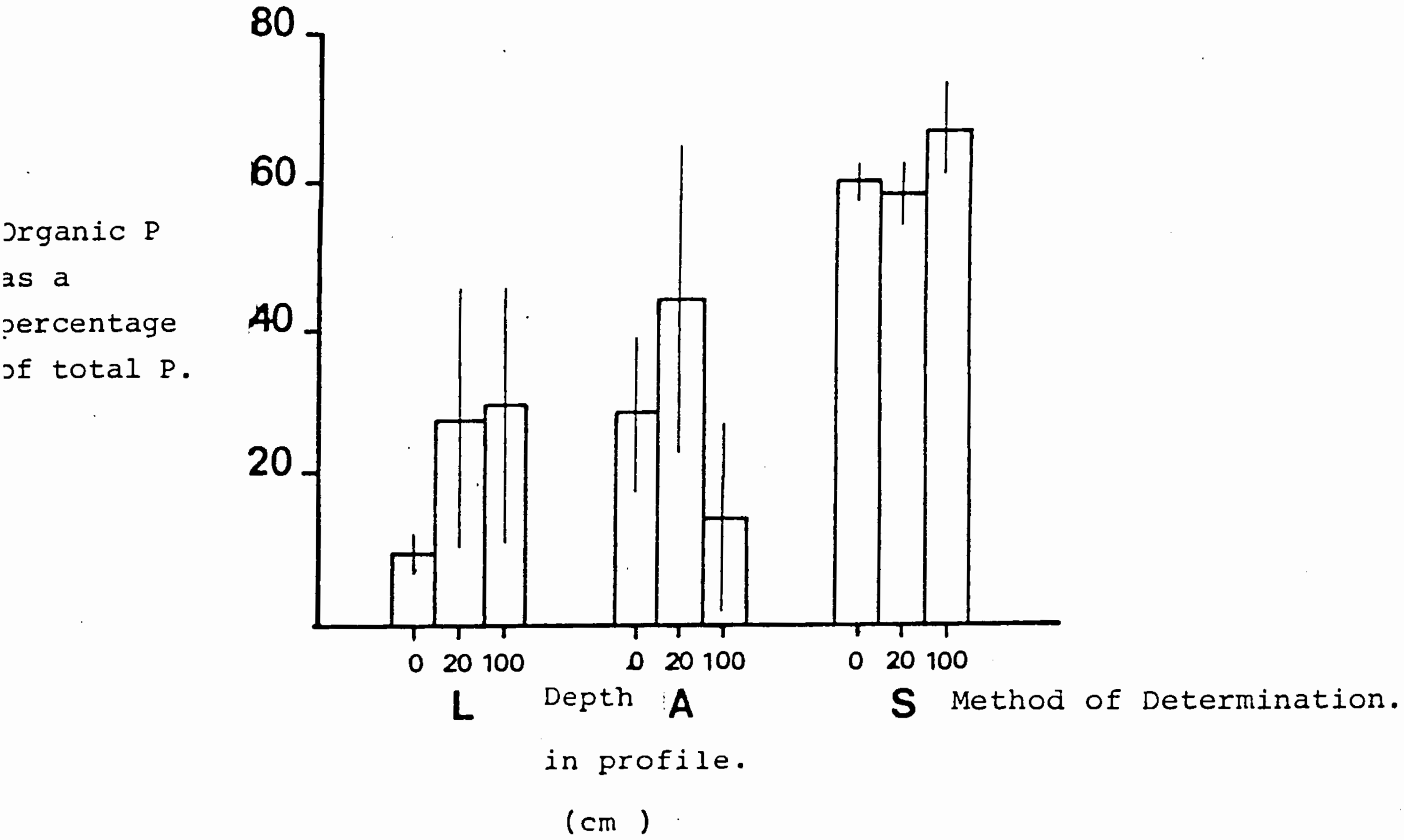


Fig.5:2. Organic phosphorus levels as a percentage of soil total phosphorus from Clovelly soil at 0,20 and 100 cm depths in the soil profile. Each value represents a mean of 7 replicates per depth, vertical bars represent twice the SEM. From soil samples collected in June 1979.

Key.

L Legg and Black (1965)
Ignition Method.

A Anderson (1960)
Extraction Method.

S Steward and Oades (1972)
Extraction Method.

Table.5:1. Carbon(C), nitrogen(N), organic matter(OM), pH total soil phosphorus and soil iron levels in the Clovelly soil form at 0, 20 and 100 cm depths.

					$\mu g, g^{-1}$ dry soil	
Depth	C%	N%	OM%	pH	Total P.	Iron
0 cm	1,05	0,056	1,19	3,98	33,87	1677
20 cm	0,426	0,028	0,90	4,02	26,31	1715
100 cm	0,227	0,011	0,43	4,55	32,92	1808

levels expressed as µg P g^{-1} dry soil mass and nitrogen and carbon levels in the soil. There was, however, a positive correlation using a multiple linear regression (R=0,71;df=20;$P<0,01$) between organic phosphorus levels determined using the Steward and Oades (1972) extraction method expressed as a percentage of total phosphorus and the nitrogen and carbon levels within the soil. The ratios of C:N:Organic phosphorus obtained in these trials are shown in Table 5:2. There was no significant change in the percentage of organic phosphorus of the total soil phosphorus down the profile using the Steward and Oades (1972) extraction method. However the C:N:Organic phosphorus ratios did increase significantly from 18,7:1:0,32 at the soil surface to 20,7:1:1,97 at 100 cm depth.

5.2. Inorganic Phosphorus.

The size of various fractions of inorganic phosphorus and organic matter and iron content at 0, 20 and 100 cm depth in the Clovelly soil are summarised in Fig.5:3. and Table 5:1. The greatest proportion of inorganic phosphorus was in the iron bound form (67-71% of the total inorganic fraction). The other forms of inorganic phosphorus ranged in values from 4 to 8% of total inorganic phosphorus. At all depths the levels of iron bound phosphorus were significantly higher than the other fractions using one way analysis of variance (F=18,96;df= 5,35;$P<0,001$ at 0 cm; F= 34,47; df= 5,35;$P<0,001$ at 20 cm and F= 69,26;df=5,35;$P<0,001$ at 100 cm). There was no significant change in the size of any of the phosphorus fractions down the soil profile. The levels of iron within the soil ranged from 1,5 to 2,5 mg Fe g^{-1} dry soil mass (Table 5:1).

Table 5:2. Ratios of carbon:nitrogen: organic phosphorus in the Clovelly soil form at 0, 20 and 100 cm depths using the two extraction methods (Anderson 1960 and Steward and Oades 1972) and the ignition method of Legg and Black (1965).

Depth	A	B	C
0 cm	18,75:1:0,11	18,75:1:0,17	18,75:1:0,32
20 cm	15,21:1:0,32	15,21:1:0,53	15,21:1:0,57
100 cm	20,64:1:0,92	20,64:1:0,36	20,64:1:1,97

Method of Determination.

A. Legg and Black (1965).

B. Anderson (1960).

C. Steward and Oades (1972).

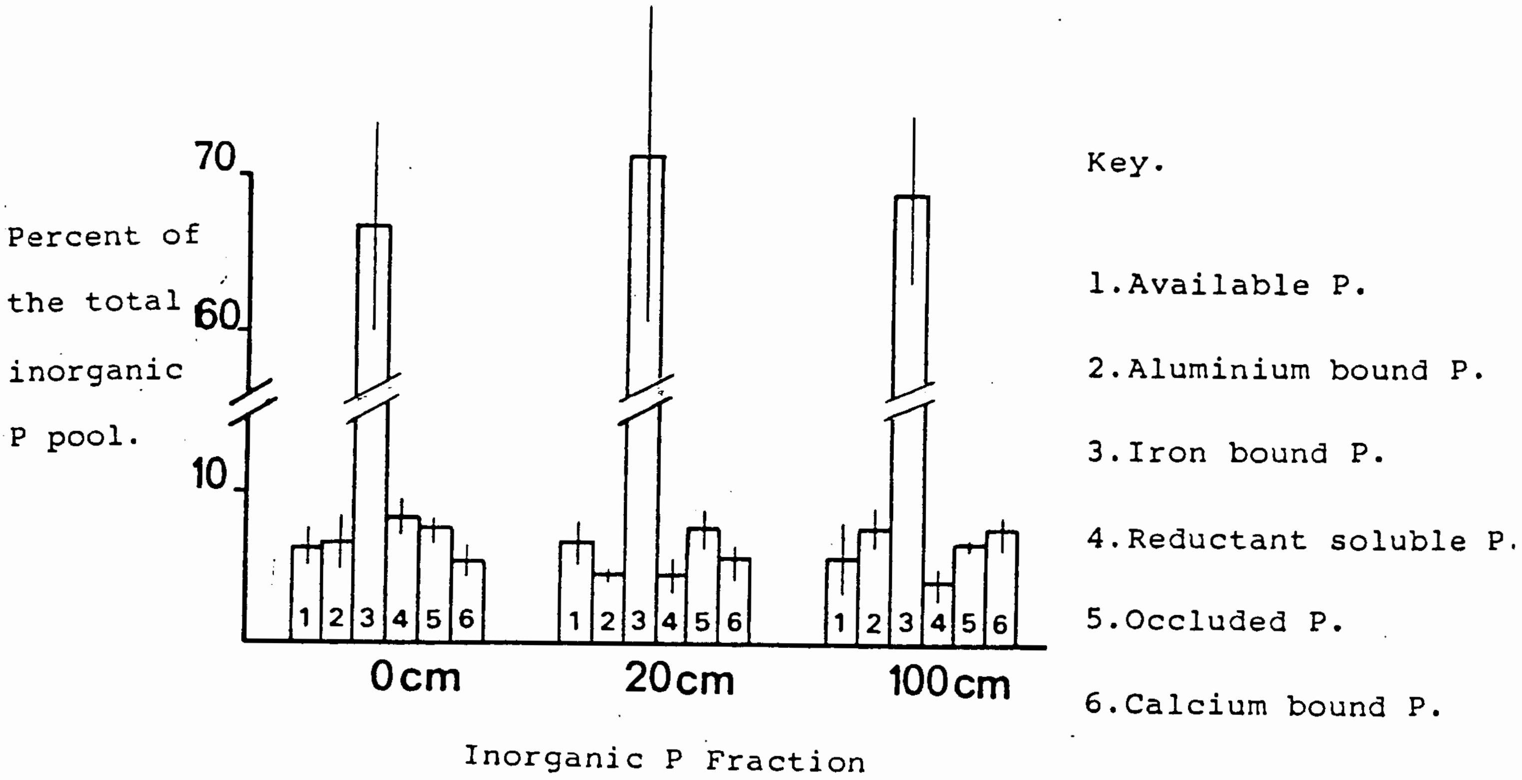


Fig.5:3. Inorganic phosphorus fractions at 0, 20 and 100 cm depths in the Clovelly soil form. Each value represents a mean of 7 replicates at each depth. Samples collected in June 1979. Vertical bars represent twice the SEM.

5.3. Discussion.

The different methods of extraction of soil organic phosphorus yielded three different sets of results and it was necessary to determine which of these methods most accurately represented the actual levels within the Clovelly soil. The levels of organic phosphorus yielded by the Steward and Oades (1972) extraction were more consistent between replicates than results of either of the other methods. Both the method of Legg and Black (1965) and that of Anderson (1960) yielded negative values (ie. the soils contained more inorganic than total phosphorus) in several of the samples. The levels of organic phosphorus yielded by the Steward and Oades (1972) extraction when expressed as a percentage of the total phosphorus were within the range obtained globally in soils (Williams and Walker 1967, Williams et al. 1970, Dalal 1977, Syers and Walker 1969a, Bornemisza and Igue 1967, Guttierez Jerez et al. 1979). Using multiple linear regression analysis, it was possible to demonstrate positive correlation between nitrogen, carbon and organic phosphorus as a percentage of total phosphorus obtained when using the Steward and Oades (1972) extraction. This correlation has been demonstrated in other less oligotrophic soils (Dalal 1977, Walker and Adams 1958, Williams et al. 1970). This was taken as an indicator of the greater veracity of the Steward and Oades (1972) extraction in the soils of the Pella site compared with the method of Legg and Black (1965) and Anderson (1960). All three methods of extraction have been criticized.

The ignition method now appears to be widely condemned (Hesse 1971, Dalal 1977, Anderson 1960, Steward and Oades 1972) and its major weakness is that the solubility of native inorganic soil phosphorus is increased on ignition and soil organic phosphorus is generally overestimated (Hesse 1971). Bornesizma and Igue (1967) reported that this method underestimated levels of organic phosphorus as a result of the formation of aluminium phosphates in high sesquioxide soils during ignition. Williams et al. (1970) stated that the method suffered from the incomplete oxidation and volatilization of organic phosphorus during ignition and incomplete extraction of mineralised organic phosphorus. This latter problem also occurs in Andersons' (1960) method (Steward and Oades 1972). This method also entails long and tedious extraction procedures. The method of Anderson (1960) uses a very large solution:soil ratio and this combined with the very low levels of total phosphorus within the soil makes accurate quantitative analysis of phosphorus within the samples very difficult. The extraction method developed by Steward and Oades (1972) using ultrasonic vibrations to break up colloidal particles required a considerably reduced solution:soil ratio. A shorter time of analysis was involved resulting in a higher phosphorus concentration within the soil extracts. The major criticism of the Steward and Oades (1972) method is that the sodium hydroxide used as an extractant can cause the hydrolysis of organic phosphorus (Dalal 1977). The alternative is the use of acetylacetone as an extractant but this has been found to be an inefficient method (Anderson 1960). Therefore it was assumed that the results obtained for organic phosphorus levels using the Steward and Oades (1972) extraction method most accurately represented the true organic phosphorus status of the Clovelly soil form.

The fractionation of inorganic phosphorus by the Chang and Jackson (1957) method has been criticised (Fife 1959, Bache 1963, 1964, Saunders 1959, Khin and Leeper 1960 and Smith 1965) and has undergone many modifications (Chang and Jackson 1958, Williams and Walker 1969a). The modified procedure of Williams et al. (1967) appears to be the most effective and the residue in the soil after extraction was found to compose largely of organic phosphates. Criticisms have been made about the entire chemical fractionation technique (Larsen 1967, Hesse 1971). The reagents involved in the extraction may cause a redistribution of phosphorus during the extraction (Larsen 1967). The assumption by Chang and Jackson (1958) that aluminium and ironbound phosphorus in the soil was in the form of discrete crystalline phases such as variscite and strengite has been queried (Bache 1963, 1964, Williams and Walker 1969b). The alternative'dispersed phosphorus' theory (Williams and Walker 1969b) regards aluminium and iron-bound phosphorus in soils as consisting of phosphate ions chemisorbed onto the surfaces or occluded within the matrices of phosphate-retaining soil components such as either gibbsite, goethite or amorphous alumino silicates.

The organic phosphorus levels in Clovelly soil, expressed as a percentage of the soil dry mass are very low when compared with soils of higher total phosphorus status (Perez Mendez et al. 1979, Williams and Walker 1967, Chater and Mattingly 1979, Bornezisma and Igue 1967). When organic phosphorus is expressed as a percentage of total phosphorus the proportion of the total phosphorus in the organic form is high (58-60%). The C:N:Organic phosphorus ratios in the Clovelly soil form at Pella showed a lower N:Organic phosphorus and higher C:N ratio when compared to New Zealand (Walker and Adams 1958, 1959) and Indian soils (Mehta et al. 1971).

The Clovelly soil form is a weathered acidic sandy soil of moderate iron content. It is expected that the major fraction of inorganic insoluble phosphorus would be in an iron bound form

(Chang and Jackson 1958, Williams Syers and Walker 1967), and is the slightly soluble sodium hydroxide extractable iron phosphates precipitated on iron oxides . This fraction is evenly distributed throughout the profile and accounts for 65-70% of the inorganic insoluble soil phosphorus. The less available reductant-soluble iron-bound phosphate occluded within iron oxides (Chang and Jackson 1958) occurs in similar proportions to the other minor fractions (4-8% of the total inorganic phosphorus).

The calcium phosphate extracted is probably hydroxylapatite as all other forms of calcium phosphate are dispersed at low pH values (Larsen 1967). In the pH range 3-7 a stable alumino hydroxyl phosphate forms a surface complex on more soluble minerals eg.variscite (Bache 1963) and this is probably the major form of aluminium bound phosphorus at Pella. Iron tends to form soluble iron hydroxyl phosphates in freely draining soils and the amorphous and crystalline iron oxides are correlated with phosphate adsorpton (Kuo and Mikkelson 1979). Phosphorus adsorbed onto these compounds is generally considered to be labile.

The predominance of iron bound phosphates may be an indication of the degree of soil weathering (Smeck 1973, Westin and de Brito 1969, Williams and Walker 1969a). As the soil is weathered, the pH declines (Larsen 1967, Choudari et al.1977, Williams and Walker 1969a) with a corresponding decrease in the size of the calcium bound phosphorus pool and an increase in the importance of the aluminium and later iron bound phosphorus fractions. The phosphorus released from calcium products is initially mainly taken up by aluminium hydroxides but this is eventually converted partially or wholly to iron bound phosphorus (Hsu 1964). These processes are so regular and predictable that the degree of their occurrence has been used to determine the amount of weathering that a soil has undergone (Smeck 1973).

Chang and Jackson (1958) stated that the drift from aluminium to iron bound phosphorus was a result of the higher solubility products of iron phosphates. This implies that the relative amounts of aluminium and iron bound phosphorus are influenced by soil maturity more than by soil composition. This interpretation of the data was questioned by Williams and Walker (1969b) who pointed out that a nutrient poor soil (such as the ones under investigation) would not support a level of phosphate in the soil of sufficient size to initiate the precipitation of either variscite or strengite. They proposed that this behaviour of aluminium and iron in the soil is more readily accounted for qualitatively in terms of the dispersed phosphate theory which predicts that secondary inorganic phosphate is distributed between the various soil mineral phases in amounts directly related to the phosphate retaining capacity of the soil which is, in turn, related to the size of aluminium and iron pools within the soil.

6. Variations in Phosphorus Levels in Plant Rhizospheres.

Phosphorus is essentially an immobile element within the soil and levels of soluble phosphates are quickly depleted within the rhizosphere of active root systems (Larsen 1967). The extent of this depletion will be related to the rate of active phosphorus uptake by the plant and its rate of diffusion within the soil. This chapter evaluates the total and available phosphorus pools as well as soil pH and organic matter within the rhizosphere of four representative plant species (P.cephalantha, S.distachya, P. repens and L.parile) growing on the Clovelly soil form.

6.1. Results.

The rhizosphere levels of total, resin extractable and Bray#2 extractable phosphorus are shown in Fig 6:1, 6:2 and 6:3. There were no significant differences in total and Bray#2 extractable phosphorus levels between the rhizosphere soils of the four species. One way analysis of variance showed that resin extractable phosphorus levels varied significantly between the various rhizospheres ($F= 3,96$; $df= 4,24$; $P<0,05$). Very low levels of resin extractable phosphorus ($0,25-0,5$ $\mu g\ g^{-1}$ dry soil) were encountered within the ericoid (ie. P.cephalantha) and restioid (ie.S.distachya) root zones while the proteoid (ie.L.parile and P.repens) and open areas had similar levels of resin extractable phosphorus of 2-3 $\mu g\ g^{-1}$ dry soil. There were no significant differences in the pH and organic matter levels of the different rhizospheres (Figs 6:4 and 6:5). There was no correlation between resin extractable phosphorus and either pH or organic matter.

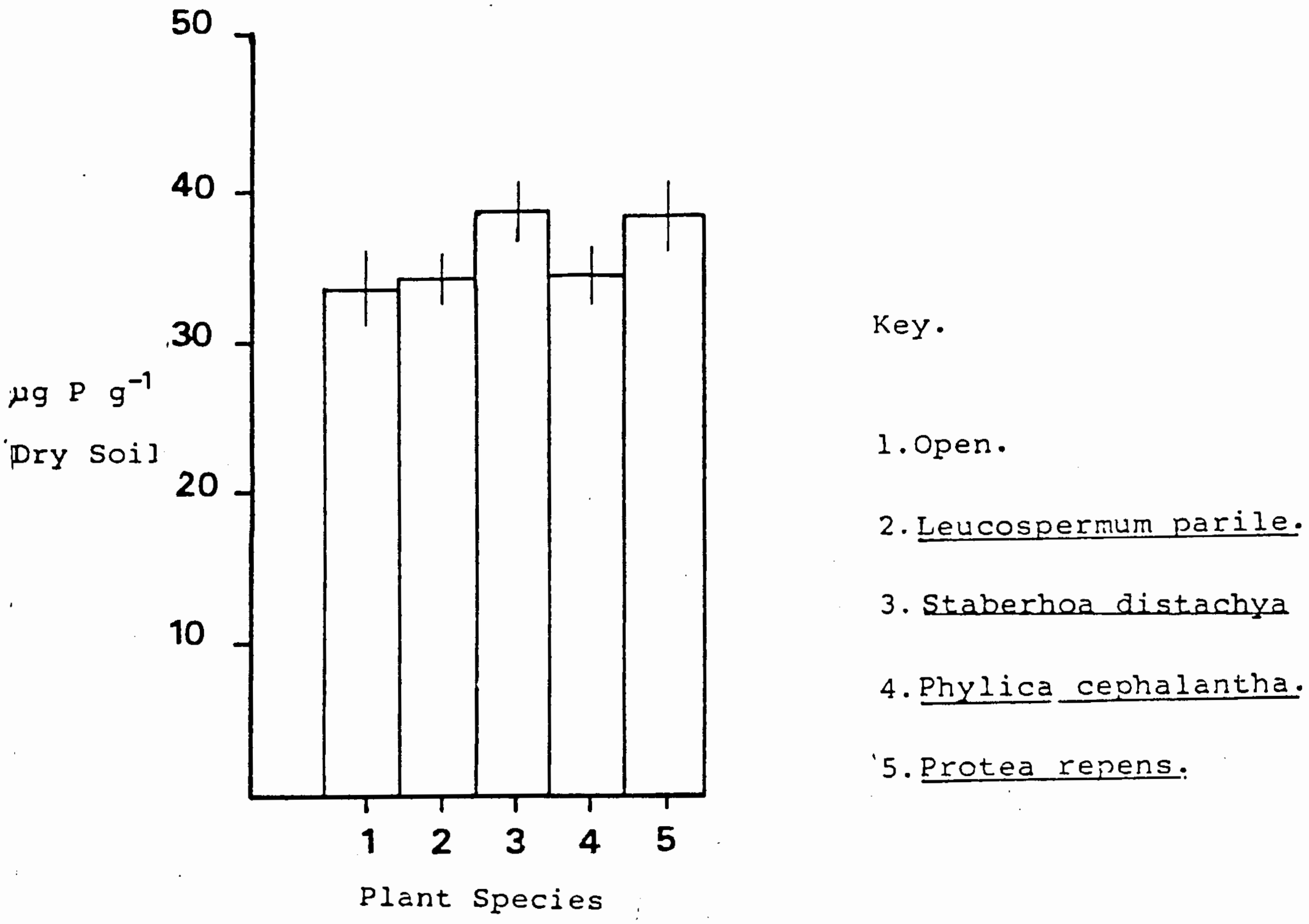


Fig. 6:1. Levels of total soil phosphorus found within the rhizosphere zones of four fynbos species grown on Clovelly soil plus an open site. Values are means of 6 replicates, Vertical bars represent twice the SEM.

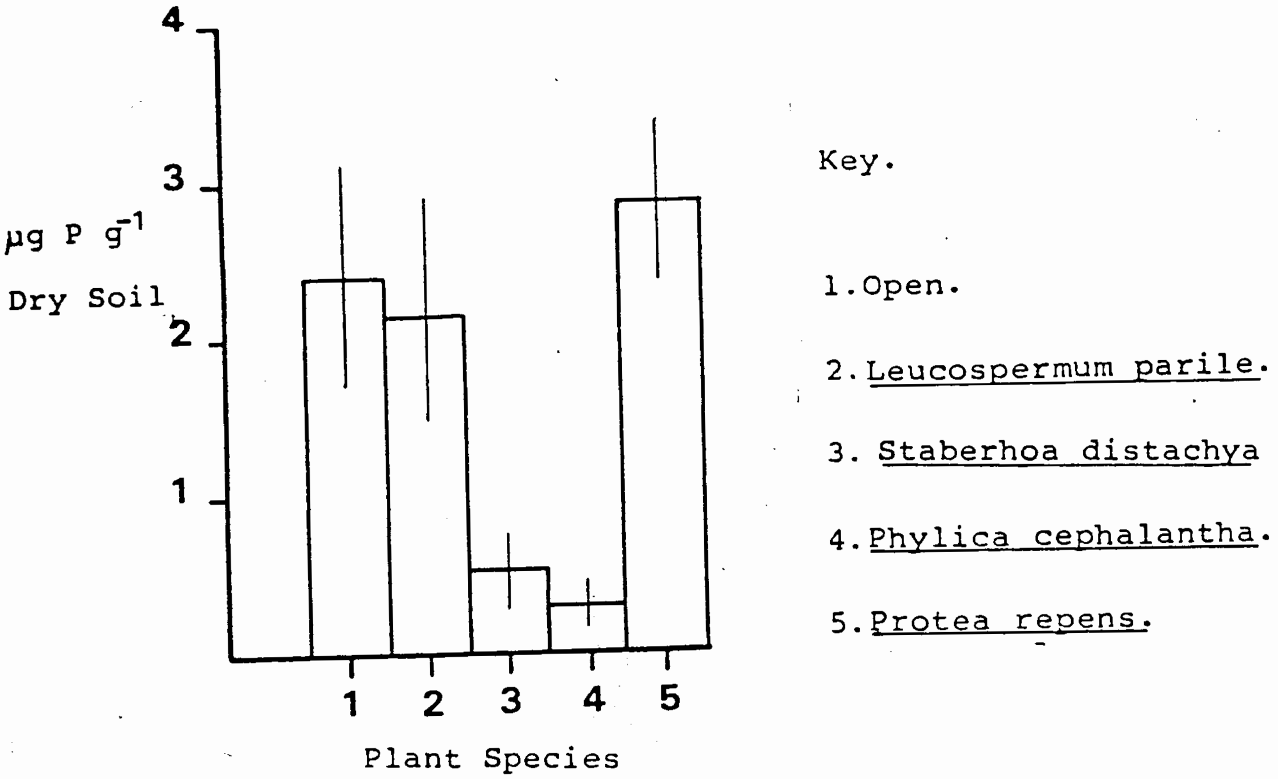


Fig. 6:2. Levels of resin extractable phosphorus found within the rhizosphere zones of four fynbos species grown on Clovelly soil plus an open site. Values are means of 6 replicates. Vertical bars represent twice the SEM.

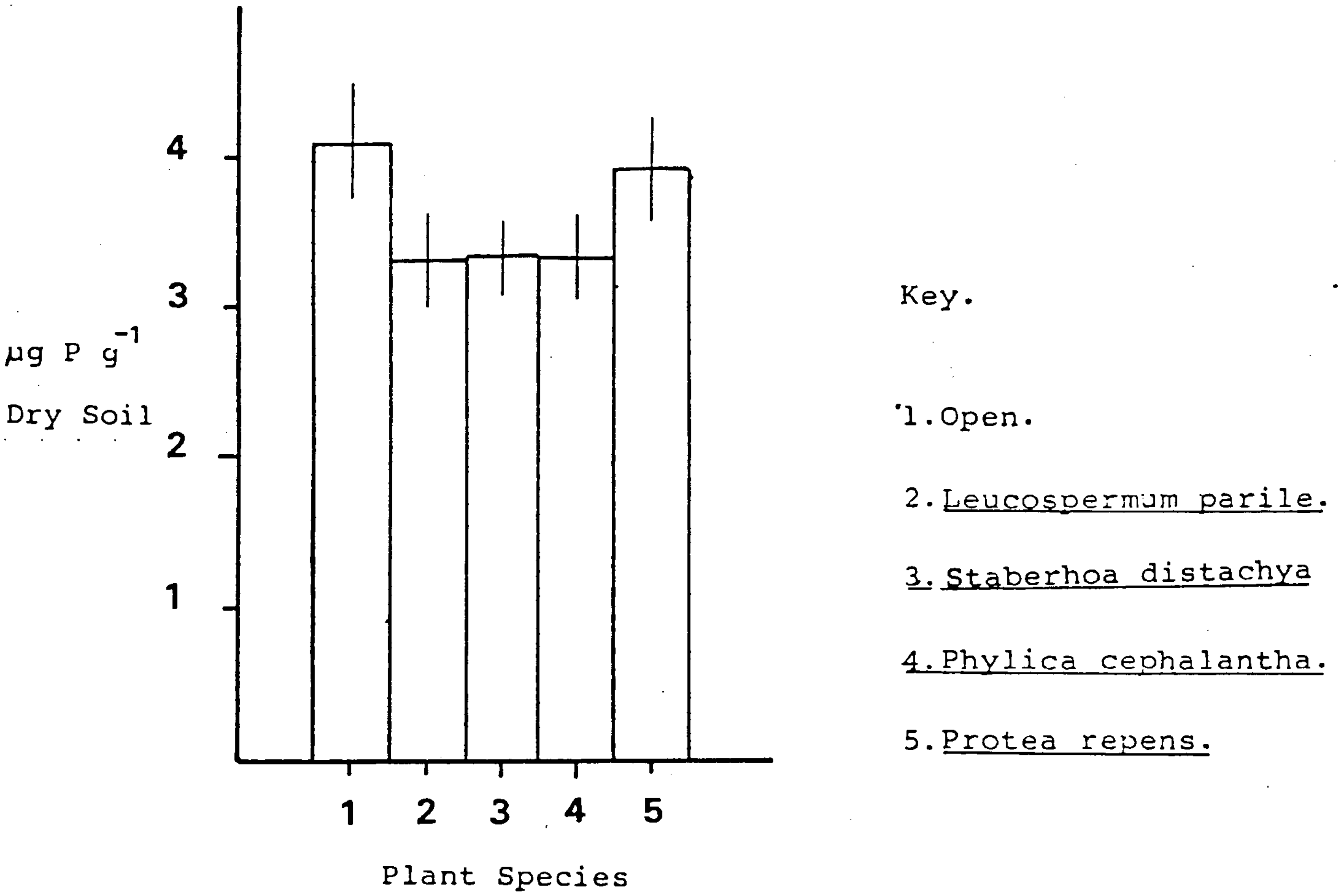
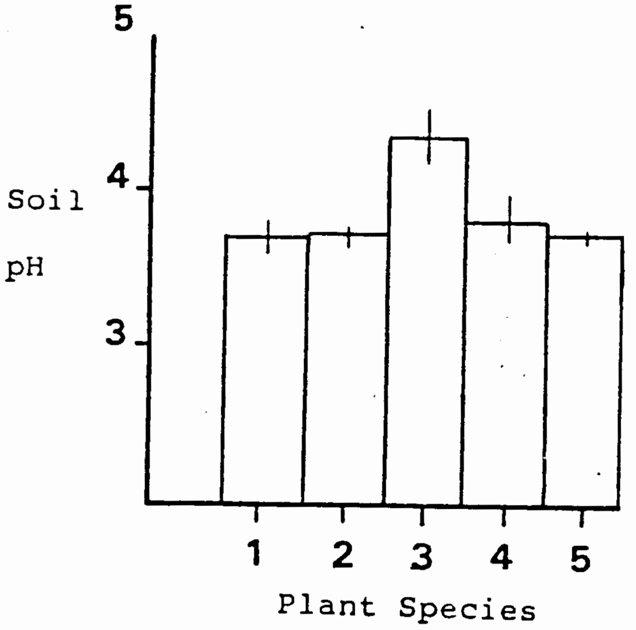


Fig. 6:3. Levels of Bray#2 extractable phosphorus found within the rhizosphere zones of four fynbos species grown on Clovelly soil plus an open site. Values are means of 6 replicates. Vertical bars represent twice the SEM.



Key.

1. Open.
2. *Leucospermum parile*.
3. *Staberhoa distachya*
4. *Phylica cephalantha*.
5. *Protea repens*.

Fig. 6:4. Soil pH found within the rhizosphere zones of four fynbos species grown on Clovelly soil plus an open site. Values are means of 6 replicates. Vertical bars represent twice the SEM.

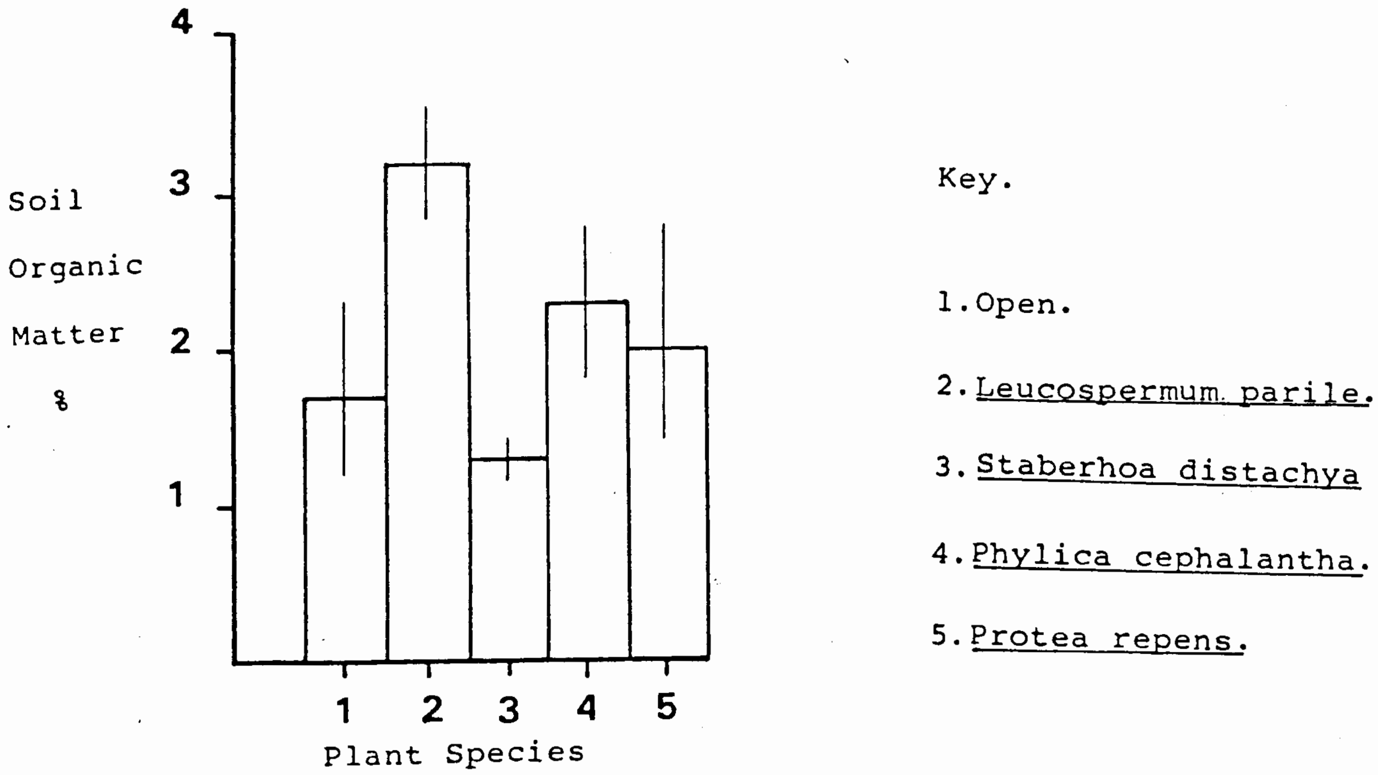


Fig. 6:5. Levels of soil organic matter found within the rhizosphere zones of four fynbos species grown on Clovelly soil plus an open site. Values are means of 6 replicates, Vertical bars represent twice the SEM.

6.2. Discussion.

The lower levels of resin extractable phosphorus observed in the rhizosphere zone of the restioid and ericoid elements may be the result of either lower rates of replenishment or greater removal of the soluble phosphorus pool by the root systems. As phosphorus movement through the soil is very slow (Russell 1973) with diffusion rates of only 10 μm day^{-1} in dry oligotrophic soils (Bieleski 1976), then soluble phosphorus levels are lower in the rhizosphere than the non-rhizosphere regions. The lower levels of resin extractable phosphorus within the rhizosphere may therefore be an indication of active phosphorus uptake by plant roots and consequently root growth. The root systems of the restioid and ericoid elements of the vegetation have not been studied as thoroughly as those of the proteoid elements. Restioid elements have been described as having capillaroid roots (Lamont 1982) and the ericoid elements may have endotrophic mycorrhizas (Mitchell pers.comm.).

7. Soil Survey,

A major emphasis at the Pella site has been the study of the chemical and physical properties of the Clovelly soil form. This is not only the commonest soil form encountered at the site (See Fig 2:1) but is also the mid-point in a weathering sequence of well- drained soils (See Chapter 2 for a full site description). However, the degree of interform variation in soil characteristics has not been determined and it is not known how representative the results obtained from the Clovelly soils are in relation to the other forms of the fynbos biome. Alaskan soils of similar structure to those encountered at Pella (ie.sandy, well- drained and highly leached) were found to exhibit great variability in chemical and physical properties within single soil landforms (Everett 1980). It was found that these variations were related to morphological features which in turn were strongly conditioned by site stability and drainage. As the Pella site exhibits topographical and corresponding hydrological variations (See Site Description Chap.2), the soils within the site may also exhibit significant variations in physical and chemical properties. This chapter evaluates inter and intra-form soil variations (See also Chap.9) and relates differences to the pedogenetic processes involved in their formation.

7.1. Results.

The results of the soil phosphorus survey carried out at the Pella Intensive study site in August 1980 are shown in Figs. 7:1, 7:2, 7:3, and 7:4. Levels of total and Bray#2 extractable phosphorus were low throughout with values ranging from 23-34 µg g dry mass of soil for

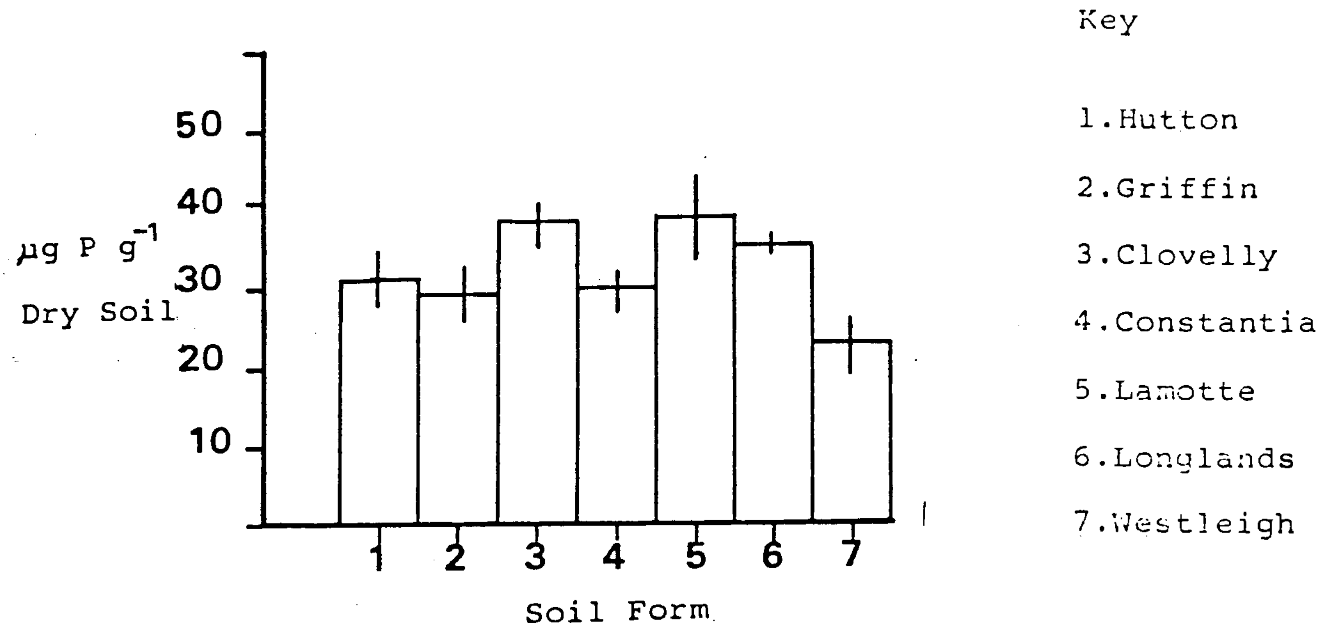


Fig.7:1.Levels of total soil phosphorus found in the different soil forms at Pella. Each value represents the means of three sites with 4 replicates per site. Vertical bars represent twice the SEM.

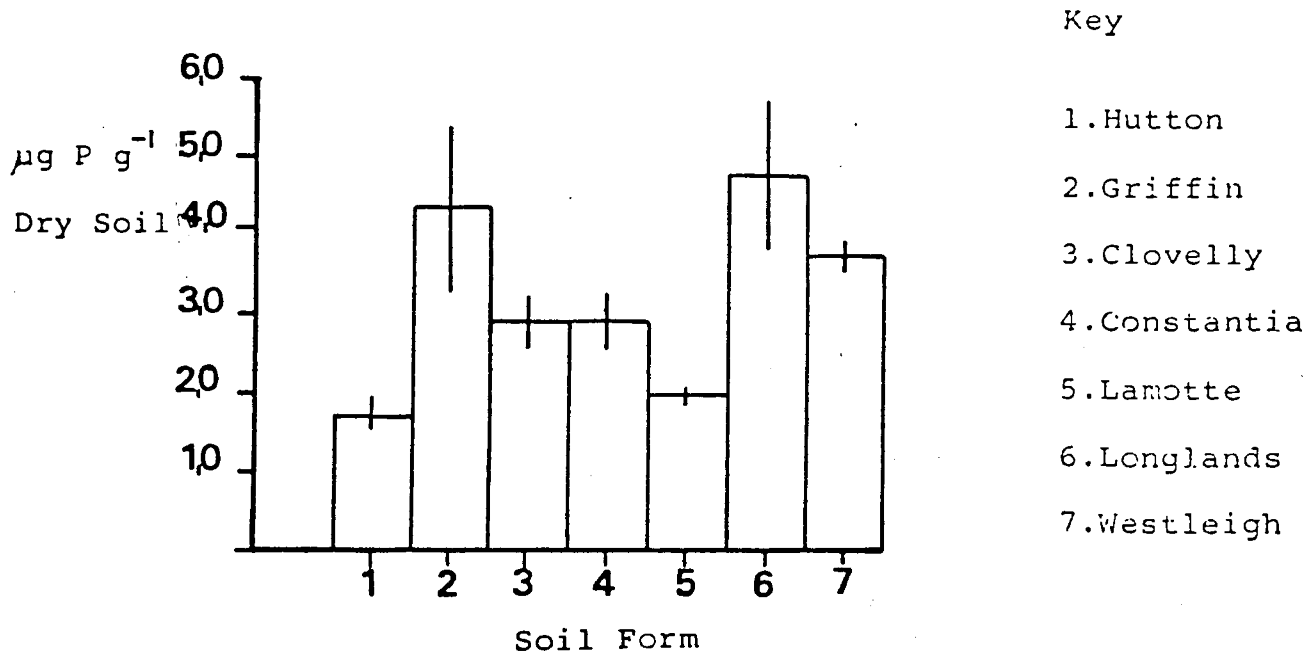


Fig.7:2.Levels of Bray#2 extractable phosphorus found in the different soil forms at Pella. Each value represents the means of three sites with 4 replicates per site. Vertical bars represent twice the SEM.

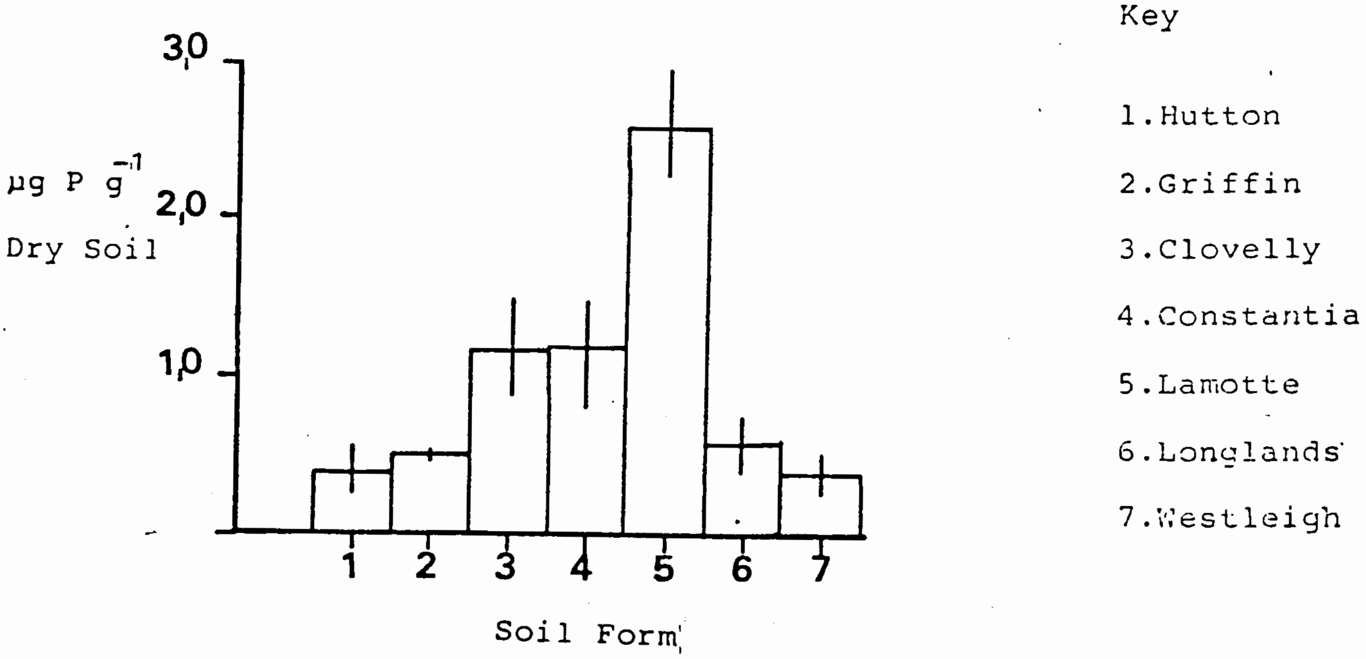


Fig.7:3.Levels of resin extractable phosphorus found in the different soil forms at Pella. Each value represents the means of three sites with 4 replicates per site. Vertical bars represent twice the SEM.

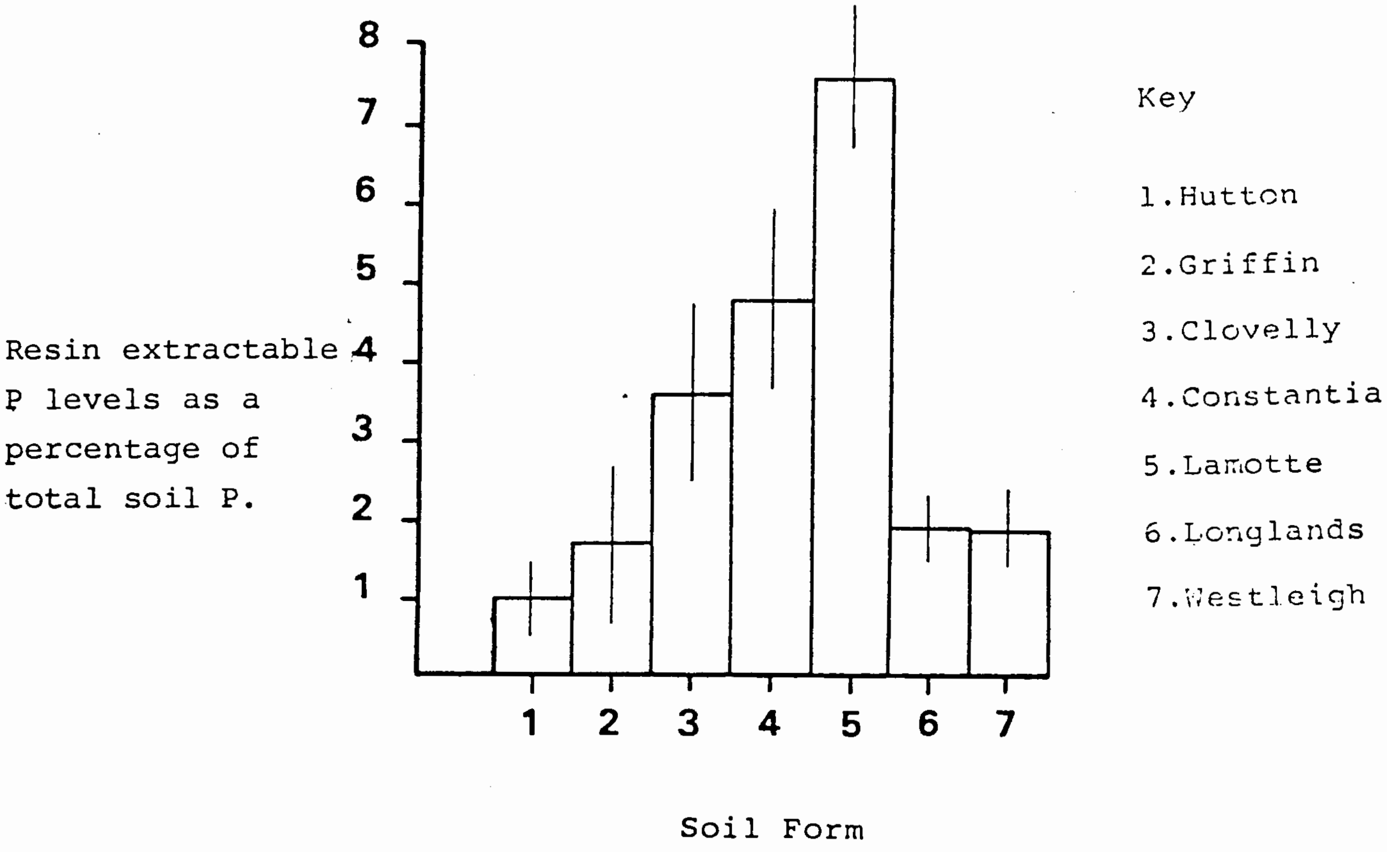


Fig.7:4.Resin extractable phosphorus as a percentage of total soil phosphorus found in the different soil forms at Pella. Each value represents the means of three sites with 4 replicates per site. Vertical bars represent twice the SEM.

total phosphorus (Fig 7:1) and 1,7 to 4,6 μg P g^{-1} dry soil mass for the Bray#2 extractable phosphorus (Fig 7:2). The soils were all acidic with pH values ranging from 4,5 to 4,8 and had organic matter levels of between 1,4% to 3,6% (Table 7:1). None of these values varied significantly between forms. Bulk density values were also similar (Table 7:1).

Resin extractable phosphorus levels changed significantly along the catina when compared using one way analysis of variance (F= 2,91; df= 6,32; $P<0,05$). Levels decreased from a maximum of 2,5 μg P g^{-1} dry soil in the Lamotte soil form to 0,4 μg P g^{-1} dry soil mass in the Hutton form (Fig 7:3). Despite these relatively large differences in resin extractable phosphorus levels in the soil, the overall values obtained are low. When resin extractable phosphorus levels are expressed as a percentage of the total soil phosphorus, this trend becomes more emphasized (Fig 7:4) with a decrease in values from 7,5% of total phosphorus in a resin extractable form within the Lamotte soil to slightly over 1% in the Hutton form. There was no correlation between either total phosphorus or Bray#2 extractable phosphorus levels with pH, organic matter, and soil iron levels of the soil forms investigated.

Soil iron levels varied significantly between forms when compared using one way analysis of variance (F=4,19; df=6, 32; $P< 0,05$), decreasing in a series along the weathering sequence discussed in Chapter 2 from 5,27 mg iron g^{-1} dry soil mass in the Hutton form to 2,14 mg iron g^{-1} dry soil mass in the Lamotte form (Table 7:1). Soil resin extractable phosphorus levels when expressed as a percentage of total phosphorus were found to be negatively correlated with soil iron levels (Fig 7:5). It appears that resin extractable phosphorus levels are correlated with the levels of iron within the soil and this relationship will be discussed in Chapter 10.

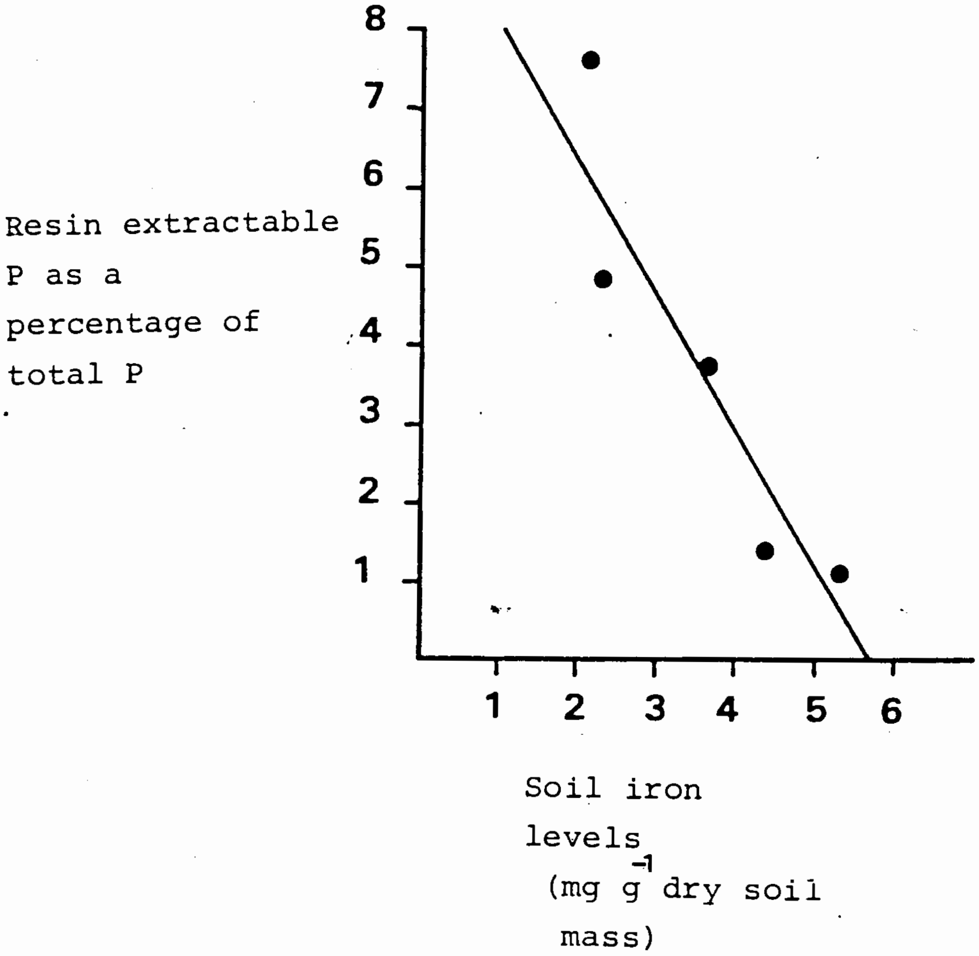


Fig.7:5. Resin extractable phosphorus levels expressed as a percentage of total soil phosphorus against total soil iron levels. Mean values obtained for each soil type from 3 sites with 4 replicates per site. The relationship is a linear one of the form $Y= 10{,}19 - 1{,}80X$ where X= soil iron levels and Y= resin extractable phosphorus levels within that soil with a correlation coefficient of $-0{,}93$ (df=4; $P<0{,}01$).

Table 7:1. Levels of soil iron (Fe), pH, organic matter (OM) and bulk density found in the seven soil forms present at the Pella site.

($\mu g\ g^{-1}$ dry mass.)

Soil type	Fe	pH	OM%	Bulk Density
Hutton	5267± 176	4,63± 0,2	1,44± 0,55	1.31
Griffin	4467± 570	6,63± 0,1	2,31± 0,04	1.37
Clovelly	3811± 400	4,77± 0,06	1,75± 0,28	1.39
Constantia	2288± 391	4,69± 0,12	1,76± 0,39	1.41
Lamotte	2140± 837	4,47± 0,08	3,35± 0,91	1.20
Westleigh	3333± 240	4,82± 0,07	2,16± 0,31	1.35
Longlands	1560± 460	4,57± 0,02	1,81± 0,01	1.35

7.2. Discussion.

This survey has shown that the very low phosphorus levels (both available and total) determined in the Clovelly soil form (See Chapter 3) occur throughout the study site. The levels of total phosphorus did not vary between soil forms. Sandy soils of similar structure and aeolian in origin in New Zealand showed losses of over 1900 kg ha^{-1} of phosphorus or over 40% of original phosphorus content over a 10 000 year period (Syers and Walker 1969a). Godfrey and Riecken (1954) working with loess derived soils concluded that a definite relationship exists between phosphorus quantity within a soil and the stage of soil development. The close similarity between these soil types with respect to chemical and physical characteristics examined (with the exception of soil iron levels) indicates a common origin and possibly similar pedogenetic history.

The two factors determining total phosphorus content of a soil are phosphorus content of the parent material (Smeck 1973) and the degree of leaching of the soil (Walker and Syers 1976). The Table Mountain Group sandstone parent material has a mean phosphorus content of approximately 300 $\mu g\ g^{-1}$ (Marchant and Moore 1978). The lower levels contained within the sandy soils at Pella indicates that considerable weathering has taken place (See Chap. 2). Low pH values and levels of soil iron may be indicative of a leached soil (Walker and Syers 1976) and a lack of calcium bound inorganic phosphorus would be expected to exist with these conditions (Hsu 1965). All of these conditions were found to exist at the Pella intensive study site. However, as these soils are of aeolian origin, it is not possible to speculate further about the correlation between total phosphorus levels and the degrees of weathering and leaching.

This study has shown a decrease in iron levels in the soil forms in the following order: Hutton, Griffin, Clovelly, Longlands, Constantia, Lamotte and Westleigh which, with the exception of the Longlands form, follows a weathering sequence (Lambrechts, pers comm.). This decrease is a diagnostic feature and can be used to distinguish the ages of soils of similar derivation and treatment (Smeck 1973, Westin and de Brito 1969, Williams et al. 1969). The Longlands and Westleigh soils did not behave in the same manner as the more freely draining soils, eg. Hutton, Griffin, Clovelly, Constantia and Lamotte. This behaviour as well as the adsorption and desorption characteristics of all the soil forms at the Pella site will be discussed further in Chapters 9 and 10.

8. Phosphorus Levels in Precipitation at Pella.

Rainwater is known to contain varying quantities of most of the dissolved ions which are essential for plant growth (Gray and Schlesinger 1981). The input of phosphorus from precipitation into ecosystems is generally assumed to be negligible ranging from 0,2 to 1,0 kg ha^{-1} yr^{-1} (Allen et al. 1968, Gore 1968, Gray and Schlesinger 1981). The origin of atmospheric phosphorus appears to be at least partly oceanic (Attiwell 1966). As Pella is only 23 km from the South Atlantic coast, phosphorus input to the Fynbos Biome Intensive Study Site from precipitation may be significant. This study was an attempt to evaluate the size and form of phosphorus input by atmospheric precipitation.

8.1. Results.

Variations of phosphorus input from precipitation and levels of rainfall from June 1980 to June 1981 are shown in Fig 8:1 and 8:2 respectively. Periods of high rainfall were generally associated with high phosphorus inputs and the annual deposition. of phosphorus from precipitation was estimated as 193,9g P ha^{-1} falling mainly between June and February. There was a linear correlation between rainfall volume and phosphorus input to the site (Fig 8:3) and a power curve relationship was obtained between rainfall and phosphorus concentration (Fig 8:4). The mean input of phosphorus to the site per mm of rain was 0,51 g ha^{-1}. The phosphorus concentration in the precipitation collected ranged from

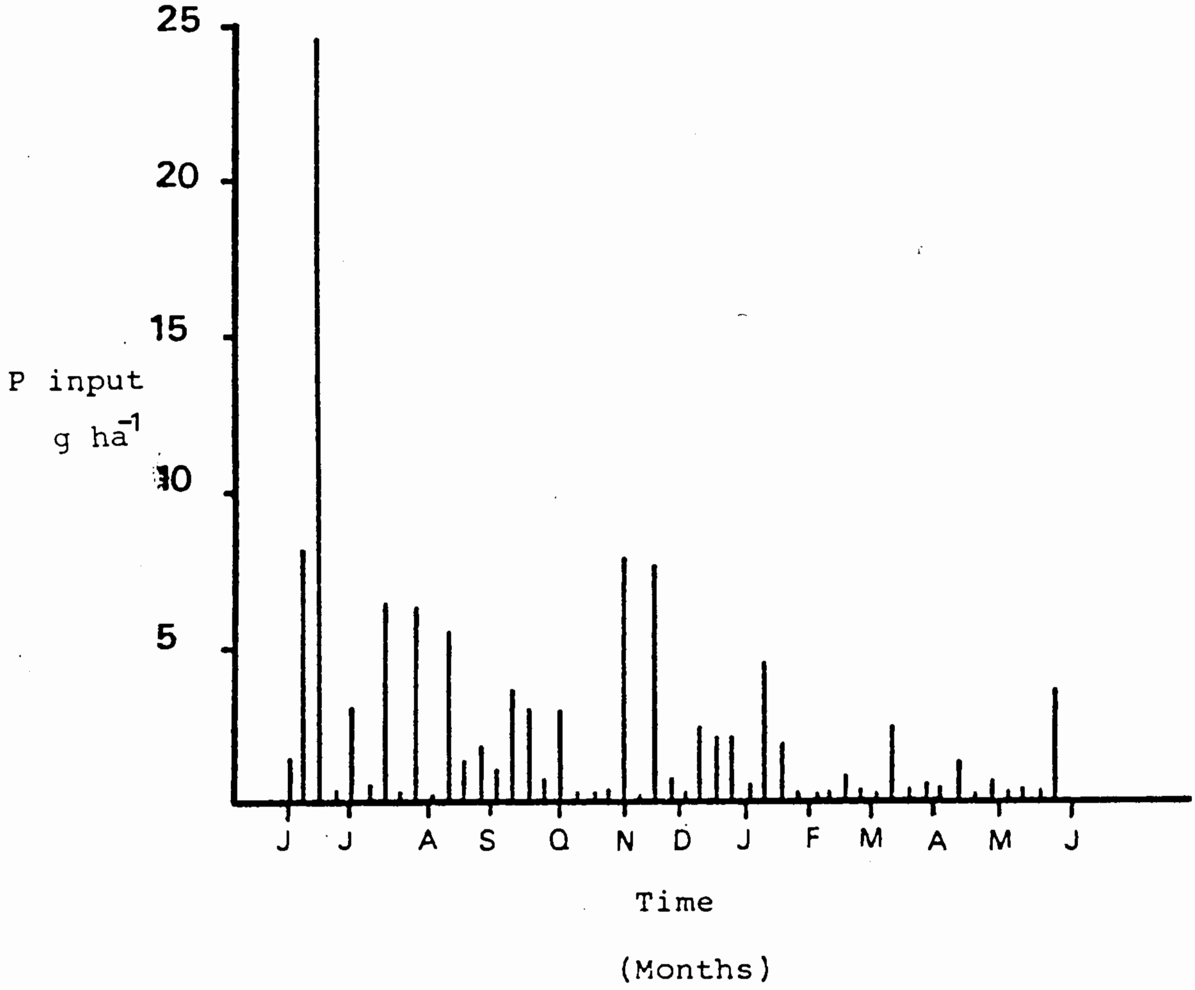


Fig.8:1.Phosphorus input into the Pella site from precipitation over a twelve month period from June 1980 to June 1981. Each value represents a mean of 5 replicates per sample.

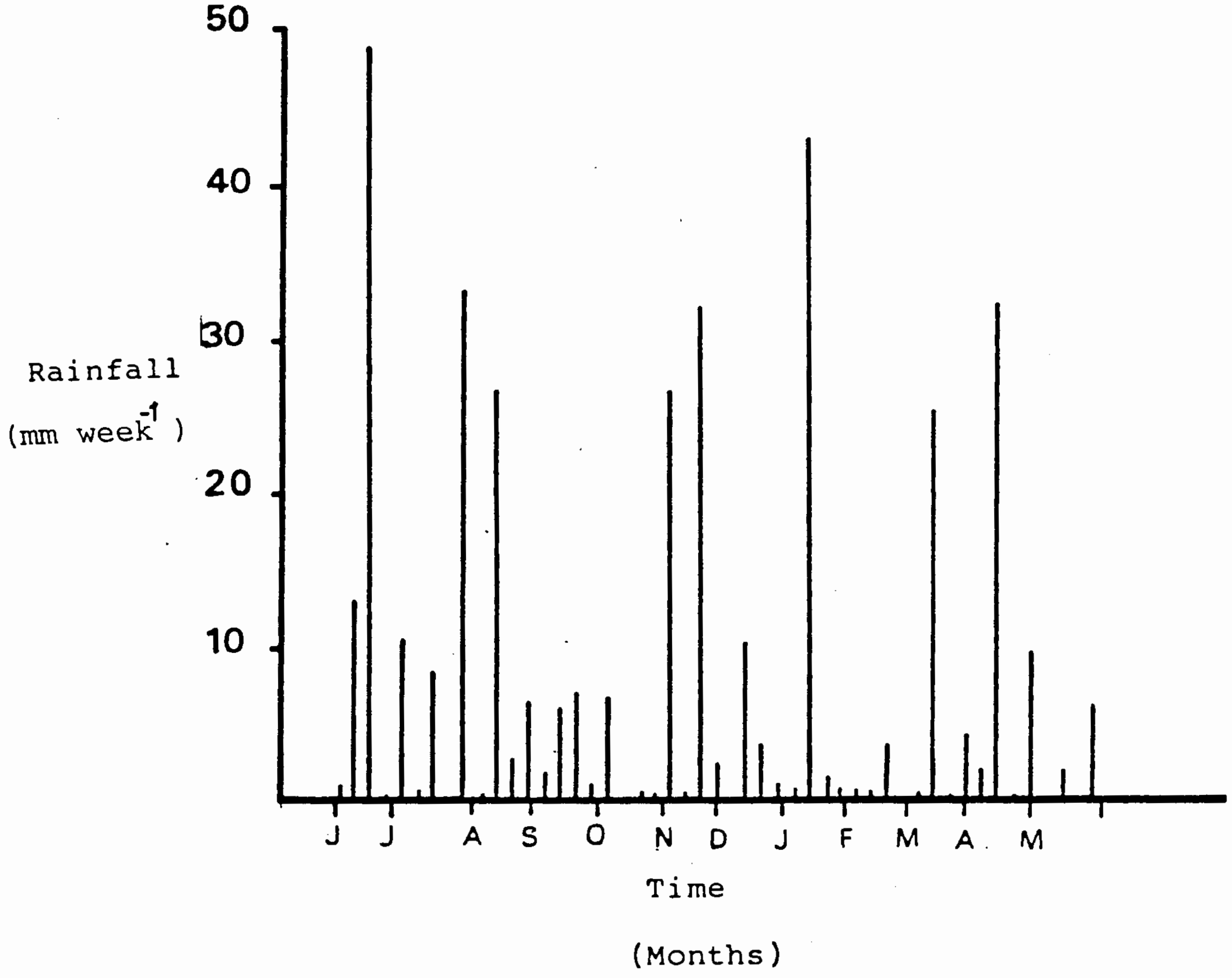


Fig.8:2.Rainfall at the Pella site over a twelve month period from June 1980 to June 1981. Each value represents a mean of 5 samples.

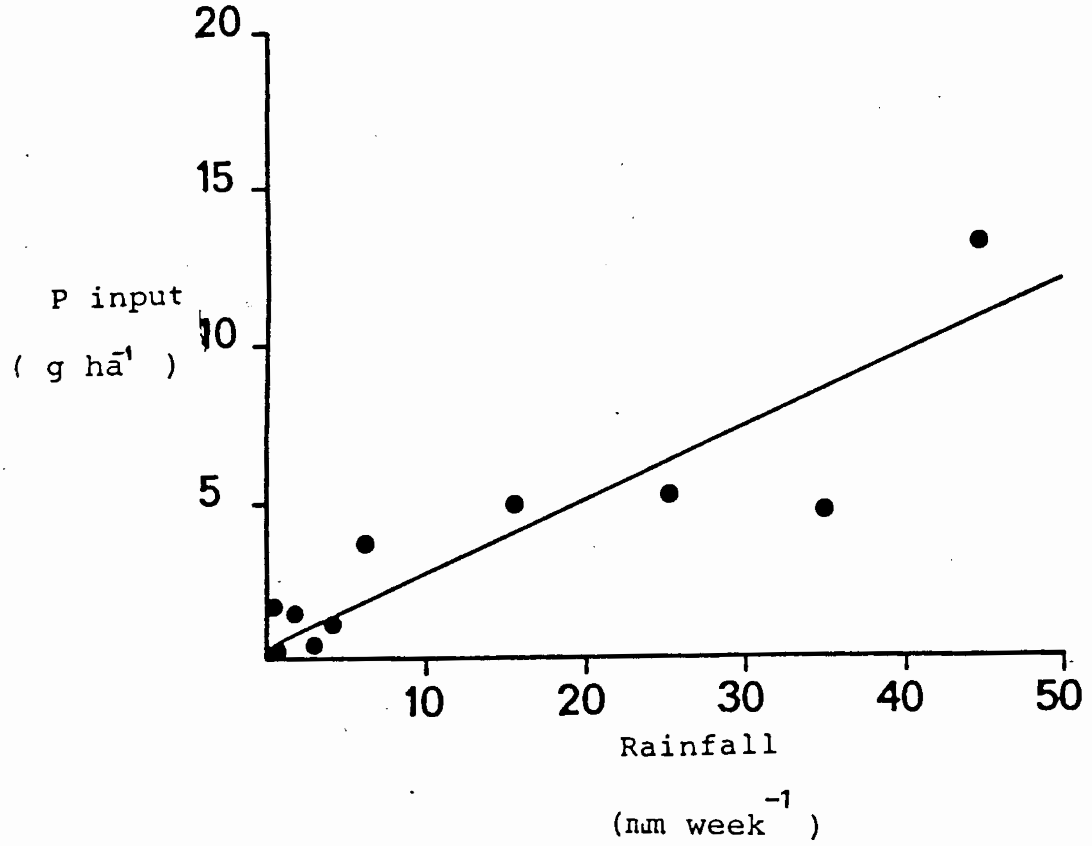


Fig.8:3. The relationship between rainfall and phosphorus input to the Pella site. The rainfall data were arranged into 10 ranges. The relationship is a linear one and of the form Y= 0,63+0,23X where X= rainfall recorded and Y= phosphorus input with a correlation coefficient of 0,89.(df=9; $P<0,001$).

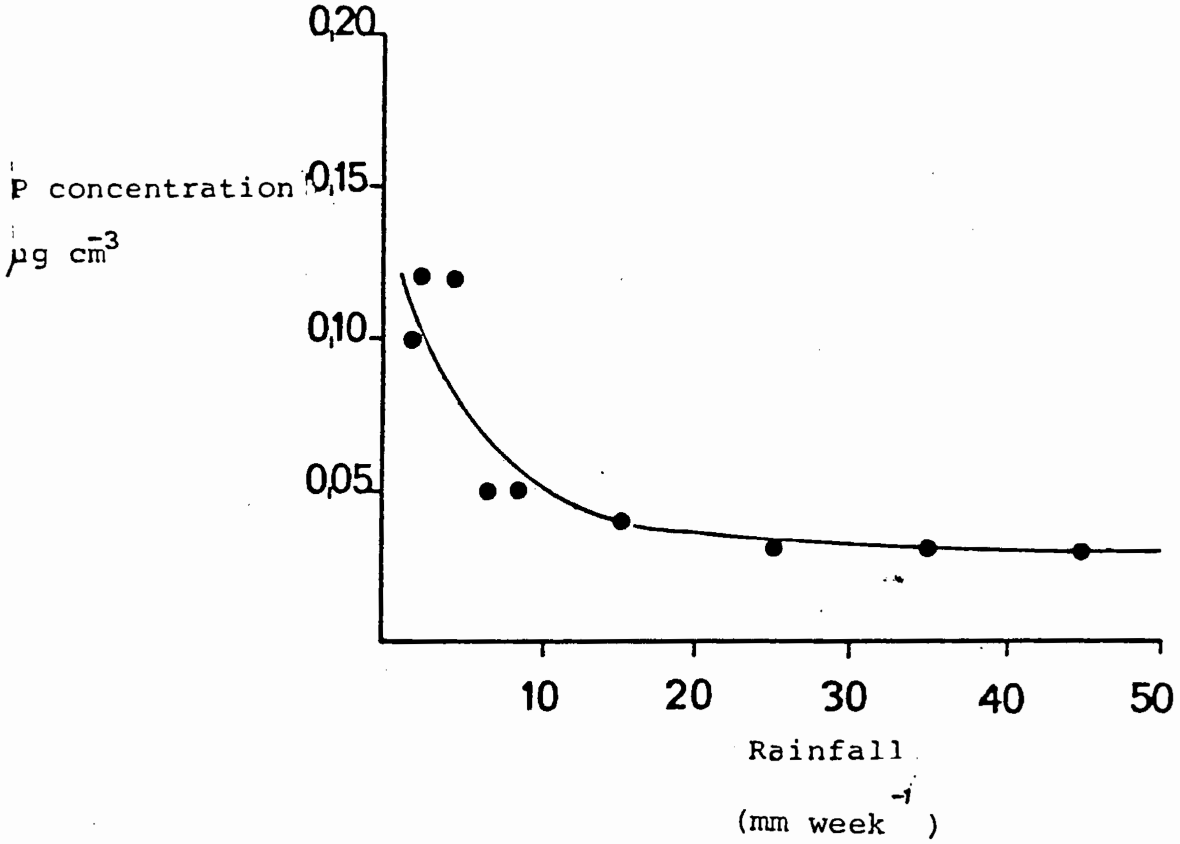


Fig.8:4. The relationship between rainfall and phosphorus concentration in the precipation. The rainfall data was arranged into 10 ranges. The relationship is a power curve of the form $Y= 0,12X^{-0,37}$ where X= rainfall recorded and Y= phosphorus concentration in that rain with a coefficient of determination of 0,83.

0,015-0,15 µg phosphorus cm^{-3} for individual samples. The concentration of most ions within rainwater generally decreases as the duration of the shower increases indicating that there is a limited pool size of nutrients which can be readily extracted from the atmosphere by wet precipitation (Attiwell 1966). In this investigation the intensity and duration of individual showers were not recorded. If phosphorus input to the Pella site was plotted against phosphorus concentration in rainfall a power curve was found to provide the best fit (Fig 8:5).

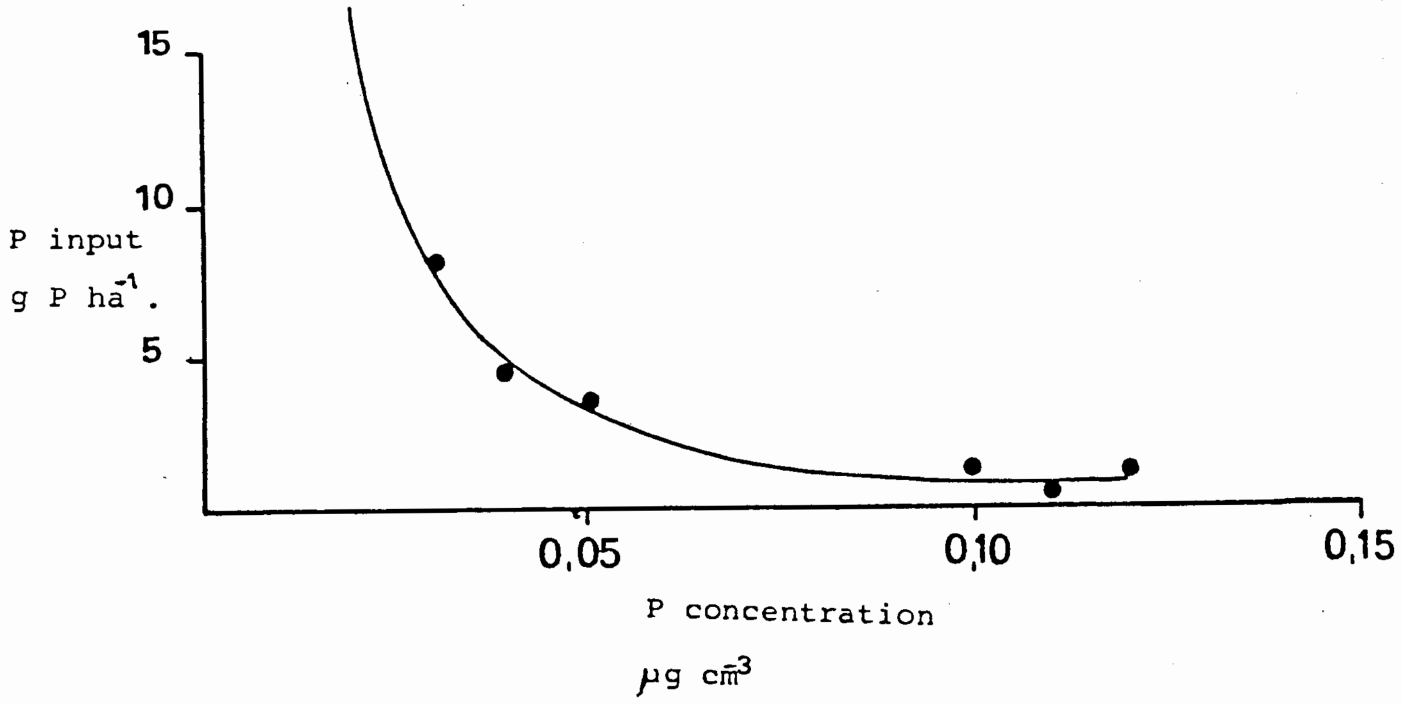


Fig.8:5. The relationship between phosphorus concentration in rainwater and phosphorus input into the Pella site. The relationship fits a power curve of the form $Y= 0{,}02X^{-1{,}64}$ where X= phosphorus concentration in the rainwater and Y= phosphorus input into the site with a coefficient of determination of 0,96 .

8.2. Discussion.

The annual input of phosphorus of 0,19 kg ha^{-1} yr^{-1} is similar to levels of input in British heathlands where additions of 0,20-1,0 kg ha^{-1} yr^{-1} have been recorded (Gore 1968, Allen et. al 1968). Considerably higher inputs occur in tropical areas and Jones (1960) working in Northern Nigeria reported inputs of 2,00 kg ha^{-1} yr^{-1}. The mean input of phosphorus per mm of precipitation was slightly higher than the values obtained for heathlands in Northern England and Scotland of 0,39 and 0,43 g mm^{-1} respectively (Gore 1968, Allen et al, 1968). In Gambia, Thornton (1965) determined a value of 0,27 g mm^{-1}, far lower than the values of 2,43 g mm^{-1} obtained by Jones (1960) in Northern Nigeria.

It is difficult to estimate the input of phosphorus from precipitation to the available phosphorus pool in the soil as data concerning runoff, leaching, fixation and adsorption rates down the soil profile are incomplete. It can be assumed that rates of runoff are low due to the relatively level topography of the Pella site (Fig 2.1). The retention of phosphorus near its place of incorporation into the soil is usually high (Russell 1973). Sharpley et al. (1981) found in the case of runoff on watersheds that the soil material acts as a "sink" rather than a "source" of phosphorus. Even though the majority of phosphorus added to the soil by rainfall is usually in the form of soluble P_2O_5 (Attiwell 1966), it is quickly immobilised or taken up by plant roots in the surface layers of the soil. Ahuja et al, (1981) found that in a sandy loam the mean depth of phosphorus penetration was between 2 and 3 mm, depending upon the period of rainfall and the type of soil.

The chemical impurities in rainwater are a result of contamination by atmospheric particles either acting as condensation nuclei or being washed out from the atmosphere by falling raindrops (Attiwell 1966). These contaminants have a number of possible sources (eg. oceanic, terrestrial, agricultural and man-made pollution). The most likely source of contaminants in the South-Western Cape are smoke from domestic fires, burns, the spraying of chemicals on nearby agricultural land and dust blowing into the collecting vessels from within the site. The contribution from marine sources as mist and sea spray may also be significant and has received little attention in other ecosystems. Svensson and Soderlund (1975) stated that the major contribution to atmospheric phosphorus is dust from terrestrial areas and sea spray. Dutkiewicz and Fuggle (1977) showed a predominance of south-westerly winds during the spring and autumn season and no dominant wind direction during winter at Mamre, 17 km from the intensive study site at Pella. The westerly wind component may provide a maritime influence to the phosphorus concentration in precipitation at Pella from spring to autumn.

The concentration of most ions in rainwater generally decreases as the duration of the shower increases indicating the limited pool size of nutrients readily extractable from the atmosphere by wet precipitation (Attiwell 1966). This is reflected in the drop in phosphorus concentration recorded with increasing amounts of rainfall and two phases of atmospheric phosphorus removal appear to occur (Fig 8:4). There is an initial rapid depletion of higher phosphorus concentrations at lower rainfall levels continuing until a stable concentration of phosphorus is encountered beyond which little depletion of phosphorus occurs despite large increases in rainfall volume. Soderlund (1981) described the relationship with respect to nitrogen and attributed the rapid depletion of high nutrient concentrations to sub-cloud scavenging of impurities by early precipitation. Another possible reason for this occurrence is that in periods of low rainfall evaporation of raindrops would concentrate the phosphorus in solution on the way to the ground (Soderlund 1981). The stable phosphorus concentrations at higher rainfall values may be the result of aerosols in the upper atmosphere acting as condensation nuclei for raindrops. This source of atmospheric phosphorus would be less susceptible to depletion than that in the lower atmosphere. Periods of high rainfall were associated with large inputs of phosphorus (See Fig 8:3) and this relationship has been previously demonstrated in British heathlands (Gore 1968). It would appear that the chief modifier of the size of the contribution of phosphorus from atmospheric deposition is the volume of precipitation.

9. Adsorption and Desorpton of Soil Phosphorus.

The availability of soil phosphorus to plants is dependent upon the phosphorus adsorption and desorption characteristics of that soil. In a soil with high desorption and lower adsorption characteristics the soluble phosphorus pool would be replenished far more rapidly than in a soil with low desorption characteristics. A plant would be able to draw on this soluble phosphorus pool for longer periods and at higher rates than would be possible if this were not so. This will have a direct bearing on the amount of phosphorus that a plant will be able to remove from a soil solution at a given concentration. Le Mare (1981) determined that exchangeable phosphorus indicates the soils potential to supply phosphorus to the plant and was closely related to the rates of adsorption and desorption of phosphorus within the soil. Nyamapfene (1981) stated that desorption studies have direct agronomic implications with regard to the plants ability to take up phosphorus from the soil. This chapter evaluates the rates of adsorption and desorption of phosphorus within the soil forms found at the Pella Intensive Study Site and compares the values obtained with levels of 'plant available' phosphorus.

9.1. Derivation of Adsorption Parameters.

The amount of phosphorus gained or lost (P moles $g^{-1} x10^{-8}$) by the soil in coming into equilibrium with each solution was determined from the gain or loss of phosphorus by the solution and plotted graphically against the resulting activity of $H_2PO_4^-$ ions ($aH_2PO_4^-$) where $aH_2PO_4^-$ = conc. $H_2PO_4^- \gamma H_2PO_4^-$. The activity coefficient $\gamma H_2PO_4^-$ was calculated from the Debye Huckel equation (Thompson 1971).

This equation is....

$$\text{Log}\,\gamma_{H_2PO_4^-} = \frac{0.5z\sqrt{u}}{1+1.5\sqrt{u}}$$

where z = valency of the ion and u = ionic strength. The X value when Y equals 0 for the curve (Fig 9:1) yields the soil Ie value for that soil. This is the equilibrium activity product or the concentration of HPO of the solution in equilibrium with the soil. The Y value when X equals 0 gives the Qo value for that soil and is a measure of the amount of surface or 'nett' exchange sites present in the soil at Ie. The slope of the line describes the amount of labile phosphorus that must be added to the soil to cause given changes in solution phosphorus concentration and is known as dQ/dI. This last value is equivalent to the soils buffering capacity (Holford and Mattingly 1976).

9.2. Results.

The phosphorus adsorption isotherms for the ten soils under investigation are given in Fig.9:2 and 9:3 and the derived adsorption parameters presented in Fig 9:4, 9:5 and 9:6. Each soil has a characteristic adsorption curve and set of sorption data. Similar variations in sorption values between closely related soil forms have been previously observed (Holford and Mattingly 1976). Clovelly soil sampled at 100 cm had the greatest buffering capacity (Fig 9:6). The mean daily rates of desorption over the ten day period are given in Fig 9:7 and the percentage change in total phosphorus during the desorption trial are given in Fig 9:8. The change in solution pH during the desorption trial is given in Fig 9:9. A negative relationship was found to exist between buffering capacity (dQ/dI) and total phosphorus desorbed (Fig 9:10).

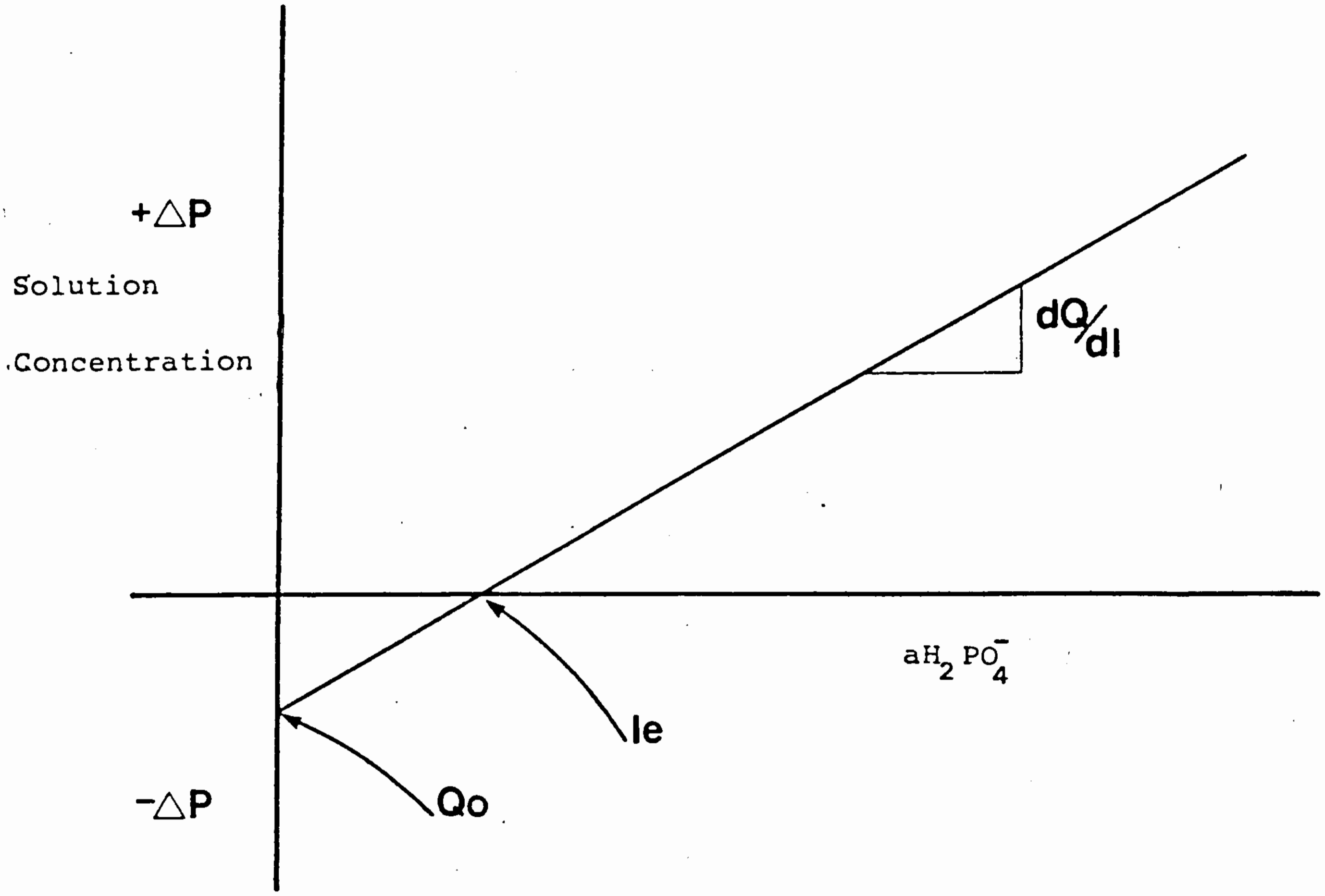


Fig.9:1. A hypothetical adsorption curve illustrating the derivation of Ie, Qo and dQ/dI values.

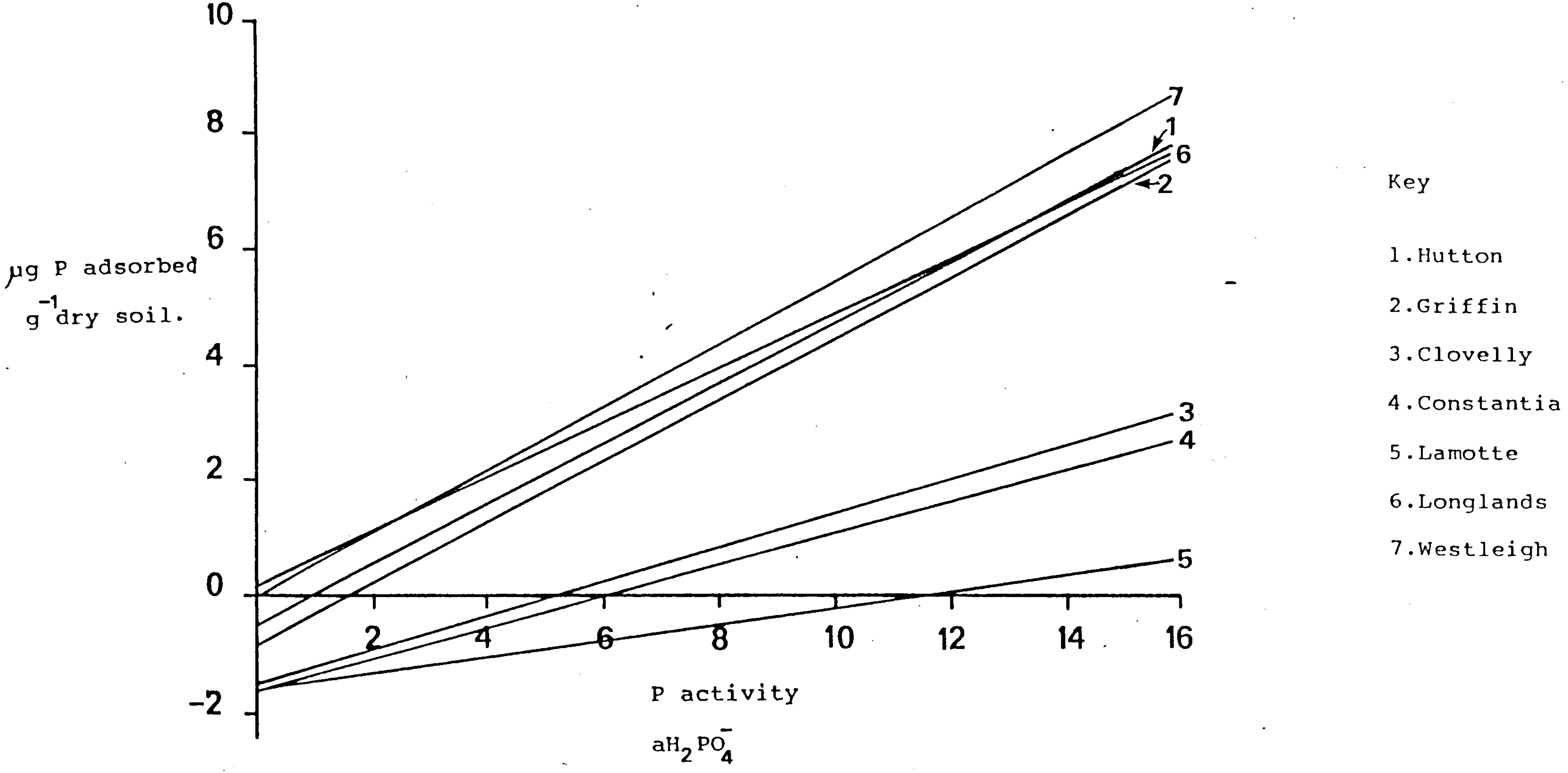


Fig.9:2.Adsorption curves for the 7 soil forms at the Pella site.4 replicates to a depth of 10 cm taken per soil form.

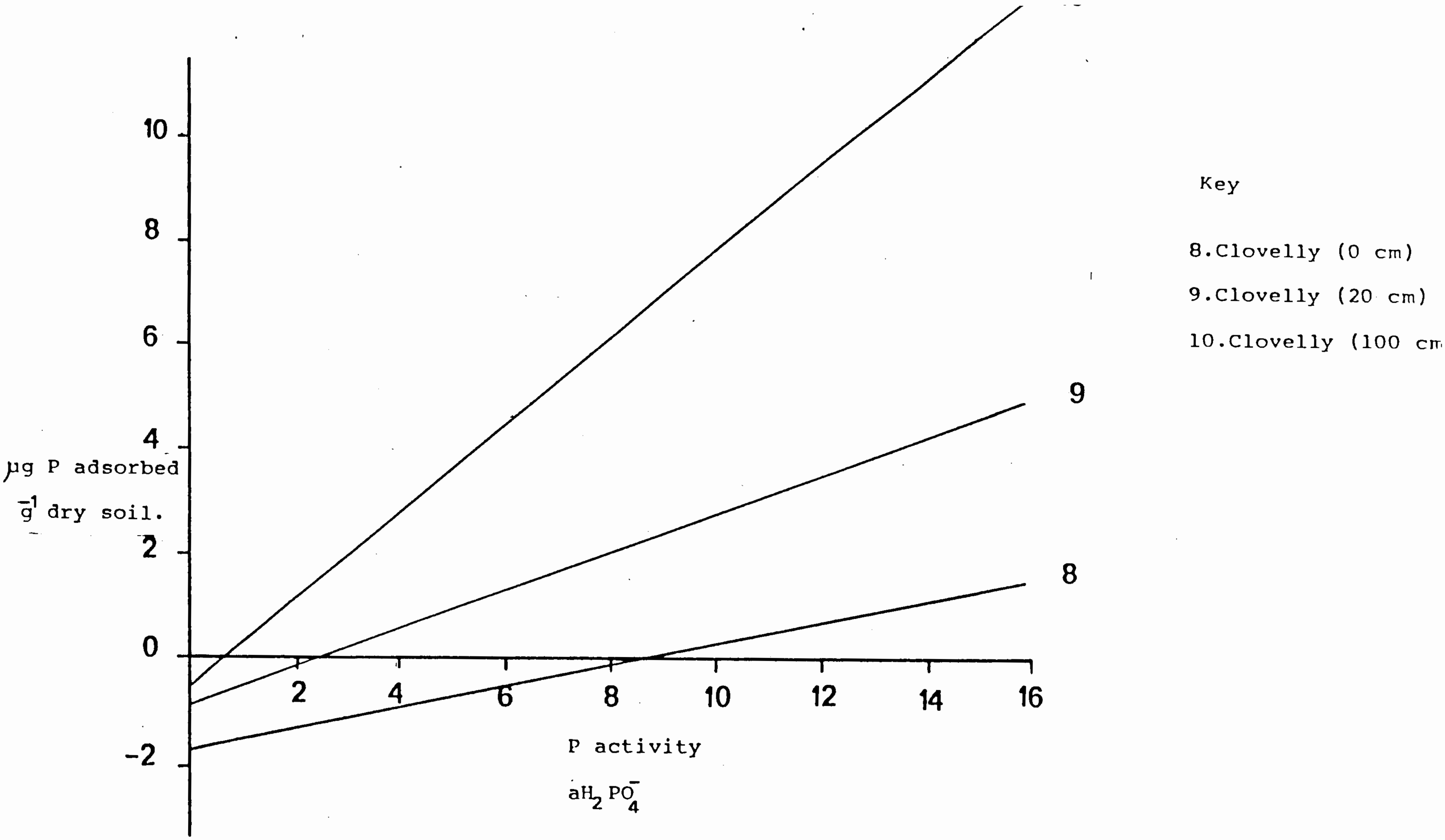


Fig.9:3.Adsorption curves for the Clovelly soil form, 4 replicates of samples collected at 0,20 and 100 cm in the soil profile.

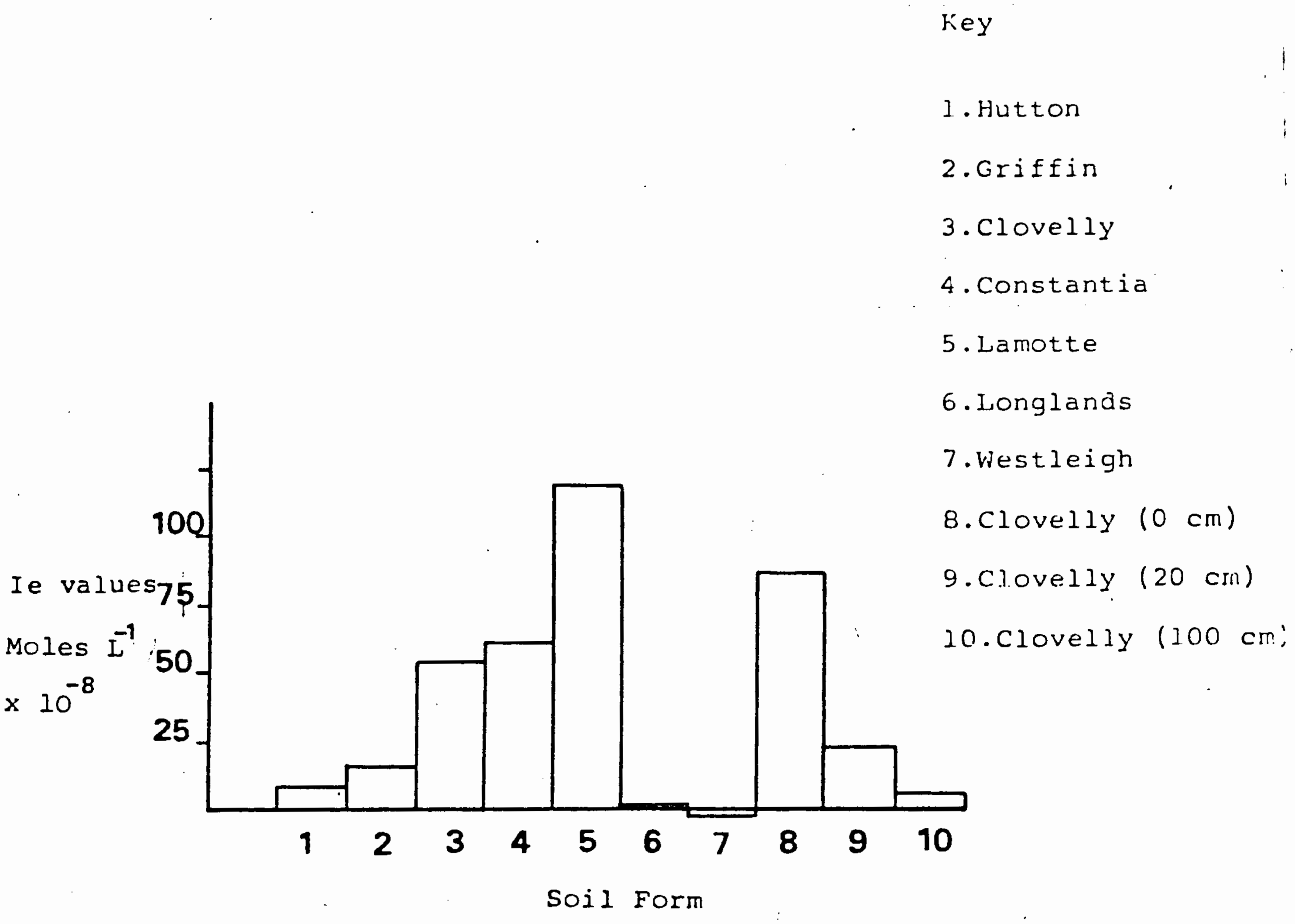


Fig.9:4.Ie values obtained for the ten soil forms investigated.

Each value is a mean of 4 replicates.

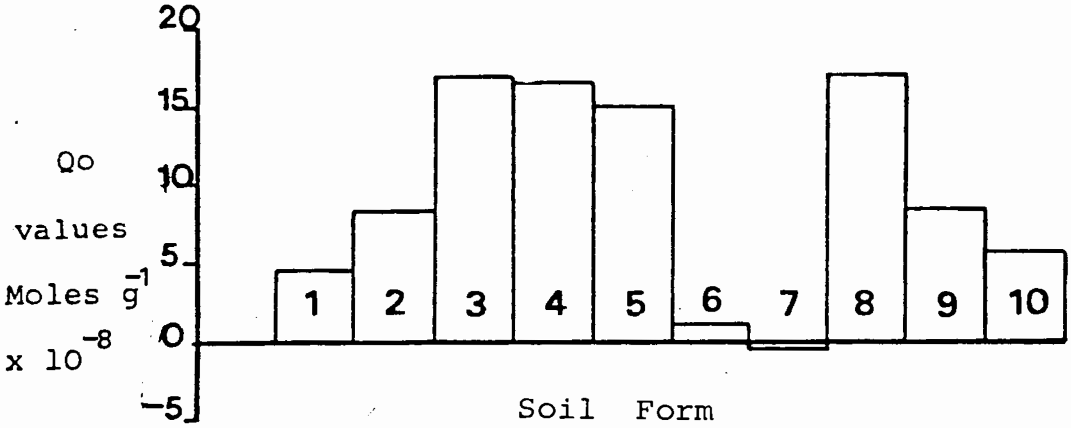


Fig.9:5.Qo values obtained for the ten soil forms investigated. Each value is a mean of 4 replicates.

Key

1.Hutton
2.Griffin
3.Clovelly
4.Constantia
5.Lamotte
6.Longlands
7.Westleigh
8.Clovelly (0 cm)
9.Clovelly (20 cm)
10.Clovelly (100 cm)

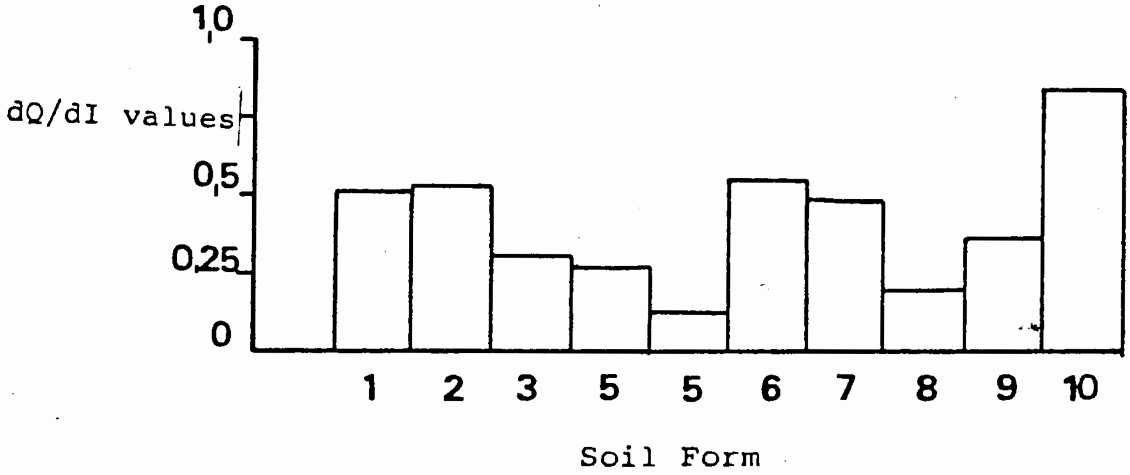


Fig.9:6.dQ/dI values obtained for the ten soil forms investigated.

At each sampling 4 replicates were taken.

Key

1.Hutton

2.Griffin

3.Clovelly

4.Constantia

5.Lamotte

6.Longlands

7.Westleigh

8.Clovelly (0 cm)

9.Clovelly (20 cm)

10.Clovelly (100 cm)

Fig.9:7. Mean rate of desorption of the ten soil forms investigated. Vertical bars represent twice the SEM. Each point represents a mean of 40 replicates

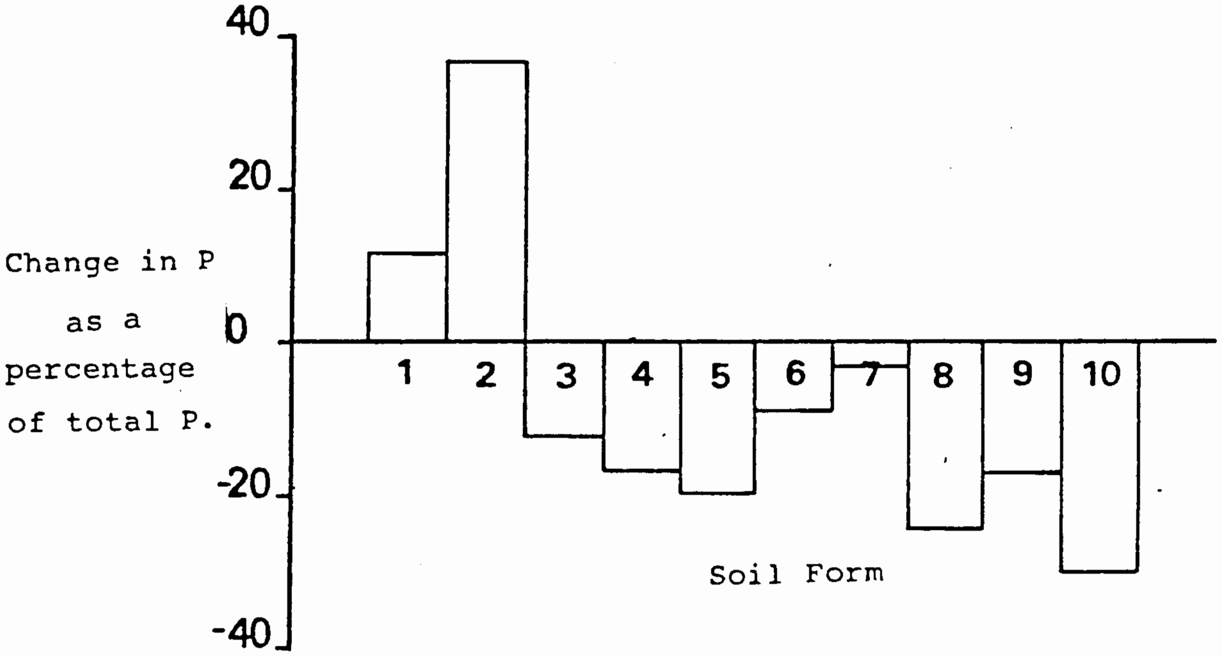


Fig.9:8.Change in levels of total soil phosphorus following addition and desorption of total phosphorus for the soil types under investigation. Results are means of four replicates per sample

Key

1.Hutton
2.Griffin
3.Clovelly
4.Constantia
5.Lamotte
6.Longlands
7.Westleigh
8.Clovelly (0 cm)
9.Clovelly (20 cm)
10. Clovelly (100 cm)

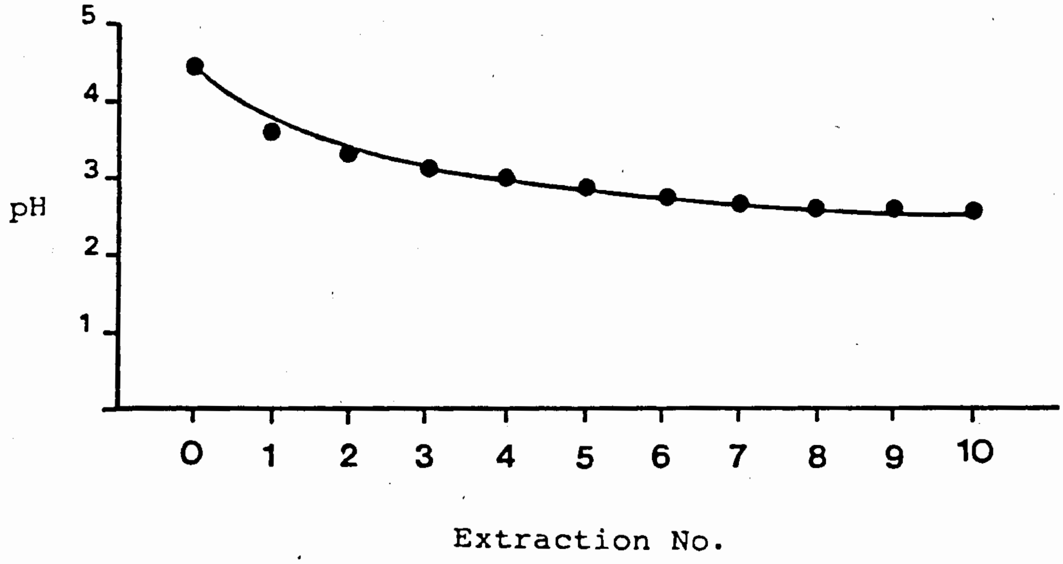


Fig.9:9. Mean change in soil pH levels in the 10 soil forms during the desorption trial. Each point represents a mean of 40 replicates. The relationship fits a power curve of the form $Y=0,99X^{0,23}$ where X= extraction number and Y= pH of the solution, with a coefficient of determination of 0,92

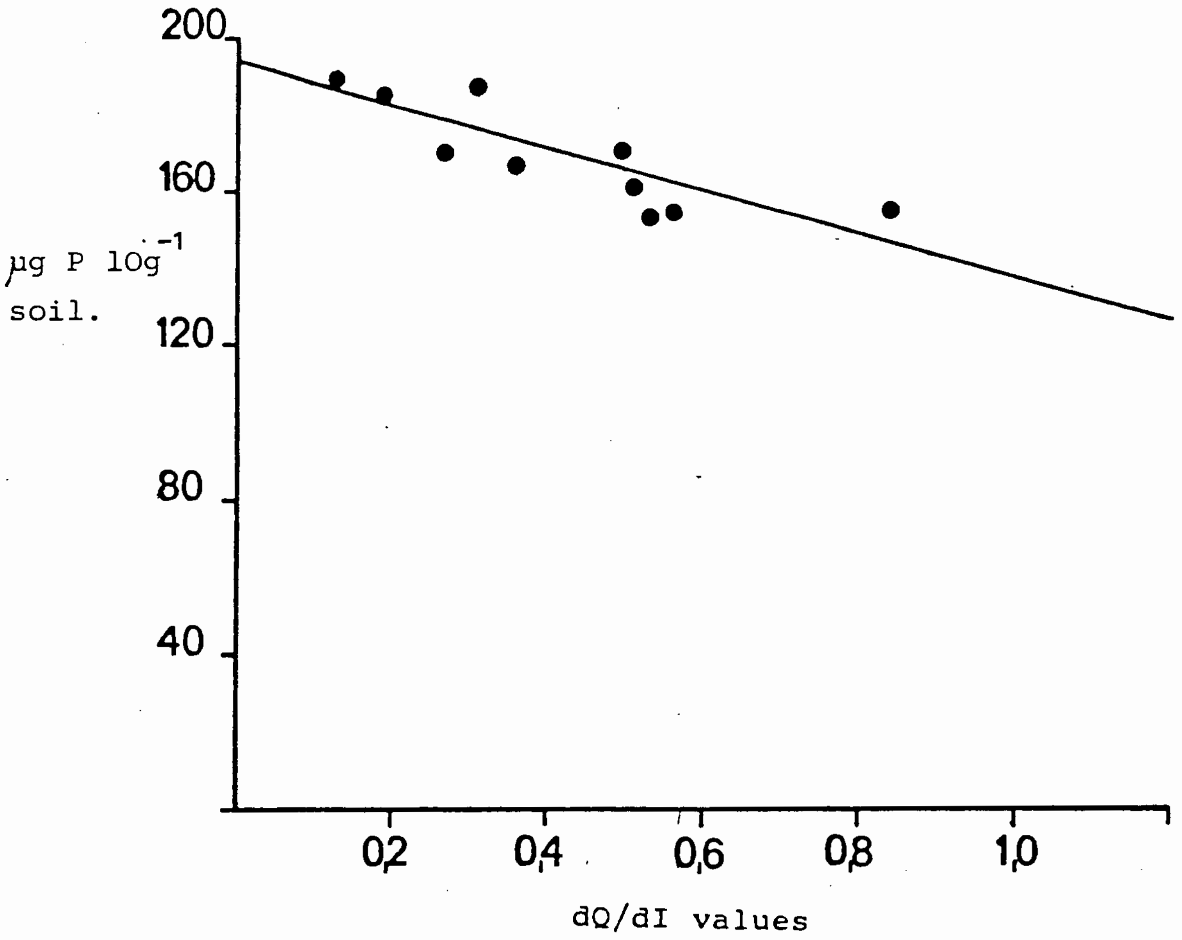


Fig.9:10. Total phosphorus desorbed per 10g sample per soil type investigated against buffering capacity (dQ/dI) of the soil. Values are means of 4 replicates per sample. A linear relationship of the form Y= 191,65-52,51X where X= soil dQ/dI values of the soil and Y=total phosphorus desorbed, with a correlation coefficient of-0,82 (df=9, $P \leq 0,01$).

The Ie values recorded increased along the soil weathering sequence from Hutton to Lamotte soil forms and decreased down the soil profile to 100 cm indicating that the equilibrium activity of the soil solution increased along the catina and up the soil profile. The Longlands and Westleigh soil forms yielded very low Ie values, inconsistent with the other closely related soils.

Over the same weathering sequence of soils, the Qo values became progressively more positive and with movement down the Clovelly soil profile the values became less positive. As Qo is a measure of the number of exchange sites present in the soil at equilibrium, a decrease in Qo values will result in less soil phosphorus being bound in unavailable forms and allow a higher equilibrium activity of phosphorus to be maintained.

The buffering capacity (dQ/dI) values for the soil follow a trend which is the reverse of that observed for Ie, with increasing degree of leaching in the catina and increasing proximity to the soil surface the value of dQ/dI decreased. The rate of release of phosphorus from the test soils was fairly constant between soil types and over time. The mean rate of desorption decreased after the second extraction and remained constant until the seventh extraction when a slight increase in phosphorus desorbed occurred (Fig 9:7). The drop in pH levels during this trial was recorded with a mean decrease from 4,47 before the first extraction to 2,33 after the last. The change in pH values when plotted were found to fit a power curve with a negative slope (Fig 9:9).

9.3. Discussion.

During the desorption trial the drop in pH observed was found to be a result of the dissociation of $HPO_4^{=}$ ions with successive resin extractions (Giskin and Larsen 1979).

With increasing soil age and proximity to the soil surface the adsorption capacity of the soils decreased as did the potential buffering capacity of the soil. The solution equilibrium activity increased, apparently as a result of the corresponding decrease in the number of surface exchange sites present in the soil at equilibrium. A soil with a large number of adsorption sites would be expected to have a high resistance to change in soil solution phosphorus content and to maintain this content at a low level.

Along the soil weathering sequence referred to in chapter 7, there is a tendency for the amount of phosphorus desorbed during the trial to change from negative values (ie. net uptake occurred) in the Hutton and Griffin forms to increasingly positive ones in the Clovelly to Lamotte soils. The Longlands and Westleigh forms both had very low rates of desorption (Fig 9:8).

Soils with high buffering capacities have lower Ie values and high Qo values as well as low rates of desorption. In Chapter 10 these and other soil characteristics are discussed in order to produce a clearer picture of the nature of phosphorus availability and sorption in soils at the Pella Intensive Study Site.

The rates of adsorption and desorption were dissimilar in all soils observed. Brewster et al, (1975) found that adsorpton and desorption were not always reversible processes and did not take place at the same rate. This occurred in the soils under investigation. While adsorption proceeded quickly desorption rates were slow resulting, in the case of the less severely weathered soils, in a build up of phosphorus after ten successive extractions. From these results it is possible to speculate that in the Hutton and Griffin soil forms which have low rates of desorption and high rates of adsorption that the amounts of phosphorus available would be lower than in the Lamotte soil where the opposite set of conditions apply.

The relatively stable rate of desorption of phosphorus observed in this study (Fig.9:7.) is not in agreement with other workers. Giskin and Larsen (1979) and Roche et al. (1980) reported marked decreases in the levels of phosphorus desorbed during similar series of extractions. This disagreement is possibly due to the steady decrease in solution pH values which occurred throughout the trial. The chief form of iron bound phosphorus within these soils FeH_2PO_4 is susceptible to attack and breakdown by acid solutions (Larsen 1967) and so the steadily decreasing pH (from 4,5 to 2,3) may have caused an artificially high rate of phosphorus desorption to occur within the soil solution as a result of the breakdown of FeH_2PO_4. With decreasing pH the major ion species of phosphoric acid would have changed from $H_2PO_4^-$ to H_3PO_4.

Another possible explanation is that because of the large pool of adsorbed phosphorus a large labile phosphorus pool was in existence within the soils and the soil solution was steadily resupplied with soluble phosphorus as its pool was depleted. Shapiro (1958) observed a similar pattern of phosphorus desorption and concluded that this pattern of release was due to the dissolution of sparingly soluble phosphorus compounds.

Working with tropical soils Rajan and Fox (1975) postulated three phases of phosphorus desorption, an initial period of rapid release, a second period of reduced desorption and a final phase of increased desorption. These phases appear to correspond to the pattern of desorption observed within this study.

The soils investigated by Thompson (1971) in Natal displayed similar phosphorus desorption characteristics to those observed in the Pella soils. The Ie values of the Pella soils are lower than those obtained by Thompson (1971) as are the adsorption maxima. The Pella soils had higher numbers of binding sites, a possible reason for the lower Ie values found in these soils. The numbers of binding sites are dependent chiefly upon the soil iron levels and the state of oxidation of the soil. This relationship is discussed in chapter 10.

10. General Discussion.

Evidence has been presented in this study that the sandy soils of coastal fynbos are of low phosphorus status. Plant available phosphorus levels fluctuate seasonally and are apparently influenced by soil moisture content and temperature.Rates of physical mineralisation of soil organic phosphorus were investigated and found to be negligible. As rates of microbial mineralisation of organic phosphates within the soil were not examined, it is not possible to determine the importance of this process to the phosphorus cycle.

The input of phosphorus to the soil from litter breakdown does not appear to be seasonally determined (Coley pers.comm.) but the input of phosphorus from precipitation occurs chiefly during the winter when levels of resin extractable phosphorus remain low in the soil. If a total phosphorus content of 53 kg ha^{-1} is known to occur in the surface 10 cm of the Clovelly soil form (See Sect.3.1.) then the annual input from precipitation is estimated to be equivalent to approximately 0,4% of the total soil phosphorus. In the case of soluble phosphorus with a mean value of 4,2 kg ha^{-1} (Sect.3.1.) for the surface 10 cm, then an annual input of 4,5% of the soluble phosphorus pool is estimated to occur from precipitation. This contribution may act as a readily available source of phosphorus to the plant for passive uptake (Bieleski 1976). This may be an important contribution to the oligotrophic soils of the fynbos biome.

As well as inputs purely from precipitation, rainfall is a major source of water which may leach appreciable amounts of phosphorus from the foliage of plants growing in the area and return it to the soil (Sharpley et al, 1981, Attiwell 1966). It was plant leachate which contributed the majority of phosphorus in soil runoff from commercial crops during heavy rainfalls with the soil acting more as a "sink" than a "source" (Sharpley et al. 1981).

The high adsorptive characteristics of these soils reported in chapter 9 would tend to prevent any movement of phosphorus in a soluble inorganic form. However organic phosphorus has been shown to be more mobile in soils than inorganic forms of phosphorus (Hannapel et al. 1964b). Up to 95% of phosphorus movement in clay soils has been attributed to the organic forms and the amounts of phosphorus leached though the profile was strongly correlated with levels of microbial activity (Hannapel et al. 1964b). Hannapel et al. (1964a) concluded that a large proportion of the organic phosphorus came from the native soil phosphorus fraction and was mobilised by the soil microbial population.

Martin (1970) also found a good correlation between organic phosphorus movement and soil microbial levels. He concluded that a large proportion of the organic phosphorus esters within the soil are released from bacterial cells and dead soil fauna and flora or are associated with cellular debris and are unavailable for plant uptake. Organic phosphorus moves within the soil in a colloidal form (Hannapel et al. 1964a,b) and as such is not taken up by plants or adsorbed by crystalline or amorphous iron compounds unless it is first mineralised by either microbial or physical activity. Therefore organically bound phosphorus as a contribution of phosphate movement through the soil profile at the Pella site requires further investigation.

The profile distribution of both total and resin extractable phosphorus was shown to be similar to the general pattern observed by Smeck (1973). The distribution of total phosphorus within the Clovelly soil profile is probably a result of depletion of the

20-70 cm zone by plant roots.

The use of the Bray#2 and resin bag extraction techniques as indicators of plant available phosphorus within the soil needs to be carefully evaluated. The actual nature of the pool of phosphorus being extracted in each case is not understood. In order to clarify the situation, 'plant available' phosphorus levels yielded by both extractions in each soil form were examined in relationship to the adsorption parameters for that soil. A positive linear relationship was found to exist between resin extractable phosphorus and the Ie values obtained for each freely draining soil type (ie. Hutton, Griffin, Clovelly, Constantia, Lamotte) (Fig.10:1). A similar relationship existed between buffering capacity and Bray 2 extractable phosphorus in the soil in all soil forms (ie. Hutton, Griffin, Clovelly, Constantia, Lamotte, Longlands and Westleigh) (Fig.10:2.)

The resin bag extraction method is essentially a measure of phosphorus which is either loosely adsorbed onto the surfaces of the soil and organic matter or freely in solution. The Bray#2 extraction method provides an indication of the size of the labile phosphorus pool within the soil under study. The proportion of which is extractable may be consistent for soils of similar physical and chemical characteristics (such as the forms investigated in this study). In freely draining soils

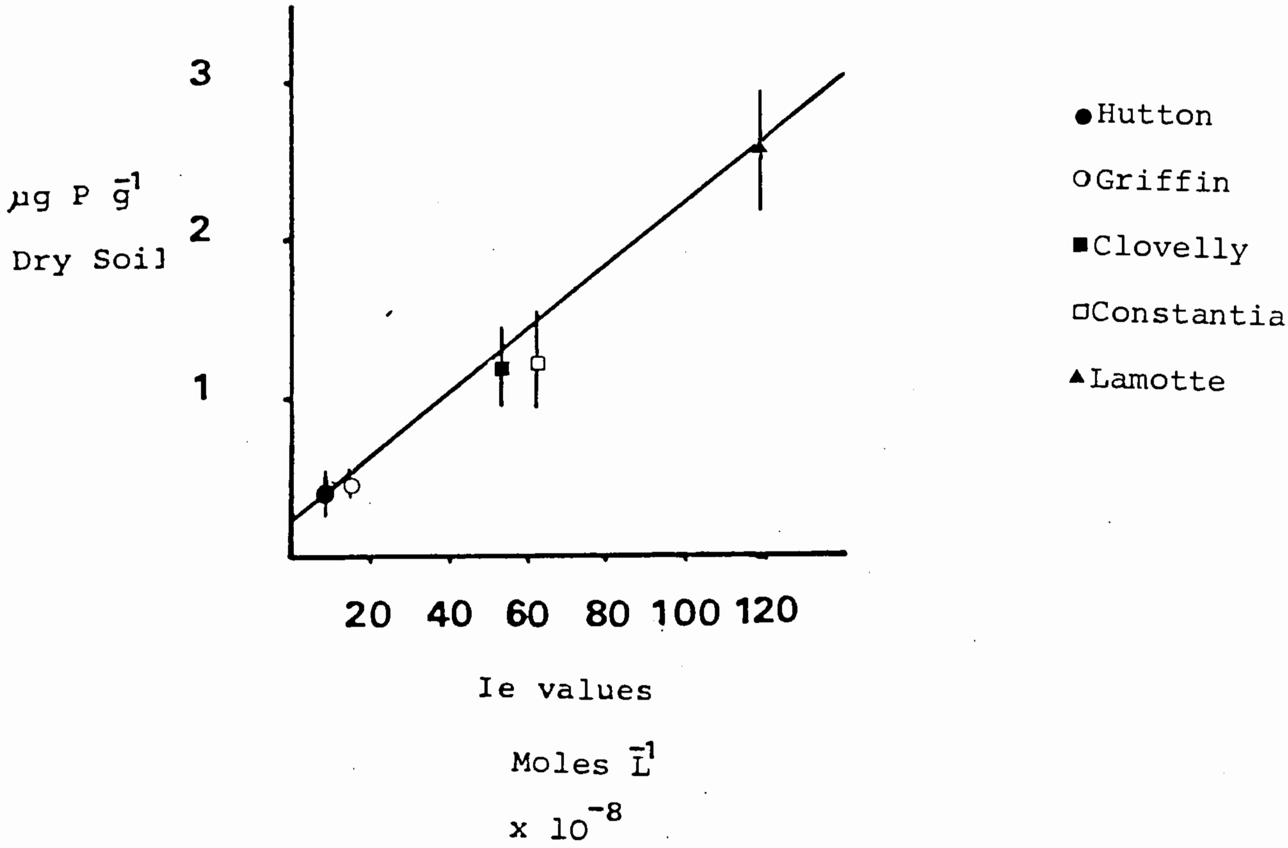


Fig.10:1. Resin extractable phosphorus levels obtained for the freely draining soils at the Pella site plotted against the Ie values obtained for the same soils with 4 replicates per sample. A linear relationship of the form Y=0,02 X+ 0,23 exists where X=Ie value of the soil and Y= resin extracable phosphorus levels in the soil with a correlation coefficient of 0,99 (df=4, $P<0,001$)

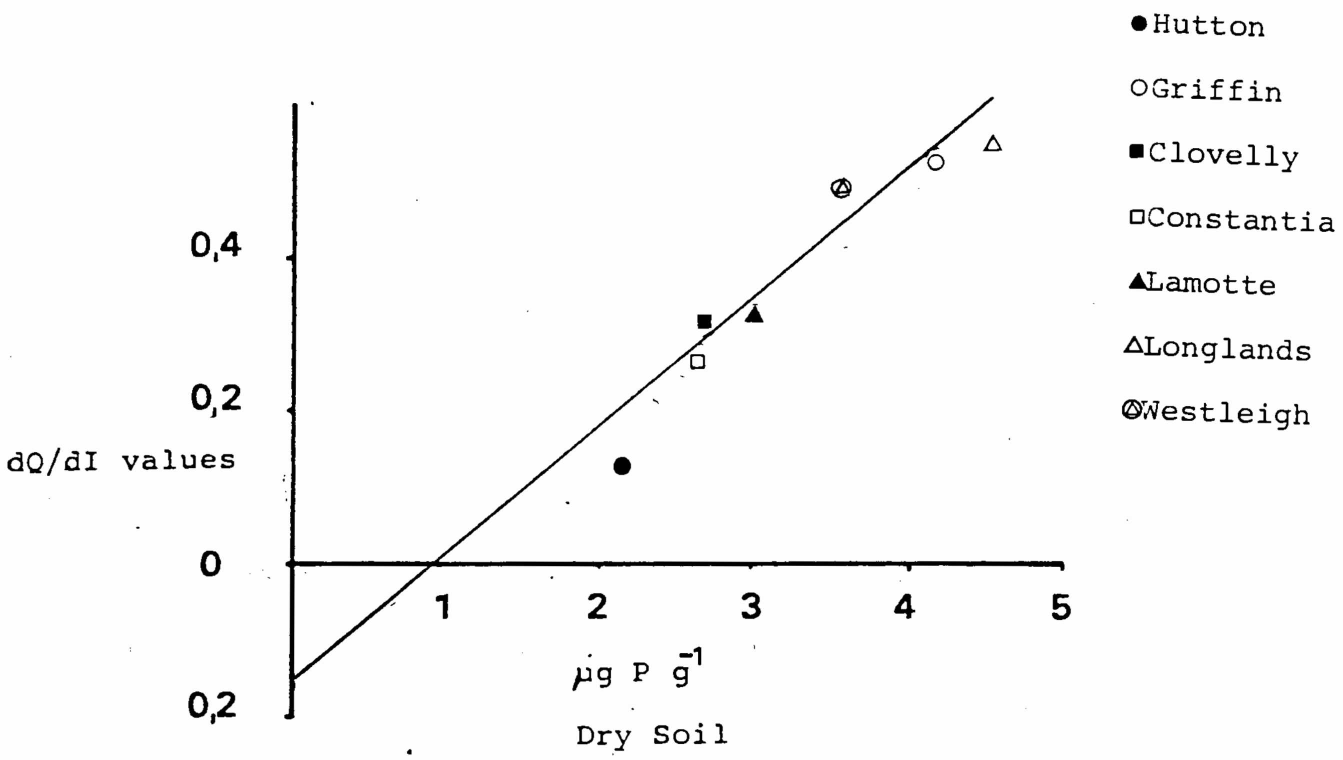


Fig.10:2. Soil dQ/dI values of the 7 soil forms at the Pella site plotted against levels of Bray$^{\#}$2 extractable phosphorus in those soils. 4 replicates were taken per sample. A linear relationship of the form Y=0,17X-0,17 exists where Y= the dQ/dI value of the soil and X= Bray$^{\#}$2 extractable phosphorus levels with a correlation coefficient of 0,96 (df=6, $P \leqslant 0,001$).

the relationship between Qo and iron levels is a significant one (Fig.10:3). This indicates that the levels of resin extractable phosphorus found within freely draining soils at the site are determined to a large extent by the iron levels within the soil. The soils of lower iron levels are thus able to maintain higher equilibrium levels of resin extractable phosphorus.

The Longlands and Westleigh soils behaved in a different manner to the other less weathered more freely draining soils eg. Hutton, Griffin, Constantia, Clovelly and Lamotte. The extremely low Ie values in the Longlands and Westleigh soils are a reflection of the strong binding forces found within these soils. The reductive conditions present in these soils appear to be responsible for this transformation of crystalline iron phosphates to amorphous types of iron phosphate precipitates (Kuo and Mikkelson 1979). Following periods of flooding, oxidation of the soils can occur with the corresponding decrease in the levels of amorphous iron oxides and phosphorus adsorption characteristics, but these levels never return to those observed prior to flooding and reduction (Willet and Higgins 1978). The amorphous iron oxides have very high reactivity with phosphorus because of their high specific surface areas (Kuo and Mikkelson 1979). The crystalline iron oxides operative in phosphorus adsorption in well drained soils do not appear to play a prominent role in phosphorus immobilization. The variation in the three adsorption parameters reported in Chapter 9 along the soil catina from Hutton to Westleigh and down the soil profile are of great importance when the nature of phosphorus found in these soils is considered.

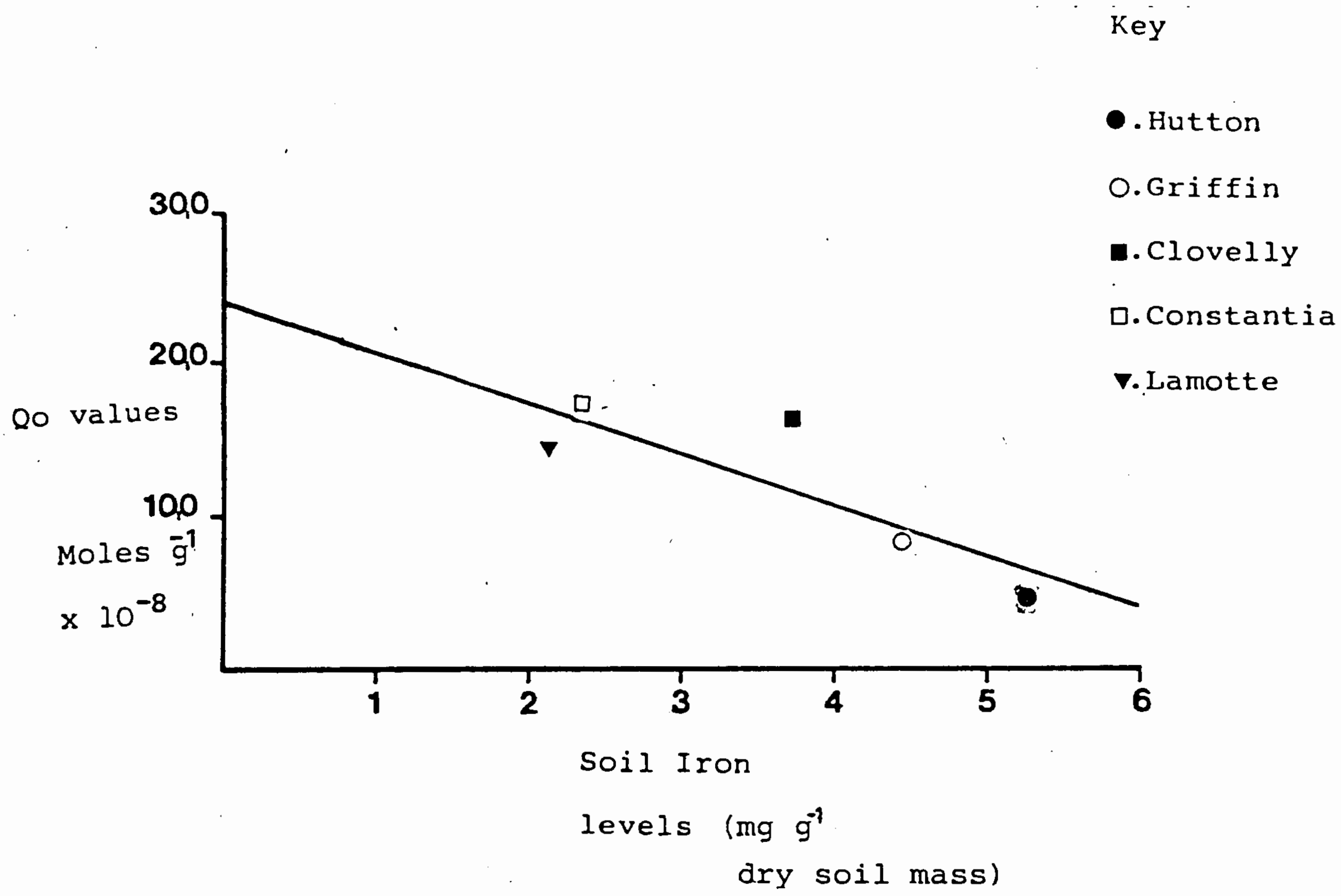


Fig.10:3.Qo values for the freely draining soils of the Pella site plotted against iron levels in those soils. Each point is a mean of 4 replicates. A linear relationship of the form $Y=24,35-3,38X$ exists where X= soil iron levels and Y= Qo values of the soil with a correlation coefficient of-0,83 (df=4 $P= 0,05$).

In these phosphorus-poor soils the vegetation appears to have very efficient phosphorus uptake mechanisms (Jongens-Roberts pers.comm.) and conversely very low rates of return in the litter (Coley pers.comm.). Fire returns the phosphorus held in the vegetation and litter to the soil without appearing to cause any long term effects on the physical characteristics of the soil (eg.organic matter levels or soil pH). The sudden increase in the size of the soluble phosphorus pool within the surface soil immediately after a fire is a result of the return to the soil of nutrients from the pyrolysis of the plant and litter layer. This enriching of the surface soils and the deposition of ash and charcoal creates ideal conditions for regeneration of the vegetation.

The influence of fire on the soil is rather short-lived. After 12 months the levels of resin extractable phosphorus are still elevated but after 5 years the levels had almost returned to their prefire values and soil organic matter content and pH have stabilised. This was revealed during a comparison of Clovelly soil of 0, 5 and 20 years post-fire at Pella during the soil survey (Brown unpublished data). Comparing seasonal behaviour of the soil pre and post-fire indicated that basically the same trends occur in both sets of data, the major difference being a loading of large amounts of soluble phosphorus into the soil post-fire. The prefire summer levels of resin extractable phosphorus were higher at the surface than those observed in winter where lower levels occurred throughout the profile.

The low levels of 'plant available' phosphorus found within the soils of the Pella site are compensated for by a number of soil characteristics. Smith (1965) demonstrated a positive correlation between the size of the iron bound phosphorus pool and the labile phosphorus fractions in soils with low levels of nutrients. A high proportion of inorganic phosphorus in the non-occluded form would therefore indicate a large pool of labile phosphorus within the soil. This would have the effect of buffering the soil solution phosphorus levels and allow withdrawal of phosphorus from this pool without depleting it. This may be of great significance in the cycling of phosphorus in the soils of the fynbos biome.

In a soil with low phosphorus status such as the Clovelly form, some of the organically bound phosphorus compounds as well as orthophosphates may also be available for plant uptake (Dalal 1977). This includes the easily hydrolysable fraction of organic phosphorus that forms water- soluble complexes with iron and aluminium (Dalal 1977). Mitchell and Read (1981) demonstrated that mycorrhizal endophytes of ericaceous plants were able to utilize different organic phosphorus sources as well as their insoluble forms. In the soils of the Pella site which have low 'available' phosphorus status and a large proportion of total soil phosphorus in organic forms, the ability to utilize a broad spectrum of unavailable phosphates would confer substantial advantages upon the plants which are mycorrhizal.

Plants of the Proteaceae growing on these soils are not mycorrhizal but have proteoid root systems which they use for taking up and storing soluble phosphates until required (Mitchell pers.comm.). Jeffrey (1964) working with Banksia species (an Australian protea) suggested that young plants (presumably with active proteoid roots) were able to absorb orthophosphate at high rates when it was available. This was stored as inorganic polyphosphate which was released within the plant when the external supply was low.

Non-proteoid roots of Leucospermum parile at Pella appear to have the lowest phosphorus concentrations within the plant (Jongens-Roberts pers.comm.). Therefore if phosphorus is mainly taken up by the proteoid roots, the rhizosphere regions of the non-proteoid roots will not be depleted in phosphorus. This was observed in Chapter 6 where the rhizosphere zones of proteoid plants at Pella had high levels of resin extractable phosphorus.

This study has achieved its basic aims concerning the cycling of phosphorus within soils of the fynbos biome. Some areas have yet to be investigated and the sizes of their fluxes evaluated. The most important of these, net microbial mineralisation rates, has not yet been investigated nor have the factors affecting these rates been positively identified and quantified. Rates of input of phosphorus from bedrock breakdown can be assumed to be almost zero as the soil is aeolian in origin. The role of fire in returning phosphorus to the soil has been shown to be important.

The rates of retention and release of soil phosphorus were a major differentiating factor between the soil forms present at the site. These rates were found to control the levels of resin extractable phosphorus within the soil.

An attempt has been made in Fig 10:4 to illustrate the present knowledge of the forms of phosphorus within the soil and the extent of their fluxes. The importance of these forms and, in some cases, seasonal variation in their pool sizes have not been determined. The ability of fynbos species to take up phosphorus in the various forms normally considered to be unavailable may be significant and requires further investigation.

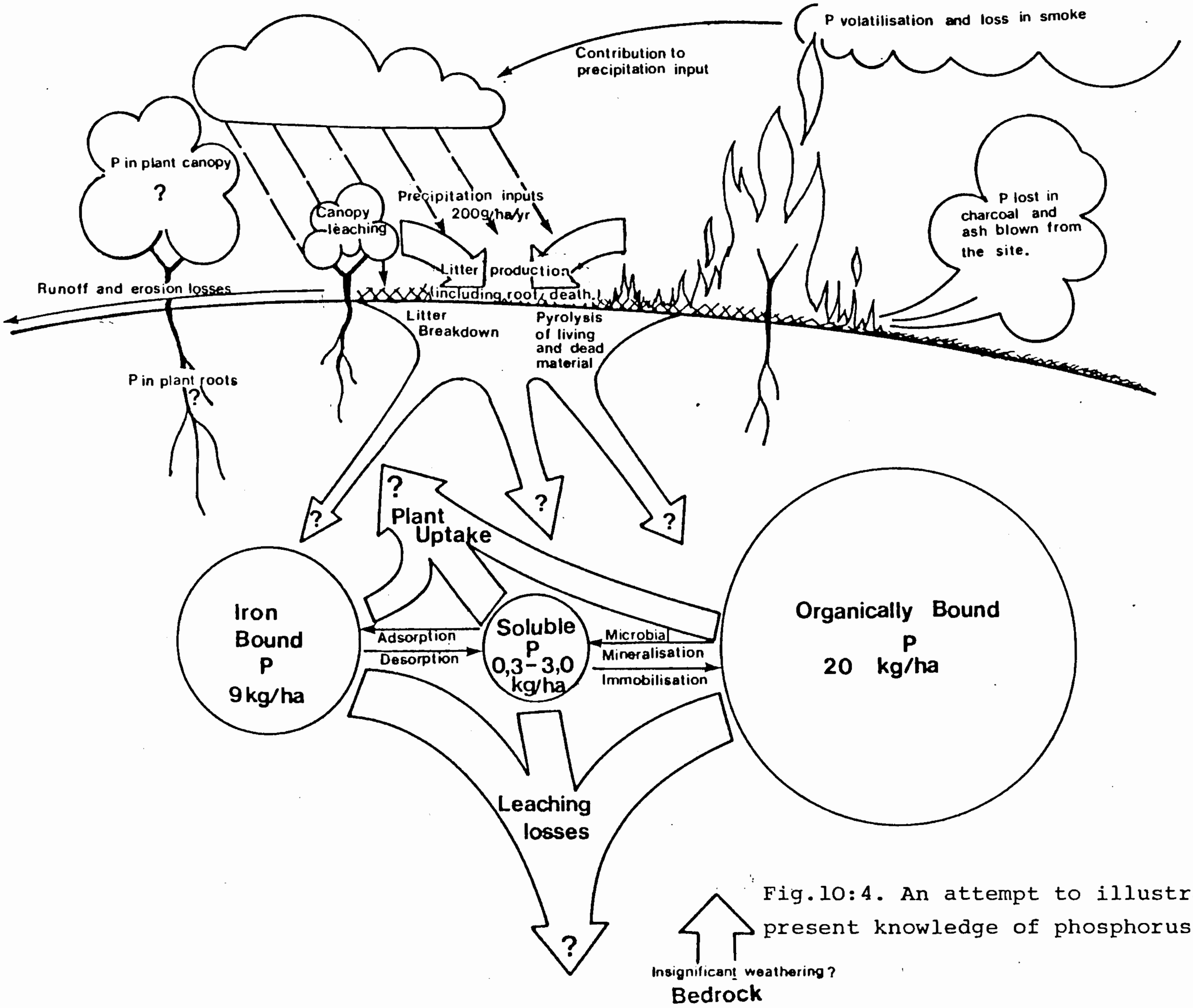


Fig.10:4. An attempt to illustrate schematically present knowledge of phosphorus cycling in coastal fynbos

11. References.

Abbott,J.L. 1978.
Importance of the organic phosphorus fraction in
extracts of calcareous soils.
Soil Science Society of America Journal.42:81-85.

Adamson,R.S. and Salter,T.M. 1950.
Flora of the Cape Peninsula.
Juta and Co.
Cape Town. 889 pp.

Ahuja,L.R. Sharpley,A.N. Yamamoto,M. and Menzel,R.G. 1981.
The depth of rainfall-runoff-soil interaction as
determined by P-32.
Water Resources Research.17:969-974.

Allen,S.E. Carlisle,A. White,D. and Evans,L.T. 1968.
The plant nutrient content of rainwater.
Journal of Ecology.56:497-504.

Anderson,G. 1960.
Factors affecting the extraction of phosphate esters in soil.
Journal of the Science of Food and Agriculture.11:497-503.

Anonymous. 1974.
Manual of soil analysis methods.
FSSA publication No.37.

Attiwell,P.M. 1966.
The chemical composition of rainwater in relation to cycling
of nutrients in mature Eucalyptus forest.
Plant and Soil.24:390-407.

Bache,B.W. 1963.
Aluminium and iron phosphate studies relating to soils,1.
Journal of Soil Science.14:113-124.

Bache,B.W. 1964.
Aluminium and iron phosphate studies relating to soils,2.
Journal of Soil Science.15:110-116.

Bartlett,E.M. and Lewis,D.H. 1973.
Surface phosphatase activity of mycorrhizal roots of beech.
Soil Biology and Biochemistry.5:249-257.

Beadle,N.C.W. 1962.
An alternative hypothesis to account for a generally low phosphate content of Australian soils.
Australian Journal of Agricultural Research.13:434-442.

Bieleski,R.L. 1976.
The passage of phosphate from soil to plant.
In:The efficiency of phosphorus utilization.
Reviews in Rural Science 3.
University of New England Press.Armidale.

Bornemisza,E and Igue,K. 1967.
Comparison of three methods for determining organic phosphorus in Costa Rican soils.
Soil Science.103:347-352.

Boucher,C. and Shepherd,P.
The plant communities at the Pella
Research Site.
Unpublished CSIR report.

Bray,R.H. and Kurtz,L.T. 1945.
Determination of total,organic and available phosphorus
in soils.
Soil Science.59:39-45

Brewster,J.L., Gancheva,A.N. and Nye,P.H. 1975.
The determination of desorption isotherms for soil phosphate
using low volumes of solution and an anion exchange resin.
Journal of Soil Science.26:364-377.

Chang,S.C. and Jackson,M.L. 1957.
Fractionation of soil phosphorus.
Soil Science.84:133-144.

Chang;S.C. and Jackson,M.L. 1958.
Soil phosphorus fractions in some representative soils.
Journal of Soil Science.9:109-119.

Chater,M. and Mattingly,G.E.C. 1979.
Changes in organic phosphorus contents of soils from
long continued experiments at Rothamsted and
Saxmundham.
Rothamsted Report, Part 2.pp 41-61.

Christensen,N.L. and Muller,C.H. 1975.
Effects of fire on factors controlling plant growth in
Adenostoma chaparral.
Ecological Monographs.45:29-55.

Choudari,J.S., Jain,S.V. and Mathur,C.M. 1977.
Phosphorus fractions in some soil orders of Rajasthan and their sequences at weathering stages.
Annals of Arid Zone.18:260-266.

Coley,P.G.F. and Mitchell,D.T. 1981.
A preliminary study of mineral cycling:
a.Production and decomposition of plant litter.
b.Organic matter distribution in the soil and the distribution and action of microorganisms in the soil.
CSIR Annual Fynbos Report No.3.

Dalal,R.C. 1977.
Soil organic phosphorus.
Advances in Agronomy.29:83-117.

De Bano,L.F. and Conrad,L.E. 1978.
The Effects of fire on nutrients in a chapparal ecosystem.
Ecology.59:489-497.

Dutkiewicz,R.K. and Fuggle,R.F. 1977.
Air pollution survey of greater Cape Town.
Unpublished Interim Report.(1).

Everett,K.R. 1980.
Distribution and variability of soils near Atkasook Alaska.
Arctic and Alpine Research.12:433-446.

Fife,C.V. 1959.
An evaluation of ammonium flouride as a selective extractant for aluminium bound soil phosphate,1.
Soil Science.87:13-21.

Floate,M.J.S. 1970.
Some factors effecting the mineralisation of soil organic phosphorus.
Journal of the British Grasslands Society.25:295-302.

Fry,M. 1982.
Unpublished M.Sc.Thesis.
University of Stellenbosch.

Gauch,H.G. 1972.
Inorganic plant nutrition.
Dowden Hutchinson and Ross.
Strouberg Pa.

Giskin,M.L. and Larsen,S. 1979.
Stepwise extraction of phosphate from soil by means of an anion exchange resin.
Royal Veterinary and Agricultural University Yearbook. pp.72-83.
Copenhagen.

Godfrey,C.L. and Riecken,F.F. 1954.
Distribution of phosphorus in some genetically related loess derived soils.
Soil Science Society of America Proceedings.18:80-84.

Godwin,D.C. and Wilson,E.J. 1976.
Prospects for selecting plants with increased phosphorus efficiency.
Reviews in Rural Science.3:131-137.

Gore,A.J. 1968.
The supply of six elements by rain to an upland peat area.
Journal of Ecology.56:483-495.

Gray,J.T. and Schlesinger,W.H. 1981.
Nutrient cycling in mediterranean-type ecosystems.In
In:Resource use by chapparal and matorral:a comparison of vegetation function in two mediterranean type ecosystems.
Miller,P. (Ed.)
Springer Verlag.New York.

Groves,R.H. 1982.
Nutrient cycling in Australian heath and South African Fynbos.
In:Mediterranean-type ecosystems. The role of nutrients.
Kruger,F.J., Mitchell,D.T. and Jarvis,J.U.M. (Eds.)
Springer Verlag. New York.

Gutierrez Jerez,F., Fernandez Caldas,E., Caldas,E., Mendez,J.A. and
Trujillo Jacinto Del Castillo. 1979.
Estudio Comparitivo de metodos para la determinacion de fosforo organico total en andosoles.
Anales de edofologia y Agrobiologia.38:981-989.

Hall,A.V. 1978.
Endangered species in a rising tide of human population growth.
Transactions of the Royal Society of South Africa.43:37-49.

Hannapel,R.J., Fuller,W.H., Bosma,S. and Bullock,J.S. 1964a.
Phosphorus movement in a calcareous soil.1.
Predominance of organic forms of phosphorus in phosphorus movement.
Soil Science.97:350-357.

Hannapel,R.J., Fuller,W.H. and Fox,R.H. 1964b.
Phosphorus movement in a calcareous soil.2
Soil microbial activity and organic phosphorus movement.
Soil Science.97:421-427.

Harrison,A.F. 1975.
Estimation of readily available phosphate in some English Lake District Woodland soils.
Oikos.26:170-176.

Harrison,A.F. and Helliwell,D.R. 1979.
A Bioassay for comparing phosphorus availaility in soils.
Journal of Applied Ecology.16:497-505.

Hesse,D.R. 1971.
A textbook of soil chemical analysis.
John Murray.London.

Holford,I.C.R. and Mattingly,G.E.C. 1976.
A model for the behaviour of labile phosphate in soil.
Plant Soil.44:219-229.

Hsu,P.H. 1964.
Adsorption of phosphate by aluminium and iron in soils.
Soil Science Society of America Proceedings.28:474-478.

Hsu,P.H. 1965.
Fixation of phosphate by aluminium and iron in acidic soils.
Soil Science.99 :398-402.

Jeffrey,D.W. 1964.
The formation of polyphosphates in Banksia ornata,an Australian heath plant.
Australian Journal of Biological Science.17:845-854.

Jones,E. 1960.
The contribution of rainwater to the nutrient economy of soil in Northern Nigeria.
Nature.188:432.

Jongens-Roberts,S.M. 1979.
Studies on Phosphorus Cycling processes in the fynbos biome.
CSIR Fynbos Biome Annual Report 1.

Jongens-Roberts,S.M., Brown,G.J. and Mitchell,D.T. 1980.
Studies on Phosphorus cycling processes in the fynbos biome.
CSIR Fynbos Biome Annual Report 2.

Jongens-Roberts,S.M., Brown,G.J. and Mitchell,D.T. 1981.
Studies on Phosphorus cycling processes in the fynbos biome.
CSIR Fynbos Biome Annual Report 3.

Joubert,G.D.P. 1965.
Die Verband tussen opstandsboniteit van Pinus radiata en grondeienkappe.
M.Sc.Thesis.University of Stellenbosch.

Kempers,A.J. 1975.
Determination of submicroquantities of plant available
phosphate in aqueous soil extracts.
Plant and Soil.42:423-427.

Khin,A. and Leeper,G.W. 1960.
Modifications in Chang and Jacksons procedure for
fractionating soil phosphorus.
Agrochimica.4:246-254.

Kruger,F.J. 1979.
South African Heathlands.
In:Heathlands and Related shrublands of the World.
A descriptive series. pp 19-79.
R.L.Specht.(Ed)
Elsevier Scientific Publishing Co.Amsterdam.

Kuo,S. and Mikkelson,P.S. 1979.
The distribution of iron and aluminium in flooded and
unflooded soil profiles and their relation to phosphorus
adsorption.
Soil Science.127:18-24.

Lambrechts,J.J.N. 1979.
Geology,geomorphology and soils in fynbos ecology:
In:Fynbos ecology:
A preliminary synthesis.
Day,J., Siegfried,W.R., Louw,G.N. and Jarman,M.L.(Eds.)
CSIR Report 40.pp 17-26.

Lamont,B. 1982.
Strategies for maximising nutrient uptake in two
mediterranean-type ecosystems of low nutrient status.
In:Mediterranean-type ecosystems.The role of nutrients.
Kruger,F.J., Mitchell,D.T. and Jarvis,J.U.M. (Eds.)
Springer Verlag. New York.

Larsen,S. 1967.
Soil Phosphorus.
Advances in Agronomy. 19:151-210.

Legg,J.O. and Black,C.A. 1965.
Determination of organic phosphorus in soils.
2.Ignition Method.
Soil Science Society of America Proceedings.19:139-143.

Le mare,P.H. 1981.
Exchangeable phosphorus, estimates of it from amorphous iron
oxides and soil solution phosphorus in relation to phosphorus
taken up by maize.
Journal of Soil Science.32:285-299.

Low,B. 1980.
Preliminary observations on specialised root morphology in
plants of the Western Cape Province.
South African Journal of Science.76:513-516.

Marchant,J.W. and Moore,A.E. 1978.
Geochemistry of the Table Mountain Group.
2.Analysis of two suites of Western Graafwater rocks.
Transactions of the Geological Society of South Africa.81:353-357.

Martin,J.K. 1970.
Organic phosphate compounds in water extracts of soils.
Soil Science.109:362-375.

Mehta,N.C., Legg,J.O., Goring,C.A.I. and Black,C.A. 1954.
Determination of organic phosphorus in soils:
1.Extraction methods.
Soil Science Society of America Proceedings.15:443-449.

Mehta,P.C., Puntamkar,S.S. and Seth,S.P. 1971.
Vertical distribution of phosphorus in the soils of Western Rajasthan.
Indian Journal of the Society of Soil Science.19:389-391.

Mitchell,D.T. 1980.
The status of nutrient relation studies in the fynbos biome project.
Terrestrial Ecosystems Newsletter.14:1-4.

Mitchell,D.T. and Read,D.J. 1981.
Utilization of inorganic and organic phosphates by the mycorrhizal endophytes Vaccinium macrocarpon and Rhododendron ponticum.
Transactions of the British Mycological Society.76:255-260.

Murphy,J. and Riley,J.P. 1962.
A modified single solution method for the determination of phosphate in natural waters.
Analytico Chimica Acta.27:31-36.

Norton,B.E. and McGarrity,J.W. 1965.
The effect of burning native pasture on soil temperatures in Northern New South Wales.
Journal of the British Grasslands Society.20:101-105.

Nyamapfene,K.W. 1981.
Phosphate desorption studies on three highly weathered tropical soils.
Communications in Soil Science Plant Analysis.12:407-414.

Perez Mendez,J.A., Gutierrez Jerez,F., Fernandez Caldas,E. and Trujillo Jacinto del Castillo, I. 1979.
Fosforo organico en andosoles y su relacion con otros parametros del suelo.
Anales de Edafologia y Agrobiologia.38:1199-1208.

Poldervaart,A. 1955.
The Crust of the Earth:A Symposium.
Geological Society of America Special Paper.62:119-144.

Rajan,S.S.S. and Fox,R.C. 1975.
Phosphate adsorption in soils.
2.Tropical soils.
Soil Science Society of America Proceedings.39:846-851.

Robertson,R.A. and Davies,G.E. 1965.
Quantities of plant nutrients in heather ecosystems.
Journal of Applied Ecology.2:211-219.

Roche,P., Griere,L., Babre,D., Calba,H. and Fallavier,P. 1980.
Phosphorus in tropical soils: assessing deficiency trends and phosphorus requirements.
Institute Mondial du Phosphate.Scientific publication.No.2.

Rundel,P. 1982.
The impact of fire on nutrient cycles in Mediteranean-type ecosystems.
Mediterranean-type ecosystems.The role of nutrients.
Kruger,F.J., Mitchell,D.T. and Jarvis,J.U.M. (Eds.)
Springer Verlag. New York.

Rundel,P.W. and Parsons,D.J. 1979.
Stuctural changes in chamise (Adenostoma fasiculatum) along a fire induced age gradient.
Journal of Range Management.32: 462-466.

Russell,E.W. 1973.
Soil Conditions and Plant Growth.
Longmans.

Saunders,W.M.H. 1959.
Aluminium extracted by neutral citrate dithionate reagent.
Nature.184:2034.

Savage,M.J. 1980.
The Effect of fire on grassland microclimate.
The Commonwealth Bureau of Pasture and Field Crops.
Herbage Abstracts.50:588-603.

Schofield,R.K. and Taylor,A. 1955.
The Measurement of Soil pH.
Soil Science Society of America Proceedings.19:164-167.

Schulze,B.R. 1947.
The climate of South Africa according to the classifications of Koppen and Thornthwaite.
South African Geographical Journal.29:32-42.

Shapiro,R.E. 1958.
Effect of organic matter and flooding on availability of soil and synthetic phosphates.
Soil Science.85:267-272.

Sharpley,A.N., Menzel,R.G., Smith, S.J., Rhoades,E.D. and Olness,A.E. 1981.
The sorption of soluble phosphorus by soil material during transport in runoff from cropped and grassed watersheds.
Journal of Environmental Quality.10:211-215.

Sibbesen,E. 1977.
A simple exchange resin procedure for extracting plant available elements from soil.
Plant and Soil.46:665-669.

Sibbesen,E. 1978.
An investigation of the anion exchange resin method for soil phosphorus extraction.
Plant and Soil.50:305-321.

Smeck,N.E. 1973.
Phosphorus:An indicator of pedogenetic weathering processes.
Soil Science.115:199-206.

Smith,A.N. 1965.
Distinction between iron and aluminium phosphate in Chang and Jacksons procedure for fractionating inorganic soil phosphorus.
Agrochimica.9:162-168.

Smith,V.R. 1979.
The influence of seabird manuring on the phosphorus status of Marion Island.
Oecologia.41:123-126.

Soderlund,R. 1981.
Dry and wet deposition of nitrogen compounds.
Terrestrial Nitrogen Cycles.Ecological Bulletin:123-130.
Clark,F.E. and Rosswall,T.(Eds.).

Sokal,R.R. and Rohlf,F.J. 1969.
Biometry:The principles and practices of statistics in biological research.
Freeman and Co.San Francisco.

Specht,R.L. 1953.
The ecology of the heath vegetation in the Upper South East of South Australia.
Ph.D.Thesis.University of Adelaide.

Specht,R.L., Moll,E.J., Pressinger,F. and Sommerville,J. 1982.
Moisture regime and nutrient control of seasonal growth in in mediterranean ecosystems.
In:Mediterranean-type ecosystems.The role of nutrients.
Kruger,F.J., Mitchell,D.T. and Jarvis, J.U.M.(Eds.)
Springer Verlag.New York.

Steward,J.H. and Oades,J.M. 1972.
The determination of organic phosphorus in soils.
Journal of Soil Science.23:38-48.

Street,H.E. and Lowe,J.S. 1950.
The carbohydrate nutrition of tomato plants.
Annals of Botany.14:307-314.

Svensson,B.H. and Soderlund,R. 1975.
Nitrogen,phosphorus and sulphur:global cycles.
Scope Report 7.
Ecological Bulletin 22.Stockhholm.

Syers,J.K. and Walker,T.W. 1969a.
Phosphorus transformations in a chronosequence of soils developed in wind blown sands in New Zealand.
1.Total and organic phosphorus.
Journal of Soil Science.20:57-64.

Syers,J.K. and Walker,T.W. 1969b.

Phosphorus transformations in a chronosequence of soils developed in wind blown sands in New Zealand.

Journal of Soil Science.20:318-324.

Taylor,H.C. 1978.

Capensis.

In:Biogeograghy and ecology in southern Africa.

Werger,M.J.A.(Ed).

Junk,The Hague.pp 171-229.

Taylor,H.C. and Kruger,F.J. 1978.

A first attempt to measure temperature of fire in fynbos

Bothalia.12:551-553.

Thompson,G.R. 1971.

Studies on P retention in some Natal soils.

M.Sc. Thesis.

University of Natal.

Thornton,I. 1965.

Nutrient content of rainwater in Gambia.

Nature.205:1025.

Van Wazer,J.R. 1958.

Phosphorus and its compounds.Vol.1.

Wiley Interscience.New York.

Van Wilgen,B. and le Maitre,D. 1980.
The release of nutrients from above ground plant parts following fire in fynbos at Zacchariashoek,Paarl.
Forestry Report. Unpublished.

Vitousek,P.M., Gosz,J.R., Grier,C.C., Melillo,J.M., Reiners,W.A. and Todd,R.L. 1979.
Nitrate losses from disturbed ecosystems.
Science.204:469-474.

Wagle, R.F. and Kitchen,J.H. 1972.
Influence of fire on soil nutrients in a Ponderosa pine type.
Ecology.53:118-125.

Walker,T.W. and Adams,A.F.R. 1958.
Studies on soil organic matter.
1.Influence of phosphorus content of parent material on accumulation of C,N,S and organic phosphorus in grassland soils.
Soil Science.85:307-318.

Walker,T.W. and Adams,A.F.R. 1959.
Studies on soil organic matter.
2.Influence of increased leaching at various stages of weathering on levels of C,N,S,organic and total phosphorus.
Soil Science.87:1-10.

Walker,T.W. and Syers,J.K. 1976.
The fate of phosphorus during pedogenesis.
Geoderma.15:1-19.

Wells,C.G. 1971.
Effects of prescribed burning on soil chemical properties and nutrient availability.
Prescribed burning symposium.Proceedings of the South Eastern Forest Experimental Station.Charleston. pp 86-99.

Westin,F.C. and de Brito,J.G. 1969.
Phosphorus fractions of some venezualen soils as related to their stage of weathering.
Soil Science.107:194-202.

Wicht,C.L. 1971.
The influence of vegetation in South African mountain catchments on water supplies.
South African Journal of Science.67:201-209.

Willet,I.R. and Higgins,M.L. 1978.
Phosphate sorption by reduced and reoxidised rice soils.
Australian Journal of Soil Research.16:319-326.

Williams,C.H. 1980.
Soil acidification under clover pasture.
Australian Journal of Experimental Agricultural Animal Husbandry.20:561-567.

Williams,J.D.H. and Walker,T.W. 1967.
Comparison of ignition and extraction methods for the determination of organic phosphorus in rocks and soils.
Plant and Soil.27:457-459.

Williams,J.D.H., Syers,J.K. and Walker.T.W. 1967.
Fractionation of soil inorganic phosphates by a modification of Chang and Jackson's procedure.
Soil Science Society of America Proceedings.31:736-739.

Williams,J.D.H., Syers,J.K., Walker,T.W. and Shah,R. 1969.
Apatite transformations during soil development.
Agrochemica.13:491-501.

Williams J.D.H. and Walker,T.W. 1969a.
Fractionation of phosphate in a maturity sequence of New Zealand basaltic soil profiles.1.
Soil Science.107:22-30.

Williams,J.D.H. and Walker,T.W. 1969b.
Fractionation of phosphate in a maturity sequence of New Zealand basaltic soil profiles.2.
Soil Science.107:213-219.

Williams,J.D.H., Syers,J.K., Walker,T.W. and Rex,D.K. 1970.
A comparison of the methods for the determination of soil organic phosphorus.
Soil Science.110 13-17.

Zar,J.H. 1974.
Biostatistical Analysis.
Prentice Hall.
New Jersey.

12. Appendix.

12.1. Reagent Preparation.

12.1.1. Murphy and Riley Solution.

Dissolve 20g ammonium molybdate in 500 cm^3 distilled water.

Dissolve 0,2743g potassium antimony tartrate in 100 cm^3 distilled water.

To a 500 cm^3 volumetric flask add 250 cm^3 5N H_2SO_4.

Dissolve 2.64g ascorbic acid in 150 cm^3 distilled water.

Add this to the flask.

Add a 75 cm^3 aliquot of the ammonium molybdate to the flask.

Add a 25 cm^3 aliquot of the potassium antimony tartrate to the flask.

Shake until all solids are dissolved and use within 24 hours.

12.1.2. Kempers Reagent.

To a 500 cm^3 volumetric flask add 80 cm^3 30% HCl.

Dissolve 3g ascorbic acid in 100 cm^3 distilled water and add to flask.

Add 2g ammonium molybdate to the flask.

Add 50 mg potassium antimony tartrate to the flask.

Shake until all solids are dissolved.

Make up to volume and use immediately.

12.1.3. Bray#2 Solution.

Measure 600 cm^3 ammonium flouride stock solution (36,1g 1000 cm^{-3}) into a 20 litre aspirator.

Add about 10 litres of distilled water.

Add 200 cm^3 of 31% mass/mass hydrochloric acid, chemically pure.

Dilute to 20 litres with distilled water.

Mix well.

12.1.4. Triacid Mix.

Nitric (HNO_3), sulphuric (H_2SO_4) and perchloric ($HClO_4$) acids were mixed in the ratios 10:1:4 and used to breakdown organic matter.

12.2. Calibration Curves Used.

The curves were all linear within the ranges used and were expressed by the formula $Y=a+bX$ where a and b are given in the following Table 12:1.

and X= absorbance and Y= μg P aliquot.

Table 12:1. a and b values for calibration curves.

Application.	a	b	Range (µg aliquot^{-1})
Total,Bray#2 P.	-0.001	0.0168	0,6-20,0
Resin extractable P	0.005	0.0042	0,2-3,5
Kempers method	0.008	0.0972	0,08-4,0
Adsorption trial	0.008	0.0026	2,9-30,0
desorption trial	0.002	0,0032	3,0-30,0
Steward and Oades method (1972).	0.0005	0.0138	0,4-30,0

In all cases five concentrations of phosphorus and a blank were employed with six replicates at each concentration. The spectrophotometer was initially zeroed using distilled water.