THE PHOSPHATE STATUS

of the

SOILS OF RIVERHEAD FOREST

in relation to

GROWTH OF RADIATA PINE

by

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"HUMAN VANITY CAN BEST BE SERVED BY A REMINDER THAT,
WHATEVER HIS ACCOMPLISHMENTS, HIS SOPHISTICATION,
HIS ARTISTIC PRETENSION, MAN OWES HIS VERY EXISTENCE
TO A SIX INCH LAYER OF TOPSOIL - AND THE FACT THAT IT RAINS."

- Quoted in "The Cockle Bur"

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(A) INTRODUCTION

Extensive plantations of exotic softwood species in New Zealand have for the major part been restricted to land considered marginal for agricultural and pastoral pursuits. On these marginal lands of relatively low fertility and difficult terrain, forestry can compete economically with agriculture.

Radiata pine (Pinus radiata D. Don), the most important of the exotic softwoods, occupies some 600,000 acres in New Zealand, but, despite its versatility and adaptability, has in some instances been established on sites which are outside the limits of its tolerance. Such is the case at the Riverhead State Forest in the Auckland conservancy. In many sectors of this forest, radiata pine, planted during the period 1926-33 on podzolized gumland clays, manifested symptoms of ill-health and unthriftiness within a short time of establishment. These symptoms gave rise to concern and stimulated a programme of research into the possible causal factors. The fertilizer trial work conducted at Riverhead up till 1958 has been reviewed by Weston (1956, 1958). Conway (1962) discussed aerial application of phosphatic fertilizers at Riverhead, while Will (1965) reported the more recent nutritional work. This nutritional work, which has included tissue analyses and the study of growth responses to phosphatic and zinc fertilizer treatments, has shown quite conclusively that unthrifty trees in the trial areas manifest a considerable response to phosphate, but not to zinc. The degree of response to the application of superphosphate has been shown to be dependent upon the prior condition of the stand and the rate of application. Topdressing at a rate of 5cwt/acre of superphosphate as a standard practice has been tentatively adopted following these trials. Will (1965) has shown that foliar analysis can be a most useful aid in assessing the need for fertilizer and in predicting the likely response to fertilizer treatment.

Throughout the period under review little emphasis has been placed on soil investigations as a means of elucidating the cause of poor tree growth. This is understandable in the short term in view of the general lack of proven technique and standards for soil testing compared with those available for foliar testing. While, however, foliar analyses and trial and error fertilizer experiments can establish the nature of an unknown deficiency and provide an indication of suitable ameliorants, they are inadequate as long term management aids. Only through an understanding of the primary causal factors of unthriftiness can the most suitable and economic corrective treatments be ascertained. A major disadvantage of tissue analysis as a means of predicting the fertilizer requirements of forest stands is that the need for corrective treatment cannot be predicted before the deficiency develops. Suitably calibrated soil tests could help to overcome this problem.

The Forest Research Institute (F.R.I.) Rotorua, throughout the period under review, has been well aware of the need to supplement the information obtained from field trials and foliar analyses with soil information, and the present investigation was undertaken with this objective in view. The approach decided upon may be conveniently summarized under the following headings:-

(1) A survey of the distribution and forms of phosphorus in selected profiles.

(2) A study of the availability of soil phosphate to radiata pine, involving an investigation of:

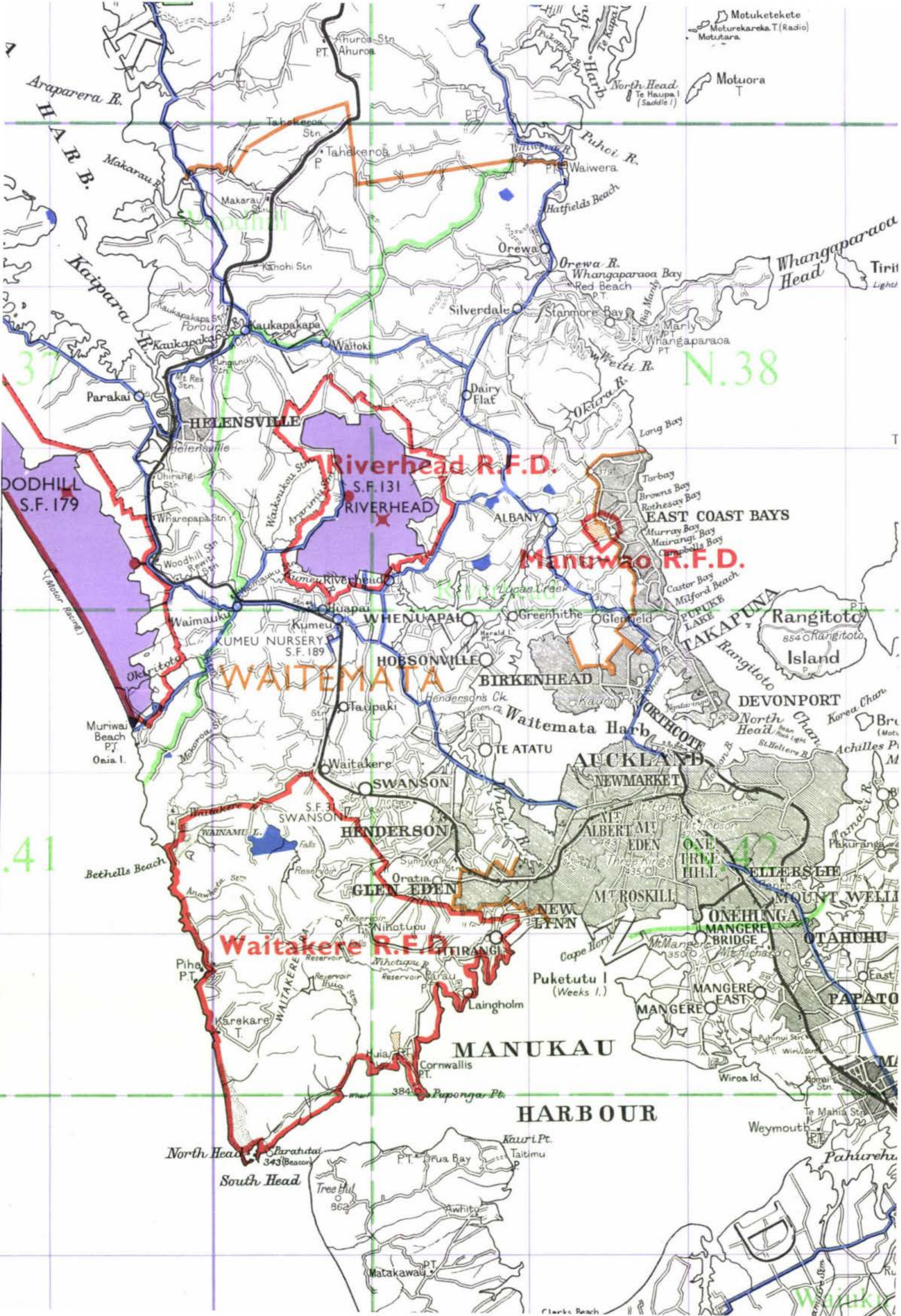
(a) The relationships among available soil phosphate levels (measured by a range of chemical extraction procedures), foliar phosphorus levels and site productivity.

(b) The contribution of site factors to these relationships.

(3) A study of the fate of a range of phosphatic fertilizers applied to the main soil types in the forest, supplemented by observations on the fate of phosphate applied to these soils in the laboratory.

Fig.1.1

MAP SHOWING THE LOCATION OF RIVERHEAD STATE FOREST



Riverhead R.F.D.
S.F. 131
RIVERHEAD
Manuwao R.F.D.
Waitakere R.F.D.
WAITEMATA
WOODHILL
S.F. 179
KUMEU NURSERY
S.F. 189
S.F. 31
SWANSON
N.38
HELENSVILLE
EAST COAST BAYS
TAKAPUNA
DEVONPORT
AUCKLAND
NEWMARKET
BIRKENHEAD
NORTHCOTE
HOBSONVILLE
WHENUAPAI
HENDERSON
GLEN EDEN
NEW LYNN
TITIRANGI
MT ALBERT
MT EDEN
ONE TREE HILL
MT ROSKILL
ONEHUNGA
MANGERE BRIDGE
MANGERE
MANGERE EAST
OTAHUHU
ELLERSLIE
MANUKAU
HARBOUR
Waitemata Harb.
Rangitoto Island
Puketutu I. (Weeks I.)
Kaipara R.
Araparera R.
Makarau R.
Puhoi R.
Waiwera
Hatfields Beach
Orewa
Orewa R.
Whangaparaoa Bay
Red Beach
Whangaparaoa Head
Silverdale
Stanmore Bay
Whangaparaoa
Weiti R.
Okura R.
Long Bay
Torbay
Browns Bay
Rothesay Bay
Murray Bay
Mairangi Bay
Campbells Bay
Castor Bay
Milford Beach
Dairy Flat
Albany
Greenhithe
Glenfield
Kaukapakapa
Waitoki
Parakai
Tahekeroa
Ahuroa
Makarau
Kanohi Stn
Woodhill Stn
Waimauku
Huapai
Kumeu
Riverhead
Taupaki
Waitakere
Swanson
Te Atatu
Muriwai Beach
Oaia I.
Bethells Beach
Piha
Karekare
Laingholm
Huia
Cornwallis
Puponga Pt.
North Head
South Head
Paratutai
Kauri Pt.
Taitimu
Orua Bay
Awhitu
Matakawau
Weymouth
Motuora
Motuketekete
Motutara
North Head
Te Haupa I. (Saddle I.)
Henderson Ck.
Oratia
Nihotupu
Sunnyvale
Cape Horn
Wiroa Id.
Clarks Beach

(B) DESCRIPTION OF RIVERHEAD STATE FOREST

The forest has a total area of almost 12,000 acres, of which about 60 per cent is planted in radiata pine.

(1) LOCALITY DATA

Riverhead State Forest, Auckland Conservancy is situated some 20 miles by road, north-west of Auckland city at the head of the Waitemata Harbour (Fig.1.1).

The precise geographic location is latitude 36°45'S
longitude 174°36'E.

The altitude varies from 50 to 400 feet above sea level.

(2) CLIMATE

G.C. Weston (1956) described the Riverhead climate as, "equable with a mean annual rainfall of 56.4 inches well distributed throughout the year, long frost free growth season, and relatively mild winters. The growth season (September-February inclusive) has an average rainfall of 24.6 inches and a mean temperature of 58.1°F. Mean annual temperature is 55.8°F. and the mean temperature of the coldest month (July) is 48.5°F. Using Thornthwaite's classification, the climate can be termed as humid mesothermal in character".

Such a climate is considered favourable for the rapid growth of radiata pine (Scott 1960).

(3) GEOLOGY

Bartrum (1924) described the geology of the Riverhead District. The immediate underlying rocks within the forest area are sedimentary beds of the Waitemata series, apparently Upper Miocene in age. These beds are predominantly feldspathic sandstones, interbedded with frequent thin layers of mudstone and claystone. Massive sandstones and thick conglomerates of dioritic pebbles, greywackes, argillites, andesites and other rocks constitute locally important sections of the Waitemata series within the forest area. Under the warm humid climate the weathering of these sedimentary beds has been intense and 'red weathering' to considerable depths is noticeable in many of the forest road cuttings. Pleistocene deposits represented by terraces of alluvium are features of most of the flat river valleys, but they are by no means extensive.

(4) SOILS

The country has moderate relief and a fairly complex drainage pattern. At the time of planting, native vegetation consisted of manuka (*Leptospermium scoparium*), fern, rushes and grasses but the evidence of charred tree stumps, pieces of gum and extensive podsolization suggests that the area once supported extensive mor-forming forests of Kauri (*Agathis australis*). It is assumed that these forests were destroyed by fire in pre-European times. During the early and mid nineteenth century the native scrub was repeatedly fired by several generations of gumdiggers inducing chemical degradation of the soil and erosion of the unprotected slopes and ridges.

The complex interaction of the various soil forming factors has produced a very variable pattern of soils throughout the forest area. The soils formed on the Waitemata sedimentary beds are mostly clays, deeply weathered, infertile, poor in structure and podzolized to varying degrees, whilst those formed on the alluvial terraces are better structured more fertile and less sticky. These soils have been provisionally mapped and classified by the New Zealand Soil Bureau (Table I.I). In some sections of the forest where gumdigging and erosion has been intense, the exposure of the parent material has produced areas of rudimentary soils.

(5) TREES

The condition of the trees in Riverhead forest is extremely variable, ranging from trees of 150 - 160 ft. in height at 40 years of age in favourable locations - typically in gullies and lower country - to trees of 20 - 30 ft. at the same age on very poor sites - typically on upper slopes and ridges from which topsoil and sometimes subsoil has been washed. Weston (1958) described the assortment of symptoms associated with the unthrifty stands.

TABLE I.I

SOILS OF THE RIVERHEAD FOREST

(N.Z. Soil Bureau Provisional Maps Nos. 9 and 10)

SOIL TYPE	SYMBOL +	PARENT MATERIAL	GENETIC GROUP*
Waikare Clay, Sandy Clay and Sandy Loam	YK	Claystone	Strongly Leached to Weakly Podzolized Northern Yellow-Brown Earth
	YKs	Massive Sandstone	
Hukerenui Sandy Loam	H	Claystone	Moderately Podzolized Northern Yellow-Brown Earth
	Hs	Massive Sandstone	
Warkworth Clay	WA	Banded Sandstone	Strongly Leached Northern Yellow-Brown Earth
Parau Clay and Clay Loam	PA	Conglomerate	Northern Yellow-Brown Earth - Brown Granular Clay Intergrave
Waitemata Clay Loam and Fine Sandy Loam	WE	Pumice Alluvium and Conglomerate	Strongly Leached to Weakly Podzolized Yellow-Brown Loam

+ These symbols will be employed to denote soiltypes throughout the test

* Updated nomenclature in substitution for that shown on the original maps (H.S.Gibbs - Pers.comm.)

This review (conveniently grouped under three main headings) is limited to work which illustrates research trends and the principles involved therein. Where possible, material has been selected from work on conifereous forest species.

(A) FACTORS INFLUENCING FOREST PRODUCTIVITY

The major factors regulating forest productivity were represented by Ralston (1964) in the following way:-

BIOLOGICAL FACTORS	SITE FACTORS
Genetic Variation	Meteorological Conditions
Stand Density	Topographic Effects
Competing Vegetation	Edaphic Variables
Insects and Disease	

CURRENT PRODUCTIVITY

|

Management Intensity

|

POTENTIAL PRODUCTIVITY

As site factors are of direct importance to the present study, greater emphasis is accorded to them than to biological factors in this section of the review.

(1) BIOLOGICAL FACTORS

(a) Genetic Variation

Growth differences between different species are well documented and appreciated (Doolittle, 1958; Jackson, 1962; and Millar and Thulin 1967a). Provenance trials have indicated hereditary variation in growth within species (Millar and Thulin 1967b) but for most commercial timber species, the content of the variation is unknown and must be treated as residual experimental error in site evaluation studies (Ralston 1964).

(b) Stand Density

Inadequate density of stock on productive land seriously limits productivity. In commercial forest plantations variation in productivity, resulting from different stocking rates, may be partially corrected for by the selection of suitable measurements of site productivity, thus enabling the influence of other factors to be studied. Measurements of some aspect of height are considered most suitable (Ralston 1964).

(c) Competing Vegetation

Competing vegetation affects forest productivity in two major ways; first, by preempting growing space and secondly, through direct competition for available moisture and nutrients. Barnes (1955) found that the height of slash pine (P. elliottii) at 25 years of age averaged 7 feet more on planted old fields than that of plantations on cutover forest sites with similar soil profiles.

(d) Disease and Insects

Gilmour (1966) reviewed the fungal, bacterial and algal pathogen that occur in New Zealand exotic forest plantations, but concluded that few diseases have caused serious loss in either native forests or exotic forest plantations in New Zealand. This was attributed to New Zealand's geographical isolation from sources of infection and the wide genetic differences between the exotic and native species, with few native pests or diseases attacking the exotics.

Losses of economic importance in New Zealand exotic forests have been attributed to sapwood decay, caused by a species of Amylosterem Biodin (Rawlings, 1958) which is now largely controlled through the introduction of parasites of the insect vector, and the Phytopthora root rot (Newhook, 1959), frequently associated with periods of abnormal rainfall on heavy clay soils.

A more recent disease, the pine needle blight, caused by Dothistroma pini Hulbary, first observed in New Zealand in 1964

(Gilmour, 1965) has caused widespread defoliation in many young pine stands throughout New Zealand, with a consequent reduction in diameter growth (Gilmour, 1967). A certain degree of control over this disease has now been obtained through aerial application of copper based fungicides.

(2) SITE FACTORS

The influence of environmental factors on forest productivity is much easier to observe and demonstrate, both in the field and by controlled experiments.

(a) Meteorological Variables

The significance of meteorological and other site variables on productivity usually depends on the range or amplitude of the particular phenomenon considered, since trees are fairly insensitive to minor fluctuations in the environment (Ralston, 1964). Meteorological effects are pronounced over relatively short distances only at altitudinal and latitudinal extremes.

Jackson (1962) reported that the majority of variation in slash pine growth between the Northern and Southern hemispheres could be explained by variation in the rainfall and diurnal temperature range of the growing season and the mean temperature of the coldest month. Growing season rainfall in excess of 20 inches was found to be detrimental to growth on shallow soils but this effect diminished rapidly as permeable surface layers thickened. Covell and McClurkin (1967) recorded an increase in the growth of loblolly pine (P. taeda) with an increase in the growing season rainfall up to 34 inches on the Southern coastal plains of the U.S.A. The effect was more pronounced the deeper the topsoil. Lemmon (1955) reported an increase in site productivity with increasing annual rainfall for Douglas fir stands of the American Pacific north-west where local precipitation varies considerably.

Studies conducted within localities where the range of meteorological variables is small, or extremes are not met with, seldom manifest any significant relationships between tree growth and meteorological variables: Myers and Van Deusen (1960) reported no significant relationship between precipitation and the growth of Ponderosa pine (P. Ponderosa) in the Black hills of South Dakota. Steinbrenner (1965) reported a significant influence of precipitation on Douglas fir growth at low but not at high elevations.

Coile (1952) reviewed the influence of climatic factors on the productivity of forested lands in the U.S.A.

(b) Topographic Variables

Literature on the influence of the major topographic variables, slope, aspect and elevation on tree growth is conflicting. Lemmon (1955) and Myers and Van Deusen (1960) reported significant negative correlations between conifer growth and the percentage slope, whilst Doolittle (1957) reported a non-significant relationship. Steinbrenner (1965) found a significant negative correlation for Douglas fir at high elevation but not at low elevations.

Copeland and McAlpine (1955) and Myers and Van Deusen (1960) reported warmer southern aspects in the Northern hemisphere to be more favourable for growth. Steinbrenner (1965) found this relationship held for Douglas fir but was more pronounced at higher than lower elevations. Doolittle (1957) reported no relationship between growth and aspect in the Southern Appalachians. Hills (1959) observed that the warmer southern aspects may be more favourable to growth in the colder Ontario area, yet may be associated with poorer growth in hotter drier climates. In areas with relatively mild humid climates, he reported little influence of aspect on growth.

Lemmon (1955) and Steinbrenner (1965) reported a significant negative correlation between elevation and the growth of Douglas fir, whilst Myers and Van Deusen (1960) reported no such relationship for Ponderosa pine.

Ralston (1964) commenting on these conflicting reports stated:

"It is interesting to note that a given physiographic characteristic may be either beneficial or detrimental to growth depending on the general climatic frame of reference."

Ralston concluded:

"The effect of elevation is significant in mountainous areas, aspect is of consequence in rugged terrain or cold latitudes and topographic position classes are helpful separations in areas of gentle relief."

Carmean (1967) suggested that significant relationships existed between topographic features and growth because these features indirectly expressed micro-climate, soil moisture and soil features important to the growth of trees.

(c) Edaphic Variables

Trees depend on the supporting soil for moisture, nutrient elements and aeration. Soil properties presumed to reflect these variables have been associated with site productivity. Such properties are normally most successful for evaluating variation in site productivity within climatic zones.

(i) Soil Types

The marked influence of soil types on the productivity of radiata pine in New Zealand has been recorded by Jackson (1965) and by Levy and Sutherland (1954). The latter authors conducted a survey on the influence of soil types on the growth of various pine species in Northland. For Radiata pine they found that good growth occurred on moderately leached Yellow-Brown Earths and strongly leached Brown Granular clays and Brown loams if well drained. A merchantable timber could be obtained from strongly leached and weakly podzolized Yellow-Brown Earths from Greywacke, even if poorly drained, but not from soils of similar stage, formed on Cretaceous claystones, which are poorly drained. Ralston (1964) suggested that the effect of soil type is expressed more subtly in the properties of the soil profile.

(ii) Soil Physical Properties

Coile (1952) reviewed the soil features which appeared to be important in influencing the growth of tree species. He concluded that significant features for satisfactory growth were the volume available for root exploration, the storage capacity of this volume and the availability of the moisture in it.

Various measurements of the soil volume for root exploration (depth of the A horizon, depth to subsoil, or depth to clay or hardpan), have been related with site productivity: Beckman (1964) reported such a relationship for radiata pine, Steinbrenner (1965) for Douglas fir, Myers and Van Deusen (1960) for Ponderosa pine and Coile and Schumacher (1953) for loblolly and shortleaf pines.

Soil texture has been commonly employed as an index of the available moisture supply. Increases in the silt and clay fraction of surface and subsoil horizons have been associated with increased productivity of many species of trees: Wilde et al. (1964 (a) and 1964 (b)) reported such a relationship for Jack and red pines, Jackson (1962) for slash pine and Gessel and Lloyd (1950) for Douglas fir. Holtby (1947) found a significant positive relationship between 'fines' and the growth of Ponderosa pine on land of moderate relief but not for rough and mountainous country. Pawluk and Arneman (1961) reported a curvilinear relationship between the growth of Jack pine and the content of 'fines': growth increased up to a critical level of 'fines', above which a depressive effect occurred. This was attributed to inadequate air space at high levels of 'fines'. Della-Bianca and Olsen (1961) reported a positive correlation between the percentage of sand in the A_2 horizon and the growth of yellow poplar.

Laboratory measurements of soil moisture supply have been reported as significantly related to tree growth (Pawluk and Arneman, 1961; Carmean, 1954; and Voigt, 1959). Other properties reflecting soil moisture and aeration regimes have been associated with the productivity of various tree species: gravel content ($>$2 mm), which modifies the soil moisture regime and the effective soil volume, was shown to be negatively associated with tree growth (Steinbrenner, 1965). Carmean (1954) reported an interaction between gravel and texture, which indicated that high gravel contents were less detrimental on fine textured soils than on sandy soils. Bulk density of the B horizon was reported as having no significant influence on the growth of Jack pine (Pawluk and Arneman (1961). Forristal and Gessel (1955) found that high bulk density reduced growth, the critical level being a function of the individual species. Site drainage conditions, which reflect the intimate relationship between the soil moisture and aeration regimes, have been associated with variation in site productivity of pine (Mader and Owen, 1961; Zahner 1954); Poutsma and Simpfendorfer (1962) reported that the vigour of both P. Pinaster and radiata pine varied significantly with the degree of seasonal surface waterlogging. Sutherland et al. (1959) suggested that partial defoliation and death of pines during a very wet winter in North Auckland could be attributed to Phytophthora attack and that the severity of the disease was influenced by soil drainage.

Rennie (1962), in a review on methods of assessing forest site capacity, distinguished between the use of correlation studies for the estimation of site capacity, and for improving knowledge of the habitat factors controlling it, so that more intelligent forest management might be practised. In Rennie's opinion the 'omnibus criteria' of soil texture and depth fulfil the first purpose but not the second. Rennie stated:-

"They are merely blurred reflections of aeration, water and nutrient availabilities and rooting space. They are useful in so far as they give broad correlations of tree growth with some easily measured habitat attribute. But they fail to pinpoint the important causal factor or factors which masquerade under the nebulous labels of texture and depth."

The silt and clay content has been shown to be related to the Ca and Mg supply (Stoeckler 1960) and the levels of available phosphate (Wilde et al. 1964(a)). The use of partial regression and correlation procedures to isolate direct from indirect effects has now become more popular in attempts to determine the relationship between site factors and forest productivity (Dahl et al.1961 ; and Wilde et al. 1964 (a) and (b)).

(iii) Soil Chemical Factors

Reports in the literature suggest that soil pH, except where extremes occur, has little direct influence on site productivity (Humphreys, 1963; and Della-Bianca and Olson, 1961). Wilde et al. (1964(b) reported a significant influence of soil pH on the growth of Red pine. Tamm (1964) suggested that relationships between soil pH and site productivity could be expected in view of the interrelationship of soil pH with soil biological, physical and chemical properties which have a direct bearing on plant productivity. Soil fertility status, as a factor limiting tree growth, has until very recently received very little attention. In 1958 Voigt wrote:

"Students of forest soils commonly come away from the literature with the impression that nearly all tree growth can be explained almost completely by the so called physical properties of the soil - particularly those related to its moisture regime."

Ralston (1964) suggested this apparent neglect could be attributed to two major reasons:

(a) Frequent correlation of variables used to describe other soil properties with nutrient supplies.

(b) Lack of soil testing techniques of known significance in relation to tree requirements.

In recent work more emphasis has been placed on the role of nutrients in limiting site productivity, particularly since the use of more advanced statistical techniques has shown that the influence of physical soil properties are frequently indirect reflections of nutrient effects (Wilde et al. 1964(a); and Stoeckler 1960), and spectacular responses to applied fertilizers have indicated that nutrient deficiencies do exist (Ruapach, 1967; Stoeckler and Arneman, 1960; and Mustanoja and Leaf, 1964).

The influence of soil phosphate levels on tree growth has received considerable attention in the literature: Lutz and Chandler (1947) reported some early German work in which Schutze (1869) found a relationship between the phosphoric acid content of certain sandy soils and the yield of pine stands. However, Hennecke (1935) failed to substantiate this finding, but later work by Heinsdorf (1964), on these sandy soils, showed a significant relationship. In Australia Young (1948) reported a significant relationship between total soil phosphate and the growth of loblolly and slash pines. Baur (1959) substantiated this relationship for slash pine but pointed out that it held only for limited localities and not over more heterogenous sites. A similar relationship was found for radiata pine at the Lidsdale state forest in New South Wales (Humphreys, 1964) and for P. Pinaster in Western Australia (Hopkins 1960). Humphreys and Lambert (1965) attributed the "ash bed effect" to increased levels of available phosphate. In America Wilde et al. (1964 (a) and (b)) reported a significant correlation between available soil phosphate levels and the growth of Jack and red pines on non-phreatic sandy soils. A similar relationship was found for yellow poplar in Southwest Michigan (Schomaker and Rudolph, 1964). Ellerbe and Smith (1963) attributed discrepancies in the predicted growth of loblolly pine on the lower coastal plains of South Carolina to the presence of phosphate marl. Atkinson (1959) found that stunted growth of radiata pine at Cornwallis, Auckland, could be attributed to phosphate starvation. Viro (1955) reported significant correlations between the growth of Scots pine and some soil nutrient levels, including phosphate. However, Dahl et al. (1961) re-analysed Viro's data, employing partial correlation methods, and found that only calcium levels and the fraction >2 mm were significant, the phosphate effect being only indirect. This clearly pointed out the problems inherent in implying causal relationships from simple correlation studies.

Evidence of other nutrients restricting the site productivity of pine stands has been reported. Potassium has been shown to limit the growth of radiata pine in Eastern Australia (Hall and Purnell, 1961) and red pine in Eastern New York (Heiberg and Leaf (1960)). A relationship between soil calcium levels and pine growth has been reported by Humphreys (1964) and Dahl et al. (1961). The limiting role of nitrogen in forest productivity has been shown in Australia (Ruapach, 1967), England (Leyton, 1958), U.S.A. (Carter and Lyle, 1966), Holland (Hagenzieker, 1958), and Sweden and Finland (Maki,1966).

The role of micro-nutrients in forest productivity has received some attention in Australia where responses in tree growth have been recorded after the application of boron, zinc and copper fertilizers (Ruapach 1967).

Several investigators have reported correlations of site productivity with the percentage of organic matter in the topsoil: Wilde et al. (1964(a) and (b)), Mader and Owen (1961) and Copeland and McAlpine (1955) all reported a significant positive correlation between site productivity of pine stands and the percentage of organic matter in the A horizon. However inverse correlations have also been observed (Della-Bianca and Olson 1961). Erratic relationships can be expected as the amount of organic matter present reflects the interaction of a number of factors contributing to the accumulation and decomposition of litter materials (Ralston (1964)).

(iv) Soil Biological Factors

The presence of ectotrophic mycorrhiza in pinus species has been associated with the stimulation of the infected trees (McComb and Griffith, 1946; and Morrison 1954). This stimulation has been attributed to the increased availability of nutrients and the provision of growth stimulating substances by the fungal component. Hatch (1937) observed an increased uptake of phosphorus, potassium and nitrogen by infected trees which was attributed to an increased root surface area. Rosendahl (1942) and Purnell (1958) attributed the stimulation to the ability of the fungal component to mobilize phosphorus from apatite. McComb and Griffith (1946) suggested the better growth of infected trees resulted from the transfer of growth stimulators from the fungus to the host.

Lack of mycorrhiza has been associated with phosphate deficiency in pine stands (Young 1940). Harley (1959) suggested that mycorrhiza have a stimulating effect on growth only when one or other of the major elements is moderately deficient, for under conditions of extreme deficiency or abundance of nutrients mycorrhizal associations are seldom formed.

(B) EVALUATION OF FOREST NUTRIENT STATUS

The most common methods employed for diagnosing the nutrient status of plants were outlined by Wallace (1957) as follows:

(i) Plant methods

(a) The use of visual deficiency symptoms

(b) The use of plant tissue analysis.

(ii) Soil analysis.

(iii) Fertilizertrials.

This section of the review is concerned with the use of plant and soil analyses in evaluating the nutrient status of forests, the advantages and drawbacks of these methods, and the nature of the information obtainable from each. Particular emphasis is placed on the value of these methods for the detection of phosphate deficiency.

(1) Plant Tissue Analysis

Plant tissue analysis as a diagnostic technique for evaluating site fertility in forests has been discussed and reviewed by Viro (1961), Tamm (1964), Qureshi and Srivastava (1966) and Raupach (1967).

The use of plant analysis is based on the concept that the plant itself is the best indicator of the availability of nutrients. Mitchell (1936) suggested that by analysing plant parts, one is using a natural biological rather than an artificial extraction method, and that such analyses constitute the closest approach to an integration of the numerous interrelated factors which affect the delivery and uptake of nutrients. Lundegardh (1951) believed that plant analysis made full allowance for the extent to which plant roots penetrated into different soil horizons. Cain (1959) suggested that perennial plants are particularly suited to the procedure of foliar analysis as the physical mass of the tree acts as a buffer against the violent fluctuations in its composition. Work on tissue analysis with forest trees has been mainly restricted to foliar analysis although Will (1965) has reported that both wood and bark analyses showed promise for the detection of phosphate deficiency.

The nutrient content of foliage has been shown to vary according to the sampling procedure adopted. Will (1957) reported considerable variation in the phosphate content of the foliage of radiata pine with needle age and crown position. Ruapach (1967) also found a variation with season when crown position and needle age were standardized. Standardized sampling procedures have been adopted to enable comparative work to be conducted. The procedure adopted for radiata pine in New Zealand was outlined by Will (1965). However, Millar (1966) found that despite employment of standardized sampling procedures for loblolly pine, discrepancies occurred between years which could be attributed to variations in weather factors. Gentle and Humphreys (1968) reported a similar variation for radiata pine in Australia.

The interpretation of foliar analyses depends upon the assumption that foliar concentrations reflect the nutrient status. However, it has been pointed out that several factors may invalidate such an assumption:-

(a) <u>Growth Effects</u>

Tamm (1964) pointed out that nutrient uptake and translocation represented only part of the processes determining the nutrient concentration in a tissue, the most important additional process being growth. Cain (1959) reported a decrease in the percentage levels of many nutrients with an increasing supply of nitrogen, which was attributed to an increase in dry matter production masking the uptake of these nutrients. Steenbjerg (1951) reported a similar effect on the concentration of a nutrient when the supply of the same nutrient was increased from extreme scarcity to optimum levels in the substrate. Steenbjerg's work was conducted on cereals, but Tamm (1964) reported a "Steenbjerg effect" for forest trees.

(b) Translocation Effects

The relative mobility of elements within the plant and their distribution and accumulation have an important bearing on the interpretation of foliage analysis data. Leyton (1958) found that, due to the greater mobility of P, the annual height growth of a conifer could be related to the phosphate levels in the current year's needles, while in the case of nitrogen the current year's growth was governed by the nitrogen reserves of the previous year due to the slower mobility of this nutrient. Cain (1959) suggested that many of the so-called antagonistic effects attributed to interaction at uptake could largely be explained by growth dilution and changes of distribution within the plant from one part to another.

(c) Ion Interaction

Reports of antagonistic and synergistic effects are common in the literature. Smith (1962) tabulated the influence of applied elements on the concentration of other elements in the foliage. As already mentioned Cain (1959) suggested caution in interpreting the causal effects of these interactions. The most common interaction reported is that between nitrogen and phosphorus. Several workers have reported decreased P levels in the foliage with increased nitrogen supplies. (Hagenzieker, 1958; Will, 1961; and Carter and Lyle, 1966). Will (1961) reported that the critical level of P in the foliage for the growth of radiata pine seedlings increased as the supply of nitrogen was increased. Similarly Travers (1965) found that the optimum P levels in culture for radiata pine seedling growth increased as the supply of nitrogen was increased. Voigt (1966) reported a reduced P uptake with increasing levels of calcium in the soil. This may be the consequence of a reduced availability of phosphate rather than an interaction at uptake (Humphreys, 1963). Humphreys and Truman (1964) found that where aluminium was readily available in the soil, radiata pine had to take up luxury amounts of phosphate to attain the same growth as those in the absence of high aluminium levels. Leyton (1956) and Leyton and Armson (1955) reported the influence of one nutrient affecting the supply of another where multiple deficiencies existed. They found that although foliar P levels were related to growth the correlations obtained were the consequence of the inter-relationship of P with nitrogen and potassium which, by partial regression analysis, were shown to be the primary limiting nutrients.

(d) Environmental Effects

Will (1965) reported that rainfall removed quite large quantities of P from the foliage of trees. With potassium and sodium, removal was very pronounced. This may in part account for the discrepancies in foliar levels between years reported by Millar (1966). Qureshi and Srivastava (1966) suggested that the influence of pH and moisture supply on absorption would influence the relationship between foliar and soil levels. Smith (1962) pointed out that environmental factors were likely to be of real significance only in studies of trees with extensive distributions, as there was considerable range in all environmental factors within which the normal mineral pattern was little affected.

Leyton (1957b) commented on the relationship between growth and the mineral nutrition of conifers:-

"For successful and consistent application of this approach, an understanding of the relationship between tree growth and mineral composition of the foliage and the factors affecting this relationship is essential. Failure to appreciate these factors and the limitations they impose on diagnostic interpretation has in many cases led to false conclusions and often invalid criticism."

The interpretation of foliar analysis data is usually based on one of the following:-

(a) Concept of Minimum Ranges

This method is based on the principle of minimum (or critical) values and ranges, each nutrient element being looked upon as an entity in relation to response. The usual procedure is to compare the nutrient content of healthy trees with poor trees of the same age and species.

Will (1961, 1965) reported a critical value (minimum value required to maintain normal healthy growth) of about 0.10 - 0.11 per cent P in the foliage of both seedlings and mature trees of radiata pine. Australian workers have reported a similar critical value for mature radiata pine (Ruapach, 1967). Although Will reported similar critical values for both seedlings and mature trees, Baur (1959) reported that there was a tendency for foliar P levels of slash pine to fall off with age. Tamm (1964) suggested such a fall off may be a true reflection of lower soil levels rather than an inherent physiological phenomenon.

Interpretation by this method may be confused by the influence of luxury consumption or the deficiency of another element producing high or low levels. Other factors, such as ion interaction and growth effects, may distort the influence of soil levels on the foliage content.

(b) Nutrient Ratios

Tamm (1964) suggested that the use of nutrient ratios, particularly for those nutrients that interact, e.g. N:P, N:K or K:P, would be valuable for intepreting foliar analysis data as they would allow for the interaction. Richards (1961) reported a decline in the productivity of loblolly pine with N:P ratios below 10.4. Raupach (1967) mentioned other workers who had successfully established critical nutrient ratios for various pine species. Leyton (1957a) reported that N:P, N:K and K:P ratios could be related to growth, but suggested that they merely represented an alternative to nutrient concentrations rather than a more fundamental expression of the complex interrelationship between nutrient supply, foliar composition and growth.

(c) Statistical Approach

Leyton and Armson (1955) suggested that the difficulties in interpretation, resulting from luxury consumption and ion interaction, could to a certain extent be avoided by extending the investigation to cover a wide range of conditions of growth and nutrient status to allow for a statistical analysis of the relationship involved.

Leyton (1956) stated:

"It would appear that the presence of a significant positive correlation between growth and the concentration of a particular nutrient may be taken as reasonable evidence for a deficiency in that nutrient, more or less independent of the level of other nutrients within the range concerned. The concentration alone, however, will not provide a direct measure of the degree of response when the supply of the nutrient is increased, though it is obvious that, within the range covered by the correlation, a lower concentration means a greater deficiency in that nutrient."

Correlations between tree growth and foliar P levels have been reported by several workers: Humphreys (1964) reported such a relationship for radiata pine; Leyton and Armson (1955) for Scots pine; Leyton (1956) for Japanese larch and Heinsdorf (1964) for pine stands on sandy soils in Germany.

Leyton and Armson (1955) suggested that where multiple deficiencies are suspected, analysis of a number of nutrients - ideally all - should be carried out and their relationships studied by multiple regressions. In their own work these authors found significant correlations between foliar N,P and K levels and the growth of Scots pine. However, an analysis of the component contributions by partial regression analysis revealed that only N and K made a significant direct contribution. The single correlation of P was attributed to its relationship with K. Similarly Leyton (1956) found that a significant single correlation between foliar P levels and the growth of Japanese larch could be attributed to its relationship with nitrogen. Gentle and Humphreys (1968) analysed the level of eight nutrients in the foliage of radiata pine by partial regression procedures and found that P levels provided the best statistical explanation of the variation in site productivity.

Leyton (1956) pointed out that foliar analysis results cannot be regarded as irrefutable evidence of a deficiency, ultimate proof being found only in fertilizer trials in the field.

Foliar analysis, according to Wilde (1958), has several practical disadvantages as a management aid in forest plantations:

(a) It is valueless for predicting the productivity of proposed sites and what fertilizer amendments may be required to bring them up to the desired production level.

(b) The use of foliar analysis in young stands provides no information on the potential fertility of reforested land in view of the different extent of the rooting system of older trees.

(c) Restricted sampling periods, and the long time required to sample even a relatively small forest, makes foliar analysis impracticable for general field work.

However, Wilde and many other workers (Viro, 1961; Mustanoja and Leaf, 1965) agreed that foliar analysis is indispensable in nursery and nutrition studies and may be useful for the detection of nutrient deficiencies.

(2) Soil Analysis

Soil analysis has long been a standard practice in agriculture for the detection of nutrient deficiencies and the determination of fertilizer requirements. A large number of extraction procedures have been utilized in the evaluation of the soil phosphate status for agricultural crops. They are largely empirical but most have been reported as being suitable for some crop growing under certain conditions. Williams (1962) reviewed the extractants that have been employed for extracting 'plant available P' from the soil, their theoretical basis and their value for particular crops and conditions. Soil analysis, employed in both agricultural and forestry practices, has in common the same objectives and some similar problems, and for this reason the following statement by Williams (1962) is of interest.

"The minimum objective in soil testing is to determine beforehand whether the status of a particular crop, with respect to nutrients, is adequate to meet the crop's demands."

He continued:

"Their use depends entirely on prior calibration of the values against crop performance in field experiments. They cannot, however be expected to integrate the numerous interrelated factors which affect the delivery and uptake of nutrients and regulate plant growth in the field, such as soil physical properties and profile characteristics, the nature of the crop, pH, temperature, moisture, aeration, biological activity, nutrient interactions, cultural practices and pests and diseases. Varying operation of these factors can seriously limit the usefulness of soil tests but their effects can be minimized by establishing correlations over suitably uniform ranges of soil, crop and climatic conditions."

Gessel and Walker (1958) pointed out some difficulties in the use of soil tests for diagnosing the nutrient status of forests. Those which have received most attention in the literature are:

(a) Lack of Information on Optimum Sampling Depth

The determination of tree nutrient requirements is complicated by a deep root system. Tamm (1964) suggested that the main rooting zone should be sampled thoroughly and consideration should be given to lower horizons where they contain notable root concentrations. In discussing this problem, Voigt (1958) pointed out that forest trees as opposed to most agricultural crops, have two distinct rooting regions; one predominantly organic, the other predominantly inorganic. He suggested that it would be doubtful if a single extracting agent could yield a valid estimate of nutrient availability in view of the behaviour differences of organic and inorganic colloids in nutrient retention. The problem of securing representative soil samples was discussed by York (1959) who outlined the difficulties caused by the heterogenous nature of both the topsoil and lower horizons of forest soils.

The need to sample subsurface horizons has been investigated by some workers: Kessell and Stoate (1938) in outlining their proposed site class distinctions based on P_2O_5 levels in the soil, stated:

> " High phosphate figures in shallow Ao horizons may prove very misleading and subsurface soils are used in these cases. In soils approaching the limits for the class, the rate at which P_2O_5 content decreases with depth becomes important. If the gradient is steep the site should ve viewed with suspicion."

This was taken into consideration in the P_2O_5 levels proposed by them as necessary for successful afforestation of radiata pine:

> "A P_2O_5 content of 400 parts per million (p.p.m) is required in the surface and subsurface soils. Three hundred parts per million may be satisfactory if this content is maintained for a depth of two to three feet."

However, later Australian work outlined by Humphreys (1963), in which the influence of nutrient elements at various depths of the profile were investigated, showed that radiata pine was basically a topsoil feeder, with soil below 15" contributing very little to the total supply. Samples at the 0 - 3" depth were reported as being the most important for phosphate, whilst samples at the 12 - 15" depth were more important for elements influencing root development such as calcium. Pawluk and Arneman (1961) reported that available P levels in the A_2, but not the B_2 horizon, were correlated with site productivity of Jack pine. Similarly, Wells (1965) found that variation in the foliar P levels of loblolly pine were explained better by available phosphate levels in the A horizon than the B horizon.

(b) Uncertainty as to which fraction of the soil P to extract

Ralston (1964) pointed out that most soil analysis techniques available are those developed for agricultural crops and as such are of unknown significance in relation to tree requirements. Evidence available suggests that trees are capable of utilizing nutrient sources unavailable to agricultural crops: Humphreys (1963) concluded that since agricultural crops would not survive, or grow successfully on land suitable for tree growth, trees could either use sources of phosphate unavailable to many plants or they did not require as much for a vastly greater growth rate. Rosendahl (1942) and Purnell (1958) presented evidence suggesting the mycorrhizal roots of radiata pine could mobilize P from apatite. Tamm (1964) suggested that the ability of trees root systems apparently to extract more nutrients from soil minerals than those of agricultural crops could be the consequence not so much of higher efficiency as of longer persistence.

The perennial nature of trees presents further problems in evaluating the nutrient status for, as Voigt (1958) pointed out, the rate of nutrient cycling, rather than the level of particular fractions in the soil may be of importance in determining whether the trees' nutrient requirements are met. Will (1964) found that nutrient cycling made an important contribution to the nutrient requirements of radiata pine 10 years after planting. However, Themlitz (1968) pointed out that conditions met in nurseries were similar to those in agriculture, in that nutrient cycling made little contribution to the plants' requirements. Humphreys (1963) suggested that one of the basic limitations of both soil and foliar analysis arose from attempting to estimate what was happening in a dynamic situation by means of static procedures.

Pritchett (1968) suggested that total P may be a more meaningful value in view of the apparent availability to trees of less soluble forms of P. In Australia, Kessell and Stoate (1938), Young (1948) and Humphreys (1964) have all reported total P values as being related to site productivity. Humphreys (1964) found that the relationship improved if it was corrected for the fraction of soil >2 m.m. Humphreys (1963) reported that the usefulness of total P figures was improved by making allowance for levels of aluminium and calcium in the soil which provided an indication of the soil's capacity to hold phosphate compared with the ability of the plant's roots to obtain it. However, Stoate (1950) found that certain anomolies arose from employing total P values for predicting the nutrient status. He reported that these anomalies could be accounted for by differences in the levels of available P extracted by one per cent citric acid. Baur (1959) also reported that total P values were related to site productivity only within limited localities and not over more heterogenous sites. Pritchett and Llewellyn (1966) found no relationship between total P and tree growth.

Despite the many suggestions that soil tests derived for agricultural purposes are unlikely to be satisfactory for forestry work, there are many reports in recent literature of significent correlations between tree growth and levels of 'available P': Wilde et al (1964 (a) and (b)) reported significent correlations between the phosphate levels extracted by Troug's reagent and the growth of Jack and red pine. Pawluk and Arneman (1961) found a significent correlation between the growth of Jack pine and phosphate levels extracted by the Bray No. 1 extractant, but not by Morgan's reagent. Viro (1955) reported a relationship between soil P levels extracted by E.D.T.A. and the growth of Scots pine. However, this relationship was later shown to be the consequence of the one between P and calcium, the latter being the primary limiting factor [Dahl, Selmer-Andersen and

Saether (1961) _7. Pritchett and Llewellyn (1966) reported significant correlations between the growth of slash pine on unfertilized sites and the soil P levels extracted by ammonium acetate (pH 4.8), acetic acid, 0.05NHCl plus $0.025NH_2SO_4$ and the Bray No. 2 reagent. Tamm (1964) reported the work of Holman (1964) who found a negative correlation between forest yield and soil P levels extracted by ammonium lactate but found a positive correlation with total P. Tamm suggested that this may have arisen from an intensely growing forest stand almost exhausting the soil supplies of easily soluble P before growth ceased.

In studies between plant P and soil P levels Wells (1965) reported that soil P extracted by the Truog and Bray No. 2 reagents was significantly correlated with foliar P levels, whereas total P was not. Similarly, Voigt (1966) found the amount of soil P extracted by the Troug and Bray No. 1 extractants and by acetic acid to be the most successful for predicting the foliar P levels of pitch pine (P. rigida). Metz, Wells and Swindell (1966), however, reported that P levels extracted by Troug's reagent explained only 17 per cent of the variation in foliar P levels of loblolly pine.

The problems of interpreting soil analysis data are similar to those associated with foliar analysis: in order to establish the presence of a deficiency it is essential to obtain a significant correlation between the tree growth and the level of the nutrient in the soil. As pointed out by Dahl et al. (1961) this does not constitute irrefutable proof of a deficiency in the element, as the relationship may be indirect through some unmeasured variable. Thus, as with foliar analysis, where multiple deficiencies are suspected, all elements should be considered and analysed by partial regression or correlation procedures.

The validity of employing critical levels, established from one set of data, for diagnosing the presence of a deficiency at another site, depends on whether the soil and climatic conditions and the type and age of the tree were covered by the range of conditions considered in establishing the critical level. Similarly, in the use of soil analysis for predicting the prospective nutrient status of proposed planting sites it is essential that the conditions are similar to those under which the prediction equation was established. This is necessary for, as Kessell and Stoate (1938) pointed out, different species differ in their nutrient requirement. It is also suspected that the nature of the nutrient supply, which is presumably reflected by the soil test, varies according to the age of the tree (Will 1964) and the type of soil (Williams 1962). Further, the availability of phosphate for plant uptake is influenced by a large number of soil properties which are not always reflected in the soil test value and consequently the soil test is only valid for the range of these properties covered in the original calibration study (Williams 1962).

Provided soil analysis results could be suitably calibrated against tree growth (and evidence suggests they can) Prichett (1968) suggested that they would have certain advantages over tissue analysis as a means of delineating nutrient deficient areas for the following reasons:

(i) They can be used for predicting the nutrient status in areas prior to planting.

(ii) Collecting and analysing soil samples may be less laborious than collecting and analysing needle samples, particularly in old stands.

(iii) It may be expected that soil analysis should reflect more nearly the available nutrient levels of the soil than a tissue test, as many environmental factors and growth phenomena influence the absorption and concentration of nutrients in the plant.

Viro (1961) suggested that soil analysis may be a more valuable basic method, while tissue analysis may be useful, especially in detecting deficiencies and in studying the nutritional status of nursery stock.

Leyton and Armson (1955) suggested that a positive relationship between tree growth and both the concentration of a nutrient in the foliage and its availability in the soil, provided the best obtainable evidence of a nutrient deficiency without recourse to fertilizer trials in the field. This combined approach was also advocated by Tamm (1964).

(C) PHOSPHATIC FERTILIZATION OF FORESTS:

The response of trees to the application of phosphatic fertilizers has been reported in many parts of the world. Stoeckler and Arneman (1960) reviewed the responses recorded in the U.S.A.; Maki (1961) those in Sweden, Hagenzieker (1958) those in Holland. Kawana (1966) those in Japan, Raupach (1967) those in Australia, Leyton (1958) those in the United Kingdom while Deetlefs and Dumont (1963) have reported a response in South Africa. Responses in New Zealand have been discussed by Weston (1956, 1958), Conway (1962) and Will (1965). The evidence presented by Conway (Fig. 2.1 and 2.2) illustrates the phenomenal responses of radiata pine to phosphatic dressings at the Riverhead state forest, Auckland.

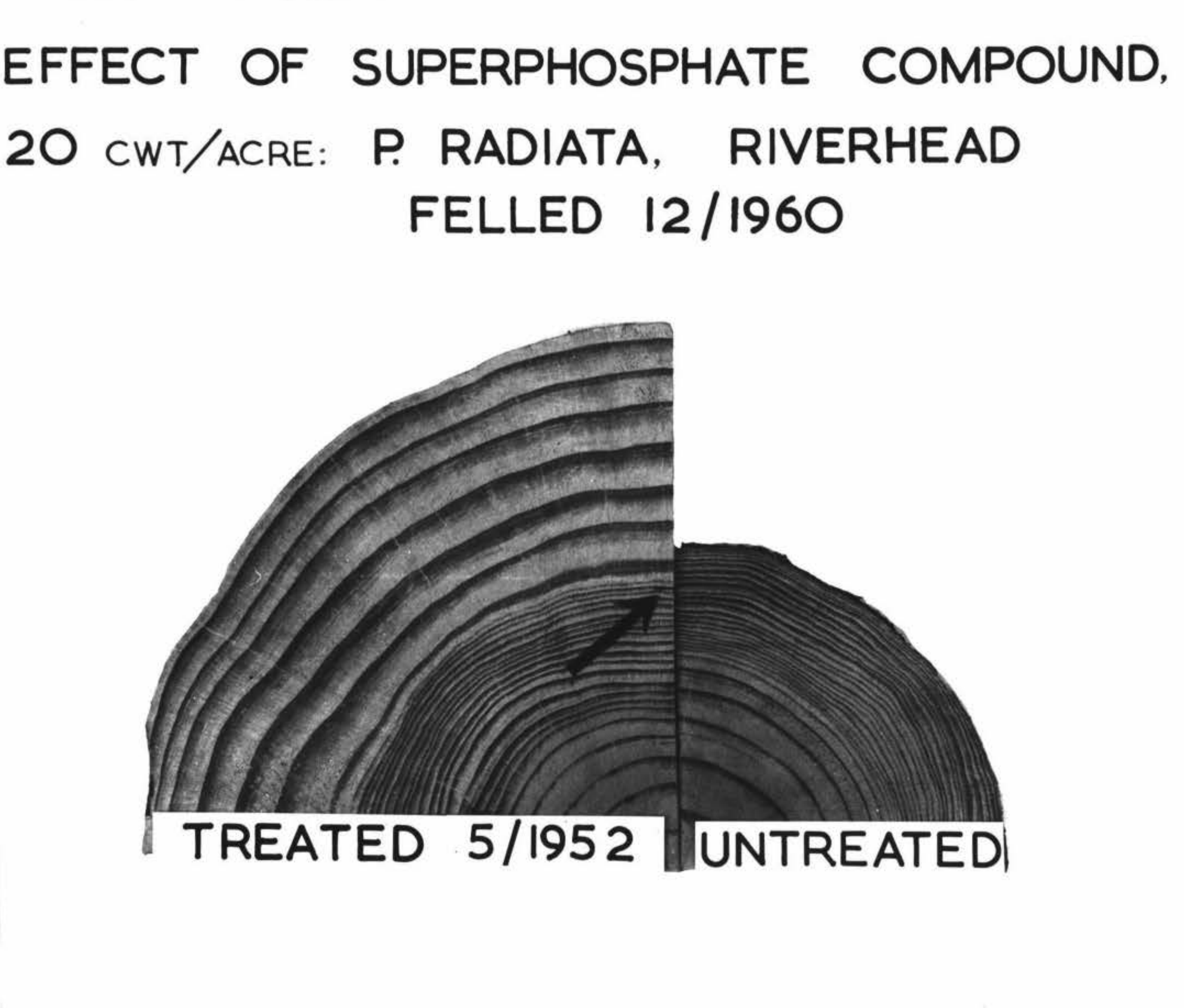
In forest fertilization several factors must be given consideration:

(1) The Value of Foliar and Soil Analyses in Predicting Fertilizer Requirements

Some attempts have been made to utilize foliar analysis data for fertilizer recommendations. Will (1965) reported that a response to superphosphate was manifested by radiata pines with foliar P levels below the critical level established for normal growth. Pritchett (1968) reported an inverse correlation between foliar P levels before fertilizer application and the response to applied superphosphate. The curvilinear regression line was dependent on the quantity of fertilizer applied and may also, according to Pritchett, be a unique function of the tree age. However, he pointed out that when other factors are more limiting than phosphate, a response to phosphatic fertilizers may not be obtained in forests with low tissue P until these factors have been corrected. Cain (1959) pointed out that the use of foliar levels for fertilizer recommendations may

FIG. 2.1 PART OF RIVERHEAD FOREST SHOWING FROM LEFT TO RIGHT STRIPS OF RADIATA PINE TOPDRESSED WITH SUPERPHOSPHATE AT 5, 10 and 20 CWT PER ACRE IN NOVEMBER 1955. (PHOTOGRAPHED IN MARCH 1961).

FIG. 2.2


EFFECT OF SUPERPHOSPHATE COMPOUND,
20 CWT/ACRE: P. RADIATA, RIVERHEAD
FELLED 12/1960
TREATED 5/1952
UNTREATED

run into difficulties because:

(a) The simple assumption that if leaf concentrations are below a given value more fertilizer should be applied is not always valid, because of variations and interactions between different nutrients, metabolic processes and growth characteristics of the species.

(b) The quantity to be applied to the soil to achieve a desired increment of concentration in the plant tissue varies greatly from place to place, even within small areas due to variations in soil and climatic factors relating to the movement of nutrients and water through the soil and the exchange of nutrients between the soil complex and the plant roots.

Soil analysis data has been used successfully to predict the fertilizer requirements of agricultural crops (McConaghy 1965). In Australia, Brockwell and Ludbrook (1962) established optimum levels of total soil P for radiata pine (the maximum level of soil phosphate at which additional response can be obtained). They reported an optimum level of 130 - 175 p.p.m. total P in the top 4 in. of soil. This value was substantiated by Beckman (1964) and compared with the 400 p.p.m. P_2O_5 found by Kessell and Stoate (1938) to be necessary for satisfactory growth of radiata pine. Brockwell and Ludbrook (1962) pointed out that the situation may be complicated on soils with a high phosphate absorption capacity where responses may be obtained despite total soil P values being well above the established optimum. Lewis and Harding (1963) reported that lower fertilizer applications were required on lighter than heavier soils to provide similar responses, despite having similar total P values. This phenomenon they attributed to the greater absorption capacity of the heavier soils. Stoate (1950) found that discrepancies between the actual and predicted growth based on total P values could be explained by variations in the levels of available phosphate present. Baur (1959) established an optimum value of 70 p.p.m. total P for slash pine and reported that values calculated to raise the total P to this figure (based on 1 cwt superphosphate per acre being equivalent to 6 p.p.m. P) corresponded closely to the quantities required to give a response in the field. A similar approach to this has been employed successfully for agricultural crops (Ozanne and Shaw 1967).

The use of available phosphate levels in conjunction with fertilizer trials is more common in the U.S.A. than elsewhere. Several workers have reported available P values above which little or no growth response has been recorded after the application of phosphatic fertilizers: Strand and Austin (1966) reported that the response of Douglas fir to phosphate dressings was very limited on soils containing 6.2 p.p.m. P extracted by Olsen's reagent, but was substantial on soils containing only 3.0 p.p.m. P. Carter and Lyle (1966) reported no response of loblolly pines to phosphate dressings where soils contained 8 p.p.m. P extracted by 0.05N HCl + 0.025N H_2SO_4. However, in both the above cases no attempt was made to establish a statistical relationship between the available P levels and the response to the applied fertilizer. Pritchett and Llewellyn (1966) nevertheless reported a highly significant inverse relationship between the levels of available P extracted by ammonium acetate prior to fertilization and the response of slash pine to applied rock phosphate and superphosphate. On the acid soils in this experiment tree responses to rock phosphate were more closely related to the levels of extracted P than were responses to superphosphate. A significant inverse relationship was also recorded between tree response and levels of soil P extracted by the Bray No. 2 reagent but not total P values. Pritchett (1968) substantiated this finding for ammonium acetate but reported a non-significant relationship for the Bray No. 2 method. He also observed that no response occurred on a soil containing 2.3 p.p.m of ammonium acetate extractable P and 5.1 p.p.m of Bray No. 2 extractable P.

(2) The Value of Different Phosphate Sources

Several fertilizer trials have included studies on the relative values of soluble and insoluble sources of phosphate as ameliorants. The two most common sources compared are superphosphate and rock phosphate. In long term fertilizer trials, Brockwell and Ludbrook (1962) and Gentle, Humphreys and Lambert (1965) found that superphosphate and rock phosphate provided similar responses when applied at equivalent rates of P. Young (1948) and Richards (1954) reported similar findings, but pointed out that rock phosphate was a more economical source being cheaper and more effective per unit weight of fertilizer applied. They also pointed out that although the initial response to rock phosphate was slightly slower than that to superphosphate, the overall responses for the trial period were the same. Hopkins (1960) found rock phosphate to be the most effective source of phosphate for P. Pinaster on the sandy coastal plains of Western Australia. This he attributed to the rock phosphate being less subject to leaching losses on these light-textured soils. Pritchett (1968) reported that although both superphosphate and rock phosphate stimulated the growth of slash pine over the four year period of the trial, superphosphate dressings provided the largest response. Gentle and Humphreys (1968) reported a comparison between the effects of superphosphate, rock phosphate and calcined crandallite - an iron-aluminium-calcium complex mineral phosphate - on the first year growth of radiata pine transplants. Over the short duration of this study superphosphate was the most effective, but rock phosphate and calcined crandallite both provided identical responses when applied at equal rates of P.

In summarizing Australia fertilizer trials, Gentle and Humphreys (1968) suggested that on soils with a large absorption capacity, banded applications of a semi-soluble source would probably be most effective as they would minimize the amount of fertilizer in contact with the reactive soil surface and improve the long term efficiency of the fertilizer by restricting the amount of phosphorus rich solution available for extending the sorption zones beyond the band. On near neutral soils, with a medium sorption capacity, they suggested that superphosphate might be the most effective, whilst on acid soils of medium to low absorption capacity rock phosphate was proposed as the most suitable source. Terman (1968) suggested that the similarity of tree response to rock phosphate and superphosphate was due to the length of time involved in the response. He stated:-

> "Plants that have a relatively long vegetative growth, and presumably large root systems, show less response to soluble fertilizers when grown to harvest provided that the applied phosphate fertilizers are soluble enough to react with the soil."

Conway (1962) pointed out that in the selection of a suitable phosphate source it may be necessary to give consideration to factors other than just the effectiveness in stimulating the tree. He reported that in New Zealand, where aerial topdressing is the most practical and economic means of application, the use of finely ground rock phosphate had to be abandoned for safety reasons and replaced with fertilizers such as aerial and serpentine superphosphate which possess physical properties making for free-flow from the aircraft hopper.

(C) Field Practices

In applying fertilizers, consideration must be given to the most suitable time of application, the rate and frequency of application and the manner in which they are applied.

Little research has been conducted towards elucidating the most suitable time for the application of phosphatic fertilizers. Where soil P values are extremely low, phosphate applications at planting have been found to be necessary (Richards 1954, Hopkins 1960). Brockwell and Ludbrook reported that younger trees responded much more rapidly to fertilizer applications than older trees. However, applications to trees over 20 years of age have produced substantial responses (Conway 1962).

Hopkins (1960) found that application to the individual stem appeared to be the most suitable when treatments were applied at planting. This reduced weed competition and loss by soil fixation through concentrating the fertilizer in the zone exploited by the young roots. He also reported that broadcast applications were found to be the most suitable in older plantations where the tree roots have fully occupied the surface soil layers.

The optimum rates of fertilizer application can only be established by field trials. Conway (1962) reported an increased response in stands at Riverhead state forest with increased applications from 5 cwt. to 20 cwt. per acre. However, he suggested that the application of 20 cwt per acre was unnecessarily heavy and expensive from a practical viewpoint. Will (1965) reported that topdressing at 2 cwt per acre at Riverhead was inadequate, whilst 4 cwt per acre provided an adequate supply for 2 years but thereafter was barely sufficient. However, 20 cwt per acre was found to provide a more than adequate source of P over the 6 years investigated.

Conway (1962) reported that the frequency of application, as well as the optimum rate of application, was important; a plot in Riverhead forest, which had received an initial dressing of 4 cwt per acre, followed by an additional dressing of 5 cwt per acre 4 years later, provided a greater response than a plot having received a single application of 20 cwt per acre. Conway pointed out that some of the response on this plot could be attributed to underscrubbing and the hand application of the fertilizer. Australian workers have reported that an initial dressing at planting may have to be supplemented by later dressings if growth is to be maintained on very poor sites (Brockwell and Ludbrook, 1962; Hopkins, 1960). Hopkins (1960) suggested this additional application should be applied just after thinning to ensure the cost of fertilizing be carried only by merchantable trees.

Stoeckler and Arneman (1960) drew attention to the need for long term fertilizer experiments in forestry, as responses recorded in early stages may vanish by the time the trees are harvested. Pritchett and Swinford (1961) recorded such a case, where significant responses found after 7 years, had disappeared after 15 years.

(D) The Economic Value of Forest Fertilization

Conway (1962) reported that aerial topdressing at 5 cwt per acre at the Riverhead and Maramarua forests was an economic proposition. He calculated that the average annual increase in merchantable volume per acre over a 5 year period was sufficient to recoup the initial expenditure. Further advantages accrued from the improved seed supply which removed the need for costly seeding or planting programmes. In Australia Young (1948) found that after 8 years it had been profitable to apply a whole range of superphosphate levels to loblolly pine stands. He reported that maximum profits resulted from an application of 7½ cwt per acre. Wilde (1958) suggested that the stimulation of older trees by fertilization was economically unsound, an opinion shared by many American workers (cf. Stoeckler and Arneman 1960). However, Rennie (1955) poined out that the recovery of the cost of the ameliorant was not the only consideration:

> "For certain conditions it has been argued - possibly quite rightly - that ameliorants cannot be afforded, but to the forester upon the nutrient poor soils anywhere, the important question is not whether the cost of the ameliorant will be recoverable by increased timber production, but whether for lack of a relatively small extra expenditure, the survival of forests and the original heavy establishment costs areto be sacrificed."

Hopkins (1960) also pointed out that although cost analysis may not be favourable enough to warrant treatment of poor compartments, they should be brought to full vigour as a preventative measure against entomological and pathological epidemics.

Carter and Lyle (1966) put forward a proposal that could have great economic significance. They suggested that fertilizer applications could replace thinning as a means of bringing stands to a merchantable size, thus removing the need to reduce the number of trees per acre.

(A) SOIL SAMPLING

Soil samples were collected from 6 profiles, 45 permanent assessment plots and 15 fertilizer plots with the aid of a one inch diameter, closed cylinder soil auger.

Profile pits were sampled by visible horizons down to the parent material.

Assessment plots (1/10th acre) were sampled at the 0 - 4" level. Twenty samples were collected randomly from each plot and bulked in the field.

Fertilizer plots (1/1000 acre) were sampled at the 0 - 4" level. Ten cores were collectedat each sampling period and bulked in the field. The sampling depth was considered adequate to recover the applied phosphate, for even on coarse textured podsols the downward movement of applied phosphate is apparently very limited (Mackay and Eaton, 1959; Maclean, 1965a).

All soil samples were air dried in the laboratory, weighed and passed through a 2 mm sieve. The fraction >2 mm was also recorded. Soils from the assessment plots were also weighed moist in the field.

The air-dried sieved soils were stored in air tight preserving jars.

Where required, subsamples were ground in an agate mortar to pass an 80 mesh sieve.

(B) FOLIAGE SAMPLING

Foliage samples were collected from two dominant and two co-dominant trees in each assessment plot (one tree from each quarter of the plot). Equal weights of these samples were bulked prior to analysis.

Sampling was conducted in December, employing the standard procedure adopted by F.R.I.Rotorua (Will, 1965) to minimize variations in the mineral content of the foliage arising from age and crown positional differences.

(C) SITE PRODUCTIVITY MEASUREMENTS

Ralston (1964) discussed the value of various methods for assessing site productivity and concluded that the most practical index, relatively free of stocking effects, was some measure of stand height. For the purpose of this study a volumetric measurement was also utilized, as it has the advantage that most forest transactions are conducted on a volumetric basis.

(1) Predominant Mean Height (P.M.H)

This is defined as, 'the average height to the green top of the tallest tree in each quarter of the plot.' Heights were determined with an altimeter.'

(2) Volume to a 3 Inch Top

The volume of timber in cubic feet per acre to a 3 inch top was calculated from the following formula, derived by Armitage (pers. comm) for Riverhead forest:

$$\frac{V}{B} = 0.326^{*}H - 2.305$$

where V = Volume of timber in cubic feet per acre to a 3 inch top.

B = Basal area per acre in square feet - calculated from breast - height diameters (4 ft 6 in.) measured with a diameter tape.

H = Predominant mean height.

* = Significant at the 0.1% level.

The relationship is linear (r = 0.982).

This formula was established from data obtained from 118 trees on a range of Riverhead sites.

(D) FIELD SITE MEASUREMENTS

A number of site factors with probable influences on phosphate availability and site productivity were measured on the assessment plot in the field.

(1) Mycorrhiza

The abundance of mycorrhizal roots in the litter and top-soil was subjectively classified into one of the classes listed in Table 3-1. This was only an approximate quantitiative assessment. No attempt was made to identify the types of fungi present.

TABLE 3.1

DESCRIPTION OF MYCORRHIZAL CLASSES

CLASS	DESCRIPTION
1	No Mycorrhizal Roots
II	Limited Infection
III	Moderate Infection
IV	Abundant Infection

TABLE 3.2

DESCRIPTION OF DRAINAGE CLASSES

CLASS	DESCRIPTION
I	Very Poor - Waterlogged Soils with Surface Water
II	Poor - Wet,Gleyed Soils
III	Average - Damp Soil with Moist Litter
IV	Good - Moist Soil with Dry Litter

(2) Field Drainage

Each plot was assigned to a drainage class (Table 3.2) on the basis of a field assessment.

(3) Slope

The slope of each plot along the dominant face was determined by use of an altimeter.

(4) Aspect

The aspect of each plot was recorded as the direction of the slope in terms of the eight major points of the compass.

(E) FIELD ADDITIONS OF PHOSPHATE

Three forms of commercial phosphatic fertilizer,

Superphosphate

Nauru Island rock phosphate

Christmas Island calcined 'C' grade rock phosphate (pelleted),

were applied at rates equivalent to 10 cwt of superphosphate per acre on single 4.4 yd. by 4.4 yd. plots on each of the five main soil types (HS, YK, PA, WA, WE). Undergrowth on all plots was cleared at the establishment date and any regrowth was cleared at subsequent sampling dates.

Soil samples were collected prior to fertilizer application and at 3 monthly intervals after application, over a period of one year. Sampling was restricted to an inner 2.2 yd. by 2.2 yd. section of each plot to avoid areas of possible uneven distribution around the perimeter of the plots.

(F) LABORATORY ADDITIONS OF PHOSPHATE

This section of the investigation was undertaken as a supplement to the field application. To ensure that phosphate distribution among the several forms of binding could be followed satisfactorily by chemical fractionation procedures, the amount of phosphate added was considerably in excess of that applied in the field investigation. Phosphate was applied at the rate of 50 mg.P per 100 gm of air dry soil, as follows.

Subsamples were taken from the three unfertilized samples of each soil type and bulked to provide composite samples. One hundred grams of each composition sample was moistened with 100 ml. of a solution of KH_2PO_4, containing 500 p.p.m.P and was mixed, air dried and subdivided into four according to the procedure outlined by Turner (1965).

The uniformity of distribution of phosphate between the four subsamples taken was tested for by determining total phosphorus on samples taken from the four subsamples of two of the soil types. The results shown in Table 3.3 indicate an acceptably even distribution of phosphate between subsamples.

Each subsample was placed in a 130 ml. screw-topped jar and 10 ml. of distilled water was added to facilitate chemical reaction between the soil and added phosphate. To reduce microbial activity a few drops of toluene-ether mixture, as employed by Kurtz, De Turk and Bray (1946) were added to the soil in each jar. The jars were stored in a dark cupboard throughout the investigation.

TABLE 3.3

AMOUNTS OF TOTAL PHOSPHORUS ESTIMATED PRIOR TO, AND IMMEDIATELY FOLLOWING, PHOSPHATE ADDITION

SOIL Subsamples (1 - 4)	TOTAL PHOSPHORUS BEFORE ADDITION mg. P%	TOTAL PHOSPHORUS AFTER ADDITION mg. P%	AMOUNT OF PHOSPHORUS ADDED TO AIR DRY SOIL - BY DIFFERENCE mg. P%
YK1	22.0	69.0	47.0
YK2	22.0	68.0	46.0
YK3	22.0	69.7	47.7
YK4	22.0	67.0	45.0
PA1	15.0	63.5	48.5
PA2	15.0	61.7	46.7
PA3	15.0	61.7	46.7
PA4	15.0	62.4	47.4

(G) ANALYTICAL PROCEDURES

(1) Determination of Phosphate

In this laboratory, the method of Dickman and Bray (1940) has been the standard procedure for the estimation of phosphate in solution. However, this procedure suffers from the disadvantage that organic matter in soil extracts causes an instability in the blue colour /_Watanabe and Olsen (1962)_/

Watanabe and Olsen (1965) reported that the ascorbic acid method of Fogg and Wilkinson (1958), as modified by Murphy and Riley (1962), was unaffected by organic matter present in water and $NaHCO_3$ extracts. Further advantages of the ascorbic acid method reported were the greater sensitivity and longer duration of a stable blue colour.

Prior to the adoption of this method a brief investigation was made of the colour stability and the influence of various ions on colour development. All readings were carried out on a Beckman model D.U. spectrophotometer at 890 mu.

(a) Stability of Blue Colour

Maximum intensity was recorded after 10 minutes, as reported by Watanabe and Olsen (1965), but a small decline was recorded between 10 and 35 minutes after which the value remained stable for periods of up to 24 hours.

All phosphate values reported are based on intensity values measured within the limits of 1 - 16 hours following colour development.

(b) Influence of Various Ions on Colour Development

The influence of fluoride on colour development, is illustrated in Table 3.4.Fluoride present in excess of 1500 p.p.m. in the final solution caused a depression of colour intensity. This interference was eliminated by use of the boric acid procedure of Kurtz (1942).

The influence of Chloride is illustrated in Table 3.5. Chloride ion in excess of 2000 p.p.m. increased the colour intensity. Phosphate solutions with Chloride concentrations in excess of this Critical level were corrected for by the use of a modified standard curve.

Other ions present in extraction reagents involved in this study were without influence on colour development.

(2) Determination of Total Phosphorus

Jackson (1958) reported on the suitability of the Na_2CO_3 fusion method for siliceous soils. Williams (1965) and Syers, Williams, Campbell and Walker (1967) found this method to be the most reliable for sandy and highly weathered soils in New Zealand.

The procedure adopted was essentially that outlined by Jackson (1958) with modifications to enable the development of phosphate in solution by the ascorbic acid method.

TABLE 3.4

THE INFLUENCE OF FLUORIDE ON COLOUR DEVELOPMENT
WITH THE METHOD OF WATANABE AND OLSEN (1965)

Concentration of Fluoride in Final Solution p.p.m.	Optical Density (0.5 p.p.m. Phosphate in Final Solution)	Optical Density (0.5 p.p.m. Phosphate in Final Solution) + Boric Acid
95	0.355	0.355
190	0.355	0.355
570	0.355	0.355
950	0.355	0.355
1425	0.355	0.355
1900	0.347	0.354
2850	0.092	0.354

TABLE 3.5

THE INFLUENCE OF CHLORIDE ON COLOUR DEVELOPMENT

CONCENTRATION OF CHLORIDE IN FINAL SOLUTION p.p.m.	OPTICAL DENSITY (0.5 p.p.m. PHOSPHATE IN FINAL SOLUTION)
177	0.355
355	0.355
710	0.355
1775	0.355
3550	0.360
7100	0.372
14200	0.387

(a) Procedure

A 0.5 - 1 gm. sample of soil (air-dry 80 mesh) was fused with Na_2CO_3 over a blast meker burner, followed by disentegration of the melt in distilled water. Centrifugation was employed to remove the curd which was then washed with distilled water and centrifuged. The supernatant from each centrifugation was decanted into a 250 ml. volumetric flask and made up to volume with distilled water. A suitable aliquot (to provide 5-50 ug.P in the final solution) was placed in a 50 ml. volumetric flask and made up to 40 ml. with distilled water. The solution was adjusted to pH 5 with concentrated H_2SO_4, using para-nitrophenol as indicator. (A precipitate presumably of $Al(OH)_3$ was sometimes formed upon acidification but it redissolved upon addition of the acid molybdate reagent). The phosphate in solution was then developed by the ascorbic acid method.

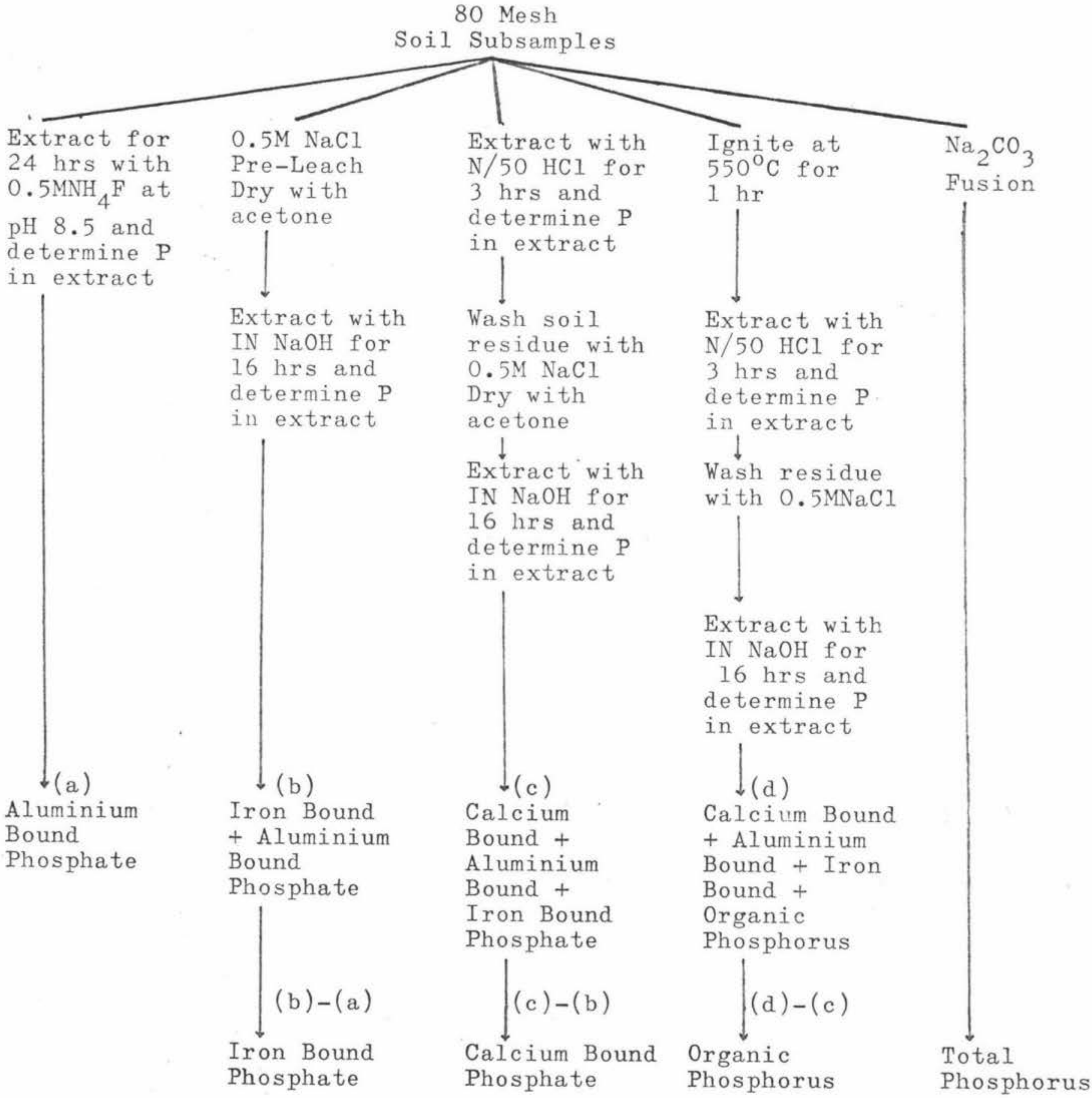
(3) Phosphate Fractionation

The general procedure adopted was that developed and used in this laboratory (fig.3.1).

Preliminary experiments were conducted to establish the most suitable reagent strengths, soil: extractant ratios and extraction periods for the soils under investigation.

FIG. 3.1

FLOW-SHEET REPRESENTATION OF THE PHOSPHATE FRACTIONATION PROCEDURE (FIFE, pers.comm).



a) Acid Extraction (N/50 HCl)

The use of too concentrated an acid for this stage of the extraction could lead to dissolution of occluded forms of iron-bound and aluminium-bound phosphate and thus produce falsely inflated values for calcium phosphates. Employing Nauru rock phosphate as illustrative of a calcium phosphate of low solubility, 80 mesh samples (0.02 gm.) were extracted for 3 hours with 25 ml. portions of hydrochloric acid ranging in concentration from 0.01N to 0.1N. Table 3.6 suggests that complete release of the phosphate was achieved with N/60 and this was confirmed by observation that complete solution was affected by this strength of acid. To ensure comparable conditions in the extraction of soils it was necessary to determine the strength of acid required to provide an equilibrium pH below 2.38, the value attained in the rock phosphate extraction using N/60 acid. On a range of soils it was found that N/50 acid achieved this objective and this concentration was therefore adopted.

(b) NaOH Extractions

An extraction period of 16 hours was adopted on the basis of a preliminary experiment (Table 3.7).

A soil: extractant ratio of 1:50 was utilized, and in view of the extremely low phosphate levels in the unfertilized soils and the complete extraction of applied phosphate for unfertilized soils it was considered impracticable and unnecessary to widen this ratio in an attempt to improve extraction efficiency.

TABLE 3.6

THE INFLUENCE OF ACID STRENGTH ON THE EXTRACTION OF Ca P. (NAURU ROCK PHOSPHATE)

ACID NORMALITY	INITIAL pH	FINAL pH	QUANTITY EXTRACTED
N/100	2.01	2.88	2.70
N/90	2.15	2.77	3.00
N/80	2.12	2.60	3.10
N/70	2.08	2.57	3.45
N/60	2.05	2.38	3.57
N/50	1.95	2.16	3.60
N/40	1.86	2.08	3.57
N/30	1.71	1.83	3.70
N/20	1.58	1.62	3.60
N/10	1.20	1.22	3.57

TABLE 3.7

AMOUNTS OF PHOSPHATE EXTRACTED BY IN NaOH
FOR A RANGE OF EXTRACTION PERIODS

SOIL	SAMPLING DEPTH (In.)	EXTRACTION PERIOD			
		8 hrs	16 hrs	24 hrs	40 hrs
		mg.P%	mg.P%	mg.P%	mg.P%
A 160/5	0-6	7.9	9.8	9.8	9.9
A98	6-12	2.0	2.80	2.82	2.89
G	2-6	0.40	0.45	0.46	0.46
P	22-28	0.30	0.35	0.35	0.35
YK + 50mg P%	0-4	48.0	54.7	55.1	55.0
YK Virgin	0-4	4.0	4.9	4.9	5.0

Organic matter interference in the development of the molybdenum blue colour was eliminated by precipitation of the humic acid fraction by mild acidification followed by centrifugation.

c) NH_4F Extraction

The procedure outlined by Fife (1962), employing 0.5MNH_4F at pH 8.5, was adopted for this estimation. For the particular soils of this study preliminary experiments were conducted to establish the most suitable extraction period, soil:extractant ratio and the possible need to correct for resorption of liberated phosphate by free iron oxides.

It was concluded that an extraction period of 24 hours was the most suitable for the range of soils considered (Table 3.8).

The extremely low P levels in the virgin soils made it impracticable to widen the soil:extractant ratio beyond 1:50 as a means of reducing resorption of phosphate by free iron oxides. For fertilized soils (Table 3.9) extraction efficiency was still increasing but the wide soil:extractant ratios presented difficulties because of the very low readings. Thus, for both unfertilized and fertilized soils correction for resorption, employing the method outlined by Williams, Syers and Walker (1967) was resorted to. A soil:extractant ratio of 1:200 was adopted for all subsequent work on fertilized soils, being both convenient and providing a desirable level of phosphate in solution.

TABLE 3.8

AMOUNTS OF PHOSPHATE EXTRACTED BY 0.5 M NH_4F
AT pH 8.5 FOR A RANGE OF EXTRACTION
PERIODS EMPLOYING A SOIL:EXTRACTANT RATIO OF 1:50

SOIL	SAMPLING DEPTH (In.)	EXTRACTION PERIOD					
		1 hr	8 hrs	16 hrs	24 hrs	48 hrs	72 hrs
		mg P%	mgP%	mgP%	mgP%	mgP%	mgP%
M	0-6	0.10	0.12	0.17	0.24	0.24	0.24
A160/5	11-17	0.26	0.32	0.34	0.37	0.37	0.37
A160/7	6-12	0.32	0.38	0.42	0.47	0.46	0.46
WE	0-4	0.53	0.65	0.83	1.05	1.07	1.05
YK + Super	0-4	4.60	6.00	6.10	6.24	6.23	6.25
YK + 50 mgP%	0-4	17.0	28.2	29.2	29.5	29.5	29.6

TABLE 3.9

AMOUNTS OF PHOSPHATE EXTRACTED BY 0.5M NH_4F AT pH 8.5 FOR A RANGE OF SOIL:EXTRACTANT RATIOS

SOIL TREATMENT	SOIL:EXTRACTANT RATIO				
	1:50	1:100	1:200	1:400	1:800
	mgP%	mgP%	mgP%	mgP%	mgP%
YK + Super	6.24	7.75	8.3	9.6	-
YK + 50 mgP%	29.5	32.4	35.8	39.0	42.0

TABLE 3.10

INFLUENCE OF QUANTITIES OF ADDED PHOSPHATE ON THE RECOVERY VALUES FOR NH_4F EXTRACTION

SOIL	SAMPLING DEPTH (In).	QUANTITY OF ADDED PHOSPHATE			
		0.1 ug/ml	0.2 ug/ml	0.4 ug/ml	0.8 ug/ml
		%	%	%	%
M	0-6	-	26	23	24
A 160/5	6-12	-	31	25	24
YK + Super	0-4	78	70	74	74

The most suitable quantities of phosphate to be added with the extraction solution for the determination of recovery values was established as 0.4 ug/ml. for both fertilized and unfertilized soils. (Table 3.10). The recovery values were sufficiently constant for a range of levels of applied phosphate to fulfil the criteria of adequacy for this procedure proposed by Williams (1965).

d) Organic Phosphorus

In recent literature there has been considerable controversy over the effectiveness of various techniques employed for the determination of organic phosphorus: Maclean (1965 b), Hance and Anderson (1960) and Enwezor and Moore (1966) reported that the ignition technique of Saunders and Williams (1955) provided larger values than the extraction procedure of Mehta et al. (1954). Bornemisza and Igue (1967) found the opposite to hold true as did Saunders and Williams (1955) for sesquioxide rich soils.

A preliminary experiment was conducted to compare the organic phosphorus values obtained by the methods of Saunders and Williams (1955) Mehta et al (1954) and the method outlined in Fig.3.1.

Table 3.II shows that similar values were obtained for the methods of both Mehta et al. and that outlined in Fig 3.I. Saunders' and Williams' method gave comparable results for one soil (podzolized) but substantially lower values for both top and subsoil of the other (Yellow Brown Earth). This latter soil is characterized by high sesquioxide levels throughout the profile. It appears likely that the lower values obtained by the method of Saunders' and Williams' can be attributed to resorption of inorganic phosphate during the 0.2N H_2SO_4 extraction.

The method outlined in Fig. II was adopted for all subsequent work.

TABLE 3.11

A COMPARISON BETWEEN THE AMOUNTS OF ORGANIC PHOSPHATE ESTIMATED BY THREE METHODS

SOIL	SAMPLING DEPTH (In).	METHOD		
		SAUNDERS AND WILLIAMS (1955)	FIFE (pers.comm)	MEHTA ET AL. (1954)
		mgP%	mgP%	mgP%
G	0-2	19.3	18.9	19.9
G	14-18	2.3	1.9	1.5
A160/7	0-48	4.7	7.7	7.2
A160/7	22-28	0.7	3.5	3.6

. (4) Phosphate Avaliability Tests

A range of chemical extractants, commonly employed in agriculture for assessing levels of available soil phosphate, were used in this study. The detail of the methods is presented in Table 3.12. All extractions, except total phosphorus, were carried out on 2 mm air-dry soil.

The modified procedures for Olsen's and Truog's methods were included to provide some measure of the organic phosphorus levels which may constitute a considerable portion of the potentially available phosphate for perennial crops Russell (1961). The modified Truog procedure involved ignition of the soil at 550°C for one hour, to convert organic phosphorus to inorganic phosphate, prior to extraction by the standard Truog reagent.

The modified Olsen's method involved hypobromite oxidation of the organic phosphorus fraction, extracted by Olsen's reagent, according to the procedure outlined by Van Diest and Black (1959).

Total phosphorus, although not normally considered as a test for available phosphate, was included in view of the reported value of this method in forestry work (Stoate, 1950).

Phosphate was determined on all extracts by the ascorbic acid procedure. The Olsen and Bray No.2 extracts were adjusted to pH 5 in the final solution prior to colour development. Fluoride ion interference in Bray No.2 extracts was eliminated by the boric acid procedure of Kurtz (1942).

(5) Foliage Analysis

Analysis of foliage samples was carried out by the staff of the Soils and Nutrition Department, F.R.I., Rotorua. The procedure for the analyses has been outlined by Orman and Will (1960).

TABLE 3.12 AVAILABLE PHOSPHATE EXTRACTION METHODS

METHOD	EXTRACTANT	pH	TIME OF SHAKING	SOIL:EXTRACTANT RATIO	REFERENCES
Bray No.2	0.03N-NH_4F/0.1NHCl	-	1 Minute	1:10	Bray and Kurtz (1945) Hanley (1965)
Olsen	0.5M $NaHCO_3$	8.5	30 Minutes	1:20	Olsen et al. (1954)
Olsen Modified	0.5M $NaHCO_3$ + Hypobromite	8.5	30 Minutes	1:20	Van Diest and Black (1959)
Truog	0.002 H_2SO + 3g$(NH_4)_2SO$	3.0	30 Minutes	1:100	Truog (1930) Peech et al. (1947).
Truog Modified	0.002 H_2SO_4 + 3g$(NH_4)_2SO_4$	3.0	30 Minutes	1:100	Truog (1930) Peech et al. (1947)
Acetic Acid	2.5% V/V Acetic Acid	2.6	2 Hours	1:40	Williams et al. (1953).
Anion Exchange Resin	Permuttit De Acidite F.F. Resin	-	16 Hours	1:50	Saunders and Metelerkamp (1962).
Total P	Na_2CO_3Fusion				Jackson (1958)

(6) Other Soil Properties

a) pH

The pH of all soils collected was determined at the water-saturation percentage point (Jackson, 1958).

b) Loss on Ignition

The loss on ignition at 550°C for one hour was expressed as a percentage of the oven-dry weight of the original sample.

c) Field Moisture Content (F.M.C.).

The moisture content of the soil, excluding the hygroscopic water, was expressed as a percentage of the field soil weight.

$$\text{F.M.C.} = \frac{\text{WET FIELD WT.} - \text{AIR DRY WT.}}{\text{WET FIELD WT.}} \times 100\%$$

d) Bulk Density (B.D.)

Bulk density of all soils was determined as

$$\text{B.D.} = \frac{\text{OVEN DRY WEIGHT}}{\text{FIELD VOLUME OF SAMPLE}} \quad \text{gm/cc}$$

The field volume of the soil was determined from the depth of sampling, diameter of the sugar and the number of cores taken.

e) Mechanical Analysis

Mechanical analysis of the soil samples collected from the 45 assessment plots was carried out according to the procedure outlined by Piper (1942).

(7) Computer Analysis

Raupach (1967) pointed out that the rate of growth of a forest can be expressed mathematically as a function of many factors. In order to distinguish between factors which contribute directly to the variation in growth, and those that contribute through virtue of their relationship with direct factors, partial regression or correlation procedures must be employed.

All data on the assessment plots was analysed on an I.B.M. 1620 computer, employing a general purpose multiple regression programme with procedures for the successive elimination of variables from the analysis. This library programme (file No. 06.0.184) provided partial regression coefficients, partial correlation coefficients and the multiple correlation coefficient of the variables, before and following the elimination of each variable in turn from the least to the most significant.

CHAPTER FOUR : RESULTS AND DISCUSSION

(A) THE DISTRIBUTION AND FORMS OF PHOSPHATE IN SELECTED PROFILES

The six profiles selected for this section of the investigation were sampled from under both fertilized and untreated stands to provide a range of site classes for both groups. (Table 4.1).

The amounts of aluminium-bound, iron-bound, calcium-bound total and organic phosphorus present are shown in Table 4.2 both on a weight in weight and weight in volume basis. The pH values for these horizons are also indicated.

The most outstanding feature of these results is the very low level of all phosphorus fractions throughout the profiles. By comparison with values presented by Wells (1962) for a large range of New Zealand soils, the levels recorded in this study are some of the lowest in New Zealand. This is in accord with studies conducted by Walker (1965) who reported a depletion in phosphorus levels for strongly weathered and leached soils. The low values are accentuated by the depleted nature of the deeply weathered parent material.

(I) Total Phosphorus

Total phosphorus values expressed on a weight basis decrease with depth in all profiles except profile G, a moderately podzolized soil where a minimum is recorded in the A_2 and B_1 horizons. This trend is less marked when the values are expressed on a volume basis but is still essentially the case for all soils except G where total phosphorus values increase with depth. The higher levels in topsoils can be attributed to the operation of the organic cycle.

TABLE 4.1

THE DESCRIPTION OF SELECTED PROFILES AND ASSOCIATED FOREST STANDS FROM RIVERHEAD FOREST*

PROFILE IDENTIFICATION	CLASSIFICATION	SYMBOL	PREVIOUS TREATMENT	SITE CLASS+
A98	Moderately to strongly leached northern yellow-brown earth.	YK	Control	IV (Poor)
A160/7	Weakly podzolized northern yellow-brown earth.	YK	Super 4 cwt/acre 1955	III(Medium)
A160/5	Moderately to strongly leached northern yellow-brown earth	YK	Super 20 cwt/acre 1955	II (Good)
P	Gleyed Northern yellow-brown earth	YKs	-	IV (Poor)
M	Weakly leached northern yellow-brown earth.	YKs	-	III(Medium)
G	Podzolized northern yellow-brown earth.	H	-	II (Good)

* Detailed profile descriptions are presented in appendix 1a-f.
\+ Quality of stands (Weston 1956).

TABLE 4.1

THE DISTRIBUTION OF PHOSPHORUS IN SELECTED PROFILES FROM RIVERHEAD FOREST

SOIL	HORIZON	DEPTH SAMPLED (INS.)	pH	TOTAL PHOSPHORUS		ORGANIC PHOSPHORUS		ALIMINIUM PHOSPHATE		IRON PHOSPHATE		CALCIUM PHOSPHATE	
				mg.P%	mg.P/100cc	mg.P%	mg.P/100cc	mg.P%	mg.P/100cc	mg.P%	mg.P/100cc	mg.P%	mg.P/100cc
A98	A_1	0 - 6	5.5	20.2	11.4	6.9	3.9	1.7	1.0	1.7	1.0	A	A
	A_3	6 - 12	5.3	14.8	10.2	4.9	3.4	Tr	Tr	2.6	1.8	A	A
	B_1	24 - 30	5.2	9.0	8.2	3.2	2.9	1.0	1.9	1.6	1.5	A	A
	B_2	36 - 42	5.0	6.0	10.5	0.8	1.4	A	A	0.5	0.9	Tr	Tr
	C	42 - 46	4.8	5.4	8.2	0.6	0.9	A	A	Tr	Tr	A	A
A160/7	A_1	0 - 4	5.5	23.2	12.8	9.4	5.2	4.8	2.6	2.6	1.4	1.1	0.6
	A_2	6 - 12	5.3	16.3	11.7	6.8	5.0	2.2	1.7	1.5	1.1	A	A
	B_1	13 - 19	5.2	12.6	10.8	3.1	2.6	0.5	Tr	3.5	3.0	A	A
	B_2	22 - 28	5.2	11.2	9.1	3.4	2.8	1.5	1.2	2.3	1.9	A	A
	B_3	30 - 36	4.9	8.4	11.7	1.0	1.4	A	A	0.6	0.8	Tr	Tr
	C	36 - 42	4.9	5.3	7.3	0.8	1.1	A	A	Tr	Tr	Tr	Tr
A160/5	A_1	0 - 6	5.0	25.8	17.5	5.5	3.7	5.7	3.9	4.3	2.9	3.0	2.0
	A_3	11 - 17	5.0	13.6	10.2	1.8	1.4	1.2	0.9	2.2	1.7	A	A
	B_1	22 - 28	5.0	10.2	9.5	3.4	3.2	1.0	0.9	1.5	1.4	A	A
	B_2	30 - 36	4.8	9.9	10.4	2.2	2.3	0.5	0.5	1.5	1.6	Tr	Tr
	C	40 - 44	4.8	5.4	8.2	0.6	0.9	A	A	Tr	Tr	A	A

A = undetectable

Tr = < 0.5 mg.P%

cont:-

TABLE 4.1 cont'd:

SOIL	HORIZON	DEPTH SAMPLED (INS.)	pH	TOTAL PHOSPHORUS		ORGANIC PHOSPHORUS		ALIMINIUM PHOSPHATE		IRON PHOSPHATE		CALCIUM PHOSPHATE	
				mg.P%	mg.P/100cc	mg.P%	mg.P/100cc	mg.P%	mg.P/100cc	mg.P%	mg.P/100cc	mg.P%	mg.P/100cc
P	A	0 - 4	4.9	13.8	14.5	10.6	11.1	0.5	0.6	0.7	0.8	A	A
	B	6 - 10	4.8	9.7	16.0	2.8	4.6	A	A	0.7	1.1	A	A
	C_1	12 - 18	4.7	7.9	11.8	1.6	2.7	A	A	0.6	0.9	A	A
	C_1	22 - 28	4.7	6.7	10.0	1.4	2.1	A	A	Tr	Tr	Tr	Tr
M	A	0 - 6	4.9	12.9	16.8	3.5	4.5	0.7	0.9	0.6	0.8	A	A
	B	8 - 12	4.8	12.7	16.7	3.2	4.2	A	A	0.7	0.9	A	A
	C	16 - 24	4.6	10.2	13.7	1.4	1.9	A	A	0.5	0.7	A	A
	C	26 - 32	4.4	9.7	13.2	1.1	1.5	A	A	0.5	0.7	Tr	Tr
G	O_2	0 - 2	3.7	41.2	8.2	22.8	4.6	3.4	0.7	A	A	2.0	0.4
	A_2	2 - 6	3.8	7.9	11.0	1.5	2.1	A	A	A	A	A	A
	B_1	8 - 12	4.3	7.7	11.8	0.7	1.1	A	A	0.5	0.8	A	A
	B_2	14 - 18	4.5	10.6	14.3	2.3	3.0	A	A	0.7	1.0	Tr	Tr
	C	18 - 24	4.6	8.7	14.0	2.0	3.2	A	A	1.0	1.7	A	A

The application of superphosphate has further accentuated these topsoil levels in the fertilized soils.

Total phosphorus values in the topsoil of the fertilized stands appear to be directly related to the quality of the stands on these soils, as classified in Table 4.1. However, within the untreated stands, which cover a wider range of soil types, and between fertilized and untreated stands there is no apparent relationship between site quality and total phosphorus values. Australian workers (Kessell and Stoate, 1950) have reported relationships between total phosphorus values and site quality but the above findings would appear to substantiate the work of Baur (1959), who reported that relationships between site quality and total phosphorus values are likely to be found within limited localities but not over more heterogenous sites.

(2) Organic Phosphorus

There are high amounts of organic phosphorus in the surface horizons of all profiles, accounting for 22 to 77 per cent of the total phosphorus present. The levels of organic phosphorus tend to decrease down the profile, although in the podzolized soils there is an accumulation in the B horizon at the expense of the A_2 horizon. The presence of appreciable quantities of organic phosphorus in the lower horizons shows that under the leaching conditions prevailing in this region, mobilization of organic matter and its movement down the profile is possible. Profile P is from an area of impeded drainage and the high organic phosphorus levels in the topsoil, which constitute 77 per cent of the total phosphorus present, may be attributed to a lower level of biological activity under these conditions, leading to an accumulation of organic matter. The lower levels of organic phosphorus in the topsoil of profile A 160/5 may be attributable to the stimulation of biological activity by the application of large quantities of superphosphate.

There is no apparent relationship between organic phosphorus levels and site quality either within or between fertilized and untreated stands. Although the contribution of organic phosphorus to the inorganic phosphate taken up by perennial plants cannot be discounted, the inconsistent relationship between organic phosphorus levels and site quality can probably be attributed to the variation in the level of biological activity between sites.

(3) Aluminium-Bound Phosphate

Aluminium-bound phosphate accounts for the major part of the extractable inorganic phosphate in the topsoil of these profiles. The soils under the untreated stands possess very low levels of aluminium phosphate with no detectable quantities occurring below the topsoils. The relatively large value for the topsoil of profile G may be an overestimation of the aluminium phosphate level as a portion of this quantity is extractable with 0.5MNaCl solution, the precise nature of the source being unknown. The lack of aluminium phosphates in the lower horizons of the untreated soils could in part be attributed to the very low levels of extractable inorganic phosphate in these horizons and in part to the moisture conditions and low pH levels which favour the presence of iron phosphates (Smith 1965). Aluminium phosphates decrease with depth in the profiles under fertilized stands, with detectable quantities occurring to greater depths than in untreated soils. Topsoil values increase in parallel with the quantities of superphosphate applied.

There is a relationship between site quality and the quantity of aluminium phosphates in the topsoil within both the fertilized and untreated stands. However, between the two, the relationship is not so clear; the levels in the fertilized soils all being greater than their counterparts of the same site quality in the untreated soils. Aluminium phosphate levels have been found to be closely related to the growth of agricultural crops (McLachlan 1965) and the results in Table 4.2 suggest that over a limited range of conditions a similar relationship may exist for trees.

(4) Iron-Bound Phosphate

Iron Phosphate in the untreated soils account for all the extractable inorganic phosphate in the lower horizons of these profiles. In profile P, iron phosphates constitute the major portion of the extractable inorganic phosphate in the topsoil. This can be attributed to the waterlogged condition of the profile which favours the formation of iron phosphates (Smith 1965). The absence of iron phosphates in the surface horizons of profile G and the increasing levels in lower horizons can be attributed to the eluviation of iron from upper into lower horizons during the process of podzolization. In the fertilized soils there is evidence that the superphosphate applications have increased the iron phosphate levels in the topsoil although not to the same extent as aluminium phosphate levels. Iron phosphate values in control profile A98 reach a maximum in the A_3 horizon, then decline with depth. A similar pattern is apparent in profile A160/7 although a decline is recorded in the A_2 horizon of this weakly podzolized soil. Superphosphate applied to profile A160/5 has raised the level of iron phosphates in the topsoil sufficiently to mask the trend shown in A98 and A160/7, with a maximum occurring in the topsoil followed by a decline with depth.

Neither the level of iron phosphates in the topsoil nor their distribution in the untreated profiles show any relationship to the site quality. However, the level of iron phosphates in the topsoils of the fertilized profiles are related to the site quality. Iron phosphates are generally considered to be less available to agricultural crops than aluminium phosphates due to their lower solubility (Smith, 1965), but this may not detract from their importance as a source of supply to trees, which can apparently utilize sources of phosphate unavailable to agricultural crops (Tamm, 1964).

(5) Calcium-Bound Phosphate

All the profiles studied were practically devoid of calcium phosphates. This is in accord with the relationship between the forms of inorganic phosphate and the degree of weathering recorded by Chang and Jackson (1958). The presence of calcium phosphates in the O_2 horizon of the podzolized profile G may be accounted for by the release of metallic cations from the decomposing litter in this biologically active horizon. Calcium phosphates in the A horizon of the treated soils A160/7 and A160/5 may in part be accounted for by the above explanation and in part as residues from the application of superphosphate. In view of the low pH of these soils and the long time lapse since topdressing, it appears that the former explanation is more likely. There is also the possibility that deficiencies in the fractionation scheme may contribute to this result. Thus the N/50 HC1 extraction prior to the second IN NaOH extraction may, by increasing the solubility or iron and aluminium-bound phosphates in IN NaOH, produce a falsely enhanced calcium phosphate value.

The absence of calcium phosphates in three of the soils precludes the existence of a relationship between calcium phosphate levels and site quality. However, from Table 4.2 it is apparent that the topsoils under the better quality stands all contain some calcium phosphate. This may be indicative of a higher biological activity in these soils rather than an indication of calcium phosphate levels influencing the tree growth per se.

(6) Conclusions

The extremely low levels of phosphorus throughout these profiles is the consequence of the depleted nature of their parent materials and the environmental conditions under which they were formed. Although these low phosphorus levels and the apparent relationships between site quality and the level of some phosphorus forms suggest the existence of a phosphate deficiency, the possibility of a deficiency in other nutrient elements cannot be discounted, for as Walker (1965) pointed out, on these strongly leached and weathered soils multiple deficiencies are common. In order to establish the presence of a phosphate deficiency it would be necessary to examine statistically the relationships between soil phosphorus, tissue phosphorus and site productivity as suggested by Leyton and Armson (1955). The relationship between site productivity and soil phosphorus levels or tissue phosphorus levels should, however, be studied within specific management practises for as the results in Table 4.2 show, soil phosphorus levels under fertilized stands tend to be greater than those under untreated stands of the same productivity. The results of this preliminary study suggest that the levels of phosphorus in the topsoil are likely to be the most important in determining the site quality.

Variations in the level of aluminium phosphates appears to be the best index of variation in site quality. Aluminium plus iron phosphates and the extractable inorganic phosphates also have definite promise as indicators of site quality, but it appears that total phosphorus levels are of limited value when a range of soil types are are involved.

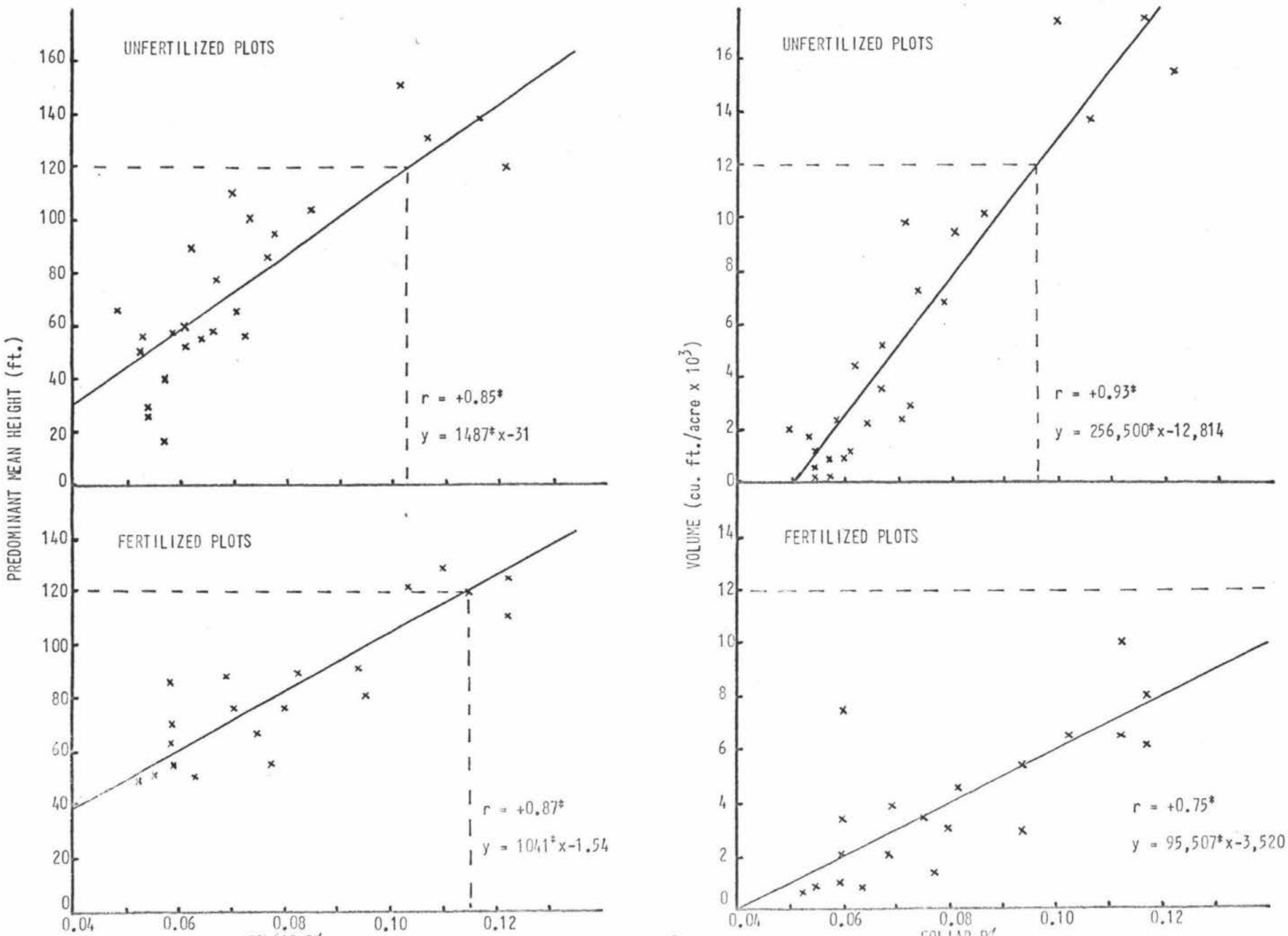
(B) THE RELATIONSHIP BETWEEN SITE PRODUCTIVITY AND FOLIAR PHOSPHORUS LEVELS

Figure 4.1 shows that there are highly significant relationships between site productivity (Predominant mean height and volume at 40 years of age) and the phosphorus content of the foliage for both aerially fertilized and unfertilized assessment plots.

Difference between the slope and intercept values of the regression lines for fertilized and unfertilized plots justifies the consideration of these relationships within specific management practices and substantiates the tentative finding in Section (A) of this chapter. The fertilized plots, which were aerially topdressed with 5 cwt of superphosphate in 1958/59 have smaller slope and larger intercept values than the unfertilized plots for the regressions of both height and volume on foliar phosphorus. However, on the assumption that all the plots represent true random samples from the same population and the fertilized plots have all received an identical superphosphate dressing at the same time, one would expect a general "shift effect" on the regression line of fertilized plots producing a lower intercept value but maintaining a similar slope value to the unfertilized regression. This is because the unfertilized trees, with foliar phosphorus levels similar to those of fertilized trees, have had the advantage of these nutrient levels throughout their entire lifespan, whereas with fertilized trees these levels are higher than those under which a considerable portion of the growth (30 years) has taken place. Thus, unfertilized plots with the same foliar levels as fertilized plots should be more productive. The failure of the results in Fig.4.1 to conform to this theoretical prediction may be attributed to several factors:-

FIG. 4.1

RELATIONSHIPS BETWEEN SITE PRODUCTIVITY AND FOLIAR PHOSPHATE LEVELS



* = significant at the 1% level

(I) Sampling Errors

The 45 plots sampled during this investigation were selected from 90 random assessment plots previously established in Riverhead forest. However, the selection of plots to be sampled from the 90 random assessment plots was itself not completely random: the pattern of topdressing over the forest and the inaccessability of some plots necessitated a personal selection in order to obtain approximately equal numbers of fertilized and unfertilized plots. Nevertheless, in view of the random nature of the sampled population, this error is unlikely to be of much significance although it could be of importance in the extrapolation of results to the entire forest.

(II) Different availability of the aerially applied phosphate.

If the aerially applied phosphate was less available on the sites of low productivity one would expect a greater "shift effect" to occur on the more productive sites, which would effectively pivot the regression line about the less productive sites producing a lower slope value and larger intercept value for the fertilized plots such as is manifested in Fig. 4.1

(III) Uneven application of the aerially applied fertilizer

Visual evidence of variability in the response of topdressed areas suggests that the aerial topdressing provided an uneven distribution of fertilizer. Thus, some deviation from the predicted response can be expected.

(IV) Other factors limiting response.

Visual evidence of response to the aerially applied fertilizer is more apparent in plots which were reasonably productive prior to fertilizer application. This suggests that the failure of the low productive sites to respond could be attributed either to the trees being too unhealthy to utilize the applied phosphate or to some factor or factors other than phosphorus deficiency being more limiting to growth on these poor sites. If this is the case a study of the relationships between the levels of soil phosphorus and site productivity of fertilized plots should reveal soil phosphorus levels which are not commensurate with the productivity of these poor plots.

A comparison between regression lines obtained, utilizing volume and height data (Fig. 4.1), reveals that the trend for fertilized plots to have smaller slope and larger intercept values is more pronounced when employing volume data. This can be attributed to the nature of the morphological response of poor trees to applied phosphate; the most pronounced change in poor trees, particularly those suffering from 'die-back', is the rapid growth of existing or new leaders. Such a response is <u>fully</u> accounted for by the height measurements but not by the volume measurements which measure volume to a 3 inch diameter top. Thus the 'shift effect' willbe more pronounced using volume data.

A foliar phosphorus content of approximately 0.10 per cent is required for the 'normal' growth of radiata pine on unfertilized sites. This value is derived from the assumption that under the Riverhead climatic conditions a height growth of 120 feet and a volume production of 12,000 cubic feet per acre is 'normal' for 40 year old radiata pine stands (Fig. 4.1). This value is in accord with Will's (1961, 1965) findings for radiata pine and those of Ruapach (1967). The foliar levels corresponding to this productivity are much greater for fertilized sites but the measured productivity is no indication of their current growing vigour. However, it is interesting to note that in very few cases do the foliar levels of the fertilized plots equal or exceed the 0.10 per cent level established as necessary for normal growth. This suggests that the application of 5 cwt of superphosphate is insufficient to maintain an adequate supply of phosphate over a 9 year period on most sites. Will (1965) reported a similar ineffectiveness of 2 and 4 cwt of superphosphate over a six year period at Riverhead.

It is reasonable to assume from these significant relationships that phospherous is a limiting nutrient in the soils of the region being examined. However, such evidence does not constitute irrefutable proof of a deficiency, as the relationship between site productivity and foliar phosphorus levels may be due wholly or in part to their common relationship to one or more other factors. Leyton (1956) reported such a case, where the significant correlation between foliar phosphorus levels and productivity could be attributed to the relationship of both to foliar nitrogen. If the observed relationships between site productivity and foliar phosphorus levels are the consequence of the mutual relationship of the two variables to a more limiting nutrient, then one would expect an erratic relationship to exist between soil phosphorus levels, as the more limiting nutrient, rather than soil phosphorus levels would be determining the foliar phosphorus levels and productivity.

(C) THE RELATIONSHIPS BETWEEN SITE PRODUCTIVITY AND SOIL PHOSPHORUS LEVELS

(I) Introductory

Correlations between site productivity and soil phosphorus levels are presented in Table 4.3. (For the purpose of this study the Na_2CO_3 fusion method, which extracts total phosphorus, is considered as a soil test). It is evident that for the unfertilized plots the correlations between site productivity and the amounts of phosphorus extracted from the soil by the various tests are independent of whether height or volume is taken as the measure of site productivity. Such is not the case with the aerially fertilized plots where there is a marked decline in the value of the correlations when volume is employed as the parameter of productivity. As indicated in Section B of this chapter, volume, unlike height, is a fairly insensitive measurement of the tree response to fertilizer application. However, the insensitivity of the volume measurement should have had little effect on the value of the correlations obtained for the fertilized plots provided the aerially applied fertilizer had been evenly distributed and had produced equivalent increases in available phosphate levels over the fertilizer plots. If, however, the aerially applied fertilizer had resulted in an uneven increase in the levels of available phosphate then an alteration in the correlation values could be expected because both height and soil measurements would reflect the uneven changes, whereas volume measurements would not. Thus the decline in the correlation values found for the volume measurements suggests that an uneven increase in the levels of available phosphate had resulted from the fertilizer application. This uneven change in available phosphate levels may have resulted from either :

TABLE 4.3

CORRELATIONS BETWEEN SOIL PHOSPHATE LEVELS[+] AND SITE PRODUCTIVITY

SOIL TEST	SITE PRODUCTIVITY			
	FERTILIZED PLOTS		UNFERTILIZED PLOTS	
	PREDOMINANT MEAN HEIGHT	VOLUME TO TOP 3"	PREDOMINANT MEAN HEIGHT	VOLUME TO TOP 3"
Bray No. 2	0.836**	0.693**	0.773**	0.745**
Olsen	0.703**	0.534*	0.804**	0.783**
Olsen Modified	0.727**	0.540*	0.764**	0.780**
Oxidized by Bromine	0.620**	0.435	0.500*	0.538**
Truog (T_1)	0.352	0.039	0.480*	0.430*
Truog (T_2) Modified	0.524*	0.367	0.693**	0.678**
$T_2 - T_1$	0.509*	0.341*	0.690**	0.685**
Acetic Acid	0.516*	0.330	0.470*	0.585*
Resin	0.679**	0.474*	0.746**	0.727**
Total P	0.699**	0.548*	0.087	0.14

** = Significant at the 1% level

* = Significant at the 5% level

\+ = Quantities extracted presented in Appendix 2

(a) an uneven distribution of the aerially applied fertilizer,

(b) a difference in the availability of the aerially applied fertilizer as between fertilized plots, or

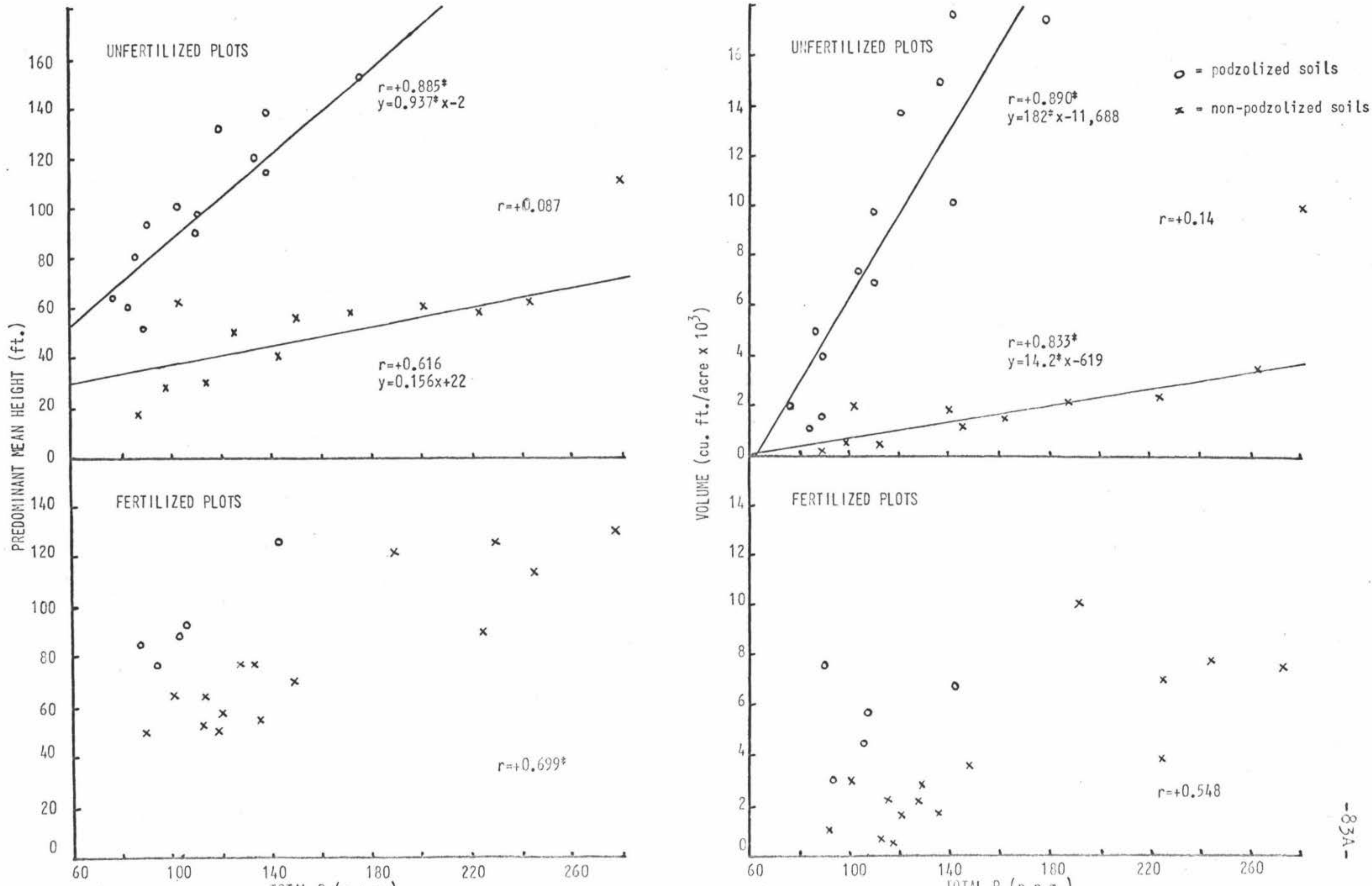
(c) a combination of the above factors.

(2) Total P and Site Productivity

Total phosphorus levels are significantly related to the site productivity of fertilized plots, but there is little or no relationship between total phosphorus levels and the site productivity of unfertilized plots (Table 4.3). A more detailed examination of the relationship between total soil phosphorus and site productivity provides an explanation for the very low correlation values obtained for the unfertilized plots (Fig. 4.2). This shows that there are two very distinct groups of points within each relationship, the distribution of which is such that the correlation coefficient for the combined data is virtually zero. Taken separately, however, the correlation coefficients for the two groups are highly significant. The existence of the two distinct groups can be attributed to a difference in the soil forming process involved. Plots on podzolized soils are more productive per unit of total phosphorus present than plots on non podzolized soils. If soil phosphorus is the factor limiting productivity on these soils, then these results suggest that some fraction of the total soil phosphorus, rather than total phosphorus per se, is the critical factor determining productivity. Assuming then that 'available' phosphate levels control productivity, one can expect a significant relationship to exist between total phosphorus levels and site productivity only for those soils where a sensibly constant relationship exists between total phosphorus and available phosphate levels. In the soils of this study, the properties determining the relationship between total phosphorus

FIG. 4.2

RELATIONSHIPS BETWEEN SITE PRODUCTIVITY AND TOTAL PHOSPHORUS



‡ = significant at the 1% level

and available phosphate are apparently those associated with the presence or absence of podzolization. It is interesting to note that the process of podzolization is considered to produce a degeneration in the nutritional status of a soil. However, in the apparently phosphate deficient forest soils of this study the process of podzolization produces an improvement in the phosphate status of the soils insofar as it is related to the growth of radiata pine. This may be attributed to several factors:

(a) The process of podzolization reduces the phosphate fixing capacity of the surface horizons. Thus the rate of nutrient cycling, which appears to be important in meeting the nutritional requirements of older trees (Wills 1964) will be less impeded by competition from the soil for the mineralized phosphorus;

(b) Occluded phosphate levels are reduced during podzolization (Walker 1965) and thus may enrich the organic cycle;

(c) mycorrhizal activity is enhanced by lower pH values (Harley 1959).

The influence of podzolization on the relationship between total phosphorus levels and site productivity of fertilized plots is less pronounced, but this may be attributed to the disproportionate ratio of non-podzolized to podzolized soils in the fertilized plots.

The significant relationships between site productivity and total phosphorus level reported by several Australian workers (Kessell and Stoate 1938; Young 1948; Humphreys 1964; and Hopkins 1960), can be attributed to these relationships having been derived from forests planted on the relatively homogenous soils derived from sandy coastal plains and massive sandstone deposits. Baur (1959) found that an erratic relationship occurred when more heterogenous sites were covered. Humphreys (1964) reported that although inter-forest variations in productivity were adequately accounted for by variations in the total phosphorus content of the soil, intra-forest variations were not. The findings of this study are in accord with the discrepancies reported for this method by the latter two authors.

Provided a satisfactory relationship between site productivity and total phosphorus levels can be shown, total phosphorus has certain advantages over available phosphate measurements for prediction purposes for the following reasons :

(a) The quantities of phosphorus involved and the range between deficient and sufficient quantities are much greater; thus there is not the need for elaborate precautions against contamination and expensive equipment required for the precise detection of small quantities.

(b) Total phosphorus values will change less during the life of a commercial tree crop, thus critical values for growth, derived from older trees, are more likely to be applicable to the delineation between deficient and sufficient sites for the growth of young trees.

Although highly significant relationships between total soil phosphorus and site productivity within soil types have been established in this study, the use of this method for general survey work in Riverhead forest would require more intensive mapping (existing 1:1 scale maps are inadequate) or the employment of trained personnel to collect the survey samples.

(3) Bray No. 2 P and Site Productivity

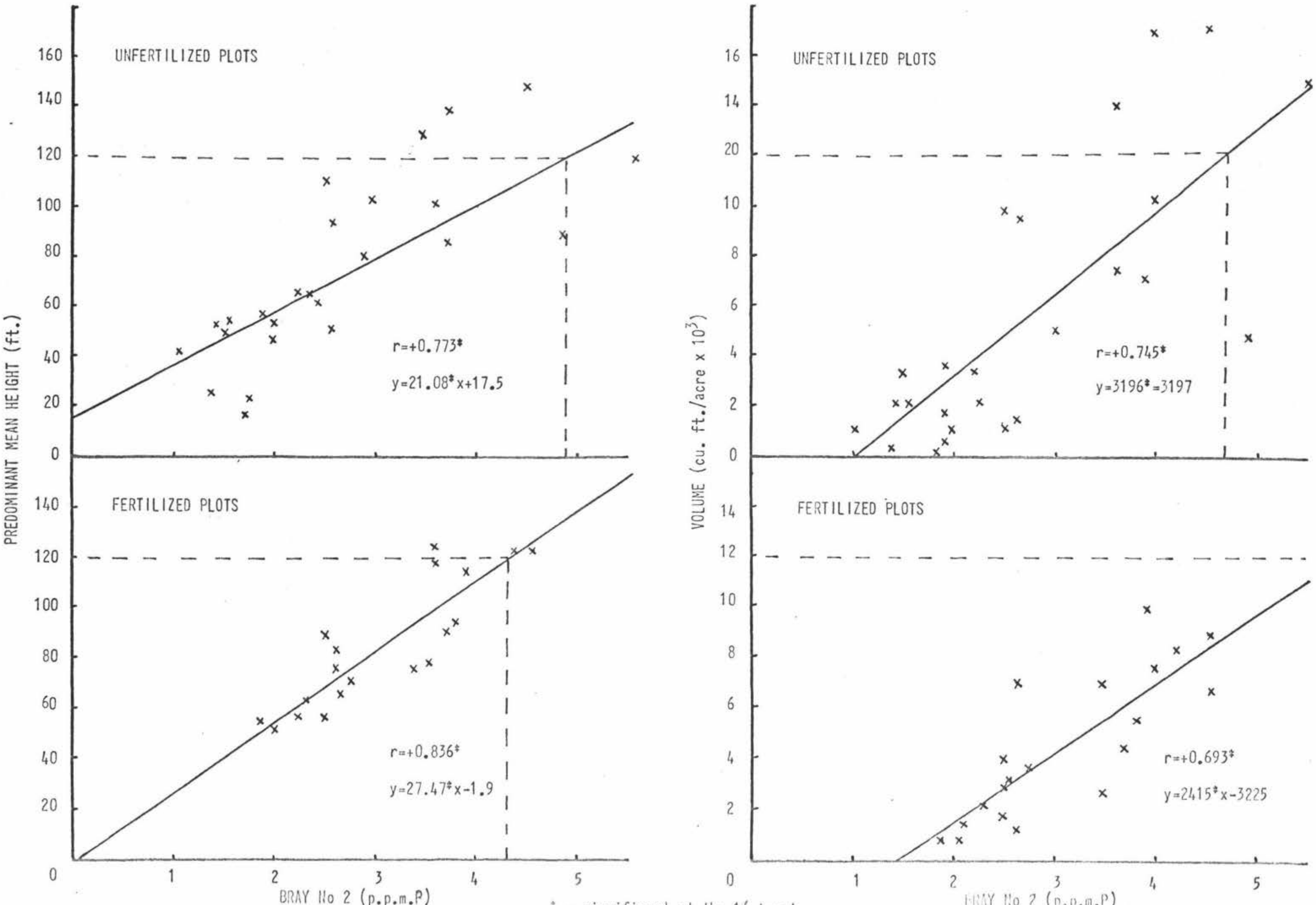
'Available' soil phosphate levels extracted by the Bray No. 2 extractant are significantly related to the site productivity of both fertilized and unfertilized plots. (Table 4.3). The Bray No. 2 Test is the most significant of all tests on the fertilized plots.

The Bray acid NH_4F extractant removes phosphate from iron and aluminium bound sources (Grigg 1961). These two sources were found to be the most suitable for explaining the variation in the site productivity of the stands investigated in the preliminary phosphate fractionation work. Thus the success of the Bray No. 2 extractant substantiates the tentative conclusion put forward in Section A of this chapter.

The detailed relationships between Bray-extracted phosphate and site productivity are presented in Fig.4.3. Employing height as the productivity variable, the regression line for the fertilized plots has a larger slope and smaller intercept value than the unfertilized regression line. However, with volume as the productivity variable the fertilized regression line has a smaller slope and a similar intercept value to the unfertilized regression line. As in the relationship between foliar phosphorus levels and productivity a 'shift effect' could be expected in the fertilized regression if the same assumptions were made. However, the direction of the 'shift effect' should depend on the extractant employed. Thus, if a powerful extractant is employed the 'shift effect' should produce a lowering of the fertilized regression line as the quantity of phosphate extracted from the phosphate remaining from the fertilizer application should more than offset any increase in productivity resulting from the response to the applied fertilizer. This right hand 'shift effect' should be more pronounced when the less sensitive volume measurement is employed as the productivity variable. However, with a weak extractant, the 'shift effect' should raise the fertilized regression line; for nine years after the fertilizer application the easily extractable phosphate levels, reduced by plant uptake and soil fixation, would probably have returned almost to their pre-fertilizer application levels. Thus the plant growth would have had the benefit of greater levels of phosphate than recorded in the soil test, giving the fertilized plots a greater productivity than their

FIG. 4.3

RELATIONSHIPS BETWEEN SITE PRODUCTIVITY AND PHOSPHATE EXTRACTED BY THE BRAY No. 2 EXTRACTANT



‡ = significant at the 1% level

unfertilized counterparts growing on soils with similar levels of easily extractable phosphate. This left hand 'shift effect' should be less pronounced when the less sensitive volume measurement is employed as the productivity variable.

The results employing height as the index of site productivity are confused. There appears to be a slight left hand 'shift effect' on the more productive plots, together with a right hand 'shift effect' on the less productive plots, resulting in a pivoting of the fertilized regression line about the centre. The failure of the regression line to illustrate a general 'shift effect' in one direction or another may be attributed to the failure of the poor plots to respond to applied phosphate whilst the response of the more productive plots over the nine-year period since topdressing is not fully accounted for by the increased levels of extractable phosphate at the end of this period. The fertilized regression line obtained employing volume as the index of site productivity illustrates a general right hand 'shift effect' although it is more pronounced on the more productive plots. In view of the insensitivity of volume to fertilizer responses, a right hand shift could be expected. However, the greater 'shift effect' on the more productive plots suggests that these plots received greater quantities of fertilizer or that the applied fertilizer is more easily extracted from the more productive plots by the Bray extractant. Thus the results using the Bray No. 2 extractant suggest that the less productive plots not only fail to respond to applied fertilizer but they apparently received less fertilizer than the more productive plots.

The quantity of Bray extracted phosphate corresponding to a volume production of 12,000 cubic feet per acre and a height of 120 feet at 40 years of age is approximately 5 p.p.m.P. Pritchett (1968) reported that slash pine failed to respond to phosphatic fertilizers where grown on soils containing greater than 5 p.p.m. of Bray No. 2 extractable phosphate. Although slash pine is less demanding in its phosphate requirement than radiata pine (Jackson 1965), the reading of 5 p.p.m. represents the quantity required for the normal growth of radiata pine and there is no indication to suggest that stands growing on soils with a value of equal to or greater than 5 p.p.m. of Bray No.2 extractable phosphate, will not respond to phosphatic fertilizers.

(4) Olsen P and Site Productivity

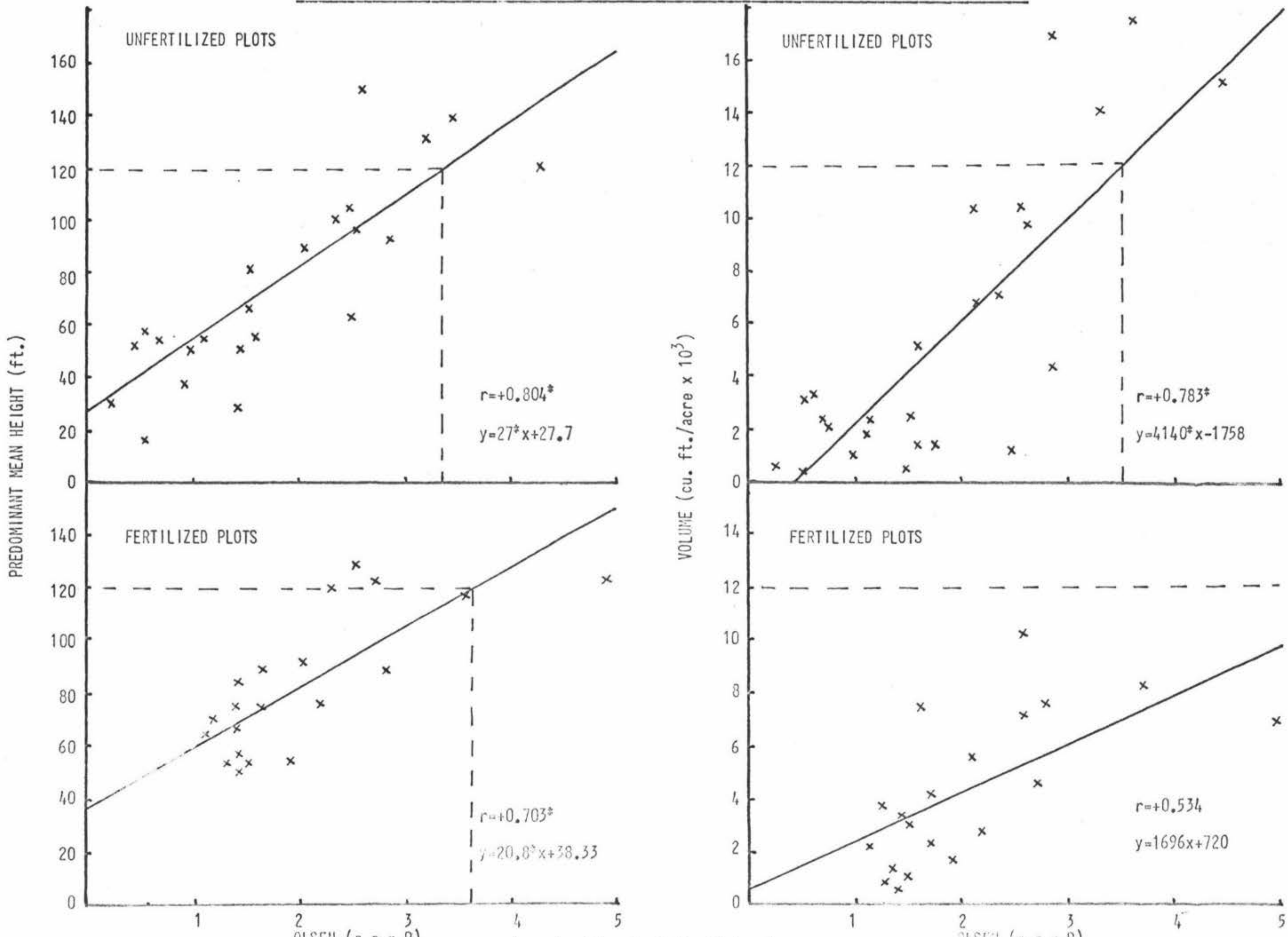
Soil phosphate levels extracted by the alkaline $NaHCO_3$ extractant are significantly related to the site productivity of both fertilized and unfertilized plots. The Olsen test is the most significant of all tests on the unfertilized plots (Table 4.3).

The Olsen extractant will remove some forms of calcium phosphate as well as exchangeable iron and aluminium phosphate. The Olsen extractant discriminates against the bonding energy of the phosphate rather than the form in which is occurs, thus the extractant tends to extract phosphate from aluminium phosphate which has a lower bond energy than iron phosphate (Smith 1965).

The detailed relationships between the Olsen extracted phosphate and site productivity are presented in Fig.4.4. When height is employed as the productivity variable, the fertilized regression line has a larger intercept and smaller slope value than the unfertilized regression line. This represents a general left hand 'shift effect' which is slightly more pronounced on the sites of lower productivity. Such a result could be expected when employing a relatively weak extractant, as the extractable phosphate levels will have fallen off to such an extent over the period since fertilizer was applied as to be inadequate to reflect the response to the fertilizer. There is no

FIG. 4.4

RELATIONSHIPS BETWEEN SITE PRODUCTIVITY AND PHOSPHATE EXTRACTED BY THE OLSEN EXTRACTANT



‡ = significant at the 1% level

evidence to suggest that the sites of lower productivity have failed to respond to the fertilizer for, if this were the case, one would expect a right hand 'shift effect' to occur on the poor sites or, at the least, no 'shift effect' to occur if all the applied phosphate was now unextractable. Volume data manifest a general right hand 'shift effect' of the fertilized regression, which is more pronounced on the more productive plots, producing a pivot effect about the poorer plots. If volume reflects only a small portion of the response then the volume data suggests that the better plots have received more fertilizer than the poorer plots.

The Olsen extracted value corresponding to normal growth on unfertilized plots of 40 years of age is approximately 3.5 p.p.m. As may be anticipated this value is less than that obtained employing the Bray No. 2 extractant.

(5) Olsen Modified P and Site Productivity

The modifications to the Olsen procedure, which provide a measure of the organic phosphorus soluble in alkaline $NaHCO_3$, improve the correlation of the standard Olsen test for fertilized plots, but reduce its value for unfertilized plots (Table 4.3). This suggests that the fraction of organic phosphorus extracted by the Olsen extractant is more closely related to the growth on fertilized plots than unfertilized plots. This may be due to stimulation of biological activity on fertilized plots and thus the rate of mineralization will have been stimulated on all the fertilized plots irrespective of their previous condition. The contribution from organic phosphorus on unfertilized plots cannot be discounted, but, in view of the range of conditions influencing the biological activity, it is likely that the contribution from organic phosphorus may be overestimated on some sites where organic matter has accumulated as a consequence of low biological activity. However, the alterations in the correlation values of the standard Olsen procedure induced by the modification are only small, which suggests either that the inorganic fraction extracted is dominant in determining the relationship between the combined organic plus inorganic phosphates and site productivity, or that the two fractions themselves are closely related.

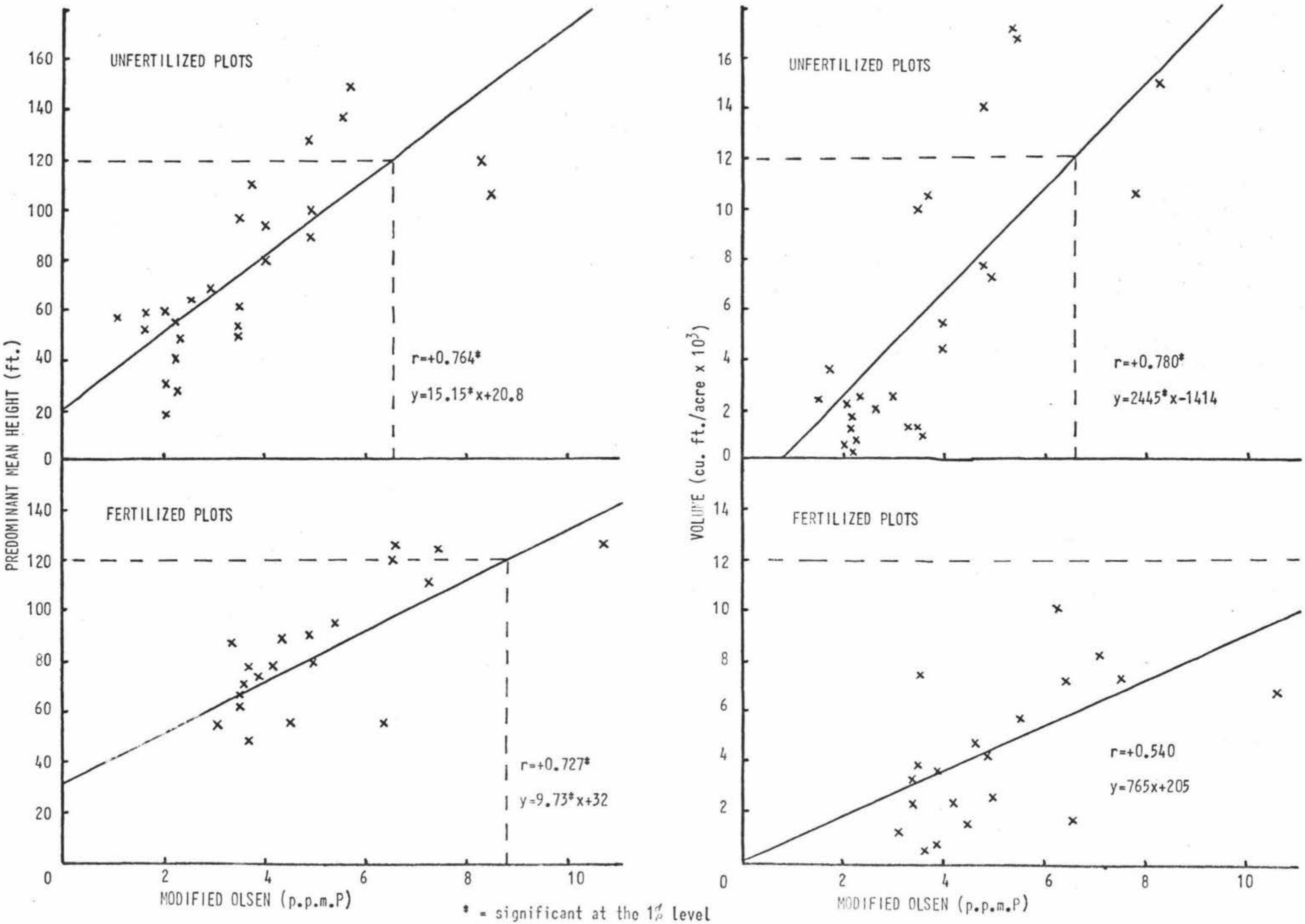
The 'shift effects' of the fertilized regression lines derived with the data from the modified Olsen procedure are identical with those obtained employing the data from the standard Olsen procedure (Fig.4.5). Thus the inclusion of the organic phosphorus fraction has little influence on the interpretation of the fertilizer effects. The level corresponding to the normal growth of unfertilized plots is almost twice that recorded for the standard Olsen procedure (Fig. 4.5). Thus of the alternatives suggested above, it appears that the similarity between the correlations obtained for both the Olsen and the modified Olsen's procedure can be attributed to the close relationship between the organic and inorganic fractions rather than a dominating effect of the inorganic fractions, as both make an equal contribution to the combined figure.

(6) Bromine Oxidation P and Site Productivity

The quantity of organic phosphate, extracted by the alkaline Olsen extractant and oxidized by bromine, is more significantly related to the site productivity of fertilized plots than unfertilized plots (Table 4.3). Although the correlations with site productivity are not as large as some of those obtained with 'available' inorganic phosphate levels, the fact that they are significant suggests that some forms of organic phosphorus contribute in some way to the productivity of the forest stands. Whether the organic phosphate levels are

FIG. 4.5

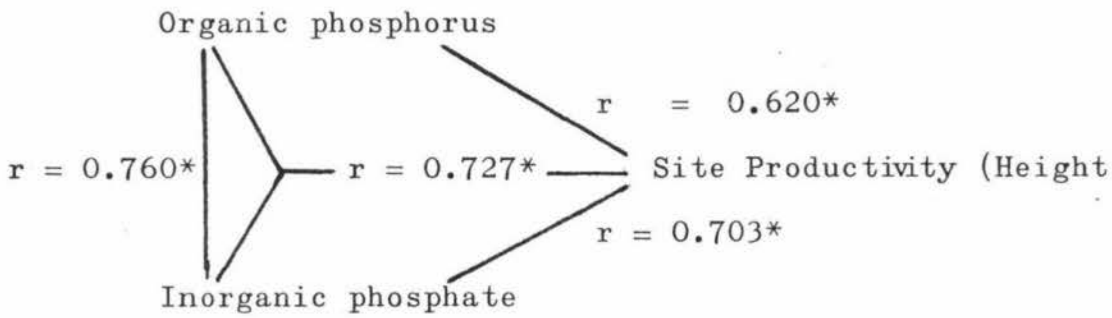
THE RELATIONSHIPS BETWEEN SITE PRODUCTIVITY AND PHOSPHORUS EXTRACTED BY THE MODIFIED OLSEN PROCEDURE



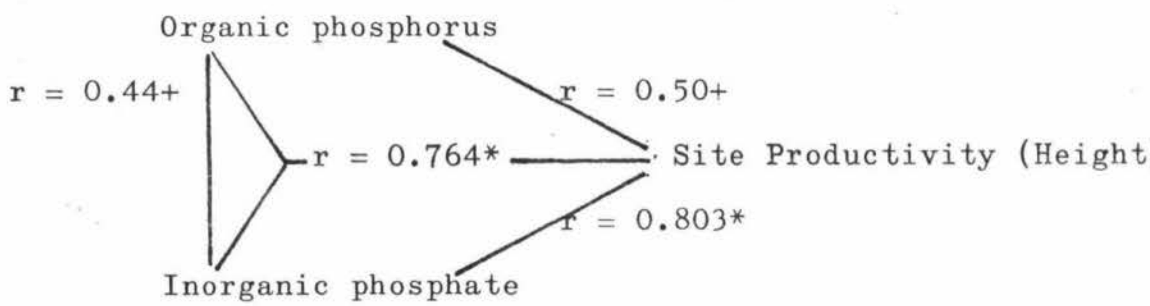
the consequence of site productivity or in fact are a contributing causal factor is difficult to delineate, but in a closed ecosystem such as exists in a mature forest stand, the establishment of cause and effect is often less important than establishing the presence of a relationship.

The interrelationships between the organic and inorganic levels extracted by the Olsen extractant are of interest. They may be presented as follows :-

(a) Fertilized plots



(b) Unfertilized plots



* = significant at the 1% level

\+ = significant at the 5% level

In the fertilized plots the larger correlation values between organic phosphorus and inorganic phosphate, and inorganic phosphate and site productivity, suggest that the relationship between site productivity and organic phosphorus is largely the consequence of their mutual relationship to inorganic phosphate. However, since the correlation between the combined organic and inorganic levels is slightly greater than the correlation between inorganic phosphate and site productivity, the organic phosphorus levels must explain some of the variability in site productivity not accounted for by variations in the inorganic phosphate levels. In the unfertilized plots it appears that the poor relationship between organic phosphorus levels and site productivity can be attributed to the poor relationship between organic and inorganic levels. The decline in the combined correlation suggests that the relationship between organic phosphorus levels and site productivity, corrected for the contribution through inorganic levels, would probably be negative. This is in accord with the earlier suggestion that on poor unfertilized plots the organic phosphorus levels may be overestimated.

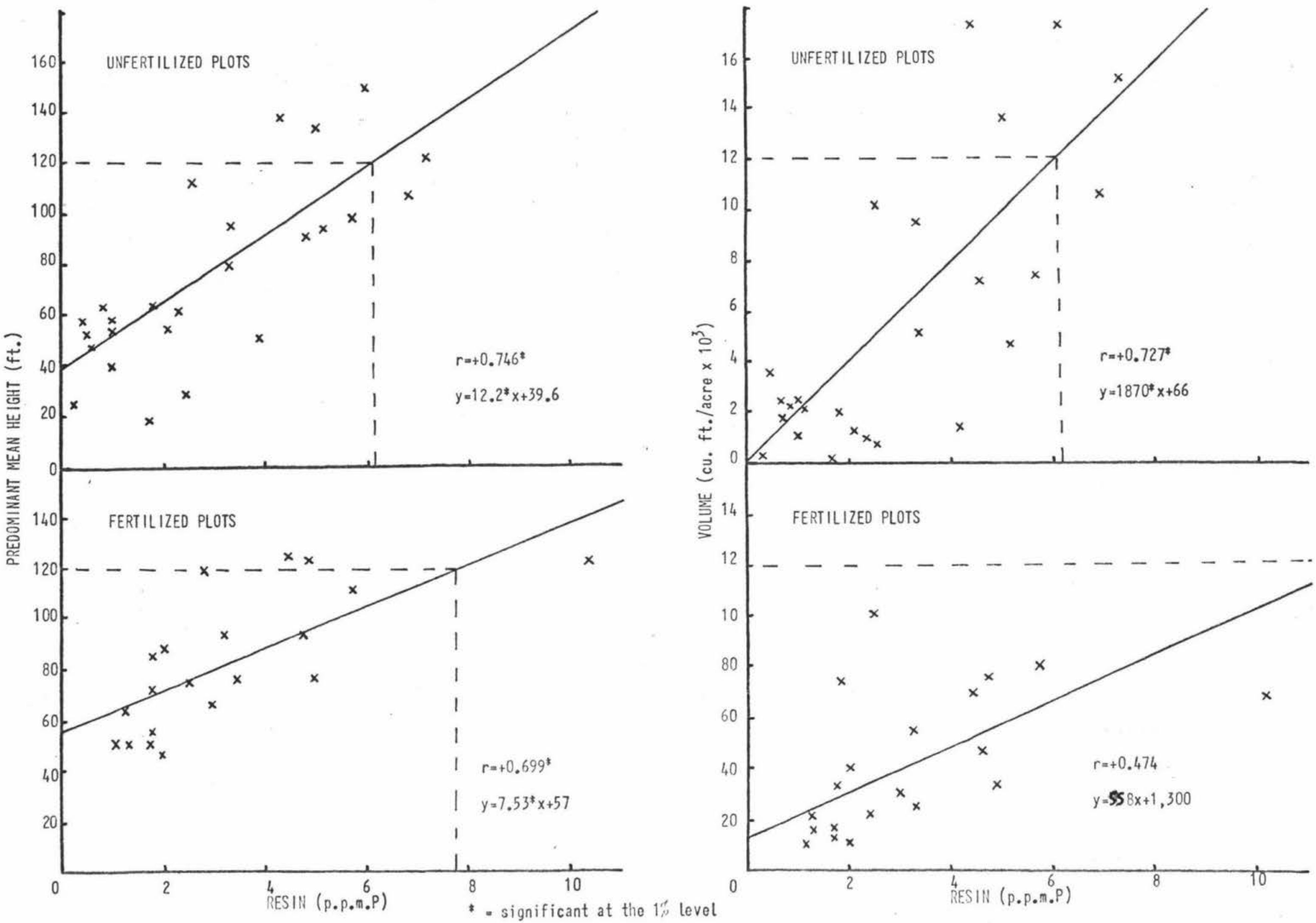
(7) Resin P and Site Productivity

Exchangeable phosphate levels extracted by the strong anion exchange resin are significantly related to the site productivity of both fertilized and unfertilized plots (Table 4.3). The anion exchange resin extracts exchangeable phosphate, descriminating against the bonding energy with which it is held and not the form in which it occurs. Thus, like the Olsen extractant it reflects soil phosphate behaviour.

The 'shift effects' manifested by the fertilized regression line are identical to those recorded for the Olsen and modified Olsen procedures and the same conclusions hold (Fig. 4.6). The extracted phosphate level corresponding to normal growth of unfertilized 40 year old trees is approximately 6 p.p.m. This value is the highest recorded for the procedures which extract exclusively from the inorganic phosphate fraction. In view of the earlier discussion on the influence of the strength of the extractant on this type of 'shift effect' to be expected, it is surprising that the resin method did not produce a right

FIG. 4.6

THE RELATIONSHIPS BETWEEN SITE PRODUCTIVITY AND PHOSPHATE EXTRACTED BY THE RESIN PROCEDURE



hand 'shift effect' on the less productive plots as did the Bray No. 2 extractant. However, on the less productive sites the resin extracted less phosphate than did the Bray No. 2 extractant, although it extracted considerably greater amounts on the more productive plots. This may be accounted for by the ability of the acid NH_4F extractant to remove the more firmly held iron-bound phosphates which form a greater proportion of the inorganic phosphate on the less productive sites (Section A).

(8) Truog P (T_1) and Site Productivity

The levels of phosphate extracted by the Truog extractant are less significantly related to site productivity than any of the other extractants employed. The relationship for the unfertilized plots is significant at the 5% level but is non significant for the fertilized plots (Table 4.3). The Truog extractant has been found to be unsuitable for use on calcerous agricultural soils due to excessive extraction of calcium bound phosphates (Grigg 1965). However, on the acid forest soils of this study this is unlikely to be of importance. The failure of the Truog extractant to reflect the availability of soil phosphate to the trees can be attributed to the resorption of dissolved phosphate during the extraction. On soils containing abundant levels of free iron oxides (Yk) the Truog extractant failed to extract any detectable phosphate, irrespective of the productivity of the site. Williams and Knight (1963) found that extractants which allowed resorption of some of the initially dissolved phosphate were the most suitable for predicting the fertilizer requirements of crops as they reflected the retention capacity of the soil. However, During (1968) reported that extractants */ were the most suitable for determining the phosphate status as they reflect the natural stratification of phosphate in the soil which determines the availability of the indigenous soil phosphate. The

*/ which prevented resorption during extraction

results of this study appear to substantiate the findings of During, as extractants which largely prevent resorption, such as the Olsen, Bray and resin extractant, provide the best indication of the phosphate status of the soils under investigation.

(9) Truog Modified P (T_2) and Site Productivity

Ignition to convert all the organic phosphorus to inorganic phosphate prior to extraction with the standard Truog extractant considerably improves the correlation obtained between the site productivity and phosphate levels extracted by the Truog extractant (Table 4.3). The improvement is more pronounced on the unfertilized than the fertilized plots. In view of the resorption which occurs during the Truog extraction this test should provide some reflection of the availability of organic phosphate once it has been mineralized, as root absorption must also compete with soil absorption for the mineralized organic phosphorus. The improved values which result from the inclusion of the organic phosphorus suggest that the availability of the mineralized organic phosphorus is of importance in determining the productivity of the forest stands. Unfortunately the conversion of organic phosphorus to inorganic phosphate is indiscriminate and a further improvement in the value would probably have resulted had the laboratory mineralization descriminated against the less readily mineralizable forms or organic phosphorus, thereby providing conditions more analogous to those in the field.

(10) T_2 - T_1 and Site Productivity

The difference between the two Truog procedures provides an indication of the availability of organic phosphorus after mineralization. The correlations employing these values are similar to those obtained with the modified Truog values (Table 4.3). These results substantiate the above conclusion that the availability of organic phosphorus is of importance in determining the productivity of the forest stands. Unlike the relationship between site productivity and the organic phosphorus extracted by the Olsen extractant, the relationship between Truog extracted organic phosphorus and site productivity cannot be accounted for by the relationship of the two variables to the inorganic levels extracted by the Truog extractant. However, it is interesting to note that the $T_2 - T_1$ values obtained on the unfertilized plots are closely related ($r = 0.78$) to the inorganic phosphate levels extracted from the unfertilized plots by the standard Olsen procedure. It appears, therefore, that tests for organic phosphorus which are likely to be most successful are those that remove quantities closely related to the easily extracted inorganic phosphate levels in the soil. This suggests that although the easily extracted inorganic phosphate levels directly determine productivity, they themselves are a reflection of the contribution from organic phosphorus.

The interpretation of organic phosphorus results is fraught with difficulty, for not only are their influences indirect but the large number of interacting factors which affect the rate of mineralization make it practically impossible to attribute variations in the relationship between organic phosphorus and site productivity to any particular condition. The interpretation is further restricted by the inadequate knowledge on what forms of organic phosphorus are being extracted and the rate at which such forms are mineralized. However, the results of this study suggest that the organic phosphorus plays an important part in meeting the phosphate requirements of the trees, thus substantiating the findings of Will (1965).

(11) <u>Acetic Acid P and Site Productivity</u>

The acetic acid extractant was the weakest of all extractants employed. Phosphate levels extracted by this extractant were very low on nearly all soils investigated. The low readings must cast some doubt on the validity of the relationships obtained, as a large proportion of the values were below accurately detectable quantities. However, even if the values obtained are assumed to be accurate, their relationships with site productivity are significant at the 5% level only, which suggests that not only are very weak extractants impracticable on these depleted soils but they also fail to reflect the availability of soil phosphate to the tree.

(12) Conclusions

In the Riverhead forest, where a range of soil conditions and types are met with, soil extractants which remove the 'available' fraction of soil phosphate, as distinct from total phosphorus, provide the best index of variation in the site productivity. This appears to refute the theory on the intense feeding habits of trees. The most suitable tests appear to be those that disciminate against the energy with which phosphate is held on the soil absorption complex. The results are also in accord with the findings of During (1968) that extractants which prevent resorption of phosphate during extraction are the most suitable for determining the phosphate status of the soil. There are indications that organic phosphorus makes an important contribution to the phosphate nutrition of these older trees although this contribution appears to be reflected in the levels of easily extractable inorganic phosphate.

Evidence obtained suggests that deviations of the relationship between the site productivity of fertilized plots and soil phosphorus levels from the theoretical pattern can be attributed to the uneven application of the aerial topdressing. However, the possibility of the presence of a more limiting factor on the less productive sites cannot be ignored.

The significance of the relationships between 'available' soil phosphate levels and site productivity suggests that the measurement of available soil phosphate levels offers an accurate means of estimating the site capacity of these forest soils. These significant relationships may also be taken as reasonable evidence that phosphate deficiency is limiting productivity in Riverhead forest. However, caution must be employed in placing too much weight on this evidence for deficiency, for as in the case with the relationships between foliar phosphorus levels and site productivity, the relationships may be due to the mutual relationship of the two variables involved to some other site variable. When, however, these relationships are considered in the light of the significant relationships between site productivity and foliar phosphorus levels, found in Section B of this chapter, the possibility of some other nutrient limiting productivity throughout the forest becomes more remote; it would be necessary for this 'limiting' nutrient to be related not only to the foliar phosphorus levels but also to the available soil phosphate levels. In view of the range of soil types considered, such a relationship is most unlikely.

The relationships derived between soil phosphate levels and site productivity cannot be employed to assess the <u>potential</u> productivity of forest soils, as there is no evidence that the level of available phosphate found for the topsoil under mature forest stands is the same as the level existing prior to planting. Wilde et al (1964a) reported that the phosphate levels in the topsoil actually increased as forest stands matured. They attributed the increase to an increase in the organic phosphate levels under the action of the organic cycle. Irrespective of whether there is an increase or a decrease, or only an alteration in the form of the phosphorus, accurate prediction of the potential productivity of forest soils requires the establishment of a relationship between the available soil phosphate levels prior to planting and the consequent productivity. The relationships established in this study serve only to indicate the nature of the phosphate supply to the tree and the dependence of tree growth at Riverhead on the available soil phosphate levels.

(D) THE RELATIONSHIPS BETWEEN FOLIAR AND SOIL PHOSPHORUS LEVELS

(1) Introductory

The correlations between foliar phosphorus and soil phosphorus levels extracted by the soil tests are presented in Table 4.4

The foliage of radiata pine trees in Riverhead forest renews itself completely once every 3 to 4 years (Will pers. comm.). If the current phosphate supply determines the level of phosphorus in the current foliage, the relationships between soil and foliar phosphorus levels should be independent of the fertilizer treatment applied 9 years previously, provided the soil tests reflect the nature of the current supply. If the nature of the current supply differs from the nature of the long term supply which determines productivity, then the success of the various extractants in reflecting productivity and foliar phosphorus levels should differ.

However, from Table 4.4 it is apparent that the relationships between soil and foliar phosphorus levels are not independent of the fertilizer treatment as the correlations obtained with the various tests for fertilized and unfertilized plots differ to almost the same extent as do those obtained in the site productivity study employing height as the index of productivity (Table 4.3). A comparison between the results in Table 4.4 and 4.3 also reveals that the order of success of the extractants in reflecting productivity and foliar phosphorus levels is almost identical.

This failure of the relationship between soil and foliar phosphorus levels to be independent of the fertilizer treatment may be attributed to several factors :-

(a) Sampling Errors

The fertilized and unfertilized plots selected may not represent true subsamples of the same initial population. Thus differences may arise which are the consequence, not of the fertilizer treatment, but of inherent differences arising from the different range and proportions of soil types considered in each group.

(b) Foliar Phosphorus levels are not determined by the current supply.

The large mass of the tree and the mobility of the phosphate ion in the tree may effectively buffer the influence of the current supply on foliar phosphorus levels. Thus the foliar phosphorus levels of the fertilized plots may partially reflect the available soil phosphate levels prior to the decline in availability to the existing levels.

(c) The soil tests do not reflect the availability of phosphate .

Although some of the tests may reflect the availability of phosphate for either fertilized or unfertilized plots, the difference in the nature of the supply between the two, which may have resulted from the fertilizer application, may be such that the tests are unable to reflect the availability for both. The failure of trees on some fertilized plots to utilize the applied phosphate may result in the

TABLE 4.4

CORRELATIONS BETWEEN SOIL PHOSPHATE AND FOLIAR PHOSPHORUS LEVELS

SOIL TEST	FOLIAR PHOSPHORUS LEVELS		
	FERTILIZED PLOTS	UNFERTILIZED PLOTS	COMBINE PLOTS
Bray No.2	0.836**	0.742**	0.784**
Olsen	0.785**	0.790**	0.818**
Olsen Modified	0.824**	0.777**	0.798**
Oxidized by Bromine	0.730**	0.527**	0.620**
Truog (T_1)	0.432	0.474*	0.505**
Truog (T_2) Modified	0.540*	0.701**	0.590**
$T_2 - T_1$	0.534*	0.722**	0.596**
Acetic Acid	0.558*	0.573**	0.605**
Resin	0.708**	0.688**	0.704**
Total P	0.587**	0.146	0.297*

** = Significant at the 1% level.

* = Significant at the 5% level.

soil tests providing a false indication of the level of available phosphate on such plots.

The similarity in the order of success of the extractants in reflecting productivity and foliar phosphorus levels suggests that the nature of the current and long term supplies are similar.

(2) Bray No. 1 and Foliar P Levels

The regression line for the fertilized plots has a greater slope and smaller intercept value than the unfertilized regression line (Fig. 4.7). The fertilized regression 'shift effects' are similar to those recorded in the relationship between height and available soil phosphate levels extracted by the Bray No. 2 extractant. The more productive plots exhibit a left hand 'shift effect' whilst the less productive plots show a right hand 'shift effect'. These results suggest that the foliar P levels of the more productive plots still reflect the improvement in the phosphate status which resulted from the fertilizer application, while the soil test only reflects the current phosphate status, which, due to the plant uptake and soil fixation, is considerably lower than that immediately after the fertilizer application. On the less productive plots the soil levels have increased to a greater extent than the foliar levels, which suggests that the trees on these poorer plots have failed to utilize the applied phosphate.

The Bray No. 2 extractant is the most successful test for reflecting the foliar levels of fertilized plots. The quantity of phosphate extracted by the Bray No. 2 Test corresponding to the critical foliar level of 0.10 per cent is approximately 5 p.p.m.P for the unfertilized plots. This value is identical to the critical level obtained for the unfertilized plots in the productivity study.

The results obtained with the Bray No. 2 extractant substantiate the suggestion that foliar P levels are not determined exclusively by the current supply. However, failure of the Bray No. 2 extractant to reflect the actual availability of phosphate on the poorer plots may partially account for this.

(3) Olsen and Foliar P Levels

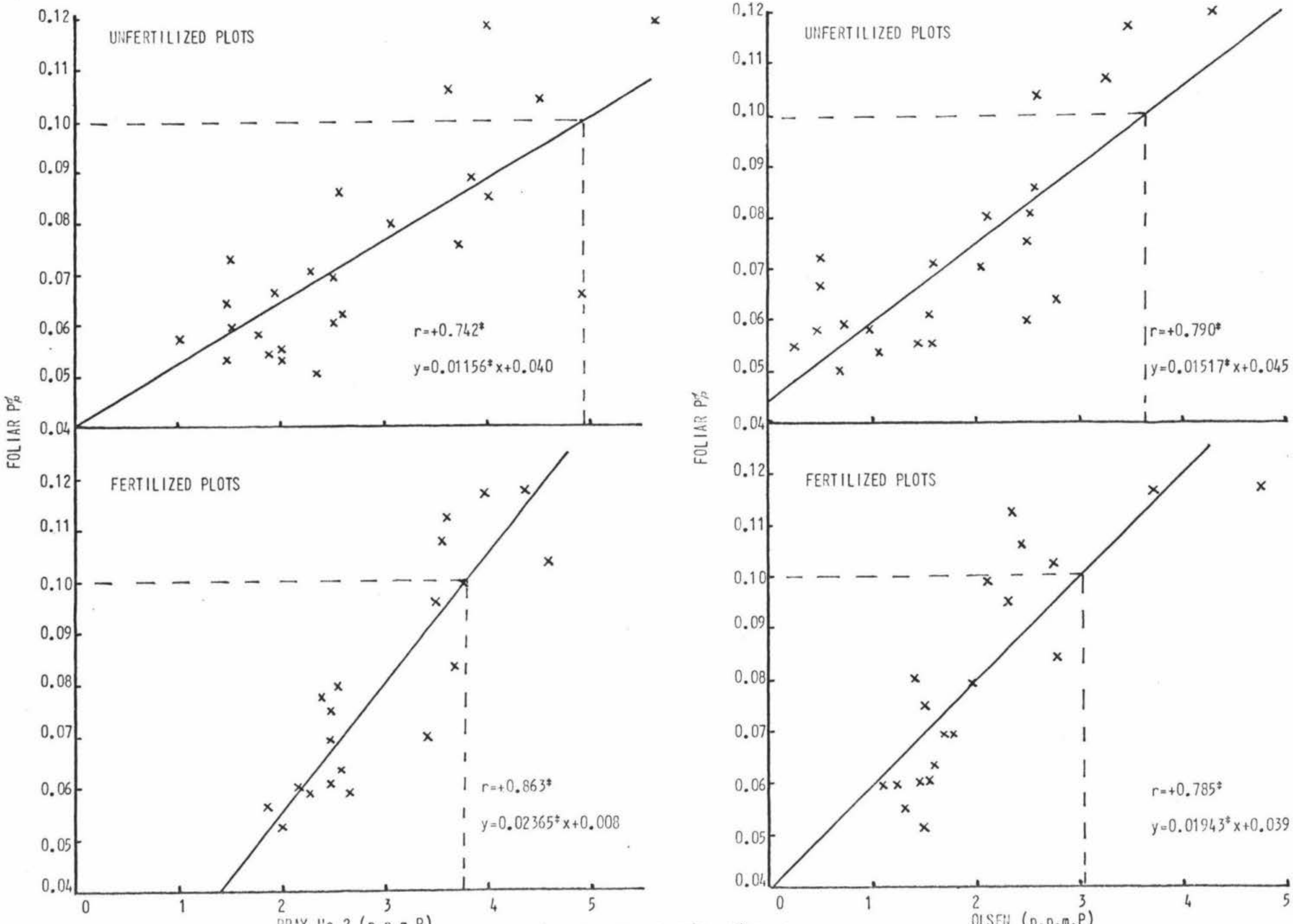
The 'shift effects' for the regression line for the fertilized plots are similar but less pronounced than those recorded with the Bray No. 2 extractant (Fig. 4.7). This can be expected as the weaker Olsen extractant will remove less of the unutilized phosphate on the less productive plots. The less pronounced 'shift effects' recorded with the Olsen extractant indicate that the Olsen extractant provides a better reflection of the phosphate supply for the combined fertilized and unfertilized plots. Thus the apparent dependence of the foliar P levels on the previous fertilizer treatment may arise more from the inability of some tests to reflect the supply for the combined plots than from the current supply not determining the foliar P levels.

The Olsen extractant is the most successful test for reflecting the foliar levels of unfertilized plots. The critical Olsen value for the unfertilized plots is identical to the value obtained in the productivity study.

(IV) Olsen Modified and Foliar P Levels

The 'shift effects' for the fertilized regression line obtained for the modified Olsen procedure are very small (Fig. 4.8). The fertilized regression line illustrates a small general right hand 'shift effect'. Thus, the inclusion of the organic fraction with the inorganic fraction extracted by the Olsen test has altered the 'shift effect' for the more productive plots from a slight left hand 'shift effect' to a slight right hand 'shift effect'. This suggests that

FIG. 4.7 RELATIONSHIPS BETWEEN FOLIAR AND SOIL PHOSPHORUS LEVELS (Bray No. 2 and Olsen extractants)



* = significant at the 1% level

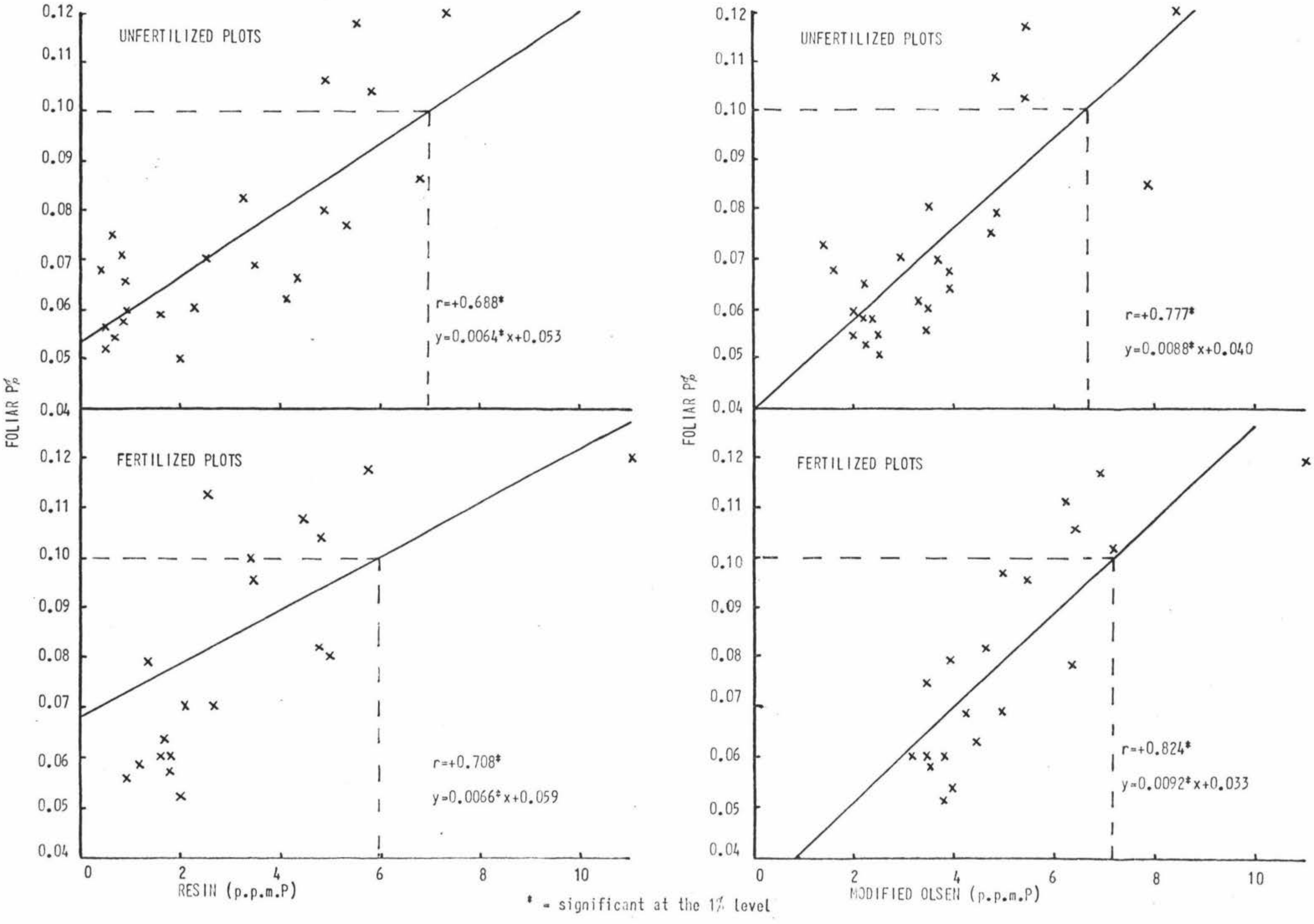
the fertilizer application has increased the amounts of organic phosphorus soluble in alkaline $NaHCO_3$ on the more productive plots, but not on the less productive plots where the 'shift effects' for the standard and modified Olsen tests are the same. In view of the earlier evidence that the more productive plots received more fertilizer than the less productive plots (Section C), it appears that the amounts of organic phosphorus soluble in alkaline $NaHCO_3$ are increased in proportion to the quantity of fertilizer applied.

The modified Olsen test is even more successful in reflecting the phosphate supply for the combined plots than is the standard Olsen test. Thus the $NaHCO_3$ soluble organic phosphorus accounts for some of the variations in supply between the fertilized and unfertilized plots not accounted for by the inorganic phosphate extracted by the standard test. However, these results cannot be taken as evidence for the current supply determining the foliar P levels. This is because the improvement resulting from the inclusion of the organic phosphorus fraction may be due to the inclusion of a factor which provides a reflection of the earlier fertilizer effect which may, due to the buffering action of the tree mass, still be reflected in the foliar P levels.

(5) "Oxidized by Bromine" and Foliar P Levels

The amounts of organic phosphorus extracted by the alkaline $NaHCO_3$ are more closely correlated with the foliar P levels of the fertilized plots than the unfertilized plots (Table 4.4). Similar results were recorded in the productivity study (Table 4.3). However, for fertilized plots, the correlation with foliar P levels is appreciably greater than the correlation with height in the productivity study, while for unfertilized plots the correlation values are almost

FIG. 4.8 THE RELATIONSHIPS BETWEEN FOLIAR AND SOIL PHOSPHORUS LEVELS (Resin and modified Olsen procedures)



identical. This may be accounted for by the foliar P levels being more responsive than height growth to the increased availability of the organic phosphorus which resulted from the fertilizer application.

(6) Resin and Foliar P Levels

The regression lines for the fertilized and unfertilized plots obtained with the anion exchange resin are almost identical (Fig. 4.8). However, the fertilized regression line does exhibit a very slight general left hand 'shift effect'. The quantities of exchangeable phosphate extracted from the fertilized plots by the anion exchange resin therefore represent a slight underestimation of the soil levels which have contributed to the foliar P levels. Despite the resin extraction providing the best reflection of the supply for the combined fertilized and unfertilized plots, the existence of a slight dependence on the fertilizer treatment suggests that the foliar P levels are not completely determined by the current soil supply.

(7) Truog (T_1) and Foliar P Levels

The Truog test provides a very poor indication of the phosphate supply (Table 4.4) as was the case in the productivity study (Table 4.3). Since it is apparent that the nature of the current and long term supplies are similar, the reasons for the failure of the Truog test may be equated with those put forward to explain its failure in the productivity study.

(8) Truog Modified (T_2) and Foliar P Levels

The correlations between the amounts of phosphate extracted by the modified Truog test and foliar P levels are almost identical to the correlations between the modified Truog values and height in the productivity study. Thus, possible interpretations of the influence of the organic fraction on the value of the Truog test will be the same as those proposed in the productivity study.

(9) $T_2 - T_1$ and Foliar P Levels

The correlations between the values obtained by difference from the two Truog procedures and foliar P levels are similar to those obtained between the $T_2 - T_1$ values and height in the productivity study. However, they are slightly higher for both fertilized and unfertilized plots in the foliar P study, suggesting that the contribution from organic phosphorus is slightly more important in determining foliar P levels than productivity. This may be accounted for by the fact that the organic phosphorus contributed to the soil supply throughout the period during which current foliar P levels were determined, whereas the organic phosphorus contributed to the supply throughout only a portion of the period during which productivity was determined, for as Will (1964) pointed out, the contribution of nutrients from the organic cycle is insignificant during the early growth years of the tree.

(10) Acetic Acid and Foliar P Levels

The acetic acid extraction provides a poor reflection of the phosphate supply (Table 4.4) as was the case in the productivity study. However, the correlations between the amounts of phosphate extracted by the acetic acid test and foliar P levels are greater than the correlations between the acetic acid values and height. The improvement is most marked on the unfertilized plots. Since the acetic acid is a weak extractant, one would expect an improvement in its predictive ability when used for reflecting a less intense supply. Thus the foliar supply appears to be slightly less dependent on an intense removal from the soil than does the long term supply.

(11) Total P and Foliar P Levels

The correlations between total P values and foliar P levels are similar to those obtained between total P values and height in the productivity study (Tables 4.3 and 4.4). The failure of the total P values to reflect the supply for the unfertilized plots can be attributed to the same factors as suggested for the failure in the productivity study (Section C(2)). For the fertilized plots the correlation between foliar P levels and total P values is smaller than that between height and total P values. As for the acetic acid extraction this indicates that the foliar supply is slightly less dependent on intense phosphate removal from the soil than is the long term supply.

(12) Conclusion

Evidence from the soil tests employed in this study suggests that the level of P in the foliage is not determined completely by the current soil supply. It appears that the resevoirs of phosphorus in the tree mass must buffer the influence of this supply on the foliar levels. However, since the relationship between foliar P levels and phosphate levels extracted by some of the soil tests are almost independent of the fertilizer treatment, the marked influence of the fertilizer treatment on the relationships obtained with other soil tests can be attributed to the failurė of these tests to reflect the nature of supply to the combined fertilized and unfertilized plots. Soil tests which descriminate against the bonding energy of the soil phosphate (e.g. Olsen's method and resin procedure) appear to be the most suitable for reflecting the availability of phosphate in the combined plots.

The nature of the current and long term phosphate supplies are similar, although there are slight differences as shown by the greater contribution of organic phosphorus to the current supply, and the fact that some tests are more successful at reflecting the short term than the long term supply and vice versa. The existence of only a slight difference between the nature of the current and long term supplies may be attributed to the age of the trees studied and the characteristics of the nutrient supply in commercial stands of radiata pines. Will (1964) reported that, after the first 10 years of growth the nutrient requirements of radiata pine were met largely through the action of the organic cycle, prior to which they were met by a nett withdrawal from the soil. Thus for 40 year old trees the nature of three-quarters of the long-term supply will have been identical with the nature of the current supply. It may be assumed that had this study been conducted on younger trees, the difference between the nature of the two supplies would have been more pronounced.

The results in this study are in accord with those of Wells (1965) who reported that soil tests which extract the 'available' phosphate from the soil provide a better reflection of the foliar levels than tests which remove the total phosphorus.

The significance of most relationships between available phosphate levels and foliar P levels suggest that the foliar P levels of radiata pine in Riverhead forest are determined by the levels of available phosphate in the soil and not the influence of some other factor on their uptake. Thus the presence of foliar P levels below the critical level may be taken as reasonable evidence that a phosphate deficiency exists.

In view of the significant relationships between both foliar and soil levels, and site productivity it may be justifiably assumed that available soil phosphate levels are controlling the productivity of radiata pine in the Riverhead forest. Thus the responses recorded to superphosphate applications in the Riverhead forest can be attributed to the phosphate component of superphosphate and not to other components such as calcium and sulphate.

Having established the presence of a phosphate deficiency it is of interest to investigate the influence of other site factors on growth in order to establish whether they influence growth directly or through their influence on available phosphate levels. This aspect of the investigation is covered in the following section.

(E) THE RELATIONSHIPS BETWEEN SITE VARIABLES AND PRODUCTIVITY (HEIGHT)

(1) Introductory

Rennie (1962) pointed out that the purpose in studying the relationships between site variables and productivity can be two-fold: it is either to establish a relationship which can be employed for the estimation of site capacity or to improve knowledge of factors controlling productivity. The use of simple correlations to study the relationships between site variables and productivity fulfils the first purpose, but not the latter, as no causal relationship can be inferred from a significant single correlation. This is because there is a possibility that the correlation may be due to the relationship of the factor under study to an underlying causal factor. More elaborate statistical techniques are required to enable distinction between variables having an indirect effect and those having a direct effect on productivity.

Riverhead forest, with its relatively small area and lack of meteorological extremes, can be considered as a homocline with meteorological factors contributing little to variation in site productivity.

For the purpose of this study, biological factors such as genetic variation, competing vegetation and disease are also taken as having little influence. Topographic and soil variables should explain the majority of the variation in site productivity of forest stands at Riverhead. Aspect, one of the topographic variables considered, has to be coded before the relationship between it and site productivity can be studied. The code utilized here is the Southern Hemisphere equivalent of that employed by Carmean (1967)for work in the Northern Hemisphere, with numbers assigned to the points of the compass in order from the coldest to the warmest faces as follows :-

6
N

8 NW NE 4

7 W E 2

SW SE
5 1

S
3

(2) <u>As Revealed By Simple Correlations</u>

Simple correlations between the site variables and productivity of both fertilized and unfertilized plots are presented in Table 4.5. Available soil phosphate levels are represented by the most successful test for the fertilized and unfertilized plots.

(a) <u>Unfertilized Plots</u>

There is a significant positive correlation between the slope and site productivity. However, the influence of slope on productivity is unlikely to be direct but rather indirect through its relationship with soil moisture and other soil features important to growth.

Aspect is significantly related to site productivity. The positive sign of the correlation suggests that the lack of moisture is not a limiting factor in the growth of radiata pine in Riverhead forest (Hills 1959). This is not unexpected in view of the temperate nature of the Riverhead climate. The relationships for both aspect and slope could be employed for the estimation of the potential capacity of land since both these variables are constant features of the tree environment.

The highly significant positive correlation between site productivity and the abundance of mycorrhizal roots is not unexpected in view of the importance of mycorrhiza in the phosphate nutrition of infected trees (Harley 1959). However, personal bias in the assessment of the mycorrhizal abundance may have contributed to the value of the correlation. This relationship is of little value for the estimation of the potential capacity of land, as assessment depends upon measurement of a component of the tree.

Site drainage classes are significantly correlated with productivity. The positive sign of the correlation suggests that poor drainage limits productivity in some manner. However, Will (pers. comm.) is of the opinion that site drainage is a function of site productivity rather than the opposite, because the application of superphosphate to poorly drained plots in the Riverhead forest led to a considerable improvement in the drainage conditions of the plots. If this is the case, drainage classes are of little value for estimating the potential site capacity of forest land. As in the case of the correlation between the abundance of mycorrhiza and site productivity, personal bias in the assessment of the site drainage class may have

TABLE 4.5

SIMPLE CORRELATIONS BETWEEN SITE VARIABLES+ AND SITE PRODUCTIVITY (HEIGHT)

\+ The values of the site variables are presented in Appendix 3A and 3B
** Significant at the 1% level.
* Significant at the 5% level.

SITE VARIABLES	ABREVIATIONS	SITE PRODUCTIVITY (HEIGHT)	
		UNFERTILIZED PLOTS	FERTILIZED PLOTS
Slope	Slope	+ 0.397*	- 0.270
Aspect	Aspec	+ 0.494*	+ 0.380
Mycorrhiza	Mycor	+ 0.647**	+ 0.250
External Drainage	Exdrn	+ 0.590**	+ 0.740**
pH	pH	- 0.600**	- 0.364
Moisture Content	Mocon	- 0.270	+ 0.103
% Clay	Clay	- 0.290	- 0.390
% Silt	Silt	+ 0.014	+ 0.504
% Fine Sand	Fsand	+ 0.210	+ 0.094
Loss on Ignition	O.M.	- 0.120	+ 0.110
Bulk Density	B.D.	+ 0.110	- 0.504*
Field Moisture	Fldmo	- 0.350	- 0.142
Bray No. 2 Phosphate	BrayP	+ 0.773**	+ 0.836**
Olsen Phosphate	OlsenP	+ 0.803**	+ 0.703**

contributed to the value of the correlation.

There is a highly significant negative correlation between pH and site productivity. Such a relationship may be due to the interrelationship of pH with soil biological, physical and chemical properties which have a direct bearing on productivity (Tamm 1964). The importance of this highly significant correlation lies in the fact that soil pH values could be employed to estimate the potential site capacity of unfertilized land in the Riverhead forest. However, it provides no information as to why productivity is lower on less acidic soils.

The correlations between 'available' soil phosphate levels and site productivity are highly significant. Evidence presented in previous sections of this chapter suggests that phosphate levels influence productivity directly. However, the value of these relationships for assessing the potential capacity of forest land is questionable as there is doubt as to whether the phosphate levels extracted by the reagents employed remain constant throughout the life span of the tree.

No other site variables considered are significantly correlated with site productivity. However, a cursory examination of the signs of the remaining correlations is of interest. The correlations of all variables related in some way to the moisture status of the sites are negative, for example, moisture content, field moisture and clay. The negative correlation of the relationship with clay may be the consequence of its influence on the phosphate absorption capacity of the soil, whereas the positive correlations of the relationships with fine sand and silt may be due to their inverse relationship with clay.

(b) Fertilized Plots

Any alteration in the correlation values between unfertilized and fertilized plots may be attributed to,

(i) the fertilized and unfertilized plots not being true subsamples of the same initial population;

(ii) different responses of the fertilized plots to the applied fertilizer. This could arise from an uneven application of the aerially applied fertilizer or differences in the availability of the applied fertilizer between plots;

(iii) the influence of the aerially applied fertilizer on the variables. If the applied fertilizer had produced an uneven alteration in a site variable between plots without producing a parallel effect on productivity, one would expect an alteration in the correlation value of that variable.

The correlation between slope and site productivity, unlike that for the unfertilized plots, is non significant and negative. This may have arisen from either more fertilizer having been applied to those plots on land of gentle relief* being more responsive to the applied fertilizer.

The correlations of both aspect and mycorrhiza illustrate a decline in value as compared with their respective correlations for unfertilized plots. The marked decline of the correlation for mycorrhiza may be attributed to the greater stimulation of mycorrhizal formation on poor plots which were previously devoid of mycorrhizal roots. The decline of the correlation for aspect suggests that aspect influences the availability of the applied phosphate.

There is a highly significant positive correlation between the site drainage class and productivity. The value of the correlation

* or from the plots on land of gentle relief

is even greater than its equivalent for the unfertilized plots. This improved relationship may have resulted from either the influence of the drainage class on the response to the aerially applied fertilizer or the influence of the response on the drainage class.

Both silt and bulk density are significantly related to the site productivity of fertilized plots, but not to that of unfertilized plots. The improved relationship for silt may be due to the relationship of silt to such factors as clay and moisture status which influence the availability of the applied fertilizer. The negative correlation between bulk density and site productivity implies that the applied phosphate is less effectively utilized on the more dense soils; this may arise from an interrelationship between bulk density and such factors as moisture status, aeration and effective rooting volume.

The correlation between pH and site productivity is negative but non-significant. The reduction in the correlation value as compared to that for the unfertilized plots may be attributed to the influence of the pH on the availability of the applied phosphate, or the influence of the applied phosphate on the pH; the former possibility is the more likely.

As in the case with unfertilized plots, the relationships between 'available' phosphate levels and site productivity are highly significant. Thus despite the application of fertilizer, the productivity of the fertilized plots is still related to the available soil phosphate levels.

All other variables are non significantly related to productivity. However, it is of interest to note that the negative correlation value of the relationship for clay has increased on the fertilized plots. This is probably the consequence of the influence the clay levels have on the retention of the applied phosphate.

The relationships derived between the site variables and productivity of fertilized plots are practically valueless for assessing the potential productivity of forest land in view of the unique circumstances of their management. However, comparison between the correlations derived for fertilized and unfertilized plots serves to illustrate the interactions between the site variables and the applied fertilizer.

(3) <u>As revealed by Partial and Multiple Correlations</u>

Single correlations provide no information on the <u>independent</u> contribution of the various variables to site productivity. Such information is obtained by inspection of the partial correlations or, better still, by testing the effect of successively eliminating each of the variables on the precision of the estimate of productivity; the precision of the estimate is provided by the multiple correlation coefficient (the correlation between the actual and estimated productivity). By use of both multiple and partial correlations after the elimination of each variable in turn from the least to the most significant, it is possible to determine not only the independent contribution of the eliminated variables to the site productivity, but also the various inter-relationships between the site variables. If the elimination of a variable produces an increase in the partial correlation coefficient of another variable then the eliminated variable and the variable manifesting an increase are inter-related. If, however, the elimination of a variable produces a decrease in the partial correlation coefficient of another variable then the variable exhibiting a decrease has a greater influence on productivity within specific levels of the eliminated variables; in other words the eliminated variable modifies the influence of the variable showing a decrease.

(a) Unfertilized Plots

The partial correlations and multiple correlation of the variables after the elimination of each variable in turn are presented in Table 4.6. The variables are eliminated in order of least significance.

The very large multiple correlation coefficient obtained when all the site variables are considered is evidence that soil and topographic factors account for the majority of the variation in site productivity of forest stands at Riverhead forest.

It is apparent from Table 4.6 that external drainage, aspect, field moisture and moisture content make no direct contribution to site productivity as the multiple correlation coefficient is unaltered by their elimination. Thus the significant single correlations of both external drainage and aspect (Table 4.5) are due to the relationship of these variables with some other variables related to productivity. An examination of the alteration induced in the partial correlations of other variables by the deletion of external drainage reveals that an increase occurs in the partial correlations of mycorrhiza, slope and moisture content. With the elimination of aspect an increase occurs in the partial correlations of pH and Olsen phosphate. Although neither field moisture nor moisture content is significantly related to productivity either directly or indirectly, the relationships of these variables to the other variables are of interest. Elimination of field moisture produces an increase in the partial correlations of slope and mycorrhiza, while the elimination of moisture content produces a marked increase in the partial correlations of pH and Olsen phosphate,

TABLE 4.6

PARTIAL CORRELATIONS BETWEEN SITE PRODUCTIVITY AND SITE VARIABLES WITH SUCCESSIVE ELIMINATION OF VARIABLES (UNFERTILIZED)

	VARIABLE ELIMINATED (in order of least significance)													
VARIABLES +	-	EXDRN	ASPEC	FLDMO	MOCON	SILT	B.D.	BRAY P	O.M.	pH	SLOPE	CLAY	FSAND	MYCOR
Exdrn	0.017	-	-	-	-	-	-	-	-	-	-	-	-	-
Aspec	0.035	0.040	-	-	-	-	-	-	-	-	-	-	-	-
Fldmo	0.045	0.045	0.044	-	-	-	-	-	-	-	-	-	-	-
Mocon	0.053	0.068	0.05	0.054	-	-	-	-	-	-	-	-	-	-
Silt	0.082	0.084	0.082	0.075	0.073	-	-	-	-	-	-	-	-	-
B.D.	0.090	0.089	0.093	0.083	0.117	0.115	-	-	-	-	-	-	-	-
Bray P.	0.136	0.139	0.136	0.132	0.120	0.154	0.126	-	-	-	-	-	-	-
O.M.	0.194	0.193	0.193	0.192	0.186	0.184	0.145	0.136	-	-	-	-	-	-
pH	0.068	0.066	0.106	0.113	0.258	0.250	0.284	0.318	0.294	-	-	-	-	-
Slope	0.332	0.365	0.373	0.407	0.406	0.420	0.407	0.415	0.511*	0.468*	-	-	-	-
Clay	0.062	0.063	0.067	0.077	0.086	0.440	0.468*	0.548*	0.614**	0.580*	0.476*	-	-	-
Fsand	0.127	0.128	0.127	0.135	0.146	0.604*	0.608**	0.645**	0.639**	0.675**	0.587**	0.450*	-	-
Mycor	0.524	0.557*	0.577*	0.647**	0.652**	0.655**	0.672**	0.670**	0.683**	0.686**	0.657**	0.570**	0.529**	-
Olsen P.	0.413	0.414	0.452	0.454	0.533*	0.558*	0.583*	0.746**	0.744**	0.818**	0.815**	0.808**	0.754**	0.810**
Multiple Correlation Coefficient	0.947	0.947	0.947	0.947	0.947	0.946	0.946	0.945	0.944	0.938	0.920	0.896	0.867	0.810

** - Significant at the 1% level

* - Significant at the 5% level

+ - Abbreviations as outlined in Table 4.5

and to a lesser extent, that of bulk density. Bulk density makes no direct contribution to site productivity and elimination of this variable produces small alterations in the partial correlations of the other variables; of interest is the modifying influence of loss on ignition on bulk density.

Elimination of the silt, Bray phosphate and loss on ignition variables has very little influence on the multiple correlation coefficient. The single correlation of Bray phosphate (Table 4.5) is highly significant but this is mainly due to its close relationship to Olsen phosphate, the partial correlation of which shows a pronounced increase upon elimination of the Bray phosphate. Clay also shows a marked increase upon elimination of Bray phosphate. The elimination of silt produces a very pronounced increase in the correlation coefficients of both clay and fine sand, while the elimination of loss on ignition produces increases in the partial correlations of clay and slope.

pH has a small direct influence on productivity as its elimination produces a small decline in the multiple correlation coefficient. However, the significance of its single correlation with productivity is partially due to its relationship with Olsen phosphate, which shows an increase upon elimination of pH. The elimination of pH also produces a decrease in the partial correlations of slope and clay; thus the influence of slope and clay on productivity are modified by the pH. PH is also related to various other variables for example moisture content and aspect. After the elimination of pH, the partial correlations of all remaining variables are significant.

Slope has a direct influence on productivity. The elimination of slope not only produces a decline in the multiple correlation coefficient but also produces a decline in the partial correlations of clay and fine sand. Thus the influences of clay and fine sand on productivity are modified by the slope. The significant single correlation between slope and site productivity is partially the consequence of its direct influence and partially the consequence of its relationship to drainage, field moisture and loss on ignition.

Clay has a direct influence on productivity. The elimination of clay not only produces a decline in the multiple correlation coefficient but also produces a decline in the partial correlations of fine sand and mycorrhiza. Thus the influences of fine sand and mycorrhiza on productivity are modified by the clay levels. The failure of the single correlation for clay to be significant can be attributed to the influence of the clay being more important within specific levels of other variables than over the whole range.

Fine sand has a direct influence on productivity as well as modifying the influence of mycorrhiza and Olsen phosphate. The failure of the single correlation for fine sand to be significant can be attributed to the same cause as that for clay.

Mycorrhiza contribute directly to site productivity as shown by the decline in the multpile correlation coefficient following the elimination of the mycorrhiza variable. The elimination of the mycorrhiza variable also produces an increase in the partial correlation of Olsen phosphate. The highly significant single correlation for mycorrhiza (Table 4.5) can be attributed partially to its direct influence on site productivity and partially to its relationship to other variables such as Olsen phosphate and field moisture.

Olsen phosphate levels make by far the largest direct contribution to productivity. It is apparent that many of the variables considered influence productivity through their direct or indirect relationship with available phosphate levels. The most important of these variables are moisture content, mycorrhiza, Bray phosphate and pH.

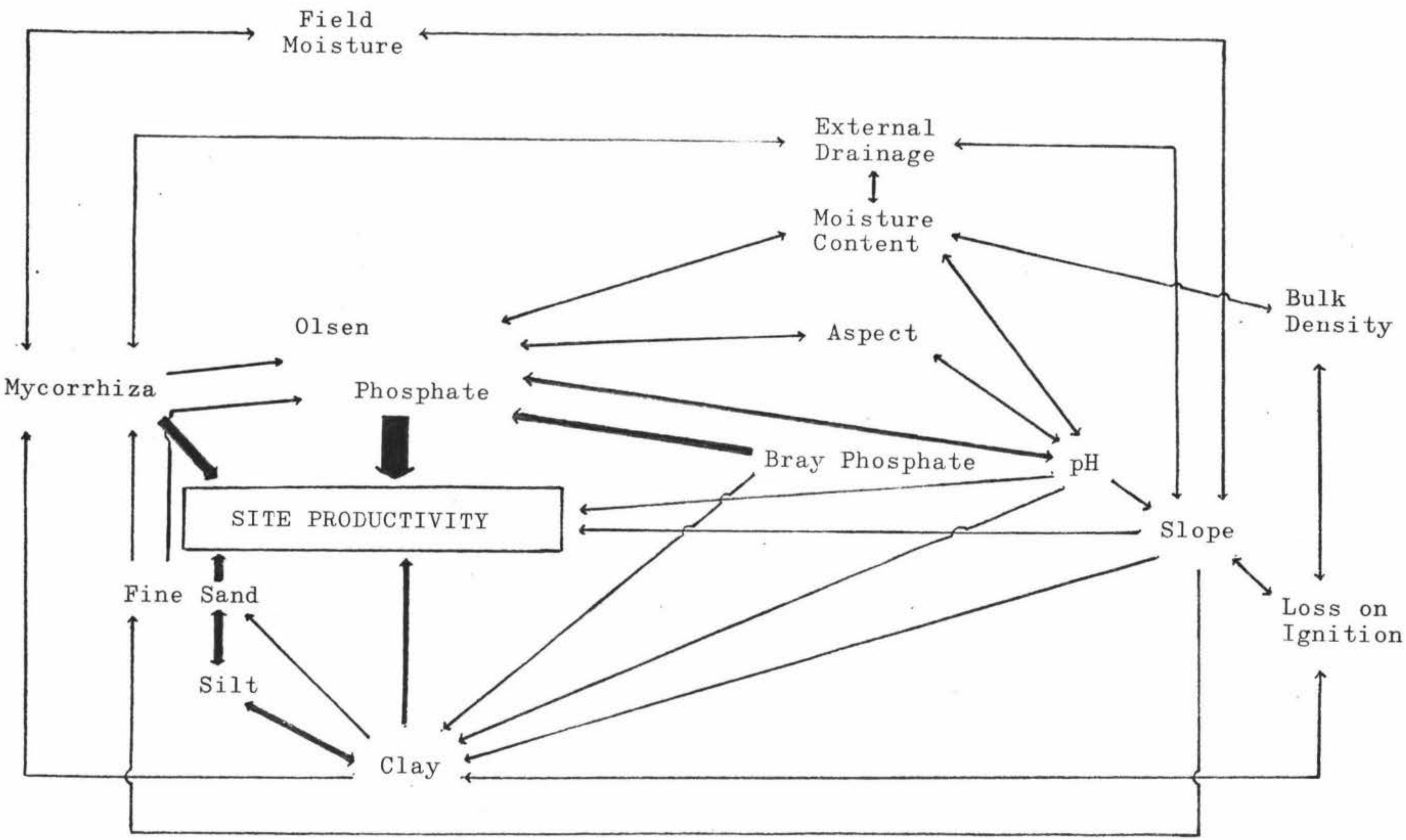
The major inter-relationships between the various site variables are summarized in Fig 4.9. Where two variables are related, no indication of the direction of the relationship is given as correlations do not involve the notion of dependence and independence, but only interdependence. However, where one variable modifies the influence of another variable and where the variables contribute directly to site productivity an indication of direction is provided. It is appreciated that variables which, according to this study, are directly related to productivity may not in fact be so, due to their possible relationship with some underlying causal factor not measured. However, in view of the independent evidence in other sections of this chapter it may be justifiably assumed that phosphate levels are directly related to productivity. The apparent direct contribution of clay to productivity may be through the influence of clay levels on the availability of other nutrients. The apparent direct influence of mycorrhiza on productivity may be due to mycorrhiza increasing the availability of other nutrients, for example potassium and nitrogen (Hatch 1937), or to the fungal component of the mycorrhiza providing the host with growth stimulators (McComb and Griffith 1946). One final point of interest arising from this study is the fact that the Olsen phosphate levels explain more of the variation in productivity when taken within specific levels of fine sand than they do when not corrected for fine sand levels. This suggests that although the Olsen test is the most suitable of those investigated, it does not completely reflect the tree-available levels of phosphate over the range of soils considered.

(b) <u>Aerially Fertilized Plots</u>

The partial correlations and multiple correlation of the

FIG. 4.9

THE INTER-RELATIONSHIPS BETWEEN SITE VARIABLES (UNFERTILIZED PLOTS)



site variables after the elimination of each variable in turn are presented in Table 4.7. The inter-relationships between the variables derived from the data in Table 4.7 are presented in Fig. 4.10. As for the unfertilized inter-relationships, the interdependence of two variables is represented by a non directional line, while a directional line is employed where one variable modifies the influence of another or makes a direct contribution to the variation in productivity.

As for the unfertilized plots, 'available' phosphate levels make by far the largest direct contribution to productivity. Other variables contributing directly to site productivity include external drainage, mycorrhiza, silt, loss on ignition and clay. 'Available' phosphate levels, clay and mycorrhiza also contributed directly to productivity on unfertilized plots. The direct contribution of external drainage to the productivity on fertilized but not unfertilized plots, suggests that following the application of fertilizer, external drainage conditions, or some underlying factor related to them but not measured, becomes limiting to productivity on certain plots, thus producing variation in productivity not accounted for by the 'available' phosphate levels. The increased direct contribution from loss on ignition following the application of fertilizer may be due to the increased rate of mineralization of organic matter contributing phosphate for tree uptake not reflected in the Bray No. 2 test. The increased direct contribution from silt may not be a real effect induced by the fertilizer application,but merely a reflection of the common properties of the silt and fine sand fraction, as these variables have in effect interchanged their positions held in Fig. 4.9.

The significant single correlation of bulk density with productivity (Table 4.5) is due to its relationship with external drainage and Bray phosphate. The failure of the single correlation

TABLE 4.7

PARTIAL CORRELATIONS BETWEEN SITE PRODUCTIVITY AND SITE VARIABLES WITH SUCCESSIVE ELIMINATION OF VARIABLES (FERTILIZED)

VARIABLES +	VARIABLE ELIMINATED (in order of least significance)													
	-	SLOPE	B.D.	FSAND	MOCON	ASPEC	OLSEN P.	FLDMO	pH	CLAY	O.M.	SILT	MYCOR	EXDRN
Slope	0.025	-	-	-	-	-	-	-	-	-	-	-	-	-
B.D.	0.038	0.031	-	-	-	-	-	-	-	-	-	-	-	-
Fsand	0.089	0.085	0.080	-	-	-	-	-	-	-	-	-	-	-
Mocon	0.102	0.133	0.136	0.136	-	-	-	-	-	-	-	-	-	-
Aspec	0.238	0.239	0.273	0.264	0.235	-	-	-	-	-	-	-	-	-
Olsen P.	0.207	0.255	0.280	0.286	0.270	0.144	-	-	-	-	-	-	-	-
Fldmo	0.102	0.112	0.186	0.174	0.256	0.240	0.202	-	-	-	-	-	-	-
pH	0.258	0.336	0.373	0.373	0.350	0.267	0.252	0.233	-	-	-	-	-	-
Clay	0.142	0.140	0.197	0.197	0.367	0.315	0.306	0.413	0.406	-	-	-	-	-
O.M.	0.461	0.464	0.461	0.461	0.502	0.549	0.559*	0.563*	0.586*	0.463	-	-	-	-
Silt	0.249	0.253	0.253	0.467	0.580	0.554	0.573*	0.626*	0.683**	0.603*	0.504	-	-	-
Mycor	0.682	0.686	0.705*	0.731*	0.725*	0.726**	0.723**	0.720**	0.701**	0.720**	0.624**	0.572*	-	-
Exdrn	0.401	0.400	0.677*	0.675*	0.771**	0.780**	0.775**	0.754**	0.790**	0.754**	0.675**	0.599**	0.413	-
Bray P.	0.526	0.594	0.640	0.674*	0.667*	0.665*	0.794**	0.813**	0.801**	0.756**	0.731**	0.771**	0.674**	0.832**
Multiple Correlation Coefficient	0.965	0.965	0.965	0.964	0.964	0.962	0.961	0.959	0.957	0.948	0.934	0.910	0.836	0.832

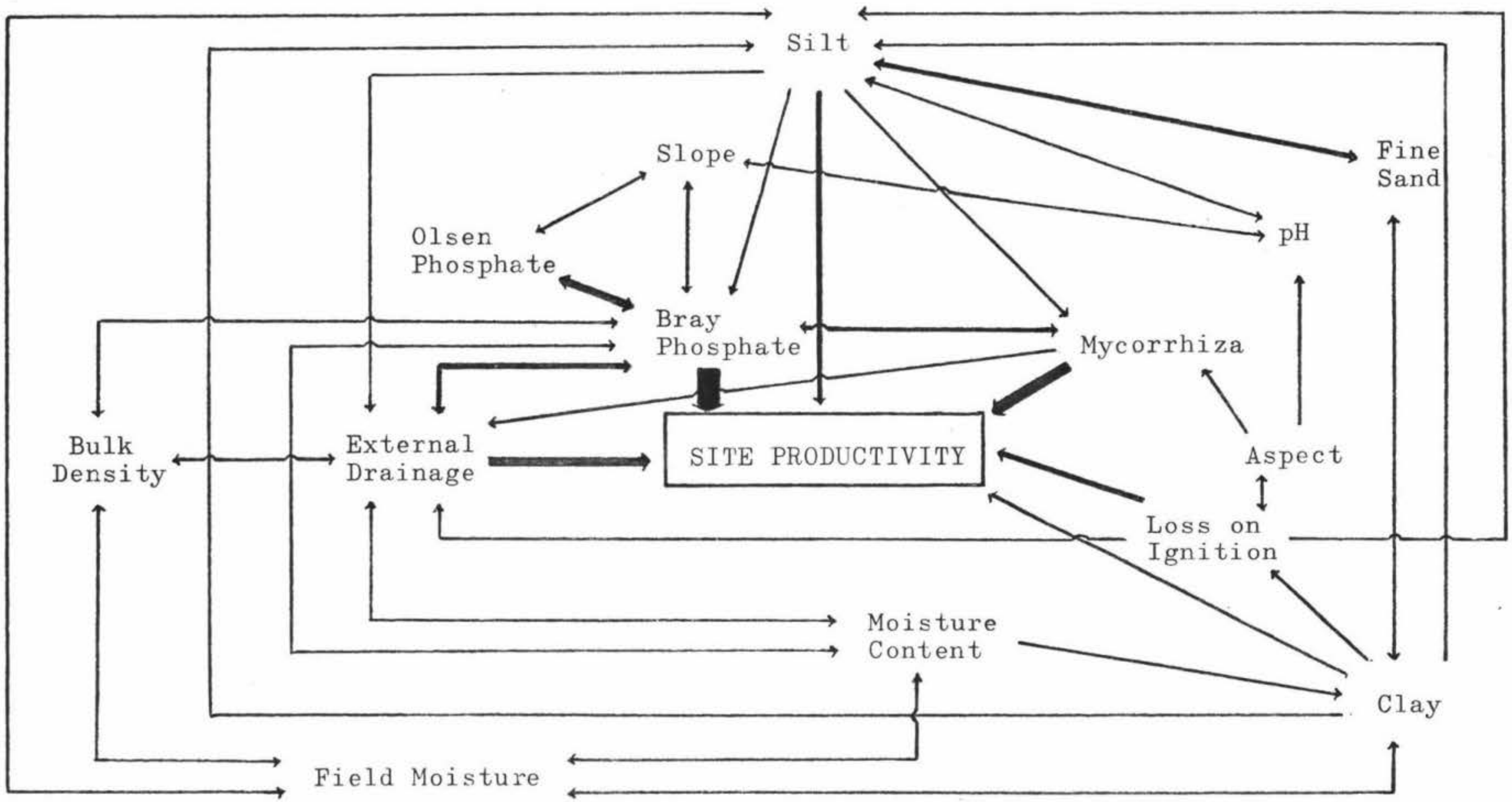
+ = Abbreviations as outlined in Table 4.5

** = Significant at the 1% level

* = Significant at the 5% level

FIG. 4.10

THE INTER-RELATIONSHIPS BETWEEN SITE VARIABLES (FERTILIZED PLOTS)



for mycorrhiza to be significant, despite its direct contribution to productivity, can be attributed to the influence of mycorrhiza being more important within specific levels of other variables than over the whole range.

Many of the variables considered influence productivity through their direct or indirect relationship to 'available' phosphate. Of particular interest, however, is the fact that Bray phosphate explains more of the variation in productivity within specific clay and mycorrhizal levels which, in view of the known influence of these two variables on the availability of phosphate (Williams, 1962; and Harley 1959), suggests that the Bray No. 2 test does not completely reflect the tree available phosphate over the range of soils considered. This is not unexpected as chemical soil tests for 'available' phosphate are empirical. Thus part of the direct contribution of both clay and mycorrhiza to productivity may be due to their reflecting differences in the availability of phosphate to the trees not reflected in the Bray No. 2 test.

(4) Conclusions

The evidence presented in this section provides further evidence of the dominant role played by available phosphate levels in the determination of tree productivity in Riverhead forest. There is some evidence that the role of available phosphate is even more important than suggested by the relationships between site productivity and the levels of 'available' soil phosphate extracted by the empirical soil tests.

The apparent relationships between site productivity and other soil variables, as manifested by significant simple correlations, are largely the consequence of the direct or indirect relationship of these variables to the 'available' phosphate levels.

Some of these relationships between site productivity and constant site features, such as slope, aspect and pH, could be employed for the assessment of the potential capacity of forest land, but they are limited as management aids in that they provide no indication of corrective measures that could be undertaken after the detection of poor sites.

There is some evidence to indicate that, following the application of phosphatic fertilizer, some other factor or factors become limiting to productivity on some of the plots. This is in accord with the earlier tentative finding that the utilization, by the forest trees, of the aerially applied phosphate on the poorer plots is restricted. This may be the consequence either of trees on these plots being too unthrifty to utilize the applied phosphate or some other factor being equally as limiting as phosphate. The possibility of multiple nutrient deficiencies on some of these depleted soils warrants investigating, for if such is the case the response to phosphatic fertilizers will be limited despite the low soil phosphate levels.

(F) THE FATE OF LABORATORY APPLIED PHOSPHATE

The amounts of NaCl soluble, organic, Ca-bound, Al-bound and Fe-bound phosphates prior to, and at intervals following the addition of phosphate are presented in Table 4.8. The increase in extractable inorganic phosphate resulting from the phosphate addition is also shown. The results are expressed as mg.P per 100 gm of air dry soil, as the phosphate solution was applied to equal weights of air dry soil.

From the results in Table 4.8 it is evident that the quantity of phosphate applied to these soils (50 m.g. P% as KH_2PO_4) is almost completely recovered in the inorganic fractions extracted by the reagents used. The slight discrepancies between the additional inorganic quantities extracted and the quantities added may be attributed to adherence of a small proportion the added phosphate to the clock-glass on which the mixing of the soil and phosphate solution was carried out (Turner 1965). However, in the case of soil WE, the increased inorganic phosphate is greater than the quantity applied, with the discrepancy becoming more pronounced on the samples which were stored for longer periods. This discrepancy can only be accounted for by the fall in the organic phosphorus levels throughout the storage period. In all the other soils which had lower initial organic phosphorus levels, there is no such trend in the organic phosphorus levels. The complete recovery of the applied phosphate in the extractable inorganic forms indicates that during the 12 month storage period there was no conversion of added phosphate to forms non-extractable with respect to the reagents used; this is in agreement with the findings of Volk and McLean (1963), but contrary to the suggestion of Fiskell and Spencer (1964) that the addition of phosphate to the

TABLE 4.8

THE AMOUNTS OF VARIOUS FORMS OF PHOSPHORUS IN FIVE SOIL TYPES PRIOR TO, AND AT INTERVALS FOLLOWING THE LABORATORY ADDITION OF PHOSPHATE

SOIL TYPE (Symbol)	TIME INTERVAL FROM COMMENCEMENT OF EXPERIMENT	FORMS OF PHOSPHORUS					INCREASED INORGANIC PHOSPHATE (Ca + Al + Fe + NaCl) mgP%
		CALCIUM PHOSPHATE mgP%	ALUMINIUM PHOSPHATE mgP%	IRON PHOSPHATE mgP%	ORGANIC PHOSPHORUS mgP%	NaCl SOLUBLE PHOSPHATE mgP%	
HS	Before Addition	0.6	1.5	Tr.	9.5	A	-
	3 Mths	Tr.	48.0	Tr.	11.4	1.5	47.2
	6 Mths	Tr.	46.0	1.4	11.7	1.4	46.5
	9 Mths	Tr.	47.2	1.5	11.7	1.3	47.7
	12 Mths	Tr.	49.0	0.6	6.4	1.2	48.5
YK	Before Addition	Tr.	4.0	Tr.	11.7	A	-
	3 Mths	Tr.	50.5	0.7	14.1	A	46.6
	6 Mths	Tr.	50.0	1.2	14.1	A	46.6
	9 Mths	Tr.	49.7	1.0	14.3	A	46.1
	12 Mths	Tr.	49.4	1.0	12.4	A	45.8
PA	Before Addition	0.9	1.8	1.0	2.7	A	-
	3 Mths	Tr.	40.0	8.8	2.6	0.5	45.6
	6 Mths	Tr.	38.2	10.9	1.7	Tr.	45.8
	9 Mths	Tr.	37.9	10.4	2.1	Tr.	45.0
	12 Mths	Tr.	37.0	11.1	3.0	Tr.	44.8

Cont:-

TABLE 4.8 cont'd:-

SOIL TYPE (Symbol)	TIME INTERVAL FROM COMMENCEMENT OF EXPERIMENT	FORMS OF PHOSPHORUS					INCREASED INORGANIC PHOSPHATE (Ca + Al + Fe + NaCl) mgP%
		CALCIUM PHOSPHATE mgP%	ALUMINIUM PHOSPHATE mgP%	IRON PHOSPHATE mg%	ORGANIC PHOSPHORUS mgP%	NaCl SOLUBLE PHOSPHATE mgP%	
WA	Before Addition	Tr.	1.7	0.7	7.9	A	-
	3 Mths	Tr.	47.8	2.3	18.0	1.2	48.5
	6 Mths	Tr.	47.5	2.0	9.5	1.0	47.7
	9 Mths	Tr.	47.8	2.0	10.4	1.0	48.0
	12 Mths	Tr.	48.0	2.2	9.5	1.0	48.4
WE	Before Addition	Tr.	3.4	0.5	16.2	A	-
	3 Mths	Tr.	50.8	3.2	11.7	0.7	50.7
	6 Mths	Tr.	51.8	3.1	10.2	0.6	51.5
	9 Mths	Tr.	51.8	3.9	9.1	0.6	52.3
	12 Mths	Tr.	51.3	4.3	8.6	0.6	52.2

A = Undetectable

Tr.= $<$ 0.5 mgP%

soil results in the formation of occluded phosphate.

It is evident from Table 4.8 that the majority of the applied phosphate is extracted by $0.5MNH_4F$ at pH 8.5. In all the soils except soil PA, this increase in the aluminium phosphate fraction following the addition of phosphate is largely independent of the length of the storage period. In soil PA there is a noticeable decline in the aluminium phosphate fraction with time, associated with which there is an increase in the iron phosphate fraction. In comparison with the increases in the aluminium phosphate fraction, the increases in the iron phosphate fraction, following the addition of phosphate, are very small. The most pronounced increase occurs in soil PA. Only in soils PA and WE is there any tendency for the iron phosphate fraction change with time; both these soils show an increase in this fraction. In soil PA, but not WE, this increase is accompanied by a parallel decrease in the aluminium phosphate fraction. However, in soil WE there may be a transfer of phosphate from the aluminium to the iron fraction which is masked by the contribution of the mineralized organic phosphorus to the aluminium phosphate fraction. The results for these two soils are in accord with those of Chang and Chu (1961) who reported that the aluminium phosphate fraction tended to decrease with the passage of time with a consequential increase in the iron phosphate fraction.

The fraction extracted by 0.5 MNaCl illustrates a decline with time for all soils in which detectable quantities occur. Assuming the amounts of this very soluble phosphate fraction inversely reflect the phosphate absorption capacity, then the soils in order of decreasing phosphate absorption capacity can be presented as follows :-

YK ⟩ PA ⟩ WE ⟩ WA ⟩ HS

Laverty and McLean (1961) reported that the kind of phosphate formed in the soil upon addition of phosphate is linked with the phosphate absorption capacity of the soil. In soils with a low absorption capacity aluminium phosphate is the chief form, but when the absorption capacity of the soil is high, iron phosphate predominates. Although the results from this study indicate that aluminium phosphate is the most important fraction in all the soils studied, there is a tendency for the iron phosphate to become more important as the absorption capacity of the soil increases; the exceptional behaviour of soil YK in this respect is however difficult to explain. The results obtained in this study are in accord with those of Bromfield (1964) who, by selectively removing iron from the soil with a biological reduction technique, found that the phosphate sorption capacity of the soil was dominated by aluminium, with iron making only a small contribution. However, the present results cannot be directly compared with those of many workers who have employed phosphate fractionation as a means of following the fate of applied phosphate due to differences in the fractionation procedure employed, particularly in the partitioning of the aluminium and iron phosphates.

(G) THE FATE OF FIELD APPLIED PHOSPHATE

(1) As Revealed by Fractionation

Phosphate fractionation was employed to follow the fate of applied phosphate only in the two most extensive and important soil types in the forest (HS and YK). The amounts of total, organic, NaCl-soluble, Ca-bound, Al-bound and Fe-bound phosphates prior to, and at intervals following the application of three phosphatic fertilizers are presented in Tables 4.9 and 4.10. The increase in extractable inorganic phosphate resulting from fertilizer application is also shown. The results are expressed on a weight per unit volume basis, as equivalent weights of the fertilizers were applied to equal volumes of soil: a fertilizer dressing equivalent to 10 cwt of superphosphate per 4 in. acre will theoretically raise the phosphorus content of the soil by 11.0 mg.P/100cc.

A cursory examination of the results in Tables 4.9 and 4.10 indicates that the type of fertilizer, rather than the soil type, is dominant in determining the forms in which the fertilizer occurs in the soil after application. In general it can be stated that the superphosphate and Christmas Island 'C' grade rock phosphate occur predominantly as aluminium-bound phosphates, while the Nauru rock phosphate occurs mainly as calcium-bound phosphate.

(a) Superphosphate

The application of superphosphate to both HS and YK results in an increase in the aluminium and calcium phosphate fractions after 3 months and a very small increase in the iron phosphate fractions. The increase in the calcium phosphate fraction can be attributed to the presence of the residual unreacted apatite component of the superphosphate (Saunders 1959). In the more acid HS soil (Table 4.11) the levels of this residual calcium phosphate fall off with time, accompanied by an increase in the aluminium phosphate fraction. The iron phosphate fraction also falls off with time, but the levels are so small that the changes may be fortuitous. In the less acidic YK soil, the level of the calcium phosphate fraction remains fairly constant for the first 9 months, but a decline is shown at the 12 month sampling date. The aluminium phosphate fraction shows a general decline with time, which may account for the slight increase in the iron phosphate fraction throughout the same period. Throughout the trial period, not only is there a slight tendency for the phosphate to redistribute itself among the various forms, but the increased levels of extractable inorganic phosphate, resulting from the superphosphate application exhibit a general decline. This decline may be ascribed to any one, or combination of the following factors :-

(i) Sampling errors

Sampling errors may have been suspected had the levels of additional inorganic phosphate extracted been random, but since a definite decline occurs, sampling errors do not appear to explain this trend.

(ii) The formation of occluded phosphate

This explanation appears unlikely as the decline in the increased levels of extractable inorganic phosphate is accompanied by a parallel decline in the total phosphorus levels. This parallel between increased levels of extractable inorganic phosphate and total phosphorus holds true for all fertilizers on both soil types.

(iii) Downward movement of phosphate below the 4" sampling depth

In view of the high phosphate absorption capacity of YK

TABLE 4.9

THE AMOUNTS OF VARIOUS FORMS OF PHOSPHORUS IN THE WAIKARE CLAY LOAM (YK) PRIOR TO, AND AT INTERVALS FOLLOWING THE ADDITION OF THREE PHOSPHATIC FERTILIZERS

FERTILIZER	TIME INTERVAL FROM COMMENCEMENT OF EXPERIMENT	FORMS OF PHOSPHORUS						INCREASED INORGANIC PHOSPHATE (Ca + Al + Fe + NaCl PHOSPHATE) mgP/100cc
		CALCIUM PHOSPHATE mgP/100cc	ALUMINIUM PHOSPHATE mgP/100cc	IRON PHOSPHATE mgP/100cc	NaCl SOLUBLE PHOSPHATE mgP/100cc	ORGANIC PHOSPHORUS mgP/100cc	TOTAL PHOSPHORUS mgP/100cc	
Superphosphate	Before Addition	Tr.	2.2	Tr.	A	6.4	13.7	-
	3 Mths	3.1	8.7	0.5	A	7.4	24.9	9.7
	6 Mths	2.8	7.2	0.6	A	7.3	22.5	8.0
	9 Mths	3.2	6.4	0.8	A	7.9	23.3	7.8
	12 Mths	1.7	5.1	1.0	A	7.3	19.4	5.2
Nauru Rock Phosphate	Before Addition	Tr.	2.3	Tr.	A	5.4	13.4	-
	3 Mths	9.7	2.7	Tr.	A	4.1	22.6	10.0
	6 Mths	9.9	2.6	0.6	A	4.4	23.3	10.3
	9 Mths	10.2	2.3	0.8	A	3.6	22.6	10.5
	12 Mths	10.0	2.3	0.7	A	3.4	21.7	10.2
Christmas Island 'C' Grade Rock Phosphate	Before Addition	Tr.	2.2	Tr.	A	6.1	12.7	-
	3 Mths	1.5	10.0	1.1	A	6.0	22.9	9.9
	6 Mths	2.4	9.8	0.9	A	6.0	23.8	10.4
	9 Mths	1.6	10.4	1.0	A	5.3	24.2	10.3
	12 Mths	1.4	9.1	1.0	A	3.5	19.2	8.8

TABLE 4.10

THE AMOUNTS OF VARIOUS FORMS OF PHOSPHORUS IN THE HUKERENUI SANDY LOAM (HS) PRIOR TO, AND AT INTERVALS FOLLOWING THE ADDITION OF THREE PHOSPHATIC FERTILIZERS

FERTILIZER	TIME INTERVAL FROM COMMENCEMENT OF EXPERIMENT	FORMS OF PHOSPHORUS						INCREASED INORGANIC PHOSPHATE (Ca + Al + Fe + NaCl PHOSPHATE) mgP/100cc
		CALCIUM PHOSPHATE mgP/100cc	ALUMINIUM PHOSPHATE mgP/100cc	IRON PHOSPHATE mgP/100cc	NaCl SOLUBLE PHOSPHATE mgP/100cc	ORGANIC PHOSPHORUS mgP/100cc	TOTAL PHOSPHORUS mgP/100cc	
Superphosphate	Before Addition	Tr.	1.0	Tr.	A	5.0	10.5	-
	3 Mths	3.8	6.2	0.7	0.8	6.3	21.2	10.0
	6 Mths	2.5	7.6	0.5	0.6	5.9	20.5	9.7
	9 Mths	0.7	8.4	Tr.	0.5	5.9	19.0	8.2
	12 Mths	0.7	6.5	Tr.	0.5	5.9	17.4	6.3
Nauru Rock Phosphate	Before Addition	Tr.	1.5	Tr.	A	4.8	11.4	-
	3 Mths	9.2	2.2	Tr.	A	3.6	20.0	10.0
	6 Mths	6.9	2.4	Tr.	A	5.1	19.3	7.9
	9 Mths	6.0	2.3	Tr.	A	4.4	18.6	6.9
	12 Mths	5.7	2.3	Tr.	A	5.1	18.8	6.5
Christmas Island 'C' Grade Rock Phosphate	Before Addition	Tr.	1.0	Tr.	A	3.7	9.0	-
	3 Mths	1.4	8.4	0.7	A	4.5	19.3	9.1
	6 Mths	1.4	8.5	0.6	A	3.6	18.7	9.1
	9 Mths	1.1	14.5	Tr.	A	4.8	26.0	14.5
	12 Mths	1.1	5.5	Tr.	A	4.9	15.2	5.5

Tr = < 0.5 mgP/100cc

A = Undetectable

TABLE 4.11

PH VALUES OF THE FERTILIZER PLOTS ON
THE FIVE SOIL TYPES PRIOR TO THE APPLICATION OF FERTILIZER

SOIL TYPE	SUBSEQUENT PLOT TREATMENT	PH
HS	Superphosphate	4.1
	Nauru	4.3
	Christmas	4.3
YK	Superphosphate	5.4
	Nauru	5.4
	Christmas	5.3
PA	Superphosphate	4.7
	Nauru	4.6
	Christmas	4.6
WE	Superphosphate	4.6
	Nauru	4.5
	Christmas	4.8
WA	Superphosphate	4.6
	Nauru	4.5
	Christmas	4.4

and reports on the very limited downward movement of applied superphosphate even on podzols with low phosphate absorption capacities (McLean 1965), this explanation appears unlikely.

(iv) Plant Uptake

This appears to be the most likely explanation for the observed decline as radiata pine rooting activity is intense in the surface horizons of both soils. It is interesting to note that if plant uptake accounts for the observed decline, then plant absorption on both soils has accounted for approximately half the applied superphosphate during the 12 month period following application. The majority of plant absorbed phosphate appears to have been derived from the calcium and aluminium phosphate fractions.

The presence of a small NaCl-soluble phosphate fraction in soil HS following the application of superphosphate is an indication of the low phosphate absorption capacity of this podzolized soil.

(b) <u>Nauru Rock Phosphate</u>

After 3 months the application of Nauru rock phosphate to both soils results in an increase in the calcium phosphate fractions, with little change occuring in the other fractions except a very slight increase in the aluminium-bound phosphate. The increase in calcium phosphate levels can be attributed to the presence of unreacted apatite phosphate, the major component of Nauru rock phosphate. In the very acid HS soil the calcium phosphate fraction declines with time. During this period there is no alteration in the levels of other phosphate fractions but a parallel decline occurs in the increased level of inorganic phosphate resulting from the fertilizer application. These results suggest that the calcium phosphate fraction is the immediate source utilized by the trees. In the less acidic YK soil, the calcium phosphate fraction and the increased inorganic phosphate levels remained almost constant throughout the 12 month period investigated. It appears therefore that the availability of the calcium phosphate fraction is related to the degree of soil acidity. Whether this is a direct effect of acidity is uncertain. Purnell (1958) reported that pines can utilize apatite through the action of the fungal component of the mycorrhizal roots. As mycorrhizae are almost non-existent in the YK soil, but abundant in the HS soil, the greater availability ofthe apatite phosphate in the latter soil may simply reflect the greater mycorrhizal activity in this soil.

Assuming any decline in the fertilizer-supplemented inorganic phosphate levels to be the consequence of plant uptake, it is interesting to note that over the period considered, Nauru, as a source of plant phosphate, is as effective as superphosphate on the acid HS soil but not on the less acidic YK soil.

(c) Christmas Island 'C' grade Rock Phosphate

In considering the trends involved in the reaction between the soils and Christmas Island 'C' grade rock phosphate, the 9 month sample taken from the HS soil will be ignored as this sample was inadvertently contaminated with phosphate as evidenced by the increased phosphate levels being considerably greater than the levels applied (11 mgP/100cc). The application of Christmas Island 'C' Grade rock phosphate to both soils results in a large increase in the aluminium phosphate fraction after 3 months, with only small increases in the calcium and iron phosphate fractions. It is difficult to distinguish whether the aluminium phosphate levels extracted are the consequence of the reaction between the fertilizer and the soil or whether they are those of the unreacted fertilizer, the major component of which is aluminium phosphate. However, the fertilizer pellets were still visible on the two soils up to the 9 month sampling date, which suggests that the recorded increased amounts in the inorganic phosphate fractions are derived from the unreacted fertilizer. In both the HS and YK soils the only marked alteration in the inorganic phosphate levels occurs at the 12 month sampling date, where a decline in the supplemented inorganic phosphate levels, largely accounted for by a decline in the aluminium phosphate fraction, occurs. This decline is most pronounced on the very acid HS soil where it is of similar magnitude to those recorded for superphosphate and Nauru rock phosphate. On the less acidic YK soil, Christmas Island rock phosphate is apparently more available for plant uptake than is Nauru rock phosphate.

(d) Conclusion

The results are similar to those obtained in the laboratory study in that, when the fertilizer reacts with the soil, the major product is aluminium phosphate. The presence of other forms of phosphate following the application of fertilizers in the field appears to be due to the presence of residual unreacted components of the applied fertilizer. As in the laboratory study, there is little evidence of a major redistribution of phosphate between the various forms during the 12 months period investigated, although the true magnitude of the redistribution, particularly between the aluminium and calcium fractions may have been masked by plant uptake. Plant uptake appears to take place preferably from the calcium phosphate fraction provided the soil conditions are conducive to the dissolution of the insoluble apatite, otherwise uptake appears to occur from the aluminium phosphate fraction. On the very acid HS soil, the less soluble rock phosphates appear to be utilized by radiata pine as effectively as the more soluble superphosphate.

This is in accord with the work of Gentle and Humphreys (1968) who found Nauru rock phosphate and crandallite (Christmas Island 'C' grade rock phosphate) to be equally effective as sources of phosphate for this species. Paauw (1965) also reported that rock phosphates were as effective as superphosphate on very acid agricultural soils, but pointed out that acid conditions most conducive to the dissolution of these insoluble fertilizers are unfavourable for growth of most species. However, for radiata pine this consideration is unlikely to be of importance as optimum pH values for its growth are well below those for most agricultural crops, (Scott 1960). On the less acidic YK soil the insoluble rock phosphates are less effective sources of plant phosphate than superphosphate over the 12 month period investigated. Of the two rock phosphates, the Christmas Island 'C' grade appears to be the most effective on the less acidic YK soil.

(2) As Revealed by The Bray No.2 'Available Phosphate' Test

(a) Introductory

Phosphate fractionation procedures are not designed to measure the availability of phosphate because they do not take into account the nature or the strength of bonding within the identified categories. In section C of this chapter, the Bray No. 2 test was found to be the most suitable for reflecting the levels of 'tree-available' phosphate on fertilized soils. However, it must be stressed that the suitability of this test was established on soils which had been fertilized with superphosphate 8 years before the tests were conducted and not immediately following the application of fertilizer.

The levels of 'available' phosphate extracted by the Bray No. 2 reagent from the five soil types prior to, and at intervals following the application of 3 phosphatic fertilizers, are presented in graphical form in Fig. 4.11.

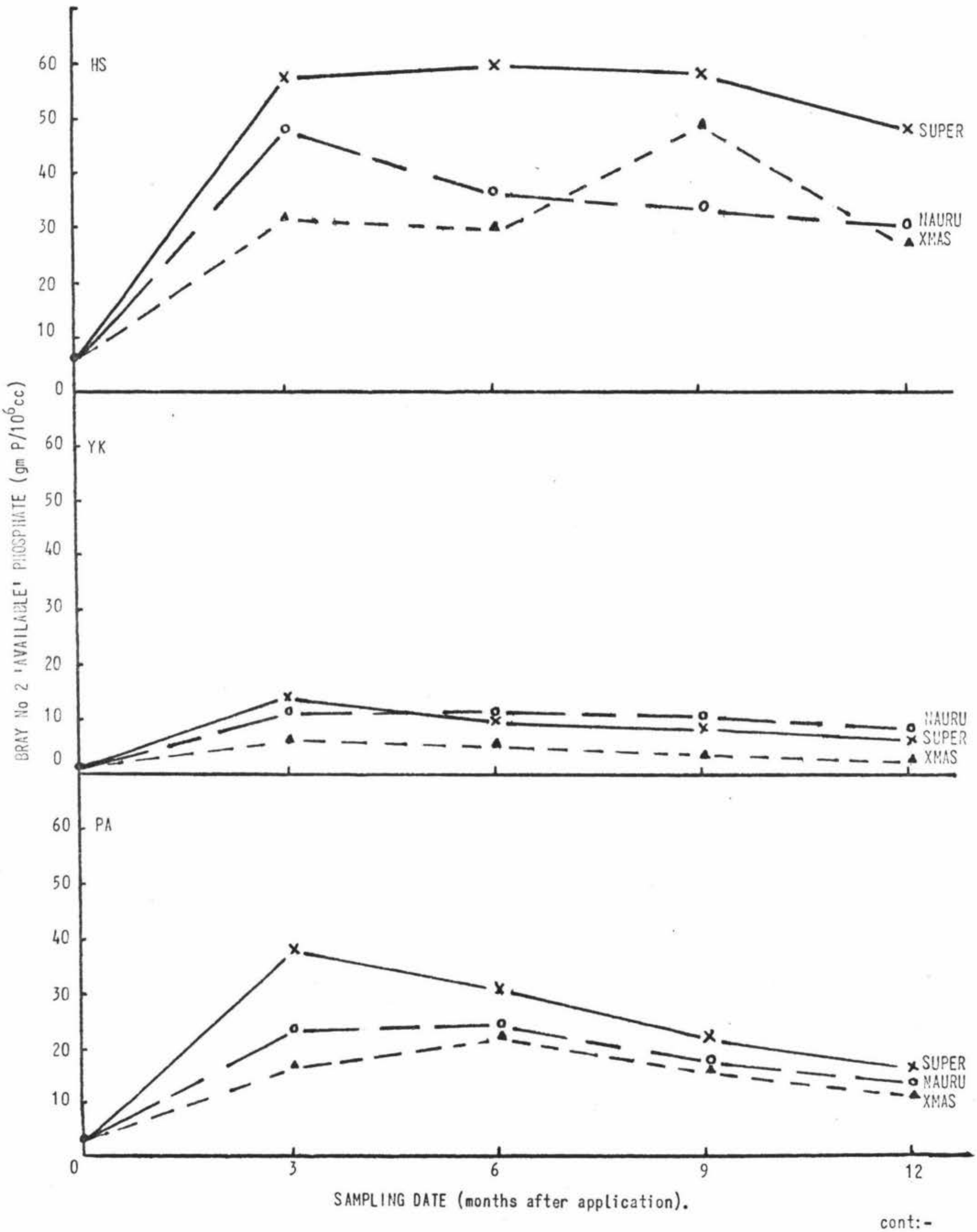
(b) Soil Type HS

Superphosphate is shown to be more 'available' than both Nauru and the calcined Christmas rock phosphates throughout the 12 month period. Nauru rock phosphate is more 'available' than the Christmas rock phosphate although the difference becomes less pronounced at the later sampling dates (the contaminated 9 month sample is not considered.). It is interesting to note that in the 3 month samples the ratio of the quantities extracted from the Nauru and Christmas plots is 5:3 whereas the ratio of the quantities extracted from the pure fertilizers was found to be 3:1. Thus it is apparent that the acid HS soil (Table 4:11) has a greater solubilizing action on the Christmas rock phosphate than on the Nauru rock phosphate.

Over time, the levels of 'available' phosphate in the superphosphate plot are approximately constant except for a decline recorded in the 12 month sample. The levels in both the Nauru and Christmas plots manifest a general decline throughout the experimental period although the decline is more pronounced in the Nauru plot. A decline in available phosphate levels may result from plant uptake and/or a decline in the extractability of the phosphate resulting from an increase in the strength of phosphate bonding. The declines recorded appear to be the consequence of plant uptake, for when the levels of 'available' phosphate are corrected for plant uptake by expressing the increased levels of available phosphate as a percentage of the increased inorganic phosphate levels obtained in the fractionation study, none of the results show a general decline with time (Fig. 4.12). The results for the Nauru plot are almost constant as are those from the Christmas plot except for an increase in the 12 month sample. The superphosphate results illustrate a general increase. This increase is difficult to explain unless the residual

FIG. 4.11

LEVELS OF AVAILABLE PHOSPHATE IN THE 5 SOIL TYPES PRIOR TO, AND AT INTERVALS FOLLOWING THE ADDITION OF 3 PHOSPHATIC FERTILIZERS



cont:-

FIG. 4.11 cont'd:

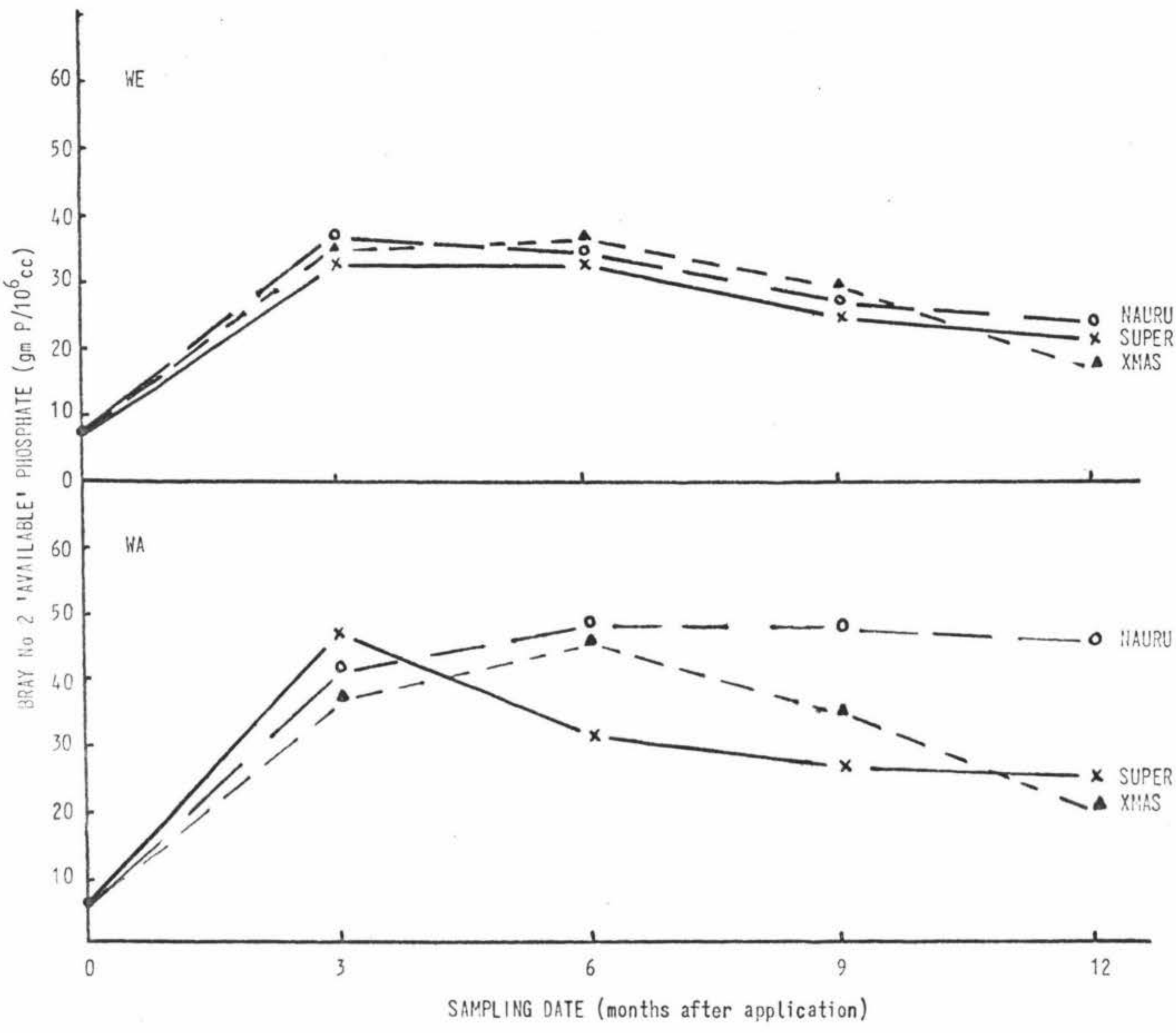
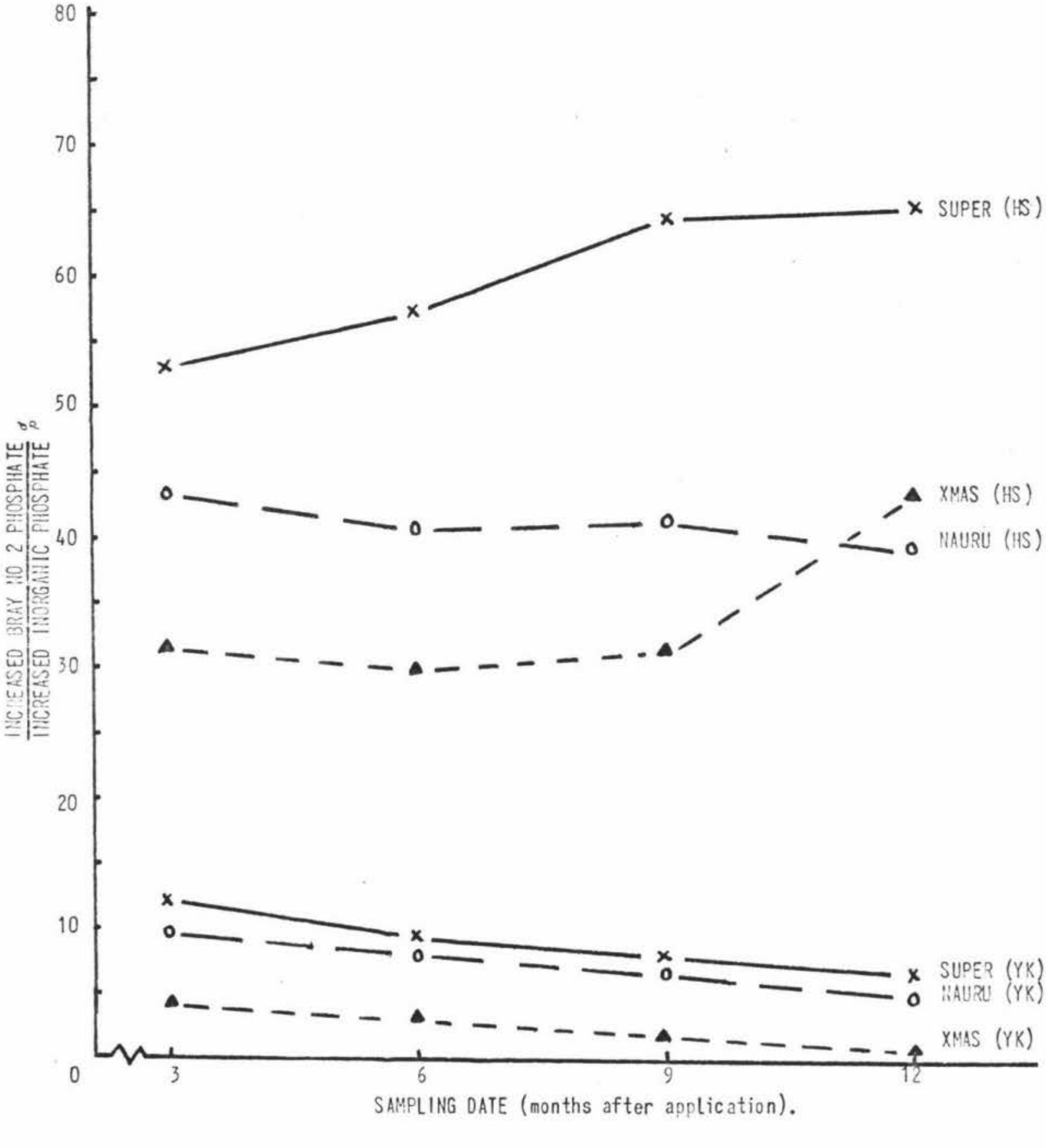


FIG. 4.12

THE PERCENTAGE OF THE INCREASED INORGANIC PHOSPHATE EXTRACTABLE WITH THE BRAY NO 2 REAGENT AT INTERVALS FOLLOWING FERTILIZER ADDITION



unreacted apatite is solubilized at a greater rate than it can be utilized by the trees as suggested by the results from the fractionation study (Table 4.10). In the Nauru plot the unreacted apatite appears to be solubilized at the same rate as plant utilization as does the solubilization of the unreacted Christmas fertilizer up to the 12 month sampling where solubilization appears to have occurred at a greater rate than plant utilization. The failure of the results from the plot which received soluble phosphate in the form of superphosphate to exhibit a decline with time is indicative of the low absorption capacity of the podzolized HS soil.

(c) Soil Type YK

At the 3 month sampling date, superphosphate is slightly more 'available' than either of the rock phosphates although the actual levels extracted from the various fertilizer plots are well below those extracted from their counterparts on soil HS. The lower levels recorded for the superphosphate plot can be attributed to the applied soluble phosphate becoming more firmly bound to the soil absorption complex than in soil HS This more intense bonding is further illustrated by a comparison between the 'availability' of the extractable inorganic phosphate levels in the unfertilized soils. In soil HS the ratio of 'available phosphate to extractable inorganic phosphate is 1:2, whereas in soil YK the ratio is 1:22. The lower levels in the Nauru and Christmas plots can be attributed to the failure of the less acidic YK soil (Table 4.11) to solubilize the rock phosphate fertilizers. Resorption during extraction of the unreacted fertilizer dissolved in the Bray No. 2 extractant may also contribute to the poorer extraction from YK.

With time, the 'available' phosphate levels extracted from the Nauru and Christmas plots show a very slight, parallel decline. The levels extracted from the superphosphate plot manifest a slightly more pronounced decline. When corrected for plant uptake (Fig.4.12) all plots still illustrate a slight decline although that of the superphosphate plot is now of similar magnitude to those of the rock phosphate plots. The decline recorded for the superphosphate plot may be accounted for by the transference of phosphate from the more soluble aluminium phosphate fraction to the less soluble iron phosphate fraction (Table 4.9). However, the declines recorded for the rock phosphate plots cannot be reconciled with the results obtained in the fractionation study, which suggested there had been little or no reaction between the applied fertilizers and soil throughout the 12 month period. It is possible, however, that there may have been a transference from the more soluble fertilizer aluminium phosphate fraction to the less soluble soil aluminium phosphate fraction in the Christmas plot, as the fractionation procedure does not enable a distinction between the two.

(d) Soil Type PA

The levels of 'available' phosphate extracted from the fertilizer plots on soil PA are intermediate between those extracted from soils HS and YK. This is in accord with the magnitude of their respective phosphate absorption capacities. Superphosphate is more 'available' than both Nauru and Christmas rock phosphate, although the difference becomes progressively smaller with time.

The 'available' phosphate levels extracted from the superphosphate plot decline with time, probably as a consequence of both plant uptake and more intense bonding, whereas the levels extracted from both the Nauru and Christmas plots reach a maximum in the 6 month sample and decline thereafter. The quantities extracted from the Nauru and Christmas plots are almost identical throughout the 12 month period which, in view of the greater solubility of the pure Nauru fertilizer in the Bray No. 2 extractant, suggests that the Christmas rock phosphate is solubilized to a greater extent than the Nauru rock phosphate in the reasonably acid PA soil, (Table 4.11).

(e) Soil Type WE

At the 3 month sampling date, the levels of 'available' phosphate extracted from the three fertilizer plots are almost identical. This suggests that the products of the reaction between the soil and superphosphate are partially insoluble in the Bray No. 2 reagent, while the rock phosphates are solubilized sufficiently to increase their solubility in the Bray No. 2 reagent, but not to facilitate their reaction with the soil.

The 'available' phosphate levels extracted from the superphosphate and Nauru plots show an identical small decline with time, whereas the levels from the Christmas plot reach a maximum in the 6 month sample, then fall off more rapidly than those from the other plots. The later peak level recorded for the Christmas plot may be due to the lower acidity of this plot (Table 4.11).

(f) Soil Type WA

At the 3 month sampling date the levels of 'available' phosphate extracted from the 3 fertilizer plots are similar. The levels extracted are all slightly higher than those extracted from their counterparts in soil WE. In view of the similar pH readings for the plots on soils WA and WE, it appears that the larger quantities extracted from soil WA are the consequence of the lower phosphate absorption capacity of soil WA. This is in accord with the finding in Section F of this chapter, that the absorption capacity of soil WA is less than that of soil WE.

The levels of 'available' phosphate extracted from the superphosphate plot decline with time, whereas those from both the Nauru and

Christmas plots reach a maximum in the 6 month sample and decline thereafter. The decline is more pronounced for the Christmas plot than the Nauru plot. This greater decline for the Christmas plot may be the consequence of the slightly lower pH of this plot making the Christmas fertilizer more available for plant uptake and/or facilitating the reaction between the soil and the fertilizer, the products of which may be partially insoluble in the Bray No. 2 reagent.

(g) Conclusions

The levels of 'available' phosphate extracted by the Bray No. 2 reagent from the superphosphate plots are inversely related to the absorption capacity of the soil(HS > WA > WE > PA > YK). If the Bray No. 2 test reflects the availability of the applied superphosphate to radiata pines, then it is evident that these results are in accord with those of Lewis and Harding (1963) who found that lower fertilizer applications were required on lighter than heavier soils to provide the same responses. The interpretation of the results obtained from the rock phosphate plots in terms of effectiveness to the tree is difficult, as there is no evidence to show that the varying solubility of the pure rock phosphates in the Bray No. 2 reagent reflects the availability of the unreacted rock phosphates to the tree. The true value of the various fertilizers as ameliorants can be ascertained only by recourse to long term investigations of tree responses. Such investigations were precluded by the limited time available for this particular study. The results obtained serve only to provide some indication of reactions between the fertilizers and the soils. However, the results do indicate that the Christmas rock phosphate appears to be solubilized, and utilized by the trees to a greater extent than the Nauru rock phosphate, particularly in soils of pH below 5. Doak, Gallaher, Evans and Miller (1965) reported that calcined 'C' grade Christmas Island rock phosphate was more effective than Nauru rock phosphate as a source of plant phosphate on moderately acid soils, and that a mixture of superphosphate and calcined Christmas 'C' grade was even more effective. The apparent superiority of the Christmas rock phosphate over Nauru is of considerable practical importance. Use of the latter fertilizer was abandoned in the Riverhead forest because of its poor physical properties despite its effectiveness as an ameliorant (Conway 1962). However, Christmas rock phosphate, which has a similar phosphorus content to Nauru, is available in a pelleted form which makes it suitable for application by air. The encouraging tentative findings for the Christmas rock phosphate warrant the further investigation of this fertilizer in extensive field trials. The possible advantages of a superphosphate-calcined Christmas 'C' grade mixture also warrant investigation, for as Doak et al., (1965) pointed out, such a mixture not only has the advantage of the rock phosphate of costing less per unit of phosphorus than superphosphate, but the physical properties of the mixture are superior to those of either fertilizer alone.

(A) GENERAL DISCUSSION

The results of the work undertaken in this study have been thoroughly discussed in relation to the role of soil P in determining productivity and the nature of the P supply to the tree. However, it is of interest to examine the practical implications of some of the more important findings.

Weston (1958) and Conway (1962) showed that radiata pine on a few selected poor sites in the Riverhead forest responded to the application of superphosphate. Field trials such as these, conducted over limited areas and without accompanying soil or foliar analyses, cannot be extrapolated to the forest as a whole, and fail to differentiate between responses due to the major fertilizer element and other elements present in the fertilizer. However, evidence obtained from this present study that soil P is the primary limiting factor to growth in Riverhead forest, suggests that the responses recorded in these early fertilizer trial were in fact due to the phosphate component of the fertilizer. Further, the presence of a linear relationship between soil P levels and site productivity over all the random plots considered, suggests that the productivity of both poor sites and those at present regarded as satisfactory may benefit from the application of phosphatic fertilizers.

The highly significant relationships obtained between site productivity, foliar P levels and soil P levels provide statistical verification of Will's (1965) suggestion that the foliar P content is a good indicator of the soil P supply. However, these relationships also indicate that the soil P supply to radiata pine is adequately reflected by soil chemical tests. In fact, the levels of soil P extracted by some tests are as closely related to productivity as are foliar P levels.

Thus soil analysis has certain advantages over foliar analysis as a means of determining the phosphate status of the Riverhead soils. The major advantages are :-

(i) Soil samples are easier to collect.

(ii) Soil samples, unlike foliar samples, can be collected at any time of the year.

(iii) Soil analysis can be employed to detect P deficient sites prior to planting, thus enabling corrective measures to be undertaken before the deficiency influences growth.

As previously pointed out, the relationships between productivity and soil P levels obtained in this study cannot be employed for the detection of P deficiencies prior to planting. For this purpose a relationship between the soil test levels prior to planting and consequent growth must be established. In view of the different nature of the early P supply to the tree (Will, 1964) the soil tests found to be most suitable in this present study (Olsen and Bray No. 2 'available' tests) may not apply. However, the dominant role of soil P in determining productivity, and the fact that soil chemical tests can adequately reflect the nature of the P supply to radiata pine, suggests that the selection of a soil test, which will accurately reflect the potential availability of soil P, will present few if any problems. The results in section E of chapter 4 suggest that the value of prediction equations involving soil P tests can be improved by the inclusion of variables which account for variation in the availability of soil P not reflected in the soil test; the most important of these is likely to be the clay content of the soil.

The presence of a highly significant relationship between productivity and soil P levels refutes any theory that poor productivity in the Riverhead forest is the consequence of tree diseases per se. It appears probable that the association of diseases with poor productivity (Newhook 1959) is the consequence of trees at the lower limits of nutritional adequacy being unduly susceptable to infection. Thus, the use of fertilizers to improve the vigour of trees will provide the added advantage of reducing the susceptability of trees to infection, thereby reducing the risk of epidemics.

Of particular interest from the long-term point of view is the fact that podzolized soils, although at present possessing relatively high levels of available P, which maintain adequate growth, possess only low soil P reserves as shown by their low total P content. Thus the development of a P deficiency on these soils is inevitable if successive crops, with their removal of P from the site, are to be grown. The application of maintenance phosphate dressings on these soils would be justified.

In the wake of higher production rates induced by phosphate application, the development of multiple nutrient deficiencies on these depleted soils is almost certain. Evidence obtained from the present study suggests that multiple nutrient deficiencies already exist on some of the poorer sites at Riverhead. Obviously, in the interests of obtaining optimum responses, there is a need to investigate the levels of other nutrients in the Riverhead soils so that correctly formulated fertilizers may be applied.

Evidence from this present study indicates that the aerial application of superphosphate in 1958/59 provided an uneven distribution of phosphate over the topdressed area. Whether this uneven distribution arose from the negligence of the pilots or whether it is an inherent feature of aerial topdressing is difficult to ascertain. But if this mode of application is to be employed in conjunction with accurate methods for assessing the fertilizer requirements of the soil, then it is essential to have some knowledge of the accuracy and evenness of the distribution of aerially applied fertilizer; otherwise neither the value of the fertilizer nor the accuracy of the assessment method will be used to the best advantage.

The soil and foliar analysis results both suggest that superphosphate applied at 5 cwt per acre is inadequate to maintain the P status of most soils at a desirable level for any length of time. Obviously there is a need for larger, or more frequent application of phosphate to most sites in the Riverhead forest. The results from this present study also indicate that Christmas Island calcined 'C' grade rock phosphate offers an attractive alternative to the use of superphosphate at Riverhead. It appears to be as available as superphosphate for tree uptake on the acid Riverhead soils; it is cheaper per unit of P than superphosphate, and its physical properties make it suitable for application by air. The encouraging preliminary results in this study warrant the further investigation of this source of P in order to establish its long term effectiveness over a range of soil conditions. As mentioned previously, mixtures of superphosphate and Christmas Island calcined 'C' grade rock phosphate may have advantages which also warrant investigation.

Since it is apparent that the future economic use of most of the land at Riverhead will depend largely upon the intelligent use of fertilizers, priority should be given to research into the following aspects of their use:

(i) the establishment of which other nutrient elements besides P are limiting, or are likely to be limiting to maximum productivity;

(ii) the derivation of suitable tests for delineating between the presence of sufficient and deficient levels of these limiting nutrient elements;

(iii) the establishment of which fertilizer or mixture of fertilizers are the most suitable for correcting the deficiencies;

(iv) the establishment of the most suitable methods for applying the fertilizer, and the best rates and frequency of application.

The only alternative to extensive use of fertilizers is to utilize less demanding species than radiata pine. However, such species are usually less productive (Jackson 1965) and the economics of utilizing the less productive species as against the cost of the fertilizer required to maintain the production of radiata pine would need careful consideration before the adoption of such a policy, which in any case might only produce a delay in the need for fertilizer. It must be accepted that in order to make the most efficient use of land available for afforestation, the use of fertilizers may be necessary

By way of conclusion it must be emphasised that the findings reached in this investigation apply only to Riverhead forest and have thus no general application.

(B) SUMMARY

A broad study was made of various aspects of soil phospherus in the Riverhead forest, Auckland.

A preliminary study of the distribution of forms of phosphorus in six selected profiles revealed that all forms of phosphorus were present in very low amounts throughout these strongly weathered and leached soils. Total P values tended to decrease with depth in all profiles; organic P constituted from 22-77 per cent of the total P in the topsoils; calcium phosphates were undetectable in most horizons and a high proportion of the inorganic phosphate present in the topsoils occured in the aluminium-bound fraction; iron-bound phosphates were more dominant in the lower horizons. There appeared to be a relationship between the levels of aluminium-bound phosphate and the productivity of trees growing on these soils. Neither total nor organic P levels appeared to be associated with the productivity of the site.

An investigation was made of the relationships among soil P, foliar P and site productivity on 45 random assessment plots (25 unfertilized and 20 aerially topdressed with 5 cwt per acre of superphosphate in 1958/59). A highly significant relationship was found between foliar P levels and site productivity for both fertilized and unfertilized plots. The critical foliar level corresponding to normal growth on the unfertilized plots was found to be 0.10% P. It was concluded that although these significant relationships suggested that soil P levels controlled productivity, the possibility of some other factor influencing foliar levels could not be discounted. In order to establish whether there was a relationship between soil P levels and site productivity, a range of chemical soil tests for the extraction of soil P were utilized. In addition to the conventional agricultural tests for the

extraction of 'available' phosphate (Bray No.2, Olsen, Truog, anion exchange and acetic acid), modified Olsen and Truog procedures, providing some measure of organic P, and a total P extraction were included. Highly significant relationships were found between site productivity and the levels of soil P extracted by some of the tests. Total P was found to be more closely related to productivity when considered within groups of soils possessing similar properties. 'Available' P tests which prevented resorption during extraction (Olsen, Bray No. 2 and exchange resin) were found to be the most successful tests, the Olsen test being the most suitable for unfertilized soils and the Bray No. 2 test for fertilized soils. The importance of the contribution of organic P to the P nutrition of mature radiata pines was indicated by the significant relationships between site productivity and the levels of organic P extracted by the modified Olsen and Truog tests. These levels were also closely related to the easily extractable inorganic P levels removed by the most successful 'available' P tests. It was concluded that the easily extractable inorganic phosphate levels, particularly those that reflect the contribution from the mineralization of organic P, rather than total P levels, determine the phosphate status of these soils in relation to the growth of radiata pine. In the light of the significant relationship between productivity and foliar levels, the significant relationships between productivity and soil P levels extracted by some tests were taken as reasonable evidence that the availability of soil P controls productivity throughout the Riverhead forest and that responses to phosphatic fertilizers may thus be expected. It was found that not only was aerial application of 5 cwt of superphosphate inadequate to fully alleviate the phosphate deficiency, but also that it produced an uneven response pattern over the topdressed plots. This was attributed either to an uneven distribution of the aerially applied fertilizer or to the unavailability of the aerially applied phosphate on the poor plots.

The relationships between foliar P levels and the levels of soil P extracted by the various tests were found to be almost identical to those between site productivity and the test levels. Slightly improved relationships were found for the weaker extractants and those tests providing some measure of organic P; this was this was taken as evidence that the current and long-term supplies to radiata pine differed slightly. This slight difference was attributed to an alteration in the P supply from one met predominantly by a nett withdrawal from the soil during the early years of growth, to one met predominantly through the action of the organic cycle in the more mature stands.

The relationships between site productivity and a number of soil and topographic variables were studied. Utilizing simple correlations, it was found that several of the variables considered were significantly related to site productivity: slope, aspect, mycorrhizal levels, external drainage conditions and pH were significantly related to the site productivity of unfertilized plots, while %silt, bulk, density and external drainage conditions were significantly related to the site productivity of fertilized plots. However, analysis of the data employing partial and multiple correlations revealed that most of these significant relationships were the consequence of the relationships of these variables to available phosphate levels, which made by far the largest direct contribution to the determination of productivity on both the fertilized and unfertilized plots. Other than available P levels, mycorrhizal levels, %fine sand, %clay, slope and pH made small direct contributions to the determination of productivity on unfertilized plots, and external drainage conditions, mycorrhizal levels, loss on ignition and %clay made a small direct contribution on fertilized plots. The direct contribution from the external drainage conditions on fertilized but not unfertilized plots was taken as evidence of the drainage conditions, or some underlying factor related to them, limiting the response to the applied fertilizer. It was found that soil and topographic factors explained the bulk of the variation in the productivity of radiata pine stands in Riverhead forest. The results from this section of the work substantiated the findings in the other sections that 'available' soil phosphate levels are dominant in determining productivity. The finding that 'available' soil phosphate levels explained more of the variation in productivity when considered within specific levels of other variables was taken as evidence that soil P levels accounted for more of the variation in site productivity than suggested by the relationships between the extracted soil P levels and productivity.

The fate of three commercial phosphatic fertilizers (superphosphate, Nauru rock phosphate and Christmas Island calcined 'C' grade rock phosphate) applied to the main soil types in the forest was followed over a 12 month period by phosphate fractionation and extraction with the Bray No. 2 'available' P test at three monthly intervals. Phosphate fractionation revealed that superphosphate occured initially as aluminium-bound and residual calcium phosphate both in an acid podzolized soil and a less acid non-podzolized soil. Over time it was found that the levels of recoverable phosphate decreased in both soils, accompanied with which there was a decline in the calcium phosphate fraction in the acid soil and a decline in the aluminium phosphate fraction in the less acid soil. These declines were attributed to phosphate uptake by the trees. The Nauru rock phosphate occured predominantly as residual unreacted calcium phosphate in both soils at the three month sampling date. Thereafter a parallel decline in the calcium phosphate fraction and recoverable phosphate occured in the acid soil, but no alterations were recorded in the less acid soil. The Christmas Island rock phosphate occured predominantly in the alumium-bound form in both soils at the three and six month sampling dates. Thereafter a parallel decline occured in the aluminium phosphate fraction and the recoverable phosphate of both soils, but the decline was more pronounced in the acid soil. Utilizing the Bray No. 2 test, it was found that all three fertilizers were more available in the acid soil than in the less acid soil. It was also revealed that in these soils the Christmas Island rock phosphate was solubilized to a greater extent than the Nauru rock phosphate. The apparent declines over time in the availability of the applied fertilizers in the acid soil was found to be accounted for by the removal of phosphate by plant uptake. However, in the less acid soil, plant uptake failed to account for the decline in the availability of phosphate over time and the decline was attributed to a more intense bonding of the applied phosphate. In three less extensive soil types in the forest, the Bray No. 2 test revealed that the Christmas Island rock phosphate was solubilized to a greater extent than the Nauru rock phosphate. The results also revealed that the availability of the fertilizers between the various soils was dependent upon the phosphate absorption capacity of the soils. It was concluded from this fertilizer study that, of the two rock phosphates, Christmas Island 'C' grade was the superior ameliorant, and that it provides an attractive alternative to the use of superphosphate at Riverhead.

A supplementary study on the fate of laboratory applied soluble phosphate was made. Fractionation results revealed that all the applied phosphate was recoverable in the aluminium and iron-bound fractions. The majority of the applied phosphate was recovered in the aluminium-bound fraction, although there was a tendency for the iron-bound fraction to increase in those soils with a larger phosphate absorption capacity. There was no indication of a change in the distribution of the forms of phosphate over time.

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BIBLIOGRAPHY

Atkinson, I.A.E. 1959. Soils and the growth of Pinus radiata at Cornwallis, Auckland. N.Z.J.Sci., 2, 443 - 72.

Barnes, R.L. 1955. Growth and yield of Slash pine plantations in Florida. Univ. Fla. Sch. For. Res. Rep., 3, pp.23.

Bartrum, J.A. 1924. The geology of the Riverhead-Kaukapakapaka district, Waitemata county, Auckland. Trans. N.Z. Inst., 55, 139 - 53.

Baur, G.N. 1959. A soil survey of a Slash pine plantation, Barcoongere, New South Wales. Aust. For., 23, 78 - 87.

Beckman, G.G. 1964. Mount Crawford forest reserve. C.S.I.R.O. Div. Soils Rep. 4/64 pp.35.

Bornemisza, E., and Igue, K. 1967. Comparison of 3 methods for determining organic phosphorus in Costa Rican soils. Soil Sci., 103, 347 - 53.

Bray, R.G., and Kurtz, L.T. 1945. Determination of total, organic and available forms of phosphorus in soils. Soil Sci., 59, 39 - 45.

Brockwell, J., and Ludbrook, W.V. 1962. The response to phosphate of pinus grown on infertile soils in New South Wales. C.S.I.R.O. Div. Pl. Ind. Div. Rep., 22, pp.9.

Bromfield, S.M. 1964. Relative contribution of Fe^{3+} and Al^{3+} in phosphate sorption by acid surface soils. Nature, 201, 322.

Cain, J.C. 1959. Plant tissue analysis. Duke Univ. Sch. For. Bull. 15, pp. 184.

Carmean, W.H. 1954. Site quality for Douglas fir in South-West Washington. Soil Sci. Soc. Amer. Proc., 18, 330 - 34.

____ 1967. Soil survey refinements for predicting Black oak site quality in South Eastern Ohio. Soil Sci. Soc. Amer. Proc., 31, 805 - 10.

Carter, M.C., and Lyle, E.S. 1966. Fertilization of loblolly pine on two Alabama soils. Effects on growth and foliar mineral content. Ala. Agric. Expt. Sta. Bull., 370, pp.18.

Chang, S.C., and Chu, W.K. 1961. The fate of soluble phosphate applied to soils. J. Soil Sci., 12, 286 - 97.

____ and Jackson, M.L. 1957. Soil phosphate fractions in some representative soils. J. Soil Sci., 9, 109 - 19.

Coile, T.S. 1952. Soil and the growth of forests. Advan. Agron., 4, 329 - 98.

____ and Schumacher, F.K. 1953. Relation of soil properties to the site index of loblolly and shortleaf pines in the Piedmont region of the Carolinas, Georgia and Alabama. J. For., 51, 739 - 44.

Conway, M.J. 1962. Aerial application of phosphate fertilizers to radiata pine forests in New Zealand. Commw. For. Rev., 41, 234 - 45.

Copeland, O.L., Jr. and McAlpine, R.G. 1955. The interrelationship of littleleaf site index, soil and ground cover in Piedmont shortleaf pine stands. Ecology, 36, 635 - 40.

Covell, R.R., and McClurkin, D.C. 1967. Site index of loblolly pine on Ruston soils in the southern coastal plain. J. For., 65, 263 - 64.

Dahl, E., et al. 1961. Soil factors and the growth of Scots pine: A statistical re-interpretation of data presented by Viro (1955). Soil Sci., 92, 367 - 71.

Deetlefs, Du T.P.P., and Dumont, M. 1963. The early response of Pinus radiata to fertilizer treatment. Forestry in S. Africa, 3, 101 - 19

Della-Bianca, L., and Olson, D.F.Jr. 1961. Soil site studies in Piedmont hardwood and pine upland forests. For. Sci., 7, 320 - 29.

Dickman, S.R., and Bray, R.H. 1940. Calorimetric determination of phosphorus. Indus. Engin. Chem. Analyt. Ed., 12, 665 - 668.

Doak, B.W., et al. 1965. Low temperature calcination of 'C' grade phosphate from Christmas Island. N.Z.J. Agric. Res., 8, 15 - 29.

Doolittle, W.T. 1957. Site index of scarlet and black oak in relation to southern Appalachian soil and topography. For. Sci., 3, 114 - 24.

____ 1958. Site index comparisons of several forest species in the southern Appalachians. Soil Sci. Soc. Amer. Proc., 22, 455 - 58.

During, C. 1968. Equilibrium concentration of inorganic phosphate and phosphate sorption properties in soils under permanent pasture: some practical applications. Trans. IX Intnl. Cong. Soil Sci., II, 281 - 92.

Ellerbe, C.M., and Smith, G.E. 1963. Apparent influence of phosphate marl on the site index of loblolly pine in the lower coastal plain of South Carolina. J. For., 61, 284 - 86.

Enwezor, W.O., and Moore, A.W. 1966. Comparison of 2 methods for determining organic phosphorus in some Nigerian soils. Soil Sci., 102, 284 - 85.

Fife, C.V. 1962. An evaluation of ammonium fluoride as a selective extractant for aluminium bound soil phosphate. III. Detailed studies on soils. Soil Sci., 93, 113 - 23.

Fiskell, J.G.A., and Spencer, W.F. 1964. Forms of phosphate in lakeland fine sand after 6 years of heavy phosphate and lime applications. Soil Sci., 97, 320 - 27.

Fogg, D.N., and Wilkinson, N.T. 1958. Calorimetric determination of phosphorus with ascorbic acid. Analyst, 83, 407.

Forristal, F.F., and Gessel, S.P. 1955. Soil properties related to forest cover type and productivity on Lee forests, Snohomish county, Washington. Soil Sci. Soc. Amer. Proc., 19, 384 - 89.

Gentle, S.W., Humphreys, F.R., and Lambert, M. 1965. An examination of _Pinus radiata_ fertilizer trial 15 years after treatment. For. Sci., 11, 315 - 24.

____ ____ 1968. Experience with phosphatic fertilizers in man made forests of _Pinus radiata_ in New South Wales. Ninth Commw. For. Cong. (India).

Gessel, S.P., and Lloyd, W.J. 1950. Effect of some physical properties on Douglas fir. J. For., 48, 405 - 10.

____ and Walker, R.B. 1958. Diagnosing nutrient deficiencies of forest trees. Better crops, 42, 20 - 27, 30 - 31.

Gilmour, J.W. 1965. N.Z. For. Service Rept. for 1964. pp.64.

____ 1966. The pathology of forest rees in New Zealand. The fungal, bacterial and algal pathogens.
N.Z. For. Service Tech. paper, 48, pp. 82.

____ 1967. Distribution and significance of the needle blight of pines caused by <u>Dothistroma pini</u> in New Zealand.
Plant Disease Reporter, 51, 727 - 30

Grigg, J.L. 1961. Forms of soil phosphorus and their solubility in various extractants. J.N.Z. Inst. Chem., 25, 136 - 37.

____ 1965. Inorganic phosphate fractions in South Island soils and their solubility in extractants. N.Z.J. Agric. Res., 8, 313 - 26.

Hagenzieker, F. 1958. Fertilizing forest trees. World crops, 10, 369 - 72.

Hall, M.J., and Purnell, H.M. 1961. Potassium deficiency in <u>Pinus radiata</u> in Eastern Australia. Austr. For., 25, 111 - 15.

Hance, R.J., and Anderson, G. 1962. Methods for the study of soil organic phosphorus. J. Soil Sci., 13, 225 - 30.

Hanley, K. 1965. Phosphorus in some Irish soils.
Min. Ag. Fish. Fd. Tech. Bull., 13, 103 - 29.

Harley, J.L. 1959. 'The biology of mycorrhiza'. (Leonard Hill - London).

Hatch, A.B. 1937. The role of mycorrhizae in afforestation.
J. For., 34, 22 - 29.

Heiburg, S.O., and Leaf, A.L. 1960. Potassium fertilization of coniferous plantations in New York.
Trans. VII. Intnl. Cong. Soil Sci., 3, 376 - 83.

Heinsdorf, D. 1964. Correlations of the nutrient content of the soil and of needles with growth in pine plantations on sands with a low water table. Arch. Forstw., 13, 865 - 88.
(abstracted from F.A., 25 No. 1885).

Hills, G.A. 1959. Soil-forest relationships in the site regions of Ontario. 'First North American Forest Soils Conference', 190-212.
(T.D. Stevens and R.L. Cook, eds.).

Holmen, H. 1964. Forest ecological studies on drained peat land in the province of Uppland, Sweden.
Studia Forestalia Snecica, 16, pp. 236.

Holtby, B.E. 1947. Soil texture as a site indicator of ponderosa pine stands. J. For., 45, 824 - 25.

Hopkins, E.R. 1960. The fertilizer factor in <u>Pinus pinaster</u> plantations on sandy soils of the Swan coastal plain, Western Australia.
West. Aust. For. Dept. Bull., 68, pp. 26.

Humphreys, F.R. 1963. Some limitations in the use of foliage and soil analysis. Tech. paper For. Comm. N.S.W., No. I pp.6.

Humphreys, F.R. 1964. The nutrient status of pine plantations in central New South Wales. Appita, 18, 111 - 20.

——— and Truman, R. 1964. Aluminium and the phosphorus requirements of Pinus radiata. Pl. Soil, 20, 131 - 34.

——— and Lambert, M.J. 1965. An examination of a forest site which has exhibited the ash bed effect. Aust. J. Soil Res., 3, 81 - 94.

Jackson, D.S. 1962. Parameters of site for certain growth components of slash pine. Bull. Duke Sch. For., 16, pp. 118.

——— 1965. Species siting: climate, soil and productivity. N.Z. J. For., 10, 90 - 102.

Jackson, M.L. 1958. "Soil Chemical Analysis." (Prentice-Hall. N.J.).

Kawana, A. 1966. Methods of forest fertilization. Pot. Rev., 22/18, pp. 5.

Kessell, S.L., and Stoate, T.N. 1938. Pine Nutrition. W. Aust. For. Dept. Bull., 50, pp.45.

Kurtz, L.T. 1942. Elimination of fluoride interference in the molybdenum blue reaction. Indus. Engin. Chem. Analyt. Ed., 14, 855.

———, Deturk, E.E., and Bray, R.H. 1946. Phosphate adsorption by Illinois soils. Soil Sci., 61, 111 - 24.

Lemmon, P.E. 1955. Factors effecting productivity of some lands in the Willamette basin of Oregon for Douglas fir timber. J. For., 53, 323 - 30.

Levy, J.W., and Sutherland, C.F. 1964. The soil problem in reforestation in Northland. N.Z. Soc. Soil Sci. Proc., 1, 3 - 4.

Lewis, N.B., and Harding, J.H. 1963. Soil factors in relation to pine growth in South Australia. Aust. For., 27, 27 - 34.

Leyton, L. 1956. The relationship between the growth and mineral composition of the foliage of Japanese larch. Pl. Soil, 7, 167 - 77.

—— 1957(a). The relationship between the growth and mineral composition of the foliage of Japanese larch. Pl. Soil, 9, 31 - 48.

—— 1957(b). The relationship between the growth and mineral nutrition of conifers. "Physiology of Forest trees." p. 323 - 46. (Thimann. ed.).

—— 1958. Forest fertilization in Britain. J. For., 56, 104 - 6.

——, and Armson, K.A. 1955. The mineral composition of the foliage in relation to the growth of Scots pine. For. Sci., 1, 210 - 18.

Lundegardh, H. 1951. "Leaf Analysis." (Translated by R.L. Mitchell - Hilger and Watts, Lond.).

Lutz, H.J., and Chandler, R.F. "Forest Soils." (Wiley and Sons).

Mackay, D.C., and Eaton, J.B. 1959. Penetration of radioactive superphosphate into a podzol soil. Can. J. Soil. Sci., 39, 215 - 21.

Maclean, A.A. 1965(a). Residual effect of phosphorus fertilizer in long term fertilizer plots. Can. J. Soil Sci., 44, 223 - 27.

—— 1965(b). Organic phosphorus in some New Brunswick soils. Can. J. Soil Sci., 45, 185 - 88.

Mader, D.L. and Owen, D.F. 1961. Relationships between soil properties and red pine growth in Massachusetts.
Soil Sci. Soc. Amer. Proc., 25, 62 - 65.

Maki, E.T. 1966. Need for fertilizers in wood production.
Unasylva, 20, 49 - 54.

McComb, A.L., and Griffith, J.G. 1946. Growth stimulation and phosphorus absorption of mycorrhizal and non mycorrhizal northern white pine and Douglas fir seedlings in relation to fertilizer treatment.
Pl. Physiol., 21, 11 - 17.

McConaghy, S. 1965. Studies on the availability of phosphorus in the soils of northern Ireland. Min. Ag. Fish. Fd. Tech. Bull., 13, 38 - 48.

McLachlan, K.D. 1965. The nature of available phosphate in some acid soils and the comparison of estimating procedures.
Aust. J. Expt. Agric. An. Husb., 5, 125 - 32.

Mehta, N.C., et al. 1954. Determination of organic phosphorus.
Soil Sci. Soc. Amer. Proc., 18, 443 - 49.

Metz, L.J., Wells, C.G., and Swindel, B.F. 1966. Sampling soil and foliage in a pine plantation. Soil Sci. Soc. Amer. Proc., 30, 397 - 99.

Millar, W.F. 1966. Annual changes in foliar N, P and K levels of loblolly pine with site and weather factors. Pl. Soil, 24, 369 - 78.

Millar, J.T., and Thulin, I.J. 1967(a). F.R.I. Res. Leaflet, 17, pp.4.

____ ____ 1967(b). F.R.I. Res. Leaflet, 18, pp.4.

Mitchell, H.L. 1936. Trends in the N, P, K and Ca. content of leaves of some forest trees during the growing season. Black Rock For. Pap., 1, 30 - 44.

Morrison, T.M. 1957. Mycorrhiza and phosphorus uptake. Nature, 179, 907.

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

Mustanoja, K.J., and Leaf, A.L. 1965. Forest fertilization research 1957 - 1964. Bot. Rev., 31, 151 - 246.

Myers, C.A., and Van Deusen, J.L. 1960. Site index of ponderosa pine in the Black hills from soil and topography. J. For., 53, 323 - 30.

Newhook, F.J. 1959. The association of Phytophthora spp. with the mortality of Pinus radiata and other conifers. N.Z. J. Agric. Res., 2, 808 - 43.

Olsen, S.R., et al. 1954. Estimation of available phosphorus in soils by extraction with $NaHCO_3$. U.S.D.A. Circ., 939.

Orman, H.R., and Will, G.M. 1960. The nutrient content of Pinus radiata trees. N.Z. J. Sci., 3, 510 - 22.

Ozanne, P.G., and Shaw, T.C. 1967. Phosphate sorption by soils as a measure of the phosphate requirements for pasture growth. Aust. J. Agric. Res., 18, 601 - 12.

Paauw, Van der, F. 1965. Factors controlling the efficiency of rock phosphates for potatoes and rye on humic sandy soils. Pl. Soil, 22, 81 - 98.

Pawluk, S., and Arneman, H.F. 1961. Some forest soil characteristics and their relationship to Jack pine growth. For. Sci., 7, 160 - 72.

Peech, M., et al. 1947. Methods of soil analysis for soil fertility studies. U.S.D.A., Circ., 757, pp.25.

Piper, C.S. 1942. "Soil and Plant Analysis." (Hassell Press - Adelaide).

Poutsma, T., and Simpfendorfer, K.J. 1962. Soil moisture conditions and pine failure at Waare, near Port Campbell, Victoria. Aust. J. Agric. Res., 13, 426 - 33.

Pritchett, W.L. 1968. Progress in the development of techniques and standards for soil and foliar diagnosis of phosphorus deficiency in slash pine. In "Forest Fertilization - Theory and Practise" p.81 - 87.

____ , and Llewellyn, W.R. 1966. Response of slash pine to phosphorus in sandy soils. Soil Sci. Soc. Amer. Proc., 30, 509 - 12.

____ , and Swinford, K.R. 1961. Response of slash pine to colloidal phosphate fertilization. Soil Sci. Soc. Amer. Proc., 25, 397 - 400.

Purnell, H.M. 1958. Nutritional studies of Pinus radiata. (i) Symptoms due to deficiencies of some major elements. Aust. For., 22, 82 - 87.

Qureshi, I.M., and Srivastava, P.B.L. 1966. Foliar diagnosis and mineral nutrition of forest trees. Indian For., 92, 447 - 60.

Ralston, C.W. 1964. Evaluation of forest site productivity. Intnl. Rev. For. Res., 1, 171 - 201.

Raupach, M. 1967. Soil and fertilizer requirements for forests of *Pinus radiata*. Advan. Agron., 19, 307 - 53.

Rawlings, G.B. 1958. Problems of forest entomology in exotic forests in New Zealand. Proc. X. Intnl. Cong. Ent., 4, 241 - 46.

Rennie, P.J. 1955. The uptake of nutrients by mature forest growth. Plant and Soil, 7, 49 - 95.

____ 1962. Methods of assessing forest site capacity. Trans. Intnl. Soc. Soil Sci. Comm., IV and V, 770 - 85.

Richards, B.N. 1954. The effect of phosphate on slash and loblolly pines in Queensland. Qld. For. Serv. Res. Notes, 5.

____ 1961. Fertilizer requirements of *Pinus taeda* in the coastal lowlands of subtropical Queensland. Qld. For. Dept. Bull., 16, pp. 24.

Rosendahl, R.O. 1942. The effect of mycorrhizal and non mycorrhizal fungi on the availability of difficulty soluble potassium and phosphorus. Soil Sci. Soc. Amer. Proc., 7, 477 - 79.

Saunders, D.H., and Metelerkamp, H.R. 1962. Use of an anion exchange resin for the determination of available soil phosphate. Trans. Intnl. Soc. Soil Sci. Comm., IV and V, 847 - 49.

Saunders, W.M.H. 1959. Effect of phosphate topdressing on a soil from andesitic volcanic ash. II. Effect on distribution of phosphorus and related chemical properties. N.Z. J. Agric. Res., 2, 445 - 62.

Saunders, W.M.H., and Williams, E.G. 1955. Observations on the determination of total organic phosphorus in soils. J. Soil Sci., 6, 254 - 67.

Schomaker, C.E., and Rudolph, V.J. 1964. Nutritional relationships affecting height growth of planted yellow poplar in S.W. Michigan. For. Sci., 10, 66 - 76.

Scott, C.W. 1960. Pinus radiata. F.A.O. For. Prod. Stud., 14, pp.328.

Smith, A.N. 1965. Aluminium and iron phosphate in soils. J. Aust. Inst. Agric. Sci., 31, 110 - 126.

Smith, P.F. 1962. Mineral analysis of plant tissue. Ann. Rev. Pl. Physiol., 13, 81 - 108.

Steenbjerg, F. 1951. Yield curves and chemical plant analysis. Pl. Soil, 3, 97 - 109.

Steinbrenner, E.E. 1965. The influence of individual soil and physiographic factors on the site index of Douglas fir in W. Washington. In "Forest-Soil Relationships in N. America."

Stoate, T.N. 1950. Nutrition of the pine. Commw. For. Timb. Bur. Bull., 30, pp.61.

Stoeckler, J.H. 1960. Soil factors affecting the growth of quaking aspen in the lake states. Minn. Agric. Expt. Sta. Tech. Bull., 233, pp.43.

____ , and Arneman, H.F. 1960. Fertilizers in forestry. Advan. Agron., 12, 127 - 195.

Strand, R.F., and Austin, R.C. 1966. Evaluating fertilizer and other materials to speed growth of planted Douglas fir. J. For., 64, 739 - 44.

Sutherland, C.F., Newhook, F.J., and Levy, J. 1959. The association of Phytophthora with mortality of Pinus radiata and other conifers. N.Z. J. Agric. Res., 2, 844 - 58.

Syers, J.K., Williams, J.D.H., Campbell, A.S., and Walker, T.W. 1967. The significance of apatite inclusions in soil phosphorus studies. Soil Sci. Soc. Amer. Proc., 31,752 - 56.

Tamm. C.O. 1964. Determination of the nutrient requirements of forest stands. Intnl. Rev. For. Res., 1, 115 - 70.

Terman, G.S. 1968. Fertilizer, soil and plant properties affecting crop responses to phosphorus fertilizers. In "Forest Fertilization - Theory and Practice." p.77 - 80. (T.V.A.)

Themlitz, R. 1968. The indication value of soil and needle analysis. Pot. Rev., 22/19, 7 - 8.

Travers, W.W.G. 1965. The mineral nutrition of Pinus radiata seedlings. N.Z. For. Res. Note, 40, pp. 11.

Truog, E. 1930. The determination of readily available phosphorus of soils. J. Amer. Soc. Agron., 22, 874 - 82.

Turner, M.A. 1965. A laboratory study of the behaviour of added phosphate in an allophanic soil. M.Ag.Sc., Thesis, Massey University, N.Z.

Van Diest, A., and Black, C.A. 1959. Soil organic phosphorus and plant growth. Soil Sci., 87, 100 - 4.

Viro, P.J. 1955. The use of E.D.T.A. in soil analysis. II. Determination of soil fertility. Soil Sci., 80, 69 - 74.

____ 1961. Evaluation of site fertility. Unasylva, 15, 91 - 97.

Voigt, G.K. 1958. Plant and soil factors in chemical soil analysis. First North American Forest Soils Conference, p.31 - 41. (T.D. Stevens and R.L. Cook - eds.).

____ 1966. Phosphorus uptake in young pitch pine. Soil Sci. Soc. Amer. Proc., 30, 403 - 6.

Volk, V.V., and Mclean, E.O. 1963. The fate of applied phosphorus in four Ohio soils. Soil Sci. Soc. Amer. Proc., 27, 53 - 7.

Walker, T.W. 1965. The significance of phosphorus in pedogenesis. In "Experimental Pedology", p.295 - 315. (E.G. Hallsworth and D.V. Crawford - eds.).

Wallace, T. 1957. Methods of diagnosing the mineral status of plants. In "Plant Analysis and Fertilizer Problems", p.13 - 22. (I.R.H.O.).

Watanabe, F.S., and Olsen, S.R. 1962. Calorimetric determination of phosphorus in water extracts of soils. Soil Sci., 93, 183 - 88.

____ ____ 1965. Tests of an ascorbic acid method for determining phosphorus in water and $NaHCO_3$ extracts from soil. Soil Sci. Soc. Amer. Proc., 29, 677 - 78.

Wells, C.G. 1965. Nutrient relationships between soils and needles of loblolly pine. Soil Sci. Soc. Amer. Proc., 29, 621 - 24.

Wells, N. 1962. Data on soil profiles. N.Z. Soil Bur. Info. Series, 7, pp.131.

Weston, G.C. 1956. Fertilizer trials in unthrifty pine plantations at Riverhead forest. N.Z. J. For., 7, 35 - 46.

____ 1958. The response of radiata pine to fertilizers. N.Z. Soc. Soil Sci. Proc., 3, 13 - 19.

Wilde, S.A. 1958. Diagnosis of nutrient deficiency by foliar and soil analysis in silvicultural practice. First North American Forest Soils Conference, p. 138 - 40.

____, et al. 1964(a). Growth of Jack pine plantations in relation to fertility of non phreatic sandy soils. Soil Sci., 98, 162 - 69.

____ ____ 1964(b) Growth of red pine plantations in relation to fertility of non phreatic sandy soils. J. For., 10, 463 - 70.

Will, G.M. 1955. Removal of mineral nutrients from tree crowns by rain. Nature, 176, 1180.

____ 1957. Variations in the mineral content of radiata pine needles with age and position in the crown. N.Z. J. Sci. Tech., B38, 699 - 706.

____ 1961. The mineral requirements of radiata pine seedlings. N.Z. J. Agric. Res., 4, 309 - 27.

____ 1964. Dry matter production and nutrient uptake by Pinus radiata in New Zealand. Commw. For. Rev., 43, 57 - 70.

Will, G.M. 1965. Increased phosphorus uptake by radiata pine in Riverhead forest following superphosphate applications. N.Z. J. For., 10, 33 - 42.

Williams, E.G. 1962. Chemical soil tests as an aid to increased productivity. Trans. Intnl. Soc. Soil Sci. Comm., IV and V, 820 - 34.

____, et. al. 1952. Readily soluble phosphorus values and crop responses for different soils. Trans. Intnl. Soc. Soil Sci. Comm., II and IV, 2 84 - 91.

____, and Knight, A.H. 1963. Evaluation of soil phosphate status by pot experiments, conventional extraction methods and labile phosphate values. J. Sci. Fd. Agric., 14, 555 - 63.

Williams, J.D.H. 1965. Forms of soil phosphate in some genetically-related New Zealand soils. Ph.D. Thesis, Lincoln College, N.Z.

____, Syers, J.K., and Walker, T.W. 1967. Fractionation of soil inorganic phosphate by a modification of Chang and Jackson's procedure. Soil Sci. Soc. Amer. Proc., 31, 736 - 39.

York, E.T. 1959. Agronomic view point of field experiments in tree nutrition. Duke Univ. Sch. For. Bull., 15, pp.184.

Young, H.E. 1940. Fused needle disease and its relation to the nutrition of *Pinus*. Qld. J. Agric., 45, 45-54; 156-177; 278-315; 374-392; 434-453.

____ 1948. The response of loblolly and slash pine to phosphate manures. Qld. J. Agric. Sci., 5, 77 - 105.

Zahner, R. 1954. Estimating loblolly pine sites in the gulf coastal plains. J. For., 52, 448 - 49.

APPENDIX 1(a)

PROFILE DESCRIPTIONS

IDENTIFICATION:	Profile A98 (described wet).
LOCATION:	Compartment 8. Riverhead State Forest, Auckland.
SLOPE:	7°.
ASPECT:	S.E.
ALTITUDE:	200 ft.
RAINFALL:	60 - 80 inches.
PARENT MATERIAL:	Strongly weathered siliceous claystone.
DOMINANT VEGETATION:	P. radiata and Genisotoma ligustrifolium.

O	1 - 0 in.	Decomposing litter.
A_1	0 - 6 in.	Very dark greyish brown (10YR 3/2) silty clay loam; friable and spongy; well developed crumb and nutty structure; contains some ironstone nodules; abundant roots and a few mycorrhiza; distinct wavy boundary.
A_3	6 - 24 in.	Dark yellowish brown (10YR 4/4) silty clay; friable; well developed medium nutty structure; many medium ironstone nodules; many roots but no mycorrhiza; indistinct boundary.
B_1	24 - 34 in.	Yellowish brown (10YR 5/4) silty clay; friable; strongly developed medium nutty structure; a few medium ironstone nodules; a few roots; indistinct boundary.
B_2	34 - 42 in.	Intermingled brownish yellow (10YR 6/6) and yellowish brown (10YR 5/4 clay; compact; weakly developed fine nutty structure; very few roots; indistinct boundary.
C	42 in. ↓	On hard greyish white claystone with some yellowish red and pale brown veins; no roots.

CLASSIFICATION: Moderate to strongly leached northern yellow-brown earth.

APPENDIX 1(b)

PROFILE DESCRIPTIONS

IDENTIFICATION:	Profile A160/7 (wet).
LOCATION:	Compartment 8. Riverhead State Forest, Auckland.
SLOPE:	3^{o}.
ASPECT:	5.
ALTITUDE:	200 ft.
RAINFALL:	60 - 80 in.
PARENT MATERIAL:	Deeply weathered red siliceous claystone.
DOMINANT VEGETATION:	P. radiata and Geniostoma ligustrifolium.

O	1 - 0 in.	Decomposing litter.
A_1	0 - 5 in.	Very dark brown (10YR 2/2) silty clay loam; friable and spongy; well developed crumb and nutty structure; a few fine ironstone nodules; abundant roots and moderate mycorrhiza; distinct boundary.
A_2	5 - 13 in.	Brown (10YR 5/3) silty clay; friable; moderately developed medium nutty structure; a few medium ironstone nodules; abundant roots and a few mycorrhiza; indistinct boundary.
B_1	13 - 20 in.	Darkish brown (10YR 4/3) silty clay; friable; well developed medium to coarse nutty structure; abundant medium ironstone nodules; many roots and no mycorrhiza; indistinct boundary.
B_2	20 - 30 in.	Yellowish brown (10YR 5/4) silty clay; friable; well developed medium nutty structure; a few medium ironstone nodules; a few roots; indistinct boundary.
B_3	30 - 36 in.	Intermingled brown yellow (10YR 6/6) and reddish yellow (7.5YR 7/6) clay; compact; weakly developed fine nutty structure; no roots; indistinct boundary.
C	36 in.↓	On pale red to red (2.5YR 6/6 - 10YR 4/6) clay; massive and brittle.

CLASSIFICATION: Weakly podzolized northern yellow-brown earth.

APPENDIX 1(c)

IDENTIFICATION:	Profile A160/5 (wet).
LOCATION:	Compartment 8. Riverhead State Forest, Auckland.
SLOPE:	15^{o}.
ASPECT:	5.
ALTITUDE:	200 ft.
RAINFALL:	60 - 80 in.
PARENT MATERIAL:	Strongly weathered siliceous claystone.
DOMINANT VEGETATION:	P. radiata and Geniostoma ligustrifolium.

O	$\frac{1}{2}$ - 0 in.	Decomposing litter.
A_1	0 - 8 in.	Very dark grey (10YR3/1) silty clay loam; friable and spongy; well developed crumb and nutty structure; a few fine ironstone nodules; abundant roots and mycorrhiza; distinct wavy boundary.
A_3	8 - 20 in.	Dark yellowish brown (10YR 4/4) silty clay; friable; well developed medium nutty structure; many medium ironstone nodules; abundant roots and a few mycorrhiza; indistinct boundary.
B_1	20 - 30 in.	Light yellowish brown (10YR 6/4) silty clay; friable; strongly developed medium nutty structure; a few medium ironstone nodules; a few roots; indistinct boundary.
B_2	30 - 40 in.	Intermingled brownish yellow (10YR 6/6) and yellowish brown (10YR 5/4) clay; compact; weakly developed fine nutty structure; a very few roots; indistinct boundary.
C	40 in.↓	On hard, greyish white claystone with some yellowish red and pale brown veins; no roots.

CLASSIFICATION: Moderately to strongly leached northern yellow-brown earth.

APPENDIX 1(d)

IDENTIFICATION:	Profile P. (wet).
LOCATION:	Compartment 3. Riverhead State Forest, Auckland.
SLOPE:	6°.
ASPECT:	S.E.
ALTITUDE:	200 ft.
RAINFALL:	60 - 80 in.
PARENT MATERIAL:	Deeply weathered massive sandstone.
DOMINANT VEGETATION:	P. radiata, umbrella fern and mosses.

A	0 - 4 in.	Very dark grey (5YR 3/1) silty clay loam with a few red (2.5YR 4/6) mottles; sticky; weakly developed nutty structure; abundant roots but no mycorrhiza; indistinct boundary.
B	4 - 10 in.	Dark reddish brown (5YR 3/2) clay, with abundant red (2.5YR 5/6) and grey (5YR 5/1) mottles; sticky; massive; few roots; indistinct boundary.
C	10 - 28 in.	Yellowish brown (10YR 5/6) clay with frequent small red (2.5YR 5/6) mottles and pronounced vertical grey (5YR 5/1) streaks which widen to dominate the horizon colour lower in the horizon; sticky; massive; no roots.

CLASSIFICATION: Gleyed northern yellow-brown earth.

APPENDIX 1(e)

PROFILE DESCRIPTIONS

IDENTIFICATION: Profile M (wet).

LOCATION: Compartment 3. Riverhead State Forest, Auckland.

SLOPE: 12^{o}.

ASPECT: E.

ALTITUDE: 175 ft.

RAINFALL: 60 - 80 in.

PARENT MATERIAL: Strongly weathered massive sandstone.

DEOMINANT VEGETATION: P. radiata and Leptospermum scoparium.

A 0 - 7 in. Yellowish brown (10YR 5/6) silt loam; firm; weakly developed nutty structure; abundant roots and a few mycorrhiza; indistinct boundary.

B 7 - 15 in. Light yellowish brown (10YR 6/4) silt loam with large reddish yellow (5YR 6/8) mottles; firm; very weakly developed fine nutty structure; abundant roots but no mycorrhiza; indistinct boundary.

C 15 - 32 in. Pale brown (10YR 6/3) intermingled with brownish yellow (10YR 6/8) fine sandy silt loam; firm; massive; a few roots.

CLASSIFICATION: Weakly leached northern yellow-brown earth.

APPENDIX 1(f)

PROFILE DESCRIPTIONS

IDENTIFICATION:	Profile G. (wet).
LOCATION:	Compartment 3. Riverhead State Forest, Auckland.
SLOPE:	9^{o}.
ASPECT:	S.E.
ALTITUDE:	150 ft.
RAINFALL:	60 - 80 in.
PARENT MATERIAL:	Strongly weathered massive sandstone.
DOMINANT VEGETATION:	<u>P. radiata</u> and gorse.

O_1	1 - 0 in.	Decomposing needles.
O_2	0 - 2 in.	Black (10YR 2/1) loamy mor humus; friable and spongy; fine granular structure; abundant roots and mycorrhiza; distinct wavy boundary.
A_2	2 - 7 in.	Light grey (10YR 6/1) silt; friable; massive with some fissures; abundant roots but few mycorrhiza; distinct irregular boundary.
B_1	7 - 13 in.	Pale brown (10YR 6/3) silty clay with many light grey (10YR 6/1) and brown (10YR 5/3) mottles; firm and slightly stricky; weakly developed fine nutty structure; abundant roots; indistinct boundary.
B_2	13 - 18 in.	Brownish yellow (10YR 6/6) silty clay with a few brown (10YR 5/3) mottles; firm and slightly sticky; moderately developed coarse nutty structure; abundant roots; indistinct boundary.
C	18 - 24 in.	Pale brown (10YR 6/3) silty clay; firm; massive; few roots.

CLASSIFICATION: Podzolized northern yellow-brown earth.

APPENDIX 2A

PHOSPHATE LEVELS* EXTRACTED BY A RANGE OF CHEMICAL EXTRACTANTS (UNFERTILIZED PLOTS)

PLOT IDENTIFICATION	BRAY NO. 2	OLSEN	OLSEN MODIFIED	BROMINE OXIDATION	TRUOG	TRUOG MODIFIED	$T_2 - T_1$	ACETATE	RESIN	TOTAL
A 98	1.96	0.55	1.64	1.09	A	3.10	3.10	0.15	0.44	266
A 98/4	1.03	0.94	2.22	1.28	A	3.36	3.36	0.29	0.92	142
A 95	1.45	1.11	2.20	1.10	A	2.28	2.28	0.15	0.92	192
A 96	1.50	0.70	2.04	1.34	A	2.32	2.32	0.15	0.62	222
A 97 C	1.49	0.50	1.54	1.04	0.77	2.52	1.75	0.15	0.62	236
A160/9	1.99	1.09	2.23	1.14	A	3.92	3.92	0.17	0.62	139
A 90 C	2.00	1.66	3.44	1.78	A	8.25	8.25	0.04	2.20	163
A100	1.94	1.48	2.30	0.82	0.72	10.90	10.18	0.92	2.55	98
A101	1.84	0.50	2.15	1.65	A	8.50	8.50	0.48	1.67	90
A103	1.39	0.29	2.04	1.75	A	4.20	4.20	0.08	0.35	113
M	2.22	1.58	3.02	1.44	A	10.00	10.00	0.44	0.88	103
G	2.58	2.56	3.42	0.86	4.80	20.40	15.60	1.47	3.26	110
17	2.42	2.01	3.67	1.66	0.36	14.50	14.14	0.37	2.50	140
19	2.52	2.47	3.44	0.97	1.97	18.80	16.83	0.87	2.29	84
20	2.64	1.57	3.34	1.77	2.86	18.30	15.44	1.47	4.20	89
22	3.90	2.11	4.90	2.80	3.04	22.80	19.76	1.16	4.75	112
24	2.29	0.73	2.45	1.72	0.90	9.70	8.80	0.40	1.85	79
25	3.06	1.55	4.05	2.50	2.16	16.00	13.84	1.19	3.38	87
42	6.35	4.40	8.30	3.90	7.15	35.60	28.45	4.10	7.25	133
60	3.74	2.42	4.80	2.40	3.74	27.20	23.46	2.24	5.80	103
62	4.00	2.50	7.80	5.30	3.08	11.80	8.72	1.22	6.90	280
65	4.50	2.54	5.60	3.06	0.37	15.00	14.63	0.70	6.10	179
69	3.62	3.23	4.77	1.50	3.56	30.00	26.44	2.11	4.85	118
70	3.93	3.43	5.52	2.09	1.26	24.80	23.54	0.88	4.30	138
71	4.95	2.86	4.05	1.19	6.80	19.80	13.00	1.78	5.30	90

*Expressed as p.p.m. of oven dry soil   A - Undetectable

cont:-

APPENDIX 2B

PHOSPHATE LEVELS EXTRACTED BY A RANGE OF CHEMICAL EXTRACTANTS (FERTILIZED PLOTS)

PLOT IDENTIFICATION	BRAY NO. 2	OLSEN	OLSEN MODIFIED	BROMINE OXIDATION	TRUOG	TRUOG MODIFIED	$T_2 - T_1$	ACETATE	RESIN	TOTAL
A 187 B	2.53	1.49	3.47	1.98	0.90	12.10	11.20	0.57	2.94	101
4	3.52	2.57	6.50	3.93	0.75	10.70	9.95	0.75	4.45	275
7	4.60	2.72	7.40	4.68	3.56	14.50	10.94	1.01	4.75	228
14	3.93	3.66	7.10	3.44	1.65	20.50	17.85	1.02	5.7	244
45	3.70	2.84	4.65	1.81	2.16	17.70	15.54	1.12	4.7	104
47	2.48	1.92	6.40	4.48	2.57	2.95	0.38	0.28	1.32	135
53	3.40	1.70	4.30	2.6	2.58	10.50	7.92	0.53	2.55	129
55	3.55	2.22	5.00	2.78	2.55	12.80	10.35	1.05	3.38	130
56	2.65	1.53	4.50	2.97	1.45	6.35	4.90	0.61	1.80	94
57	2.06	1.45	3.76	2.31	5.60	9.95	4.35	0.44	2.02	118
63	3.80	2.08	5.50	3.42	3.60	16.60	13.00	0.72	3.26	105
64	2.60	1.43	3.86	2.43	2.86	21.60	18.74	0.10	5.00	93
67	1.86	1.35	3.92	2.57	2.73	8.40	5.67	0.24	1.10	115
68	2.34	1.16	3.40	2.24	0.36	9.80	9.44	0.32	1.28	117
73	2.57	1.56	3.38	1.86	2.16	12.60	10.44	0.60	1.89	88
75	2.42	1.70	4.90	3.20	A	13.00	13.00	0.50	2.07	226
81	3.60	2.34	6.25	3.91	8.00	11.70	3.70	0.56	2.50	190
86	2.22	1.43	3.07	1.54	A	7.30	7.30	0.40	1.85	121
89	2.70	1.23	3.60	1.37	0.74	4.25	3.51	0.24	1.80	148
90	4.35	5.00	11.20	6.20	6.25	62.50	56.25	4.55	11.10	142

APPENDIX 3A

SITE VARIABLES OF UNFERTILISED PLOTS

SITE VARIABLES (ABBREVIATED AS IN TABLE 4.5)

PLOT	P.M.Ht	VOLUME	FOLIAR P%	SLOPE	ASPEC	MYCOR	EXDRN	pH	MOCON	CLAY	SILT	FSAND	O.M.	B.D.	FLDMO
A 98	58	3429	0.067	7.0	1	II	IV	5.45	9.18	52	27	31	18.4	0.63	45.5
A 98/4	41	1117	0.058	12.0	5	I	II	5.00	5.32	52	26	29	13.0	1.04	31.6
A 95	56	2278	0.064	7.0	3	II	II	5.15	7.64	58	26	26	18.3	0.85	32.4
A 96	58	2294	0.059	2.0	1	II	IV	5.35	9.02	50	29	27	18.7	0.66	32.2
A 97 C	54	2533	0.073	3.0	1	II	III	5.55	8.68	48	29	33	19.0	0.65	33.4
A160/9	52	1848	0.054	6.0	1	I	II	5.05	5.78	53	25	31	11.3	0.95	28.0
A 90 C	55	1346	0.055	9.0	5	I	I	4.60	4.16	60	23	27	13.7	0.94	35.6
A100	28	567	0.055	9.5	2	I	II	4.45	1.86	31	28	51	6.7	1.16	26.4
A101	18	153	0.058	10.5	8	I	II	4.55	2.24	35	30	45	6.4	1.21	26.0
A103	30	377	0.055	5.0	1	I	I	5.20	3.64	42	30	37	5.8	1.00	32.3
M	66	2290	0.071	12.0	2	II	III	4.65	2.06	33	23	52	6.5	1.30	20.5
G	95	9833	0.081	9.0	1	IV	III	3.95	1.16	29	26	54	6.7	1.11	19.0
17	110	10455	0.070	24.0	5	IV	IV	4.50	3.86	46	22	42	11.7	0.94	16.6
19	60	1084	0.060	4.0	5	I	I	4.05	1.56	30	21	58	7.5	1.04	26.8
20	53	1312	0.061	9.0	1	I	III	4.30	1.24	23	32	54	6.5	1.07	28.0
22	88	7220	0.079	7.0	3	III	II	4.40	2.00	27	29	52	7.9	1.19	23.0
24	64	2069	0.050	12.0	4	I	I	4.65	2.14	32	30	48	6.0	1.24	23.3
25	80	5095	0.067	10.0	1	III	II	4.45	1.16	30	24	55	5.5	1.18	22.4
42	120	15210	0.122	11.0	7	II	III	3.70	1.10	22	27	58	7.5	1.03	24.6
60	99	7419	0.076	5.0	5	IV	IV	4.15	2.78	23	30	56	5.2	0.95	24.8
62	103	10444	0.086	4.0	7	IV	IV	4.10	3.98	47	27	35	21.2	0.71	33.5
65	151	17294	0.103	14.0	8	II	IV	4.55	4.02	43	35	30	10.2	1.06	27.4
69	131	13837	0.107	8.0	6	II	IV	3.80	1.62	26	33	47	4.5	1.20	28.4
70	138	17613	0.118	17.0	6	IV	III	4.05	2.32	35	26	48	8.7	1.09	23.3
71	92	4299	0.063	12.0	6	II	III	4.20	1.20	34	29	46	5.3	1.47	20.8

APPENDIX 3B

SITE VARIABLES OF FERTILIZED PLOTS

SITE VARIABLES (ABBREVIATED AS IN TABLE 4.5)

PLOT	P.M.Ht.	VOLUME	FOLIAR P%	SLOPE	ASPEC	MYCOR	EXDRN	pH	MOCON	CLAY	SILT	FSAND	O.M.	B.D.	FLDMO
A187 B	65	3067	0.074	8.0	2	III	IV	4.40	2.58	40	29	42	12.2	1.06	21.0
4	125	6925	0.107	11.0	5	II	IV	4.65	6.30	40	45	25	17.6	0.83	28.6
7	122	7086	0.102	0.0	9	II	IV	5.10	2.84	32	30	46	11.5	1.00	25.9
14	113	7924	0.117	6.0	7	II	IV	4.45	4.54	56	27	29	14.3	0.91	24.4
45	87	4630	0.082	9.0	8	IV	IV	4.45	1.88	31	26	56	7.7	1.27	20.9
47	52	1509	0.078	3.0	8	IV	III	4.90	4.20	52	26	33	12.5	1.08	25.6
53	74	2204	0.069	14.0	2	II	II	4.80	4.72	43	33	33	9.4	1.10	26.4
55	76	2591	0.096	14.0	1	IV	III	4.60	3.48	36	29	45	8.8	1.14	26.3
56	52	1001	0.063	7.0	1	II	II	4.70	2.94	50	31	30	19.6	1.11	24.2
57	50	760	0.053	7.0	4	I	I	4.65	2.50	41	35	33	8.5	1.14	27.2
63	90	5617	0.094	17.0	4	IV	III	4.55	2.28	35	34	39	7.5	1.23	24.8
64	74	3212	0.079	15.0	4	III	III	4.30	1.46	29	30	50	7.1	1.25	22.1
67	52	805	0.056	9.0	5	I	I	4.80	3.20	53	25	32	9.9	1.05	34.2
68	63	2220	0.059	6.0	5	II	II	4.85	2.92	42	32	35	6.9	1.21	24.3
73	84	7501	0.060	12.0	3	II	III	4.55	2.20	36	27	45	6.4	1.23	19.1
75	87	4028	0.069	11.0	3	II	III	4.55	6.40	59	27	23	10.9	1.00	29.4
81	120	10214	0.112	6.5	5	III	IV	4.45	2.46	41	34	33	10.4	0.95	21.8
86	55	1282	0.060	14.5	8	I	II	4.75	3.52	52	28	30	10.6	1.14	27.6
89	70	3489	0.059	9.0	1	II	IV	4.80	4.38	48	29	32	12.4	0.87	25.4
90	122	6443	0.117	0.0	9	IV	IV	3.70	1.82	25	43	42	9.6	0.94	26.2