A STUdy of Soil Sequences
In Relation to the Growth
of Pinus Radiata in Nelson

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I

INTRODUCTION
This study has two principal aims; firstly to investigate the effect of topography and in particular erosion as a soil-forming factor and secondly to investigate the reasons for the existence of Pinus radiata showing symptoms of nutrient deficiency in Nelson.

Hans Jenny in his book "Factors of Soil Formation", wrote "Topography as a soil-forming factor has not received the attention it deserves. It is true, of course, that a considerable amount of information on runoff and erosion in relation to slope is at hand, but it deals primarily with the removal and destruction of soil and not with soil formation."

This statement, made nearly 30 years ago, is still true. One method of assessing the importance of topography as a soil-forming factor is the recognition and investigation of a Toposequence wherein the remaining four soil-forming factors are kept constant or ineffectively varying. Observed differences between the soils of the sequence are then considered to be the result of differences in topography since the initial point of soil development. One such sequence had been identified in 1964 by Mr.E.J.B. Cutler of the Soil Science Department, Lincoln College on strongly weathered granite at Kaiteriteri. In addition, another was postulated within the Mapua hill soils developed on the seaward end of the Moutere gravels, an area of very old, very strongly weathered and leached alluvial greywacke gravels in Nelson. Associated with both these postulated sequences was Pinus radiata showing nutrient deficiencies and consequent variations in growth.

This study is probably the first to thoroughly investigate
differences in soil development attributable to the down-cutting effects of erosion exposing fresh parent material for soil development. Each erosion cycle has provided a new groundsurface for profile formation and, taken together, the various groundsurfaces identified provide a soil sequence where the gains, losses, transformations and redistribution of many organic and inorganic parameters are attributable to the effects of relief in general and erosion specifically.

The strong weathering and leaching undergone by even the youngest groundsurface in both sequences means that the stage of soil development encompassed in this study is considerably more advanced than in most other sequence studies. These have tended to concentrate on the rate of build-up of organic matter and associated fractions in relatively young soils. One exception is the study by P.R. Stevens of a chronosequence of soils near the Franz Josef glacier in Westland, which covers a range of soil development from zero time to a strongly podzolised profile. The present study includes stages of soil development even more advanced than those in Stevens' work.

The second part of the study is part of a widespread research programme being carried out by members of the New Zealand Forest Research Institute and Lincoln College into the underlying causes of a possible decline in productivity on the poorest sites in Nelson, following felling of the first crop of *Pinus radiata*. If this fall-off in productivity is indicative of a future general decline in other areas of low fertility the implications for the expanding New Zealand forestry industry would be quite serious. For this reason, considerable effort has been and is being expended to investigate the problem in Nelson. Recent work by Dr. H. Holstener-Jorgensen in the area has shown that the postulated productivity
decline in the area may be a result of different establishment practices between the two crops rather than an irreversible decline. Consequently the present study has tended to concentrate on the causes of the undoubted growth differences present within the regeneration crop. A combination of methods was used to investigate this problem as well as the causes of similar nutrient deficiencies in young planted *Pinus radiata* growing on areas of the Kaiteriteri granite soils.

The thesis follows the traditional form with an extensive review of literature covering previous studies of topo- and catenary sequences with a section devoted to the influence of relief as a soil-forming factor and the evolution of landscapes, particularly hillslopes. Field work and analytical procedures are covered in the section on materials and methods which is followed by the presentation of results and ensuing discussion. Literature references, Tables, Figures, Plates and Appendices are bound in a separate volume.

It is relevant to comment upon the value of such a study. The identification and study of monofunctional soil sequences is a prerequisite to the understanding of the processes of soil formation. All sequence studies suffer from the assumption that it is possible to say definitely that all other factors of soil formation have remained constant during the development of the soils concerned. However, this does not diminish the usefulness of the physical, chemical and mineralogical information which can be gained from the study of such sequences. The information concerning these soils and the foliage data obtained should prove valuable in helping to elucidate the problems of forestry management which have and will undoubtedly continue to appear in future years in the Nelson province.
II

REVIEW OF LITERATURE
II 1. SOIL FORMATION

II 1.1 Theoretical Considerations

Dokuchaev's original theory of soil formation was expressed in the equation:

\[ \Pi = (K, o, \gamma) B \]

where \( \Pi \) = soil, \( K \) = climate, \( o \) = organisms, \( \gamma \) = geologic substratum and \( B \) = age of soil.

Dokuchaev also recognised the importance of relief although no relief factor appeared in his equation.

Dokuchaev's work was used as a basis by Jenny in a series of papers (1941, 1946, 1958, 1961), in which he attempted to give pedology a more quantitative background. Jenny (1941, 1946) evolved a Fundamental equation of Soil-Forming factors:

\[ S = f (cl, o, r, p, t) \]

which considered any soil property, \( S \), to be a function of the five soil forming factors:

\( cl \) = environmental climate

\( o \) = organisms and their frequencies

\( r \) = topography, also including certain hydrologic features (e.g. water table).

\( p \) = parent material, defined as the state of the soil at the soil formation time zero.

\( t \) = period of soil formation (time).

Any other additional factors are signified by the incomplete nature of the function. The five soil-forming factors as defined by Jenny are independent variables that define the soil system.
In two subsequent papers, Jenny extended his ideas to include the ecosystem. In his 1958 paper, he illustrated sequences and functions of soil-forming factors with large hypothetical models of ecosystems and in 1961 extended this approach by developing a general State Factor Equation based on the fluxes and potentials of matter and energy through the boundaries of the ecosystem. This equation had the form:

\[ l, s, v, a = f(Lo, Px, t) \]

i.e. ecosystem properties \( l \), soil properties \( s \), vegetation properties \( v \), or animal properties \( a \), are a function of

1. The initial state of the system \( Lo \) (PM and topography).
2. The external flux potentials \( Px \) (climate and biotic factor.)
3. The age of the system \( t \).

Thus for soils alone, the state-factor equation reduces to the Fundamental Equation of soil-forming factors viz.

\[ S = f(cl, o, r, p, t) \]

On differentiation of this equation, considering all the variables as independent, one obtains the partial equation:

\[ \frac{ds}{dt} = \left( \frac{dS}{dc} \right)_{o,r,p,t} dc + \left( \frac{dS}{lo} \right)_{cl,r,p,t} do + \left( \frac{dS}{lr} \right)_{cl,o,p,t} dr + \left( \frac{dS}{lp} \right)_{cl,o,r,t} dp + \left( \frac{dS}{lt} \right)_{cl,o,r,p} dt \]

It follows that the degree of change in any soil property depends upon the sum of the total changes in the soil-forming factors, while the magnitude of the partial derivatives are indices of the relative importance of the individual factors. Further, by keeping all factors but one constant or ineffectively varying, Jenny considered it should be possible
to discover the role played by each of the soil-forming factors. Jenny (1946) had noted the difficulty of satisfying the required constancy of factors in the field but suggested that "useful approximations to single-factor functions within a given area may be obtained when the amount of change of a soil property (S) conditioned by one factor greatly exceeds the changes conditioned by all of the others."

Jenny felt that the quantitative solution of the soil-forming factor equation was "one of the most fundamental problems of theoretical soil science." Both Jenny himself (1960) and other authors (e.g., Harradine and Jenny 1958), have successfully applied statistical methods to the relationship between soil properties and state factors, using the functional, factorial, approach described above.

Jenny's ideas have been discussed by Major (1951), Crocker (1952, 1959) and Stephens (1947, 1951). Major extended Jenny's theories to plant ecology and developed the equation

$$V = f (c_1, o, r, p, t)$$

where $$V$$ = specific properties of a plant community. However Major and Crocker's greatest contribution was in clarifying the concept of the biotic factor. Crocker (1952) critically discussed Jenny's theories in some detail. He concluded that polygenetic soils were the rule, rather than the exception, and that monosequences, where only one factor effectively varied, were likely to be both short and approximate. He agreed with Jenny that although studies of polygenetic soils could yield useful information, the searching out of monosequences and their subsequent study was amongst the foremost tasks facing pedology.
Much discussion has centred on the independence or otherwise of the five soil-forming factors. Stephens (1947) and Nikiforoff (1942) felt that the factor Time was the only truly independent variable. Enlarging upon an equation by Wilde (1946)

\[ s = \int (g, e, b) \, dt \]

where \( g = \) geological substrate, \( e = \) environmental influences, \( b = \) biological activity and \( t = \) time, Stephens suggested the modified equation:

\[ s = \int f (c, o, r, w, p) \, dt \]

in which \( c, o, r, w \& p \) can have both dependent and independent status and \( w \) represents the water-table. By considering all the terms in Jenny's fundamental equation plus \( w \) (water-table) to be either dependent or independent, Stephens developed a set of simultaneous equations of partial differentials. The sum of these represented the soil property being considered.

However, Stephens, together with several other authors, appears to have misunderstood Jenny's objectives. As Crocker (1952) pointed out; "In selecting his soil-forming factors, Jenny chose those capable of acting independently and he stressed that it was not necessary that these factors never enter functional relationships among themselves. It is clear, however, that he never intended them to be used in any functional way, except as independent variables."

In a later paper, Stephens (1951) formulated equations in terms of soil-forming processes. Crocker (1952) questioned how this could achieve anything unless the soil-forming factors were fully understood first.

Jenny (1941) discussed the concept of soil maturity and noted that
not all soil components approach maturity at the same rate or at the same point in time. Jenny considered that a soil property was in equilibrium with the environment when \( \frac{\Delta s}{\Delta t} = 0 \) where \( \Delta s \) denotes a change in a soil property and \( \Delta t \) a time interval. However \( \Delta t \) must be large or true equilibrium may be confused with slow reaction rates. Jenny also mistakenly assumed that a solum is immature so long as water continued to pass vertically through it.

Much Russian work, previously unavailable, has been presented in the monograph by Rode (1961). He gave the name "comparative geography" to the sequential method of studying soils wherein the postulation is that the consecutive members of a sequence have undergone similar changes to those of preceding sequence members. He stressed that the method is not conclusive since it is impossible to say definitely that all other factors of soil formation have remained constant during the development of the soil.

To the five soil-forming factors established by Dokuchaev, Rode added three more; the earth's gravity, water (surface, soil and ground), and the economic activity of man. All eight factors determine the trend and character of the soil-forming process. Rode considered that the eight factors could be divided into separate types. Thus PM, climate, organisms, water and man's economic activity are sources of matter and energy; gravity is a source of energy; topography is the agency which redistributes the matter and energy and time is a separate factor governing the influences of the other factors on the soil, until an apparent steady state is reached.

Rode considered that the soil-forming process was basically cyclic
with each cycle contributing some residual change in the soil representing the result of that particular cycle. These residual changes are irreversible and hence irreversible processes are an inevitable feature of soil formation. The same argument can be applied to the biogeocenose (ecosystem), which Rode also insisted could never reach a state of true equilibrium. He postulated that, with constant external conditions, the process of soil formation proceeds in the course of time with declining speed. Initially, during the period of actual soil formation, the process proceeds relatively fast, but later soil formation proceeds significantly slower (often giving the illusion of coming to a halt). He concluded that rates of change during this second period could become so slow as to become undetectable.

Simonson (1959) developed a generalized theory of soil genesis in which he suggested that soil genesis be considered as 2 overlapping steps viz. the accumulation of PM's and the differentiation of horizons in the profile. Horizon differentiation was ascribed to additions of organic matter, removals of soluble salts and carbonates, transfers of humus and sesquioxides and transformations of primary minerals into secondary minerals. He postulated that these kinds of changes, as well as others, proceed simultaneously in all soils. The balance between the combination of changes and their relative importance governs the ultimate nature of the soil profile.

Simonson's concept has been extended by Arnold (1965) to the formulation of multiple working hypotheses in soil genesis. Arnold used pictorial models to illustrate soil formation and the action of the soil-forming factors.

It is thus apparent that Pedology has passed from being a purely
descriptive, qualitative subject to one bearing some claim to the title of a quantitative science. The study of soil sequences and soil profile development are only two indications of this progress. Walker (1965) demonstrated the inherent possibilities of quantitative pedology in a discussion of various chrono-, climo- and lithosequences. The place of man as a soil-forming factor was also discussed. Walker related the various soil-forming factors to the significance of phosphorus in pedogenesis, and to the gains, losses and redistribution of matter due to the various soil-forming processes.

Barshad (1964) has discussed the chemistry of soil development at some length. He placed much emphasis on establishing uniformity of PM prior to measuring changes occurring during soil formation. Barshad's methods essentially involve the idea that the clay fractions are the products of weathering and the non-clay fractions are the reactants. He detailed soil analyses necessary to obtain data for evaluating profile development, and discussed at some length, methods for evaluating clay formation and clay migration. After applying his methods to a large number of soils, he reached the following conclusions about the relationships between clay formation, clay migration and the factors of soil formation:

1. Clay formation decreases down the profile, except that maximum clay formation is not at the surface but in an intermediate horizon.

2. Clay migration is the most important process in the occurrence of any horizon of clay accumulation or clay-pan formation.

3. In the transformation of a parent material to a soil material,
clay formation is mainly responsible for the changes in mineralogical composition, but clay migrations, reflected by losses or gains of clay, are mainly responsible for the changes in chemical composition.

4. An increase in both temperature and rainfall increases total clay formation of a given PM.

5. Topographical conditions which decrease the effective drainage of a soil appear to enhance rates of clay formation.

6. Grass-type vegetation is more effective in promoting clay formation than tree-type vegetation.

7. The effect of igneous, metamorphic, or sedimentary parent materials, is important only insofar as the properties of mineralogical and chemical composition, mineralogical texture, porosity, density, structure and fabric, and degree of consolidation are affected.

8. Even under the most intense weathering conditions, as in Latosols, the annual rate of clay formation is very small, ranging from 0.001 to 0.002 g per 100 g. of PM.

Finally mention must be made of two other equations of soil formation which have appeared in the literature. Shaw (1930) produced the equation

\[ S = M ( C + V )^T + D \]

where \( S \) = soil, \( M \) = PM, \( C \) = climatic factors, \( V \) = vegetation, \( T \) = time and \( D \) is a modifying factor introduced to cover modification of the land surface by erosion or deposition.

Nikiforoff (1942) considered soil formation processes to be basic-
ally cyclic. Synthesis must be accompanied by decomposition, accumulation by leaching, any kinds of gains by losses and vice versa. Using this approach, he produced a general formula for the process:

\[ S_n = S_1 (1 - r)^n + A \left[ \frac{1 - (1 - r)^n}{r} \right] \quad (1) \]

where \( S_n \) = amount of a given substance after \( n \) years.

\( A \) = amount of the same substance synthesized in 1 year.

\( r \) = rate of decomposition expressed as a decimal portion of the amount present.

\( S_1 \) = amount of substance present at the beginning of the process.

\( n \) = number of years.

It is assumed that \( A \) is constant and \( r \) is a function of \( S \). The limiting value of equation (1) as \( n \) approaches infinity is:

\[ S_n = \frac{A}{r} \quad (2) \]

The derivation of any of these formulae is not given, although Nikiforoff's equation (1) is simply a geometrical progression formula applied to a pedological situation. However, the limiting case - equation 2 - appears to be potentially useful. The merit of Shaw's equation must be doubted. Besides its questionable derivation, the definition of the terms in it are so broad as to be meaningless in practice.

Of all the theoretical models of soil formation discussed in the preceding pages the work of Jenny appears to have gained the most widespread recognition. The following sections will attempt to relate the concepts of Jenny to the study of toposquences in general, including a discussion of catenary sequences as well as clino- and toposquences.
The Glossary of Soil Science Terms (1965) defines a toposequence as:

"A sequence of related soils that differ, one from the other, primarily as a result of topography as a soil-forming factor."

A stricter definition might be:

"A sequence of related soils formed on similar parent materials over the same time interval under conditions of similar climate and biotic influences, whose differences in properties are due to variations in topography over the period of soil formation."

If the Fundamental Equation of soil-forming Factors (Jenny 1941, 1946):

\[ S = f (c_l, o, r, p, t) \]  

is evaluated for topography a toposequence is defined as:

\[ S = f (r) c_l, o, p, t \]  

That is the magnitude of any soil property \( S \) is a function of topography if the soil-forming factors climate, biotic factor, parent material and time are kept constant or ineffectively varying.

Jenny (1946) noted that the factor topography was of a complex nature including the degree, shape and length of slope, aspect, plus certain hydrologic features, commonly referred to as drainage.

To a first approximation slope \( i \) and water table \( w \) can be regarded as independent variables and the function

\[ S = f (r) c_l, o, p, t \]  

may be rewritten as:
\[ S = f(i, w) \] cl, o, p, t ---

where \( i \) = slope

and \( w \) = water table

Now, in conditions where \( \frac{\partial S}{\partial w} \rightarrow 0 \) i.e. where the presence or otherwise of a water table has no influence on soil formation, equation (3) reduces to:

\[ S = f(i) \] cl, o, p, t ---

Equation (4) defines a **clinosequence** where soil properties \( S \) depend on differences in slope, with the other factors ineffectively varying.

In conditions where \( \frac{\partial S}{\partial i} \rightarrow 0 \) equation (3) reduces to:

\[ S = f(w) \] cl, o, p, t ---

Equation (5) defines a hydrofunction.

The situation where equation (3) is obeyed defines a **catena**. This is a sequence of soils where the soil properties are a function of both the slope and the water table with the other soil-forming factors ineffectively varying.

The concept of the catena as a soil sequence was originally introduced by Milne (1935) for use as a unit of mapping convenience. Bushnell (1945) considered that this concept built up from concrete mapping units and sequences derived by analysis of the principles of soil formation were complementary.

The catena as described by Milne (1935) consists in its simplest case of a topographically determined set of soils, originating from the weathering of a single P M under the influence of normal erosion. The
essential feature is the tendency to mechanical fractionation and elutriation of the weathering products down the slope by the action of rainfall, and consequent leaching.

Milne originally distinguished two kinds of catenas: the one developed from a single parent material and the other formed from two or more parent materials occurring at different elevations. At the same time Milne made it clear that a repetitive pattern of soils dependent on rock outcrops but unrelated to differences in level was not a catena. Bushnell (1942) published a letter he had received from Milne agreeing that the term catena should be restricted to soils on similar parent materials, defined so as to include both residual and colluvial deposits within one catena. Similarly Bunting (1953) considered it wrong to apply the term catena where soil differences result from pedogenesis in situ over various parent rocks, but he regarded different kinds of parent materials formed by denudation processes as part of the catena concept. Griffith (1952) strongly opposed restriction of the term catena to a sequence of soils on similar parent materials or parent rocks.

Milne's original concept of the catena involved the component soils of the sequence being associated geographically in a continuous sequence. However, Bushnell (1942) redefined the term catena to include soils of all possible hydrologic situations on a given P M under a uniform climate, whether or not the soils were associated together in a continuous sequence. Calton (1952) suggested examples of catenas extending through several climatic zones but both Bunting (1953) and Watson (1965) agreed that uniform climatic conditions were an essential feature of Milne's catena concept. Watson felt that the catena concept should remain as originally
defined and that other types of soil topographic association should be given new names.

The distinction between Milne's (1935) definition of a catena and Bushnell's (1942) definition should be recognised. Milne's concept has been applied almost exclusively in tropical areas whereas Bushnell's definition, which depends more on the influence of varying drainage conditions on soil profile development, has been used mainly in temperate climates, particularly the United States.
II 2.2 Clino- and Toposequences.

It is the purpose of this section to review the very small number of papers that deal with the study of toposequences. None of these papers deals with the subject from the point of view that Jenny expressed viz: a study of how topography affects soil properties when the other four soil-forming factors are kept constant or ineffectively varying. Some of the conclusions and facts cited will therefore be an attempt by the present author to reinterpret the papers from a sequential point of view.

Acton (1965) in a discussion of the influence of topography on soil type in Western Canada, recognised five soil types on a glacial landform. The type of soil occurring on a particular slope segment was found to be influenced by the gradient of the segment as well as the position of the segment in the entire slope. Willen (1965) showed that soil texture and erodibility indices were significantly related to variation in parent rock type, vegetative cover type, aspect, slope, and elevation. Lee et al (1964) studied an altitudinal soil sequence in Ireland where the present parent material is associated with the dynamism of a former and, to a lesser degree, a contemporary regime of an erosional, depositional sequence. Topographically, the area is dominated by a strongly to steeply sloping landscape (18-24°), ranging to 35° at the top of the slope. The depth of profile showed a sharp drop on the steepest slopes with a similar sharp drop in silt and clay content. Norton & Smith (1930) found a similar effect on the forested loessial soils of Illinois. A strong negative correlation between depth of the A horizon and the slope was noted. White (1964) in a discussion of the age relationships of wavy-gilgaied and non-gilgaied soils in Western South Dakota found that
wavy-gilgaied soils were most abundant where erosion was least, and thus the soil age was greatest, whereas lithosols were most abundant where erosion was greatest and the soil age was least. Non-gilgaied chestnut soils occurred in both locations, presumably where the soil age was intermediate.

The postulation that the most strongly weathered soils should exist on the highest, least sloping and most stable land surfaces, whereas less strongly weathered soils should occur where surface run-off increases, on more steeply sloping younger surfaces formed by slope retreat, is thus quite often found in the literature. However, in some situations, some other variable factor may upset the expected pattern.

Cunningham & Drew (1962) studied a sequence of three soils that have developed in loess under free drainage conditions. The soils appeared at first to represent a soil-relief sequence with differences due to variations in erosion and landsurface age. Thus Moody soils on the broad, round-topped divides grade to Nora & Crofton soils in a downslope direction as slopes get steeper. However, at the bottom of the slope it was found that the sequence repeated itself in reverse order. Differences in P M were shown to be the main reason for this, with the soils being formed on two loessial mantles of different age. Thus the soils appear to constitute a clinoquence modified by the effect of a variable P M. A similar effect was noted by Al-Janabi and Drew (1967) who found the expected theoretical pattern reversed in a Nebraskan sequence, also developed on loess. They explained this in terms of (i) a moisture regime more favourable for clay formation on lower slopes compared with higher slopes and (ii) a slower rate of accumulation of medial to late
Wisconsin loess on bevelled, lower slopes than on higher elevations.

Parsons & Balster (1966) have studied a range of soils in Oregon developed on several distinct geomorphic surfaces with slope gradients ranging from 2% to 100%. Soils on pediment remnants exhibited the greatest development as evidenced by clay films, grades of structure and low base saturation. Soils on abrupt slopes tended to be shallow and rocky with weak horizonation and appeared to have developed from the eroded remnants of soils on moderate slopes. This sequence of soils, occurring within a fairly small area, could be considered to be a toposquence or even a clinosequence as defined by Jenny, although constancy of parent material would need to be investigated further.

The importance of the careful use of nomenclature in sequence studies can be illustrated with reference to two papers by Floate (1965) and Lee & Ryan (1965). Floate (1965) investigated the distribution of O.M. and various phosphorus fractions in a topographic sequence of soils in Southern British Columbia. Although it may seem to be a toposquence study, and has been interpreted as such by some authors (Stevens 1968), the soil properties studied were interpreted by Floate himself as being the effects of climate, modified by elevation, aspect and vegetation on weakly weathered P M's. Lee & Ryan (1965) purportedly studied a clinosequence of soils on a drumlin landscape in Ireland. A clinosequence as defined by Jenny (1946) is a sequence where soil properties are a function primarily of slope factors, water-table and drainage factors having a negligible effect. The authors conceded the importance of drainage to this sequence, stating it to be the dominant difference between members of the sequence. Thus, following Jenny's nomenclature, one must term the sequence a toposquence rather than a clinosequence.
Most of the above studies have been primarily concerned with geomorphological changes and the nature of any chemical changes in soils of the different surfaces has been purely subsidiary to the place of the soil or soil sequence in the general landscape pattern. Jenny (1941) stated that "topography as a soil-forming factor has not received the attention it deserves. --- a considerable amount of information on run-off and erosion is at hand but it deals primarily with the removal and destruction of soil and not with soil formation." As can be seen from the above discussion, Jenny's comments, expressed nearly 30 years ago, are still substantially true.
2.3 Catenary Sequences.

The recognition and study of catenas has been attempted by many workers in recent years. It is intended in this section to briefly review some of these studies.

Morison et al (1948) in a study of soil-vegetation catenas and mosaics in S.W. Sudan, showed that over large areas the development of the soil on any site was mainly determined by the local topography through its effect on water movement. The effect was most marked in medium rainfall areas of the tropics, especially where slopes were not very abrupt and \( P_M \) was uniform. Vegetation on any particular site reflected its position in the catena. This last feature was confirmed by Lang Brown & Harrop (1962) in Uganda.

Morison et al also suggested three main soil complexes as forming the catena. These were:

(i) Eluvial complex occupying higher level sites which provides the material from which other complexes are built up.

(ii) Colluvial complex which occupies the slope, receives material from the eluvial complex, and loses some of it to the illuvial complex.

(iii) Illuvial complex occupying the lower level sites.

Different authors have expressed differing opinions on the mode of soil formation in tropical catenas. Thus Nye (1954, 1955), working in Nigeria, postulated that many profiles have their topsoils derived not from material directly below, but from the subsoil higher up the slope. He suggested that any particular profile must be seen as being in a continuous state of development in which the upper horizons are being removed by creep and constantly renewed by material from the top of the sedentary horizon,
while at the same time and keeping pace with this development, a mass of clay is being washed down the profile through the fabric of decomposed rock.

Webster (1965) in Northern Rhodesia showed that the soils of his catena had developed largely by weathering in situ. Any surface-wash material appeared to be removed by streams rather than contributing to profiles lower down the slope.

Watson (1964/65), working in Southern Rhodesia, postulated discontinuous soil development and suggested that stone layers in his profiles and the soil mantle were polycyclic in origin in contrast to Ruhe's (1959) description of stone layer formation and mantling during a single cycle of erosion. He suggested that although the PM of the mineral and gley horizons had been transported, the general characteristics of the soils indicated a strong relationship with the underlying granite.

Biswas et al (1962 - 1968), 1966) working in India, proposed that, in both the catenas studied, the Parent Rock of their systems had initially weathered to a uniform weathered material. In the next cycle of weathering, the eroded, transported and redistributed produce of the initial weathering constituted the PM which, under the prevailing differential drainage condition, led to the development and formation of the present catena members.

Catenary sequences have been recognised in several other areas of the world besides the tropics. Thus in the United States catenas have been recognised by Brown & Olsen (1949), Brown & Thorp (1942) and Hutcheson et al (1959). McKeague (1965) and Lee and Ryan (1965) have described
catenary sequences in Canada and on a drumlin landscape in Ireland respectively. Mention must also be made of two soil sequences studied respectively by Gunn (1967) in Queensland and by Williams (1968) in the Sudan. Both authors claimed that their sequences constituted catenas. However, in both cases, the sequence extended over more than one P M. Watson suggested that such sequences would better be called by another name, perhaps association.

Chemical and morphological changes within catenas generally mirror the sequential nature of the profiles. Thus Biswas et al (loc cit) found that the silica content decreased while total Al, Mn, Ca and Mg increased. Illite was the dominant clay mineral in the upper and middle profiles of the slope while montmorillonite was dominant in the profile at the base. Montmorillonite content increased and kaolinite decreased down the slope. C.E.C's were indicative of the types of clays present. The amount of clay increased down the slope and the amount of sand decreased - evidence that the coarse fractions were not being transferred down the slope. Changes in soil colour were noted from reddish-brown to dark grey or black concomitant with drainage conditions. This change in soil colour is a common feature of all the tropical catenas previously discussed.

Watson (loc cit), Webster (loc cit) and Nye (loc cit) all found kaolinite to be the dominant clay mineral in their catenas with Nye also showing montmorillonite to be present in the poorer - drained members of his sequence. These three African studies all show slightly different changes in chemistry along the catena, presumably, reflecting the slightly different soil-forming processes postulated for their development. Thus Watson showed a marked drop in both anion and cation exchange
capacity of the subsoils, as one went downslope. Exchangeable Ca and Mg of the subsoils initially rose quite sharply and then fell, while exchangeable Al decreased sharply from the top of the slope to the bottom. Subsoil exchangeable K showed only a slight initial rise, followed by a slight decrease. Low percentage base saturation and high exchangeable Al distinguish the hill-top profiles from the remainder. In contrast, Webster's sequence showed an increase in C.E.C. downslope, although exchangeable Mg and K still decreased, while exchangeable Ca showed an indefinite pattern. A marked drop in free iron in the lower profiles was the most marked feature of the chemistry.

The chemistry of the temperate zone catenary sequences previously mentioned shows some similarity to those of the tropics. Both Hutcheson et al (loc cit) and Wilding & Rutledge (1966) found that clay minerals ranged from dominantly illitic in the better drained members to dominantly montmorillonitic in the poorer drained members of the Memphis & Miami catenas respectively. C.E.C. values consequently increased downslope and base saturation also tended to increase.

Virtually all of the work done on catenary sequences has been concerned with the use of the catena as a soil mapping unit. Chemical and mineralogical data cited has generally been used to confirm the morphological characteristics of the sequence. This is understandable in view of the original development of the catena concept by Milne as an aid to soil mapping and classification.
II 3. LANDSCAPE EVOLUTION

II 3.1 Relief as a Soil-Forming Factor.

Relief can be considered as rather an abstract category of soil-forming influence. It is also complex because the nature of the site where soil formation is occurring modifies all the factors of the environment that act upon the soil. Joffe (1949) considered that the soil-forming factors could be divided into active and passive factors. The passive factors comprising PM, topography and time, determine the mass of material to be acted upon by the active factors, comprising climate and organisms. The indirect influences of topography will not be considered here. The following section is a discussion of the dynamic features of relief as a soil-forming factor and in particular, the influence of erosion and deposition processes on soil formation.

Much work has been done in Australia in recent years concerning the role of erosion-deposition processes in soil and landscape development. Jessup (1961), describing the Tertiary-Quaternary pedologic chronology of the S.E. Australian landscape concluded that "the alternation of pluvial and non-pluvial periods during the Tertiary-Quaternary resulted in periodicity of soil formation and landscape development. Soils were formed during the pluvial periods, when the landscape was protected from erosion-deposition by a well developed vegetative cover. Varying amounts of erosion and deposition occurred during the non-pluvial periods when the vegetative cover was sparser. The Tertiary erosional periods were characterised by water erosion-deposition and major changes of landform. During each of the Quaternary erosional periods, the climate became desertic, there was widespread wind erosion, but little modification of the landscape."
Mulcahy (1960) identified a number of erosional and depositional surfaces in Western Australia. The oldest were lateritic and the characteristics of the laterites and the associated soils were shown to vary with the age of the landsurface on which they occurred.

Lithologic discontinuities resulting from previous phases of soil formation alternating with erosion-deposition phases obviously affect the present soil profile. Ruhe (1959) has demonstrated the significance of stone-lines in the soil profile demarcating transported deposits from bedrock derived material. Stone-lines were postulated as being developed during a single cycle of erosion with an initial deposit of the stone-line and subsequent covering by the following eroded material. However, Watson (1964-1965) has suggested a polycyclic origin for stone-layers in profiles of a Southern Rhodesian catena.

The existence of widespread areas of buried soils throughout the world has led Butler (1959) to develop a framework for soil studies on the basis of landscape periodicity. Butler proposed that a succession of buried soils indicated a recurrent cycle of stable and unstable phases of landscape evolution, which he called a K-cycle. Each cycle commences with an unstable phase (Ku) of erosion and deposition and is concluded by a stable phase (Ks) in which soil formation is initiated on newly exposed erosion surfaces and adjacent fresh deposits.

Soil layering resulting from cyclic events of this kind has been reported in the plains (Butler 1959) and tablelands (van Dijk 1959) of S.E. Australia. Walker (1962 a) found similar soil layering on hillslopes in N.S.W. He identified 3 separate soil systems which he considered to be evidence of a K-cycle soil history. The evidence
suggested that K - cycle instability (Ku) has resulted from a change to relatively dry climatic conditions and had involved processes such as hill-wash, gully erosion and soil creep, whereas K - cycle stability (Ks) was characterised by soil development during relatively humid phases.

van Dijk (1959) also suggested that the cycles of soil formation he described had been initiated by climatic fluctuations.

Walker (1962 b) studied cyclic terraces and their soils developed at the same time as the K - cycle soil layers in the adjacent hill country (1962 a). He has modified Butler's original concept slightly by radiocarbon dating each of the three terraces studied and classifying each as a K - surface deposited at the same time as the corresponding K - cycle of soil formation. Each terrace surface has since developed independently of subsequent erosion-deposition phases, as compared with soil development in the usual K - cycle system where such development is the result of one or more unstable (Ku) and stable (Ks) phases.

Another type of erosion-deposition system has been described by Moss (1965) in Nigeria. Moss discussed the processes involved in the retreat of hardened plinthite breakaways, which account for the principal morphological features of the soils, especially the lower, diagnostic horizons. He showed that erosion of the highest, oldest surface takes place by relatively slow mass-wasting. However, water penetrating this surface percolates through cracks in the hard plinthite layer of the breakaway face. This water washes out the material below the hard band with consequent slumping from above and mass-wasting from the crest, with deposition on the slope below the free face.

The importance of soil creep to soil development has been a source
of speculation for many years. Young (1960) has carried out empirical research into the effect of soil creep, if any, over 3½ years on grassed slopes of various steepness in an English climate. On a 30° slope, downslope movement of about 1 mm / year was recorded. But on slopes greater than 35° with an incomplete cover, rate of movement increased rapidly with increase in slope angle. Most creep occurred in A0 horizons and Young showed that the rate of downslope movement by soil creep was about ten times as rapid as that by slopewash. The relative ineffectiveness of slopewash was explained in terms of the presence of an organic cover, the O1 horizon of grass roots or leaf litter and the O2 humus horizon. Besides the direct protective effect, the above factors also have an indirect effect through water storage during storms. The work of Nye (1954 - 1955) involving the study of a catenary sequence in Nigeria formed on a 5 per cent slope is of interest here. Nye considered soil creep to be the dominant factor in development of the profiles of the various catenary members. Such a view must be doubted when considered in conjunction with Young's experimental data showing the necessity of having quite steep slopes before soil creep becomes a significant factor in soil formation.
3.2 The Development & Evolution of Hillslopes

The importance of geomorphology to pedology has generally been ignored by many pedologists in the past. Woolridge (1949) stressed the importance of geomorphology in giving a surface for soils to form on, besides providing the parent material and also suggested that the soil mapper must take account of the effect of different surfaces on soil development. Ruhe (1960) emphasized that the point of departure for any study leading to a better understanding of the soil should be the recognition and geomorphic evaluation of the elements of the landscape and the relationship of soils to them.

During the first half of this century, hillslopes were generally discussed in the context of the downwearing (declining retreat) concept of Davis or the backwearing (parallel retreat) concept of Penck. The range of geomorphic thought on these two concepts has been well covered in two comprehensive papers (King 1953, Bryan 1940), and will not be discussed further here.

Strahler (1950) published a paper that had a large effect on future methods of hillslope evaluation and threatened to end the previous half-century of speculation. Strahler (1950, 1956) placed the investigation of hillslopes on a quantitative basis for the first time. He proposed an equilibrium theory of erosional slopes, whereby hillslopes maintain an angle determined by "prevailing conditions of climate, vegetation, bedrock and initial relief or stage." Further he concluded that hillslopes can either maintain their form with time or evolve slowly as a dynamic equilibrium is maintained within the landscape. Strahler (1950) also related mean maximum hillslope angles ($S_g$) to stream gradients ($S_c$).
by the relation $S_g = 4 S_c^{0.8}$, thereby demonstrating that steep hillslopes are associated with steep stream gradients and vice versa, and that hillslopes should not be considered apart from the other topographic features of a region.

Hillslope form involves the shape in profile, length and inclination of hillslopes. When hillslopes are observed with some attention to detail, it is evident that most are composed of several segments having different shapes. Hillslope models that have been described in some detail include the two section model of upper convex slope and lower concave slope of Gilbert (1909); the three unit model of crestslope, backslope (midslope) and footslope of Savigear (1960) and Leopold et al. (1964); the four unit model of waxing slope, free face, constant slope and waning slope of Wood (1942) or with different terms and units as suggested by King (1953) and Ruhe (1960). Recently, Dalrymple, Blong and Conacher (1968) have postulated a nine-unit landsurface model developed from observations made in the northern half of the North Island of N.Z.

Except for constructional and tectonic forms, most hillslopes owe their existence to the incision of a terrain by streams. As indicated by Strahler (1950) and Schumm (1956), the resulting hillslope form depends largely on the relief available for dissection, and on the spacing of the drainage channels or drainage density. It can be shown mathematically (Strahler 1950) that the greater the drainage density in an area of constant relief, the shorter and steeper will be the slopes, whereas the greater the relief in an area of constant drainage density the longer and steeper will be the slopes. Strahler (1950) also demonstrated statistically that maximum slope angles do not vary greatly for a sample area.
Thus the form of hillslopes may vary greatly from region to region, but within an area of similar climate and lithology, a characteristic hill-slope form can develop.

Scheidegger (1961) has attempted to use mathematical models to describe slope development. He assumed that lowering of the slope per unit time at any given point was proportional either to a constant, the height of the slope, or the slope itself. Then, by consideration of the vertical vector of weathering normal to the slope, he derived a basic, non-linear, differential equation:

$$\frac{\partial y}{\partial t} = -\sqrt{1 + \left(\frac{\partial y}{\partial x}\right)^2} \cdot \phi$$

where
- $y$ = vertical height.
- $x$ = horizontal distance.
- $t$ = time.
- $\phi$ = action of the slope.

By the use of difference equations and by setting conditions for stability involving $\Delta t$ in terms of $\Delta x$ and $\frac{\partial y}{\partial x}$, Scheidegger obtained solutions which were presented as various diagrams of slopes. The claim was made that "each theoretical model of slope formation proposed is the result of particular, specific, physical conditions. If the various results be compared with actual slopes observed in nature, then such a comparison will provide a means of ascertaining the true physical conditions that have caused the observed slope." However, the lack of any physical parameters in Scheidegger's equation, save those defined above, must lead one to question how the genesis of any particular slope can be discovered by the means suggested. Further refinements of this approach, however, could lead to significant advances in the study of slopes.
Ruhe & Walker (1968) have studied the inter-relation of geomorphic and pedologic processes, in a study of hillslope models and soil formation in both open and closed systems in Iowa. They used mathematical methods to construct landscape models and then fitted soil properties to the model. They found that the vectoral alignment of the soil system versus the hillslope landscape was determinable and showed that given a controlled hillslope model, the soil systems could be reasonably predicted. Their work showed the universality in principle of hillslope models and soil systems, even though absolute geomorphic and pedologic parameters differed. This work, the first to link soil properties with the slope forms they occur on, must be regarded as a definite forward step, in the search to establish predictive relationships between geomorphic and pedologic parameters.

The conceptual models of Penck & Davis were theoretical models of hillslope evolution based on long years of observation. However, Schumm (1966) has pointed out that these models, together with the recently developed theoretical models suffer from a basic fault in that neither type is based on an appreciation of the processes and rates of erosion. Schumm says; "Laboratory experimentation into the mechanics of the flow of water over slopes and the movement and weathering of superficial materials on sloping surfaces is a neglected technique of geomorphic research." This is certainly true and is to be regretted for much could be learned from work of this nature, as occasional attempts have demonstrated (Schumm 1956, Melton 1965, Schumm and Chorley 1966). The possibility of soil engineering research covering such ground appears to have been ignored by geomorphologists.
Some natural studies of landscapes have been performed however, with interesting results. Schumm (1956) showed that some Badland hillslopes retreat in parallel fashion under the action of rainwash but that other hillslopes will decline in angle with retreat under the action of creep. However, the removal of the hillslope sediment from the base of the slope appeared to be a prerequisite for its parallel retreat. Colluvium accumulating at the slope base tended to anchor the base of the slope and a decline in the hillslope angle subsequently occurred.

Carter & Chorley (1961) investigated the development of hillslopes in a small, 6th order, drainage basin eroded into a sandy silt terrace in Connecticut. The authors concluded that slope angles increase during stream incision to a characteristic angle and then remain constant as the streams continue to incise or to keep the base of the slope clear of sediment. When stream activity diminishes, the accumulation of sediments at the slope base permits a decline of the slope angle. Such a sequence of slope steepening, maintenance of a characteristic angle, and decline during slope retreat may also be deduced from the work of Schumm (1956) described above.

Some attempts have been made to equate specific geomorphic processes with specific slope elements. Schumm (1966) has briefly reviewed some of the factors that may result in the development of convex, concave, and straight slope segments on rocks of essentially uniform lithology.

Schumm (1966), in an excellent review of hillslope evolution and development, has discussed the present ideas on the subject. His conclusions coincide with those of Leopold et al (1964), who pointed out the tendency in geomorphology to make a sharp division between the end forms
produced by continuous subaerial denudation in semi-arid and humid regions. Both authors agreed that there is no convincing evidence that certain major landforms are restricted to any given environment. However, much information exists to show that specific processes may vary in their relative importance in different environments. Schumm concluded that, within a given area, there may be a steepening, lessening, or constancy of angles during hillslope retreat, the residual landform depending on the effects of topography, climate, geology, soil and the process operating.

The two inadequacies that stand out most strongly in geomorphic studies are the lack of basic data on fluvial processes and landforms, and the fact that virtually all research has been concerned with regressive surfaces. Considering the importance of accumulative surfaces, this lack of recognition is surprising. The first criticism appears to be recognised by many geomorphologists (e.g. Schumm 1966), and may thus be overcome in the near future. The second criticism, however, may be more difficult to overcome. Unless a radical change in emphasis occurs, (which seems unlikely), it would appear that the study of regressive surfaces will continue to be the dominating interest of geomorphologists.
3.3 The postulated development of the landscape at Kaiteriteri

In its simplest theoretical form, the development of a landscape is associated with one or more erosion cycles, each occupying a discrete portion of time and each being associated with a single new surface. This type of concept has been discussed by Butler (1959) in connection with the use of buried soils as an indicator of periodicity in landscape evolution. Butler saw the pedologist's landscape surface as being a far more specific entity than that of the geologist or geomorphologist and he proposed the term "groundsurface" to represent the materials, soils, and surfaces relating to one K cycle (Section II 3.1). The term groundsurface will be employed in the above context during the remainder of this text.

The Kaiteriteri landscape is considered to have been formed during the period of five K cycles, with each cycle being associated with downcutting into the granitic formation underlying the landscape. Profile differences are considered to be a consequence of each erosion cycle cutting into granite relatively less weathered than that on the previous groundsurface. Following Butler's nomenclature, each of the postulated groundsurfaces is given the designation of that K cycle in which it originated, from the youngest K1 groundsurface to the oldest K5 groundsurface.

The evidence for the postulated landscape development is based on the relatively limited sampling of the present study plus the results of the 1964 soil survey of the Kaiteriteri area by Mr. E.J.B. Cutler (Fig 3.) Overall therefore, the system has been examined quite extensively. It was originally intended to sample two sites on each groundsurface. Four groundsurfaces were initially identified and sampled. However, sub-
sequent analysis of profile data led to a re-evaluation of the landscape and showed that five groundsurfaces had actually been sampled. The postulated relationship between the soils originally sampled and their related groundsurfaces is shown in Table 1.
II 4. DETERMINATION OF NUTRIENT REQUIREMENTS
OF FOREST STANDS

II 4.1 Introduction

The evaluation of site fertility and the assessment of nutrient status and nutrient requirements in forest stands is of great importance to foresters. Tamm (1964) has discussed the commonly-used techniques for such determinations. These are:

(1) Diagnostic plant analysis and visual symptoms of deficiency and excess.
(2) Experimentation in culture experiments of various types.
(3) Soil analyses.
(4) Nutrient balance sheets (use of the total nutrient consumption of a crop as a measure of nutrient demand.)
(5) Experimentation in forest stands.
(6) Indicator plant techniques.

Studies involving Pinus radiata have employed the first five techniques and these will be discussed in the following sections. Unless otherwise stated, all work mentioned in this review concerns Pinus radiata. The vast amounts of research being conducted on tree nutrition precludes any discussion of other Pinus species.
Diagnostic plant analysis

Visual deficiency symptoms are useful for determining gross nutrient deficiencies (Tamm 1964). However, Gentle and Humphreys (1968) have pointed out that such symptoms may be frequently misleading because coincident deficiency symptoms may modify an individual symptom. Visual deficiency symptoms of nitrogen, phosphorus, calcium, magnesium, boron, zinc, manganese and copper have been described for *P. radiata* using culture techniques (Purnell 1958, Ludbrook 1940, 1942, Smith and Bayliss 1942, Smith 1943). With the exception of copper and manganese these deficiencies have also been reported in the field.

Raupach (1967a) has briefly discussed the criteria to be considered in the use of foliage analyses, as a method of determining the nutrient requirements of a forest stand. There must be a significant relationship between growth and the foliar nutrient content when the supply of the nutrient to the tree is progressively restricted. Other requirements are:-

(1) to have an estimate of errors within and between individual trees and between forests.

(2) to sample from material of uniform physiological age.

(3) to choose a sample position in the tree and a time of sampling which are as sensitive as possible with respect to growth changes.

(4) to continue to sample for a number of years if possible over a wide range of ages and tree quality classes in order to arrive at critical nutrient levels having taken account of season, age and tree size.

Results for *Pinus radiata* have generally been expressed as percentages of the oven-dry material rather than as weight of nutrient per needle
in the wet or dry state, and this first method will be considered here. Tamm (1964) gives a detailed and critical discussion of all these points. Tamm considers other important factors to be weather conditions prior to sampling, avoidance of diseased trees, and avoidance of sample contamination, particularly from dust particles and/or industrial pollution.

Will (1957) investigated the variation in six nutrients in the crowns of four trees by sampling various portions of the crown to give needles of differing age. The trees were, however, sampled at different times ranging from December to September. Levels obtained were greater than those previously found by Askew (1937) on a similar volcanic soil except for calcium which was about the same. Calcium, sodium and phosphorus levels increased with needle age while magnesium and nitrogen levels tended to decrease. The percentages of calcium, phosphorus and potassium present in the needles increased towards the base of the crown.

Hall & Raupach (1963), working with 8 year-old trees on a potassium-deficient podzolic soil in Eastern Victoria, also investigated changes in foliage nutrients within trees. They found that foliage contents of nitrogen, phosphorus and potassium tended to decrease with increasing needle age. Ranges of nitrogen and potassium contents were lower than those found by Will but were about the same for phosphorus.

Raupach (1967b) also found that nitrogen and phosphorus levels in the current season's needles increased towards the top of the tree. Raupach also investigated the levels of a number of trace elements in different age-classes of needles. Nickel, copper and zinc were concentrated in the young needles whereas boron, chromium and molybdenum gave higher concentrations in the older needles. Raupach concluded that sampling positions will have to be carefully considered in future work on
the minor elements in foliage.

As a consequence of these investigations New Zealand and Australian workers have adopted the following standard sampling methods. The N.Z. Forest Research Institute uses the method described by Will (1965) in which full length needles are collected in December from the current season's growth from shoots in the upper third of the green crown on young trees and a little above the midpoint of the crown on older trees more than thirty feet high. The New South Wales Forestry Commission uses the following procedure (Humphreys, pers comm.) Needles are sampled in May or June (at the end of the growing season) from the current season's growth in the active crown (preferably the top or second whorl). This method is essentially that recommended by Leyton (1958).

Critical levels for nitrogen, phosphorus, potassium and magnesium have been quoted by Will (1961a) from studies both in culture solutions and in the field. These levels, below which growth was restricted, are about 1.6% for nitrogen, about 0.10% for phosphorus, 0.7 to 1.1% for potassium and 0.08 to 0.11% for Mg. These levels have been modified by Will (1965) as a consequence of more extensive results from several N.Z. forests. Will (loc.cit.) quotes critical levels of 1.5% for nitrogen, 0.11% for phosphorus, 0.4% for potassium and 0.11% for magnesium.

Raupach (1967b) has given percentages of nitrogen and phosphorus for good, marginal and poor growth as greater than 1.4 and 0.14, about 1.2 and 0.12, and less than 1.0 and 0.10 respectively. Hall and Raupach (1963) have shown marginal and poor growth below 0.35 and 0.25 percent potassium respectively.

Besides phosphorus, nitrogen and potassium, Humphreys (1964), Humphreys and Lambert (1965) and Gentle et al (1965) have included calcium,
magnesium, sodium, aluminium, iron and manganese in results of foliage analysis. This work showed that a level of 0.10% phosphorus was sufficient for healthy growth. Aluminium levels ranged from 321 to 1412 ppm (Humphreys and Truman 1964). Manganese levels ranged from 126 to 1100 ppm and iron levels from 71 to 435 ppm (Humphreys 1964).

Raupach (1967b) has found a non-linear relationship between the nickel and phosphorus contents of needles from trees growing on lateric soils in South Australia. The significance of this relationship plus a looser association between nitrogen and copper is uncertain at this time.


Will (1961a) has emphasized the importance of nutrient ratios to plant growth, not only in the field, but particularly in pot or culture experiments. Tamm (1964) has also pointed out that N:P or N:K ratios are probably restricted to definite limits in living material. Leyton (1958) has discussed the concept of nutrient ratios in some detail. For both Japanese larch and Sitka spruce, Leyton showed that N:P and N:K ratios offered an alternative to concentrations as a means of expressing growth responses in terms of needle composition. However, if both concentrations and ratios are combined as variables, the latter inevitably failed to achieve significance.

Raupach (1967a), from a large number of observations in Southern Australian forests of Pinus radiata, considers that N:P ratios for the species may range from 5 to 16. This range, though rather large,
similar to that found by other workers for other species according to Raupach.

Viro (1961) has summarized the main disadvantages of foliage analysis. Besides the necessity of standardized sampling procedures, these are:

1. The short length of the sampling season.
2. The results are dependent on weather conditions prior to sampling.
3. The stand should ideally be sampled over a period of years to minimize variations in foliage nutrient levels from one year to another.
4. The fact that a treeless area cannot be evaluated.

However, Tamm (1964), in a detailed review of techniques of forest nutrition research, concluded that diagnostic plant analysis combined with field experiments under controlled conditions forms probably the most useful approach to such research. This dual approach has, or is, being adopted in both N.Z. and Australia (Gentle et al 1965, Will 1965, Mead 1968). The N.S.W. Forestry Commission has found that, where plantings which cover a wide range of site qualities are available, the most reliable diagnostic guideline is provided by computerised multiple regression analysis using foliar nutrient levels and site index. Sampling must be rigorously standardised and should preferably be done within one year in order to maintain comparability of levels (Gentle & Humphreys 1968.) This approach appears certain to be more widely used in the very near future.
Raupach (1967a) and Hewitt (1966) have stressed the usefulness of culture and pot techniques in tree nutrition studies, particularly as an adjunct to field experiments. Tamm (1964) suggested that advantages of this method compared with field experiments were in the more complicated experimental designs that can be used, the greater possibilities of evaluating total growth and growth response, the saving in time using seedlings and the fact that nearly complete control can be obtained over the different factors and interactions likely to be involved. Disadvantages of the method were the differences in mycorrhizal and rhizosphere organisms between forest stands and artificial systems, the different ecological system present in a pot or culture solution compared with a natural stand and, most important, the difficulty of comparing seedling nutrient requirements with those of adult trees in a forest stand. Hewitt in fact has suggested that seedling experiments should be verified and continued with more mature populations grown under special, large-scale, conditions.

Raupach (1967a) states that "experience with _P. radiata_ has shown that where soils (most often topsoils) are used and the trees are grown in pots holding 10 Kg of soil or more for periods of at least 2 years, the results in terms of foliar nutrient levels and fertilizer responses are surprisingly close to those found under forest conditions."

Ludbrook (1940, 1942) demonstrated and described the symptoms of B deficiency and toxicity and showed that the approximate optimum range of boron concentration in water cultures was between 0.05 and 5 ppm. of added boron. Smith and Bayliss (1942) and Smith (1943) have described zinc, manganese, copper and boron deficiency symptoms also using water...
cultures. Purnell (1958) presented coloured photographs of calcium, magnesium, phosphorus, potassium and nitrogen deficiencies in sand cultures. Attempts to induce S deficiency were unsuccessful and it was concluded that the sand used contained sufficient available S for the requirements of *P. radiata*. In fact, no description of sulphur deficiency has ever appeared in the literature on *P. radiata*.

Humphreys & Truman (1964), working in water culture, showed that *P. radiata* was quite tolerant to Al$^{3+}$ provided sufficient P was available. It was found that increasing amounts of phosphorus were necessary to sustain the same rate of growth when the aluminium concentration was increased. They noted the significance of this fact for forestry practice on low-phosphate soils. Kanwar (1959) had earlier offered a similar explanation of aluminium availability affecting phosphorus uptake, to account for an anomalous result in his work. Pot trials conducted by him had demonstrated N & P deficiency in an Australian soil. A phosphorus response, increased by addition of nitrogen, has also been demonstrated by Stone and Will (1963) in pot trials using soil from Waiwhero, Nelson.

Will (1961 b) has described Mg deficiency in pine seedlings in Whakarewarewa and Kaingaroa nurseries. He considered that a level of 0.10 me.% exchangeable Mg in the soil was insufficient to maintain healthy growth, the critical level probably being nearer 0.2 me.%.

Will also showed that a level of 0.12 - 0.14% magnesium in the current years foliage indicated an adequate supply.

Will (1961a) investigated the composition of nutrient solutions in sand and water culture. He found that quantities of 100 ppm nitrogen,
1 ppm phosphorus, 10 ppm potassium and 10 ppm magnesium in the nutrient solutions were sufficient to maintain good growth in seedlings. These levels are low when compared with those obtained in other pot studies (eg Travers 1965), but Will showed that they are of the same order as the concentrations found in the soil solutions of two sites known to support vigorous plantations. Will stressed the importance of having the basic nutrient concentrations similar to levels found in soil solutions. Foliage contents of 1.6% N, 0.10 % P, 1.1% K and 0.11% Mg were considered to indicate adequate supplies of each element. Will also considered that, within limits, the ratios of the concentrations of macroelements may have more influence on plant growth than have the actual concentrations. This last factor will be discussed further in a later section.
II 4.4 Soil Analyses.

Viro (1961), following an extensive European forest survey, concluded that soil analyses should be the standard method in the critical evaluation of forest-site fertility. Depending on circumstances and one's intentions, this conclusion can be justified to some degree. Gentle & Humphreys (1968) have found that soil surveys can be used for diagnosis at varying levels of reliability, with the best results being achieved using complete chemical evaluation within similar soil types. Within restricted areas, predictions were often found to be excellent using chemically based soil surveys, but comparison of soil nutrient levels across soil type boundaries was found to be unsatisfactory due to changes in nutrient availability.

Stoate (1950) proposed critical levels of hydrochloric acid soluble phosphorus for the satisfactory growth of *P. radiata*. A $P_2O_5$ content of 400 ppm was considered to be necessary in the surface and sub-surface soils, but Stoate recognised that available $P$ levels were of more importance than total $P$, and could often explain otherwise anomalous results. Brockwell and Ludbrook (1962) found an optimum level of 130-175 ppm of conc. HCl soluble soil phosphorus (the maximum level of soil phosphate at which additional responses can be obtained) for *P. radiata* growing in the southern tablelands of N.S.W. Phosphate responses have been demonstrated on poor, deep, sands in Victoria where the total $P$ content is 20 - 40 ppm. (Hall 1961).

Raupach (1967a) has shown that a trend exists over a wide range of soil types, between the average site quality of *P. radiata* and the
nitrogen and phosphorus contents of the surface soil on which they are growing.

Waring (1962b) has determined for the surface 0-3" of soil a value of 0.10% nitrogen below which responses to applied nitrogen may be expected; below 0.05%, great responses can be anticipated.

Humphreys (1964) has found that, in areas of NSW, the < 2 mm soil fraction should contain at least 2 meq.percent of calcium and that where this is not achieved, root development and development of mycorrhizae may be inhibited. A severe lack of calcium in the cation exchange complex results in aluminium being the dominant cation. Aluminium may subsequently accumulate at root surfaces and inhibit the uptake of phosphorus. Phosphorus deficiency may thus be an indirect result of the original low levels of calcium.

Boron deficiency has been reported by Proctor (1967) on Tanzanian soils containing up to 16 ppm of total boron. Proctor considered that the deficiency was more a problem of availability than one of short supply.

The use of phosphorus fractionation procedures to follow the efforts of fertilizer treatments is a recent innovation. Gentle et al (1965) investigated a P. radiata phosphate fertilizer trial 15 years after treatment. They found that superphosphate showed a strong tendency to become aluminium-bound phosphate in the soil while calcium phosphate had maintained its status in the rock-phosphate treatment. Humphreys and Lambert (1965), in an examination of a site showing the "ash-bed" effect, found that the ratio of aluminium-phosphate to total phosphate was significantly greater in the ash-bed soils than the adjacent soils and concluded that the effect was associated with increased phosphorus availability.
Ballard (1968) has investigated the relationships between soil phosphate, foliar phosphorus and site productivity on 45 plots in Riverhead forest, Auckland. Soils in the area are deeply weathered and are known to be phosphorus deficient (Weston 1956). A highly significant relationship was found between foliar P levels and site productivity on both fertilized and unfertilized plots. A number of chemical soil tests for extracting soil phosphate were used to investigate any relationship between soil phosphorus levels and site productivity. It was concluded that the easily extractable inorganic phosphorus levels, particularly those that reflect the contribution from the mineralisation of organic phosphorus, rather than total phosphorus levels, best determine the phosphate status of these soils in relation to the growth of P. radiata. Of the various tests tried, the best results were obtained with the Bray No. 2 and Olsen tests.

It is preferable in some cases, to express the results of soil analyses as contents of the total volume of soil exploited by tree roots responsible for nutrient absorption. This means taking into account bulk density (Humphreys 1964), stones, (Dahl et al 1961, Humphreys 1964), and root depth. The influence of stones on soil nutrient measurements may be quite important as shown by Dahl et al (loc. cit) in reviewing the data of Viro (1955). Following the ideas of Dahl, Humphreys (loc. cit) has shown that modification of soil phosphorus and calcium values for stones leads to much improved correlation of these variables with site quality.

A similar correction factor has been used by Czarnowski et al (1967) in the development of an equation expressing site index as a function of soil and climate characteristic in N.S.W. forests.
This equation, complex though it may be, provides a remarkably accurate means of predicting site quality over large areas. As such it must be considered a great advance on previous methods. How far it can be considered applicable to areas besides N.S.W. will have to be examined further.

The main problems encountered in using soil analyses as a diagnostic technique in tree nutrition are the difficulty in finding a method of extraction that is universally effective, the difficulties caused by seasonal variations in nutrient availability, the problem of how to express results (whether on a volume-weight or percentage basis), and the problem of which or how many soil horizons to sample (Tamm 1964). Undoubtedly, soil analyses have their place in the determination of forest nutrient requirements and when methods of extraction are better understood such analyses will certainly be used to a greater extent.
II 4.5 Nutrient Balance Sheets.

The last fifteen years has seen a growing interest in the nutrient uptake from the soil by tree crops. Such studies are particularly important in cases where the forest stand is growing under conditions of delicate nutrient balance (Raupach 1967a). Hamilton (1965) has emphasized the major ecological upheaval that occurs when a virgin system is replaced by a forest plantation. He noted an apparent decline in suitability for plant growth when virgin eucalypt scrub was replaced by *P. radiata*. Such an apparent decline in production has been measured on second crops of pines in South Australia (Keeves 1966) and is suspected in Nelson (Whyte 1966).

The preparation of nutrient balance sheets is subject to many difficulties (Ovington 1962). One of the main problems is that associated with the sampling for total tree analysis. Madgwick (1963) has pointed out that biased estimates may arise from sampling only average trees.

Ovington (1959) drew up a balance sheet for a 55 year old *P. sylvestris* plantation in England. He showed that there was a small continuous drain on soil resources but that only small amounts of nutrients were removed from the ecosystem in the harvested tree compared with the nutrients circulating through the system as a whole. However, it has been pointed out (Rennie 1955), that such removals, small though they may be in absolute terms, are an important factor in the initiation of both soil degradation and diminishing site productivity on nutrient-poor soils. Rennie considers that these two possibilities are inevitable under present forestry management techniques.
The situation is even more critical in Australasian forests which are often planted on soils considered unsuitable for agricultural production and where annual growth increments in _P. radiata_ plantations are several times greater than those in Northern Hemisphere forests (Will 1964). A nutrient balance has been calculated for _P. radiata_ (Will, _loc. cit._), on 24 trees in Whakarewarewa forest, New Zealand. The results were for a 12 year old regeneration site with one thinning and were assumed to be equivalent to a 10 year-old plantation site. Previous work (Will 1959) had established the nutrient content of annual litter fall and returns by rainfall through the year for the same and other sites in Whakarewarewa and Kaingaroa forests. Will (1964) concluded that _P. radiata_ stands put the greatest demands for nutrients on the soil during the first 10 years of the plantation's life. After this point, decomposing litter and slash from thinnings release sufficient nutrients to meet the greater part of the trees' demand. In the case of nitrogen, the full demand is met. The demand also differs between the first and second crops because considerable potential supplies of nutrients remain from the previous crop in the form of undecomposed needles, twigs, branches, bark and roots.

Will (_loc. cit._) calculated amounts of nutrients removed per crop as 200lb nitrogen, 30lb phosphorus, 250lb potassium and 170lb of calcium. Each crop was assumed to be a 35 year rotation. Losses due to burning and water movement, whether by leaching or run-off were not considered in Will's calculations. Stephens and Bond (1957) concluded that a very considerable conservation in nitrogen of up to 80% would follow any procedure which avoided the use of fire between successive crops of trees.
Ritchie (1968) has found that significant quantities of nitrogen may be leached from sandy soils under certain conditions. Bormann et al (1968) have studied the effects of removal of vegetation on nutrient cycles in a small water-shed ecosystem in New Hampshire. Increased run-off meant that the cut ecosystem exhibited an accelerated loss of nutrients relative to the undisturbed ecosystem with losses of nitrogen being estimated at about 57 Kg/ha. Losses of cations were 3 to 20 times greater than those from comparable undisturbed systems.

In the case of nutrient-poor soils, it can be seen from Will's data that the continued removal of such quantities must eventually have an effect on the productivity of successive crops. The use of fertilizers to balance such losses is one answer to the problem but Ovington (1959) has stressed that such additions should be considered in relation to the dynamics of the forest system as a whole. Australian workers (Stephens and Bond 1957, Lewis & Harding 1963) have recognised the potentially serious loss of nitrogen in particular from the nutrient cycle, because of burning the debris remaining after felling. The suggestion has been made that instead of fertilising direct, a system of alternating tree crops and pasture may need to be considered. Alternatively, leguminous understoreys could be used in combination with *P. radiata*. The use of gorse, clover and lupin understoreys as sources of nitrogen is at present being examined at several sites in Nelson (Appleton & Slow, 1966).

The use of nutrient balance sheets has applications to the determination of the nutrient requirements of forest stands (Tamm 1964). However, the method is only useful as a first approximation since it fails to distinguish any "luxury consumption" that may be taking place (Tamm loc cit).
II 4.6 Field Experimentation.

Field trials are a traditional method of testing fertiliser responses. However, due to the long time-scales involved in forestry, they are best used as a final means of diagnosis (Gentle & Humphreys 1968). When used for primary diagnosis they run the risk of entirely missing the crucial deficiency or of failing to differentiate responses between the deficient and non-deficient elements in the fertiliser used.

Failure to appreciate that *P. radiata* does have certain minimum soil requirements led to the development of considerable areas of unhealthy plantations in both Australia (Stoate 1950) and New Zealand (Weston 1958a). However, the realization that many of these stands could be rejuvenated by the use of appropriate fertilisers has meant that the extent of these areas has been greatly reduced.

The accepted method of verifying a nutrient deficiency is to provide statistical proof of a growth response following application of that nutrient (Russell 1961). A number of macro and microelement deficiencies have been identified in this manner.

Phosphorus deficiency has been the most commonly identified primary factor limiting growth in both Australia and New Zealand (Waring 1962b, Weston 1958b). Phosphorus deficiency appears to become more prevalent some time after stand establishment. Thus Will (1965) reported that trees growing on infertile "gumland" soils in northern New Zealand were usually healthy for the first few years but in many areas tree vigour deteriorated rapidly between ages five and ten years. Responses to phosphorus have been reported in Western Australia by Kessell & Stoate (1936, 1938) and Stoate (1950), in South Australia by Boomsma (1949), in Victoria by Hall (1961), in New South Wales by Brockwell & Ludbrook (1962),
Humphreys (1964) and Gentle & Humphreys (1968) and in Auckland, New Zealand by Weston (1956, 1958b), Atkinson (1959), Conway (1962), Will (1965) and Mead (1968). Recent work in Riverhead forest, Auckland (Will 1965, Mead 1968) has been concerned with the frequency and amount of fertiliser addition. Mead (loc cit) has shown that standard aerial topdressing at 5 cwt/acre is probably sufficient for only 7-8 years. Will (loc cit) has suggested that, after two applications of 5 cwt/acre of superphosphate to the first rotation, one further application may be sufficient for a considerable period.

Nitrogen deficiency symptoms in young regeneration *P. radiata* has been reported in the Tasman forest, Nelson, by Stone & Will (1965b) and Appleton and Slow (1966). The symptoms were corrected and growth rates improved by nitrogen fertilisation although Appleton and Slow felt that this improvement might only be temporary. Nitrogen responses have also been demonstrated at Blue Range, Canberra (Waring 1962a) and in N.S.W. (Waring 1969). Some evidence exists for nitrogen deficiency in newly-planted areas in coastal sand-dune forests on the West coast of the North Island (Ritchie 1968). Waring (1962a) indicated that large responses could be expected in situations where total %N in the surface soil (0-3") was less than 0.05%. However, he concluded (1962b) that growth of *P. radiata* in the field was rarely limited by nitrogen deficiency and even then only during the first few years of growth. Waring (1969) has inevitably found that nitrogen fertilisation alone causes a slight depression of growth, but that where N + P is used, the response is much greater than that obtained with P alone. Waring (loc cit) has suggested that the current common Australian practice of adding P at
planting could be supplemented by addition of N. He considered that not only were large production gains possible in the current rotation but that, as the equilibrium point of the soil organic matter was raised, the present trend towards a reduction in soil fertility could be reversed.

In a few areas, a deficiency of one of the major nutrient cations has been shown to be limiting growth. In Victoria, potassium deficiency has been identified and responses to KCl have been demonstrated (Hall and Purnell 1961, Hall and Raupach 1963). Humphreys (1964) has shown calcium deficiency to be a major factor limiting growth in N.S.W. and magnesium deficiency has been found in nurseries and young, fast-growing stands on pumice soils in the central North Island (Will 1961b).

Deficiencies of the trace elements, boron and zinc have been identified in some areas. Zinc deficiency is quite widespread in West Australia (Stoate 1950) and South Australia (Thomas 1957) and routine fertilisation is carried out at plantings in both states. Boron deficiency has been shown to be limiting growth on old, strongly weathered soils in Nelson (Will et al. 1963, Stone and Will 1965a, Appleton and Slow 1966), and on another area of old, strongly weathered soils in southwest Tanzania (Vail et al. 1961, Proctor 1967). In both cases, striking responses to applications of borax have been described.

On many of the poorer sites, there is probably more than one nutrient deficiency limiting growth. This has been shown to be the case in several instances. The need for both zinc and phosphorus fertilizers in several West Australian and South Australian forests has been recognised for a long time (Stoate, 1950, Thomas 1957). Appleton & Slow (1966) have described the superior effect of P + B rather than P or B
alone on poor sites in Nelson. The possible need for a combination of N + P + B + Mg in the Tasman forest is suspected by these authors. The N x P interaction found by Waring (1969) has been mentioned earlier in this section. A similar N x P interaction has been described by Hall (1961) although the effect appears to have been rather limited. A deficiency of both Ca and P in several forest stands in central N.S.W. has been described by Humphreys (1964). In some cases the calcium deficiency was so severe that greater supplies of calcium than was added in superphosphate were required. Humphreys (1964) has also described circumstances under which an Al x P interaction may occur. Raupach (1967b) has obtained evidence suggesting responses to Cu, Ni, N & S after addition of superphosphate on a lateric soil in South Australia. Possible interaction between nickel and phosphorus and between nitrogen and copper were also found. However, Raupach felt that the results obtained should only be regarded as exploratory and as a guide to further experimentation.

Deetlefs & Dumont (1963) have described an experiment designed to investigate the economics of applying fertilizers to a good quality site. All New Zealand and Australian work has concentrated on alleviating deficiencies rather than increasing production in healthy stands. This South African work is most interesting. It was shown that a mixture of superphosphate, potassium sulphate and lime produced an average response in height growth of 11% in two years.

The importance of using good experimental designs that enable investigation of possible interactions has been stressed by several authors (Tamm 1964, Gentle & Humphreys 1968). Undoubtedly the use of
more sophisticated statistical plot designs, will enable more thorough investigation of possible interactions to be achieved in the future.
II 5. SOIL FACTORS RESTRICTING GROWTH IN FOREST STANDS.

II 5.1 Introduction

Raupach (1967a) defined soil factors which restrict growth as those which appear to give a poorer rate of growth than expected from the terrestrial climate. According to Raupach, these are:

(1) A limited volume of exploitable soil.
(2) An unsatisfactory soil-water regime.
(3) A poor nutrient status.
(4) Unfavourable biological factors.
5.2 Limited volume of exploitable soil.

Several authors (e.g., Stevenson 1967, Cornforth 1968) have stressed the importance of effective soil volume to plant yields. Raupach (1967a) considers that the depth of soil profile is probably only important insofar as it provides (1) a nutrient and moisture source of sufficient magnitude and capacity to supply the demands of good growth and (2) a secure anchorage against windthrow.

In Argentina, Vidal (1961) reported poor results on soils less than 18 inches deep. A comparison of soils defined by soil surveys in South Australia and Argentina has shown that the growth of *P. radiata* is poorer where the soils are shallow or have impenetrable horizons of hardpan or concretionary material. (Barrett and Czarbosky 1960.) Jackson (1965) has calculated that, for red loams in Hawke's Bay, a rainfall of 35 inches per annum and a soil depth of 2½ feet are required for satisfactory growth of *P. radiata*.

The volume of exploitable soil may sometimes be limited severely by stones. Soil nutrient levels corrected for stones have been shown to give better correlations with site quality than uncorrected nutrient levels (Humphreys 1964).

The influence of horizons containing large amounts of clay on the effective soil volume is debatable. Raupach (*loc cit*) cites cases in Australia where high quality trees are growing in soils where the clay content is 60 - 90%. However, Barrett and Czarbosky (*loc cit*) reported an upper limit of about 40% clay in the B horizons of Argentinian soils. Above this limit, growth was affected. Similar values to this are found in Nelson soils where Kingston (1968) has shown a correlation
between site quality and clay content of the B horizon. However, multiple regression analysis showed that the clay content was not significantly affecting site quality. This confirms Raupach's conclusion that other soil properties should be considered along with clay content in determining growth limits.

A study of the root distribution of *Pinus radiata* is basic to an understanding of forest nutrient resources. Early studies (Lindsay 1932, Cromer 1935) showed the basic shallowness of the rooting system. Pryor (1937) observed vertical roots penetrating to 8 feet in alluvial soil with some horizontal spreading of roots from tap roots at 3 to 4 feet depth. Needle analyses at Mt. Burr, South Australia (Tiller 1957) indicated that nutrients were being absorbed from a buried volcanic soil at approximately 10 feet depth.

Recent detailed, quantitative studies of root systems by Bowen (1964), Will (1966), Ritchie (1968) and Kingston (1968), have confirmed that root concentration decreases rapidly with depth before obvious physical barriers occur. Up to 41% of the total root area was shown to be due to roots < 0.4 mm in diameter (Bowen *loc cit*). On shallow, poorly structured soils, the absence of any extensive vertical root system may lead to large-scale windthrow (Wendelken 1966). Will (*loc cit*) found a linear relationship between root weight and branch weight, but the wider application of the relationship to trees of different ages or those on different soil types needs further investigation. Bowen (*loc cit*) considers that, under conditions of adequate surface moisture, surface soil layers contribute most of the nutrients. Under drought conditions, lower roots may be expected to contribute more to nutrient uptake. Kingston (*loc
cit) has emphasized the importance of encouraging good root development in early years of growth on infertile soils, so that maximum uptake of soil nutrients by the growing tree can be achieved.
5.3 Unsatisfactory soil-water regime

The soil profile features which contribute to a soil-water regime unsatisfactory for tree growth may be thought of as depending on both the total quantity of available water present in the soil and the rate of water supply at periods of peak demand (Raupach 1967a).

Both an insufficient or excessive water supply may affect tree growth (Simpfendorfer 1959). Two types of injury have been attributed by Pryor (1947) to drought; needle cast and death of the tops of trees (autumn brown top). Reports of drought deaths appear mainly in the Australian literature, although Will (1959) has suggested that physiological drought within trees in the Rotorua area may lower the resistance of the tree to attack by the wood wasp (*Sirex noctilio* Fabr). Boomsma (1949) has reported deaths due to drought on shallow, stony soils in South Australia. Millikan and Anderson (1957) showed that autumn brown top in Victoria was associated with moisture stress on shallow soils during hot dry periods, particularly when there was a high tree density. Removal of the moisture stress enabled the tree to recover.

Johnston (1964), using trenched plots, induced drought in 4 year old *P. radiata* and showed that moderate turgidity was maintained in the needles even when soil conditions were very dry provided there was frequent precipitation in amounts sufficient to wet the foliage.

In considering the loss of trees due to excessive soil water, Poutsma and Simpfendorfer (1962) found that the vigour of *P. pinaster* and *P. radiata* varied significantly with the degree of surface waterlogging. Sutherland *et al* (1959), in a survey of 1570 *P. radiata* stands in the Auckland area found that deaths in the exceptionally wet 1956 season...
occurred on better as well as poorer-drained soils. Deaths and injury were attributed to Phytophthora attack, the amount and severity of the disease being influenced by soil drainage. Only 1 case of tree death by "drowning" was observed in the whole survey.

Raupach (1967b) made detailed observations of growth at Second Valley, South Australia. Decreases in the growth rate were not observed in excessively wet years on any of the sites, but lower growth rates were found when the rainfall was lower than average, thus demonstrating that temporary waterlogging, but not drought, can be tolerated.

Under certain conditions, high salinity may be responsible for tree failure. At Mt. Crawford, South Australia, Woods (1955) found chloride contents as high as 5.0% in foliage from dead trees, with an upper limit of 0.5% in healthy trees.

Observations on water-repellent properties of sandy surface horizons (Bond 1964) showed that water penetrates into the soil through narrow channels, with the intervening soil remaining dry. This resistance to water penetration was not as great in forests of P. radiata as it was in areas of pasture or native vegetation, but it was still present. Indications are that these areas of localised drought are of particular importance in young plantations before pine root systems have developed sufficiently to dominate the site (Raupach 1967a).
II 5.4 Poor nutrient status.

This subject has been covered in Sections II 4.4 and II 4.6.
5.5 **Unfavourable biological factors.**

The role of mycorrhiza in *P. radiata* nutrition is a very important one. Mycorrhiza are structures formed through the interaction of the mycelium of a fungus and the root of a higher plant (Rawlings 1958). The normal relationship between tree and fungus is one of symbiosis, but in cases where tree and fungus are not in symbiosis they can, under certain conditions, suffer from nutritional deficiencies resulting in severe growth limitations (Slankis 1958).

Hatch (1937) considered that mycorrhiza form symbiotically on tree roots in soils with a mineral nutrient deficiency, enabling the tree to obtain a more adequate nutrient supply, as a result of the increased effective root area available for mineral nutrient absorption. Hatch's theory was the first to logically explain the benefits mycotrophy affords the host growing on infertile soils and it has stood the test of time remarkably well. Björkman (1942) considered that mycorrhiza formed on roots as a fungal response to the surplus of carbohydrates present in the root resulting from the limitation of protein synthesis in conditions of nitrogen or phosphorus deficiency. Recent work by Handley and Sanders (1962) has emphasized that the search for other factors contributing to mycorrhizal development should not be neglected. Bowen and Theodorou (1967) have shown that uninfected, rapidly elongating parts of long roots are as efficient as mycorrhiza over short periods with respect to phosphate uptake. However this efficiency only exists for short periods while mycorrhiza are functional in the soil for several months. From a consideration of ion movement to roots, they concluded that mycorrhiza can thus feed from relatively large volumes of soil without the necessity for
hyphal growth into the soil.

It has been shown in many cases that mycorrhizal symbiosis is of decisive importance in the afforestation of forestless areas. This has particularly proved the case in the afforestation of prairie soils, where large numbers of introduced tree species have died in situations where the soils are devoid of the necessary symbiotic fungi (Hatch 1936, McComb 1938, Wilde 1968). Similar situations have been described in the establishment of *P. radiata* in Western Australia (Kessell 1927).

Routine inoculation of nursery soils with humus containing suitable mycorrhizal fungi gathered from high-quality stands, has meant that seedling failures due to poor mycorrhizal development are rare today. However, Gilmour (1958) has described a case where chlorosis of Douglas Fir in Otago forests was due to the poor development of a necessary mycorrhiza both in the heavy clay forest soils of the area and the nursery originally growing the seedlings.

Classification of the ectotrophic mycorrhizal fungi associated with *P. radiata* has been attempted in South Australia by Bowen (1963) and in Victoria by Marks (1965). Bowen (*loc cit*), Levisohn (1957) and Raupach (1967a) have discussed the desirability of using specific mycorrhizal fungi to assist the tree by such means as increasing nutrient uptake and as a protection against possible growth-retarding factors (eg. pathogens.) In support of this idea, Bowen (1965) has observed that different mycorrhizal fungi from *P. radiata* give large differences in the uptake of $^{32}$P in short-term laboratory experiments, with the poorest performer being the commonest type in South Australian soils.

Increased phosphorus uptake by mycorrhizal seedlings compared with non-mycorrhizal plants has been shown by Stone (1949), and Morrison (1954,
1957, 1962). Increased nitrogen uptake has been demonstrated by Waring (1962b) and Stevenson (1959). Uptake of other macro- and micro-nutrients is almost certainly also affected by mycorrhizal development (Hewitt 1966).

Development of mycorrhiza is influenced in a negative manner by the absence of iron, the presence of nitrogen and sometimes by phosphorus supply (Hewitt, loc cit). Hewitt has pointed out that the effects of N & P fertilisation in suppressing mycorrhiza which could be significant as absorbing mechanisms for the uptake of limited supplies of certain micronutrients, might be critical in certain cases on poor soils.

The possibility that Pinus mycorrhiza may be involved, either directly or indirectly, in fixation of atmosphere nitrogen could be an important factor in the nutrition of Pinus stands. Experiments using $^{15}$N have been performed by Stevenson (1959) and Richards & Voigt (1965) to demonstrate nitrogen fixation by *P. radiata* seedlings. However, earlier work with *P. sylvestris* failed to show any such fixation (Bond & Scott, 1955). Further work by Richards & Voigt (1964) showed that nitrogen fixation actually occurred through bacteria in the rhizosphere and that the process was stimulated by the presence of mycorrhiza-forming fungi. Supporting evidence has come from recent work by Rambelli (1967), who investigated the distribution of N - fixing bacteria in the mycorrhizal rhizosphere of *P. radiata*.

The evidence for fixation of atmospheric nitrogen in coniferous forests has been reviewed by Richards (1964). Net gains of 40-50lb/acre/ year were found to be possible, even in the absence of nodulated species in the understorey. Similar gains of 20-45lb N/acre/year have been found under exotic pines growing on nitrogen deficient soils in Queensland.
The question of whether the apparent nitrogen increase occurs through fixation is difficult to resolve. Increased nitrogen fixation under Pinus was proposed (Richards 1962) as a possible mechanism for the "underplanting phenomenon", i.e., the ability of nitrogen-sensitive species such as hoop and Kauri pines to satisfy their nitrogen requirements when underplanted to Pinus without recourse to fertilisation. However, the gains in nitrogen found by Richards and Bevege (loc. cit.) could not be explained in terms of increased soil nitrogen and the possibility must therefore be considered that the availability of soil nitrogen to underplants increases even though the total nitrogen level falls or remains stationary. A similar effect has been found by Stone & Fisher (1969).

Moore (1966) concluded that, until accurate balance sheets of the amounts, sources, and losses within ecosystems are prepared, the question of the amount and significance of nitrogen fixation in the rhizosphere of exotic pine forests should remain unresolved.

The role of mycorrhiza is not purely confined to making nutrient uptake more efficient. The effect of mycorrhiza on the prevention of root diseases has been discussed by Zak (1964) and an excellent monograph by Harley (1969) reviews all aspects of research on the biology of mycorrhiza.
II 6. PRODUCTIVITY DECLINE IN SUCCESSIVE ROTATIONS IN FOREST STANDS

II 6.1 Decline in productivity - Australia and New Zealand.

Fears of a loss in productivity with successive rotations of coniferous forests have disturbed the thoughts of many foresters since the classical example of deterioration of spruce stands in Saxony was first recorded by Wiedemann in 1923. Lutz and Chandler (1946) have advocated caution in interpreting the evidence since many factors including management practices were undoubtedly involved. Similar problems with second generation Norway spruce (Picea excelsa) have been encountered in parts of Denmark and on the plains of Switzerland (Thomas, 1957).

Evidence of a productivity decline in the second rotation of P. radiata growing on coastal sands in South Australia has been reported by Thomas (1957), Lewis & Harding (1963), Keeves (1966) and Bednall (1968). A similar decline is suspected in Tasman forest, Nelson (Whyte, 1966).

Original evidence for such a decline in South Australia was rather subjective (Thomas, Lewis and Harding, loc cit), due to the absence of adequate or reliable records concerning the first rotation. Lewis and Harding estimated that there was an average difference in site quality of one class between first and second rotation stands established after felling the first and burning the debris. Chemical analyses of surface soil horizons under virgin scrub, first rotation pines and second rotation pines established by various management practices, failed to show any significant differences.

Keeves (1966) used the few permanent sample plots for which records had been kept through both rotations, to establish statistically that, for replanted stands, a definite loss in productivity had occurred in the
second rotation. This loss was commonly of the order of one or two site quality classes, and had occurred on all sites ie of high, medium and low site quality rather than on marginal sites only, as had been suspected earlier. Estimates of productivity losses under regenerated stands were complicated by varying stand densities but a similar decline was considered probable.

The evidence for a productivity decline in Nelson will be reviewed in a subsequent section but similar problems to those experienced in South Australia have complicated analysis of the problem in Nelson.

Stephens and Bond (1957) felt that the importance of nitrogen in the nutrition of *P. radiata* on many South Australian soils was such that nitrogen deficiency could well occur in a second crop of trees, if it immediately followed the first. The potentially serious loss of nitrogen has led Lewis and Harding (loc cit) to suggest that instead of fertilising direct, a system of alternating tree crops and pasture should perhaps be considered.

Hamilton (1965) investigated changes in soil properties following development of *P. radiata* stands from native eucalypt forest. Changes occurred mainly in the Al horizon but the effects extended through the solum. These changes included increases in colour value, bulk density, pH, and C/N ratio and decreases in loss-on-ignition, organic carbon, total nitrogen, phosphorus, exchangeable cations, C.E.C., and soluble salts in the Al horizon of podzolised dry sclerophyll soils derived from both decomposed shale and granite rocks. The evidence of declining suitability for plant growth in these soils was borne out by pot trials. Hamilton suggested it was imperative that procedures for the maintenance and amelioration of areas of low actual productivity should become
routine in plantation establishment and management.

The reasons for the productivity decline in both South Australia and Nelson are unknown at this stage. Keeves (loc cit) reports that a considerable amount of fundamental research has been initiated in South Australia to investigate the causes of the problem. Florence (1967) has reviewed the edaphic factors which could have some bearing on the problem. Processes reviewed include the influence of species and species mixtures on soils, litter decomposition and nutrient return, and changes in the forest-soil microflora relationship.
6.2 Decline in productivity - Nelson.

Since the early 1960's there has been a much-discussed nutritional problem in *P. radiata* growing on Moutere gravel soils in the Nelson province. The problem can be divided broadly into two sub-problems (Holstener - Jorgensen 2):-

(i) There are significant areas showing symptoms of nutrient deficiency in both first and second rotation stands.

(ii) The widespread second rotation stands apparently have a slower initial growth rate than first rotation stands.

The problem of areas showing nutrient deficiency symptoms has been present in both first and second rotations, a point not always fully appreciated (Holstener - Jorgensen, loc cit). Moorhouse (1935) observed that topography and climate combined to produce different sites on northerly and southerly aspects in Golden Downs forest. Improved growth on northerly sites was attributed to warmer soil conditions.

Growth differences associated with topography were reported by a private plantation owner at Braeburn as early as 1925 (Slow, pers comm). Verey & Biggs (1952) reported that timber yields on the Moutere gravels varied considerably. Best stands in the area were a little better than Rotorua quality class I, with the average equal to or better than quality class II. Class III stands occurred only on the hardest sites such as ridges where trees often showed poor growth, in many instances stunted and unhealthy to a greater extent than would be expected from exposure and shallow soils alone. Such growth differences in the first rotation have tended to be minimised (Holstener-Jorgensen, loc cit) and there has been a tendency to confine the problem to the second rotation and talk about a decrease in site productivity from first to second rotation.

The second problem is one that has caused much debate due to the lack of adequate or reliable records concerning the first station. It appears to be generally accepted that height growth as well as basal area increment is lower in the second rotation regeneration stands than in the original planted stands on the same site (Whyte *loc cit*, Slow 1968). The growth rate improves in most cases after 5-7 years and subsequent annual increments are the same in both types of stands. Whyte further claims that, on a few good sites, (eg. lower slopes and gullies), height growth is even better in the second rotation than in the first. On the harder sites however, the apparent stagnation in growth may continue indefinitely.

This last conclusion has been challenged by Holstener-Jorgensen *et al*³, who found the opposite effect in combined first and second rotation stands at Waiwhero and Braeburn. They considered that Whyte's data were handicapped by the fact that only a small sample was used and that comparison to nearby first and second rotation stands was subject to the known considerable variation in site quality over small distances in the area. Furthermore, confounded in the contrast was the important effect of totally different establishment practices; controlled competition in the planted first crop compared with uncontrolled competition in the natural regeneration stand. However, the same criticisms can equally well be applied to their own data. The problems of inadequate records concerning the first rotation and differences in establishment practices would appear to preclude any reliable conclusions regarding a decline in productivity from the first to the second rotation.

Holstener-Jorgensen *et al*² feel that the most prominent problem in the Nelson province is the nutritional disorders. A number
of nutrient deficiencies have been identified both in the Tasman & Waiherau forests on the Moutere gravels and in the Kaiteriteri forest on deeply weathered granites. These include boron, nitrogen, phosphorus and possibly magnesium (Will et al 1963, Stone & Will 1963, 1965a, 1965b, Appleton & Slow 1966).

Early pilot fertiliser trials on both the Moutere & Kaiteriteri soils have been summarized by Appleton & Slow (loc cit). An extensive series of follow-up trials has been described by Holstener-Jorgensen. This work can be divided into 3 main groups:

(a) Fertiliser trials.
(b) Establishment trials.
(c) Other investigations.

The fertiliser trials involve mainly three nutrients: boron, nitrogen & phosphorus. The most exacting trial involves phosphate at 100 lb P/acre and an unfertilised control, in combination with 3 rates of nitrogen; an N, P, K, Mg plus trace elements treatment has also been included and all plots have been given a basal dressing of 20lb/acre of borax. The trial has been laid out in both a 40 year-old 1st rotation stand at Braeburn and a 14 year-old second rotation stand at Harakeke. Further legume establishment trials are also being investigated. Previous trials of this type were only partly successful.

A number of establishment trials have been initiated in recently clear-felled areas to investigate the possibility that older first rotation P. radiata may have had a better establishment than young first rotation and regeneration, resulting in a better initial growth. These trials include hand-pulling regeneration to reduce stocking rates, control of competing weed growth with weedicide sprays, surface cultivation, deep
ripping and re-establishment by planting with robust nursery stock.

Other work begun and yet to be completed includes soil moisture investigations, Phytophthora studies, the possibility of summer droughts causing retarded growth or even "top dieback", additions of nutrients to the ecosystem in rainfall and the extent of the problem using aerial photography.

Work being conducted at Lincoln College includes, as well as the present study, an investigation of the nitrogen-fixing mechanism of gorse (Ulex sp.) and the microbiological changes occurring in the slash and litter after clear-felling.

Kingston (1968) has studied the extent to which variation in tree growth can be accounted for by morphological and physical soil properties. The 'best' multiple correlation equation for predicting site index from the soil properties alone accounted for 49% of the variation in site index. The main reason for the relatively low prediction was concluded to be that some of the more important casual factors determining tree growth, such as nutrient status, were not included in the study.


III

METHODS
III 1. INTRODUCTION

This section will discuss in detail the methods applied in both the soil and foliage studies. The section begins with a description of the parent material, climate and recent vegetation of both the Kaiteriteri and Mapua study areas. This is followed by a statement of the general principles of site selection and a short description of the reconnaissance and selection of sampling sites. Parts III 4. and III 5. deal with sampling and sample preparation, and analytical methods respectively.
III 2. DESCRIPTION OF THE STUDY AREA

III 2.1 KAITERITERI GRANITE SEQUENCE

III 2.1.1 Parent material.

The soils of the Kaiteriteri sequence overlie a formation known as Separation Point granite which extends along the western boundary of the Moutere gravels from Kaiteriteri to near Murchison in the south. For most of this distance, the granite concordantly underlies the Mt. Arthur marble. Contacts show interlamination of marble and granite and no contact alteration or chilling, indicating that marble and granite were isogradic at the time of metamorphism (Grindley, 1961). Grindley suggests that a possible explanation for this is that the granite was formed in place from granitised Ordovician sediments underlying the marble.

The age of the Separation Point granite is post-Devonian and probably Carboniferous as pebbles of similar granite appear in early Permian sediments of east Nelson (Grindley, loc cit). However, a somewhat younger age may be possible in view of the Rb-Sr dating results of Aronson (1965). Pegmatite associated with the granite formation has been dated at 98–119 million years, but no definite age for the granite itself is available.

Grindley characterises the formation as consisting of light-coloured sodic to calc-alkali biotite granites, hornblende granites, syenites and quartz diorites. From this, it can be seen that quite a wide range of composition is encompassed within the formation.

A number of soil types have been mapped within the Kaiteriteri landscape, being broadly grouped into soils of the flat lands, the rolling lands, the hilly lands and the steep lands (Cutler, pers. comm). The distribution of these soil types in the study area is shown in Fig 3. A full description of all profiles sampled appears in Appendix I.
Accurate data concerning the present climate of the Kaiteriteri area is not available due to the lack of any official meteorological stations in the area. Rainfall is probably of the order of 70 inches per annum. The mean maximum temperature is 63.9°F and the mean minimum temperature 44.2°F at Riwaka, about 3 miles south-east of the study area. The difference in altitude between the Riwaka station and the study area means that these values are probably a few degrees lower at the latter site. The climate however, should still provide excellent growing conditions for *P. radiata*, comparable with those in the Tasman forest (III 2.2.2).
No evidence has been published regarding the Pre-European vegetation of the Kaiteriteri area. It would seem likely that *Nothafagus* sp. were dominant, although exposed ridges may only have carried manuka and bracken fern.

The present vegetation (Table 1) provides an interesting indication of the relative fertilities of the various sampled groundsurfaces, ranging from dense gorse and bracken on the K1 groundsurface to a sparse heath vegetation on the most strongly developed K5 groundsurface. The study area has recently been planted (mainly in *P. radiata*) as part of the development of the Motueka state forest. A large proportion of this planted area has shown signs of nutrient deficiencies, particularly boron and phosphorus (Appleton and Slow, 1966).
III 2.2  MAPUA SEQUENCE

III 2.2.1 Parent Material

The parent material of the Mapua sequence is the strongly weathered Moutere gravels. In their present form the gravels consist of deeply weathered, well-rounded pebbles and cobbles of quartzose greywacke in a clay-sand matrix (Henderson et al, 1959). They are considered to be a dissected outwash plain developed during an early Pleistocene glaciation of the Southern Alps, possibly during the Ross glaciation (Beck, 1964). Henderson et al (loc cit) suggest that they are probably Castlecliffian in age, while plant microfossils from Kina indicate a Nukumaruan age (Couper, 1954). The gravels overlie Pliocene clays, quartz sands and lignite in the west near Lower Moutere and towards Wakefield. They are thought to be up to 2000 feet thick in the south becoming thinner towards the coast (Beck, loc cit).

On the strongly rolling relief of the study area, the soil varies too widely to permit classification as one soil type. The soil has therefore been classed as Mapua hill soils, related to the Mapua sandy loam found on gentler slopes (Chittenden et al, 1966). A comprehensive discussion of three interesting features of these soils viz., the deeply weathered parent material, the thick clay-enriched B horizon, and the thin fine sandy loam topsoil is contained in Kingston (1968). A full description of all profiles sampled appears in Appendix I.
The present-day climate of the Waimea plains is one of the most favourable in New Zealand. The mean annual rainfall at Harakeke is 38.7 inches (N.Z. Met. Service, 1966). The mean maximum temperature is 62.5°F and the mean minimum temperature 45.2°F at Appleby, 10 miles south-east of Harakeke. Mountain ranges to the west and south markedly influence the regional climate. De Lisle and Kerr (1965) report that, on average, Nelson and Motueka experience calm conditions (< 4 m.p.h. winds) for 45% of the time, and that Nelson receives an average 58% of the possible sunshine each year, including an especially high level of winter sunshine.

The climate virtually provides an all year round growing season for _P. radiata_. The potential growth rate is equal to the highest elsewhere in New Zealand (Jackson, pers. comm).
Vegetation:

Pre-European vegetation of the seaward end of the Moutere gravel formation appears to have consisted of manuka and stunted bracken fern with patches of *Nothofagus* sp., *Phormium tenax* and toe-toe in the gullies (Rigg, 1952). Early farming was not successful and pasture deteriorated often reverting to indigenous scrub. Extensive apple and pear orchards were planted from 1911 to 1916 but many were abandoned and subsequently replanted in *P. radiata*. Most present forests result from this period of planting (Appleton and Slow, 1966).

With two exceptions, the selected study area carried stands of *P. radiata* D.Don that had developed from natural regeneration following clear-felling in 1954. The exceptions were the two steepland sites which carried *P. radiata* planted in 1960 and 1962 respectively. The stocking of regeneration areas is frequently high and few of these stands have received timely or adequate thinning (Appleton & Slow, loc cit). However, a "thinning to waste" had apparently occurred about five years after the 1954 clearfelling resulting in an irregular stocking pattern. Substantial growth differences are apparent in the study area, particularly between midslope ridge and gully sites. The extent of these differences can be seen in Plate 1 which shows two blocks from "average" trees on these surfaces. On the ridges and upper slopes the canopy is still open due to the poor tree growth, fine branching and spire-like crowns (Appleton and Slow, loc cit). The understorey is chiefly bracken, gorse and native grasses. In the gullies where canopy closure is more complete, ground vegetation becomes sparser and is mainly blackberry and old gorse.
III 3. PRELIMINARY FIELD WORK

III 3.1 Principles of Site Selection

Two basic considerations had to be borne in mind in the sampling of both the Kaiteriteri and Mapua sequences. The various sites chosen, while being sampled for a sequential soil study, also had to cover as wide a range of _P. radiata_ site quality as possible. Thus the following criteria were applied in choosing sampling sites:

1. Sites should be in a position on the landscape corresponding to a particular position in the toposequence eg ridge, steepland.

2. The requirements outlined by Jenny (1946) for a sequential soil study should be fulfilled as far as possible. Particularly, uniformity of _P M_ should be adhered to as strictly as a subjective analysis of the situation would permit.

3. In the case of the Mapua sequence, the sites should be in an even-aged, regeneration, _P. radiata_ stand. In the Kaiteriteri sequence, the sites should be in an area of young, planted _P. radiata_.

4. There should have been the least possible interference by man. Areas that were parts of present or imminent fertiliser trials should be avoided as far as possible.

5. The soil profile should not have been subject to the possibility of recent additions of alluvial or colluvial material.
III 3.2 Reconnaissance and Site Selection.

Basic reconnaissance of the Kaiteriteri block was carried out in 1964 by Mr. E.J. B. Cutler (then of Soil Bureau and now of Lincoln College), as part of a soil survey of the area for the N.Z. Forest Service. His report concluded that the most infertile soils occurred on easy rolling land on deeply weathered granite, with slightly more fertile soils on the hilly land and somewhat better soils on the steep slopes. Fig 1 shows the relationship between the Kaiteriteri soils and landscape postulated by Mr. Cutler together with the similar relationship postulated within the Mapua soil type (Fig 2).

The hypotheses depicted in these two diagrams were used as the basis for site selection in both sequences. Sites failing to comply with the criteria listed above were not considered. The Sherry and Braeburn soils plus the Kaiteriteri and Mapua deep phase were therefore disregarded, being subject to alluvial and colluvial deposition. Because of the limited study time available, it was realised that a balance would have to be achieved between the number of sites which could and should be analysed. It was finally decided to sample two sites on each of the different postulated surfaces. By this means, it was hoped to minimise intra-surface variation while leaving sufficient time available to complete the proposed experimental work.

The sites finally chosen for sampling at Kaiteriteri are shown in Fig 3. They included two on each of the steepland, hillslope and ridge areas with another sample being taken from an old, eroded ridge surface considered to contain the most weathered and leached solum in the sequence. In addition, an area considered to be possibly a remnant of the pre-glacial
surface was sampled, in an endeavour to investigate the effect that such pockets might have on present soil development. A discussion of the Kaiteriteri groundsurface designations is included in Section II 3.3.

The sequence on the Moutere gravels was sampled rather similarly with two sites being chosen for sampling on each of the postulated groundsurfaces. However, in this case it was also important to find an area which, besides forming part of the postulated sequence (Fig 2) also covered a wide range of Pinus radiata site quality. At the time of sampling J.D. Kingston was studying some soil properties associated with good and poor regeneration growth of radiata pine in the area of Tasman forest known as Compartment 6, and it was therefore considered preferable to sample in this area as far as possible. Consequently, six of the Mapua sites were selected from this area with two sites being chosen from each of the main, shallow, eroded ridge tops, the midslope, subsidiary ridge tops and the midslope gully sites. The midslope ridge and gully sites carried poor and good regeneration growth of P. radiata respectively and were in an area intensively sampled by Kingston (1968). The shallow, eroded ridge tops also carried poor regeneration growth of P. radiata. Examples of the Mapua shallow phase (Fig 2) are very limited being confined to a small steepland area bordering the main Nelson-Motueka highway. Two sites were selected in this area but unfortunately it was not possible to sample regeneration of the same age-class as that in Compartment 6 at Tasman. The final sites chosen are shown in Fig 4.

In both sequences, exploratory pits were dug to check the suitability of the profile being sampled but in neither area was it
thought necessary to conduct a preliminary sampling because of the considerable work previously done in other studies. The methods of sampling used in the two sequences are discussed in III 4.1. Appendix I contains full descriptions of the soils in the two toposequences and Table 1 and 2 summarise their principal environmental and pedological features.

The soil terminology used in the rest of this thesis is described in the following examples:

\[
\begin{align*}
G & = \text{Kaiteriteri}.
G 1 & = \text{Kaiteriteri, Pit one}.
G 1.2 & = \text{Kaiteriteri, Pit one, second horizon}.
M & = \text{Mapua}.
M 3 & = \text{Mapua, Pit three}.
M 3.2 & = \text{Mapua, Pit three, second horizon}.
\end{align*}
\]

In subsequent discussions, soils may be referred to either by their soil pit number eg G 1, G 2 etc., or by the groundsurface on which they occur. Thus the G 3 pit is situated on the K 2 groundsurface. The relationship between the soil and groundsurface designations is given in Table 1 and Table 2, and is discussed in more detail in Section II 3.3.
III 4. SAMPLING AND SAMPLE PREPARATION

III 4.1 Sampling procedure - soils

The sampling procedure employed differed between the Mapua and Kaiteriteri sequences. Sampling in the Mapua soils was carried out using the procedure described by Stevens (1968). Basically this consists of choosing a suitable site on the selected groundsurface and digging an exploratory pit. If the profile uncovered was considered satisfactory, the exploratory pit was deepened and widened sufficiently to allow a person to work from within it. A fixed square frame, 0.2 m\(^2\) in area, was used to delineate the sampling area. Within this frame living vegetation, L and FH layers were removed by careful scraping and packaged separately in sealed polythene bags. Each mineral soil horizon was then removed in turn with spade, trowel and knife until the arbitrary depth of 56 cm was reached. This depth on most occasions marked the top of the C horizon. Following weighing of each horizon excavated, subsamples were taken and packaged in sealed polythene bags. Most boundaries between horizons were clearly recognised. Contamination of one horizon by material from another was carefully avoided.

The two steepland sites (M1 and M2) which contained substantial proportions of stones were sampled slightly differently. Most stones larger than 2-3" were sorted and subsampled separately. The remaining soil plus smaller stones was also subsampled and packaged.

Sampling in the Kaiteriteri sequence was generally carried out rather differently, although the G1 and G2 profiles were sampled using the method described above. The remaining six profiles were sampled using volume-weight sampling tins. These brass tins of known dimensions are pushed three or four times into each horizon in turn and the
samples so obtained placed in polythene bags and sealed. Unfortunately, the degree of compaction of most of the horizons sampled meant that a certain amount of buckling occurred in the tins leading to a slight, general over-estimation of the weight of soil in a given horizon. However, the percentage error will be very similar in each case so the nett overall effect should be of little significance. In addition, a certain number of non-volume-weight "grab samples" were taken from below the 56 cm mark. Most of these "grab samples" were taken from road cuttings adjacent to the corresponding soil pit. Profile descriptions (Appendix I) were made soon after sampling.
III 4.2 Sample Preparation - soils

(i) **Litter (L):** Thoroughly air-dried, ground in a Christy and Norris mill and a portion stored in glass screw-top jars.

(ii) **FH Material:** Thoroughly air-dried, ground in a Christy and Norris mill and a portion stored in glass screw-top jars.

(iii) **Roots:** Thoroughly air-dried and stored in sealed polythene bags.

(iv) **Soils:** The various samples were weighed immediately on return to Lincoln College, thoroughly air-dried and reweighed. They were then sieved through a 2 mm square-hole sieve giving two size fractions, hereafter referred to as

- Stones :>2 mm
- Mineral soil :<2 mm

Following sieving the weight of each of these size fractions in the subsample was recorded and the A.D. volume-weight (in kg/ha) of the fractions in the particular horizon duly calculated.

Most of the larger stones from any horizon were sorted in the field and discarded after weighing. This figure was converted to kg/ha and added to the volume-weight of stones calculated from the subsample.

When a "grab-sample" was collected it was air-dried, sieved to separate the two size fractions and the percentage of mineral soil calculated. No volume-weights were calculated for these samples.

All mineral soils were milled in a Christy and Norris mill to approximately 50 mesh size (termed hereafter milled soil). In order to study the quantities of elements held within the stone fraction in certain horizons, a number of these were bulked in calculated proportions and ground to approximately 60 mesh size in the Christy and Norris mill. Results obtained using these samples were then re-applied to each of the horizons originally bulked.
III 4.3 Sampling procedure and sampling preparation - foliage.

The importance of uniform sampling methods in foliage analysis has been emphasized by several workers, including Tamm (1964). It is recognised that such sampling should be consistent with respect to time of sampling and position in the crown. The following sampling technique, essentially that used by the New South Wales Forestry Commission (Humphreys, pers comm.) was employed.

Two series of samplings were carried out in the first week of May in both 1968 and 1969. In each case, four trees were chosen from the immediate vicinity of each soil pit, giving finally the eight nearest trees to each sampled soil position. Slightly more or less than eight trees were sampled at some sites. Deformed or younger trees established subsequent to the main establishment period were ignored.

The height and generally thin crowns of the trees sampled necessitated felling of the trees to enable collection of samples to be achieved. After felling, the top whorls from each tree were immediately collected, placed in numbered cloth bags and transported to Lincoln College within 48 hours. They were then immediately dried in a forced-air oven at 80°C till all needles were completely dry. The needles were then stripped off the branches and ground in a Christy and Norris laboratory mill. The ground samples were stored in sealed polypropylene pottles.
III 5. ANALYTICAL PROCEDURES

III 5.1 Analytical methods - soils.

Unless otherwise stated, all determinations were made in duplicate.

(i) **pH:**

On mineral soil. Soil/distilled water suspensions (1:2.5) were stirred, left to stand overnight, and the suspensions read, after further stirring, on a Radiometer 23 pH meter with glass-calomel electrodes.

(ii) **Mechanical analysis:**

On mineral soil. A modified vision of the method of Bouyoucos (1962) was used. Samples were dispersed in 5% Calgon (commercial sodium hexametaphosphate) using an electric stirrer, and the coarse sand fraction separated on an 85 mesh sieve, dried and weighed. After transferring the suspension to a one litre cylinder and stirring thoroughly, hydrometer readings were taken at appropriate intervals to enable calculation of the various size fractions. All calculations were corrected to a constant temperature of 20°C. International size classifications were adopted: coarse sand 2 - 0.2 mm, fine sand 0.2 - 0.02 mm, silt 0.02 - 0.002 mm and clay < 0.002 mm.

(iii) **Carbon:**

On milled soil. The Walkley-Black wet oxidation by 1.0 N \( K_2Cr_2O_7 \) and concentrated sulphuric acid was used, followed by titration with 0.5 N ferrous ammonium sulphate. All results are reported as oxidisable carbon, because no factor was used to convert to total organic carbon.

(iv) **Nitrogen:**

On milled soil, L and FH. The semi-micro Kjeldhal method using
a cupric sulphate catalyst was employed.

(v) Cation exchange capacity, total exchangeable bases, exchangeable Ca, Mg, K and Al:

On mineral soil, L and FH. 1:1 mixtures of soil and silica sand were leached with neutral 1.0 N ammonium acetate, washed with 60% ethanol, distilled and the C.E.C. determined on the ammonia collected in boric acid. Exchangeable K was determined by flame photometry and exchangeable Ca and Mg were determined using a Techtron AA-2 atomic absorption spectrophotometer with Sr Cl₂ (1000 ppm) as a suppressant. The total exchangeable bases were calculated as the sum of exchangeable Ca + Mg + K. Exchangeable Al was determined on an aliquot of the leachate using the ferron method of Belyayeva (1966).

(vi) Total analyses for K, Ca, Mg, Al, Fe, and P:

On milled soil and stone samples. A mixture of 0.4000 g. of soil and 4.0 g of AR Na₂CO₃ was fused over a Mekker burner in platinum or palau crucibles. The melt was extracted with 1:1 HCl, digested on a water-bath, filtered and made to volume. Aliquots were taken for separate determinations of K, Ca, and Mg by flame photometer for K and by the Techtron AA-2 atomic absorption spectrophotometer for Ca and Mg (1000 ppm SrCl₂) as suppressant. Iron was determined by a slightly modified Jackson (1958) colorimetric procedure using an acetate buffer, hydroxylamine hydrochloride and 1:10 phenanthroline. Aluminium was determined on an appropriate aliquot using the colorimetric ferron method of Belyayeva (1966). The method of Dickman and Bray (1940) as modified by Fife (1959), was used for phosphorus analyses.
(vii) **Organic phosphorus:**

On milled soil. Initially the ignition method of Walker and Adams (1958) was used, except that P was determined by the method of Fogg and Wilkinson (1958). However, this method was found to be unsatisfactory (Section IV 2.4). Organic P was finally determined using the relationship \( P_o = P_t - \Sigma P_i \) where \( P_o \) is organic P, \( P_t \) is total P determined by sodium carbonate fusion and \( \Sigma P_i \) the sum of the inorganic phosphorus fractions (see following section).

(viii) **Inorganic phosphorus fractionation:**

On milled soil samples. The method of Williams *et al.* (1967) was used. This method is essentially a much-modified version of the Chang and Jackson (1957) and Glenn (1959) fractionation schemes. Samples were not duplicated in the fractionation. It was felt that the benefits of subjecting as many samples as possible to the fractionation outweighed the desirability of performing the fractionation on a smaller number of duplicated samples.

(ix) **X-ray diffraction patterns:**

Slides of fine clay \(<0.2 \mu\) and coarse clay \((0.2 - 2.0 \mu)\) were prepared from \(<2 \text{ mm}\) mineral soil samples. In each case the horizon containing the maximum clay content was sampled. Samples were treated with \( \text{H}_2\text{O}_2 \) and citrate/dithionite to remove organic matter and iron coatings respectively. Samples were then dispersed in distilled water and the clay fractions separated by appropriate centrifugation. 1% clay suspensions were prepared, saturated with \( K^+ \) and \( Mg^{++} \), and subjected to XRD analysis by Mn-filtered Fe K\(\alpha\) radiation at 50 Kv and 20 m. amps from a Phillips X-ray
spectrometer. The K⁺ saturated slides were examined at room
temperature and after heating to 110°C and 550°C. The magnesium
slides were sprayed with glycerol and examined at room temperature.

(x) **Sand mineralogy:**

Coarse sand samples separated in the course of mechanical analysis
were further separated in bromoform (ρ = 2.88). Heavy minerals
separated were examined under a polarising microscope. The
frequency of the minerals was estimated qualitatively following
the method used by the N.Z. Soil Bureau. (See Soils of New Zealand,

(xi) **Hot-water soluble Boron:**

On mineral soil. The method originally used was that of Gupta
(1967) which involves hot-water extraction of the soil sample,
filtration and determination of the boron in an aliquot of the
extract using carmine in conc H₂SO₄ as described by Hatcher and
Wilcox (1950). It was found that severe interference from organic
matter occurred, contrary to what Gupta asserts, giving grossly
inflated values for the hot-water soluble boron in those horizons
containing appreciable organic matter. The method finally adopted
involved extraction as described by Gupta, followed by centrifugation.
An aliquot was removed, evaporated to dryness, heated to 550°C for
2 hours, dissolved in 2 ml of 2N HCl, prior to transferring to a
polypropylene tube and determining boron using carmine.

(xii) **Easily reducible manganese:**

On mineral soil. 200 ml of neutral 1N ammonium acetate contain-
ing 0.2% of hydroquinone was added to 50g of soil and allowed to stand
overnight. The mixture was filtered and Mn determined in the
filtrate using a Techtron AA-2 atomic absorption spectrophotometer.

(xiii) **Bray No. 2 phosphorus:**

On mineral soil. 2g of soil was shaken for 1 minute with 20 ml of extractant (0.03 N NH$_4$F + 0.10 N HCl at pH 1.5), filtered and P determined in a 10 ml aliquot by the method of Dickman and Bray (1940).

(xiv) **Olsen phosphorus:**

On mineral soil. 5g of soil were shaken for 30 minutes with 100 ml of extractant (0.5 N NaHCO$_3$ at pH 8.5). The suspension was filtered and P determined by the method of Dickman and Bray (1940). It was found unnecessary to use charcoal to remove the organic matter colour in these soils.
III 5.2 Analytical methods - foliage.

All determinations were made in duplicate.

(i) Dry ashing:

On ground, air-dried needles. The method used was based on that of Piper (1942). 5g of sample was dried at 105°C overnight, cooled and reweighed. The samples were then slowly charred on a hot-plate, transferred to a muffle furnace and ignited at 450°C overnight. The ash was wet with 2-3 drops of water, 3 mls of 1:1 HCl were cautiously added under the covering watchglass and the sample digested for 30 minutes on a water-bath. 0.2 mls of conc. HNO₃ was then added, the solution evaporated to dryness and the dehydration completed by placing the crucible in an oven at 105°C for 1 hour. The dried salts were then moistened with 2 mls of 1:1 HCl, 10 mls of distilled H₂O was added, and the solution warmed on a water-bath for 15 minutes. The solution was then filtered and made up to 100 ml. Piper (loc cit) suggests that the insoluble silica residue should be dissolved in HF and added to the previous solution. This was not done in the present case. Extracts were stored in polypropylene bottles. Aliquots were taken for subsequent determinations.

(ii) Nitrogen:

On ground sample. A semi-micro Kjeldhal method using a selenium catalyst was employed.

(iii) Phosphorus:

On dry-ashing extract. The method of Kitson and Mellon (1944) (vanadomolybdophosphoric acid) was used.

(iv) Boron:

On ground sample. 1.000 g of sample was thoroughly wet with
3 ml of saturated Ba(OH)$_2$ and ashed at $550^\circ$C for 3 hours. The cool ash was dissolved in exactly 2.5 mls of 2 N HCl, the solution centrifuged and a 1 ml aliquot taken for analysis. Boron was determined using carmine in conc. $\text{H}_2\text{SO}_4$ as described by Hatcher and Wilcox (1950).

(v) **Ca, Mg, K, Mn, Fe, and Zn:**

On dry-ashing extract. Aliquots were taken for separate determinations of K by flame photometer and Techtron AA-2 atomic absorption spectrophotometer for Ca and Mg using SrCl$_2$ (1000 ppm) as a suppressant. Mn, Fe and Zn were also measured on the atomic absorption spectrophotometer using the appropriate cathode lamps.

(vi) **Aluminium:**

On dry-ashing extract. Al was determined on a suitable aliquot using the ferron method of Belyayeva (1966).
III 5.3 Presentation of results

In the following tables, all results have been converted to an oven-dry (OD) basis. This includes all the foliage data. Dashes in the tables usually indicate that no meaningful figure can be placed there (eg. no volume-weight figures can be given for horizons sampled on a "grab"basis). "n.d" means not determined.

Complete results appear in the tables with the exception that no L or FH data is presented. The insignificant quantities of both fractions present on nearly all groundsurfaces means that the omission of this data will not affect the results to any degree. Totals for profiles in both sequences represent the total quantity to a depth of 56 cm in all cases. In those profiles where a horizon-sampling depth did not end at exactly 56 cm, totals were calculated using the correct proportions of the horizons concerned.
IV

RESULTS - SOILS
IV 1. **INTRODUCTION**

The analytical results presented in the following two sections are divided for convenience into five groups:

1. **"Physical" parameters.** (Depths of horizons, soil pH, weights of soil material (\(<2 \text{ mm}\)) and stone material (\(\geq 2 \text{ mm}\)) and mechanical analysis).

2. **"Organic" parameters.** (Oxidisable carbon, nitrogen, C/N ratios, cation exchange analyses including exchangeable bases).

3. **"Total" analyses.** (Total calcium, magnesium and potassium, total iron and aluminium, plus citrate-dithionite soluble iron on selected samples).

4. **Phosphorus analyses.** (Total and organic phosphorus, inorganic phosphorus fractions).

5. **Mineralogical analyses.** (X-ray diffraction analyses and sand mineralogy).
IV 2. KAITERITERI GRANITE SEQUENCE

IV 2.1 "Physical" Parameters

Data showing the depths of the various horizons, soil pH and weights of the soil plus stone fractions in the various profiles are given in Table 3. In each case except the G 2 profile, the bottom horizons sampled are "grab samples" from road cuttings adjacent to the soil pit sites. The depths given for these "grab samples" are only approximate and should not be taken as particularly accurate.

Soil pH values are low in all samples and show no obvious trends, either within profiles or between soils of the sequence, although C horizon cutting samples do tend to give slightly higher values than the solum itself. Stone material >2 mm constitutes 20% of the total weight of material on the K 1 ground surface but complete weathering of the stone fraction has occurred on nearly all other ground surfaces of the sequence. The only exception is the K 2 ground surface which contains occasional buried granitic boulders. These however, are not considered in any subsequent calculations. Stevens (1968) found a general decline in tessera weight with increasing soil development in soils of the Franz Josef chronosequence. However, tessera weights in this sequence tend to be rather variable, and no such trend can be identified. This variation may well be a consequence of the sampling method (see Section III 5.1).

Results of mechanical analysis of the mineral soil fraction are given in Table 4 and graphed in Fig 5. Table 4 shows that maximum clay contents are found in the B horizons of all profiles. The most interesting feature of the data, however, is the decline in profile clay and
silt content of the two oldest groundsurfaces; a decline which coincides with an increase in the coarse sand fraction of these groundsurfaces. This decline is a little surprising as it is generally considered that increasing soil development is associated with increasing clay content of the profile concerned. One possible explanation for the decline in clay and silt and the corresponding increase in the coarse sand fraction is that a stage may be reached during soil development where conversion of the smaller size fractions into secondary mineral forms of larger particle size may occur. Sand mineralogy of the coarse sand fraction (Section IV 2.5) was not sufficiently detailed to either confirm or reject this hypothesis. Alternatively, clay-sized particles could be removed from the system by eluviation, with this loss assuming significant proportions at that stage of soil development where most or all of the weatherable silicate minerals have been converted to finer size fractions. Presumably at about this point, the rate of loss or destruction of clay in the system becomes greater than the rate of clay formation, leading to the decline in clay content of the system.
IV 2.2 "Organic" Parameters.

Analytical data illustrating the accumulation and decline of oxidizable C and N in the sequence are tabulated in Table 5 and graphed in Fig. 6. The early part of the graph, showing as it does an initial accumulation of both oxid. C and N followed by a subsequent decline, bears a close similarity to the results obtained by Stevens (loc cit) over the last 17,000 years of the Franz Josef chronosequence. The difference between the two sequences lies in the apparent attainment of a steady state in the Kaiteriteri sequence whereas Stevens had failed to reach any such state after 22,000 years. Syers and Walker (1969) also failed to reach a steady state after 10,000 years in the Manawatu chronosequence.

The failure of N-fixers prevalent in the area (eg. gorse, broom) to remain or to become established on the K4 and K5 groundsurfaces has apparently led to a situation of near equilibrium in the case of oxid. C and N with gains and losses in the system being in a state of near balance. This situation may well be a result of the very low phosphorus status of the soils concerned (see Section IV 2.4). The situation attained on the oldest groundsurfaces in this study appears to be similar to the terminal steady-state ecosystem described by Jenny et al (1969) in the pygmy forest-podsol ecosystem of the Mendocino coast in California.

Cation exchange data are given in Table 6. Percent base saturation (% B.S.) shows no consistent trend from the youngest to the oldest groundsurfaces. Depth functions for the G 1, G 4, G 6 and G 7 sites all show similarities with 14-25% B.S. in the A horizons and very low values in horizons below. The G 3 and G 5 sites show very low % B.S. values in the A horizons. This low value is a consequence of the extremely low T.E.B. value which in turn is primarily due to the very low values
for exchangeable $\text{Ca}^{++}$ in the A horizons concerned. The main feature of the data for exchangeable bases in Table 6 is the very low levels of exchangeable $\text{Ca}^{++}$, $\text{Mg}^{++}$ and $\text{K}^+$ present in all the samples, even in the G 1 profile developed on the youngest (K 1) groundsurface.

The data in Table 6 have been recalculated in Table 7 and graphed in Figs 7 and 8. Fig 7 shows an initial increase in C.E.C. to the G 4 profile on the K 3 groundsurface followed by a decline to an apparent steady state in soils on the oldest groundsurfaces. This is similar to results obtained by Stevens (loc cit) at Franz Josef with the difference that, as in the case of oxid. C and N accumulation, the curve appears to go beyond Stevens' data to a possible steady-state condition. The curve is very similar to that in Fig 5 showing the accumulation of clay and silt in the sequence. The results of multiple regression correlation analysis between oxid. C, % clay, % silt and C.E.C. will be discussed later in this section. T.E.B. values show no significant trends with increasing soil development in contrast to the small, steady increase found by Stevens (loc cit.), although large differences between individual sites are apparent.

Fig 8 shows the changes in totals of exchangeable cations per profile with increasing soil development. The only apparent trend is the slight, gradual, overall decline in exchangeable $\text{K}^+$ from the youngest (K 1) to the oldest (K 5) groundsurface. This may be due to the decreasing reserves of potassium in partly weathered rocks and pebbles as these become more weathered and finally non-existent in profiles on the older groundsurfaces. The curves for both exchangeable $\text{Ca}^{++}$ and $\text{Mg}^{++}$ show no obvious trends with quantities of both varying widely in members of the sequence.
IV 2.3 "Total" analyses.

Amounts of Total Ca, Mg and K in soils of the sequence are tabulated in Tables 8, 9, & 10 and graphed in Fig 9. Stevens (1968) found a slow, steady, decline in both Total Ca and Mg in older soils of the Franz Josef chronosequence. Total K in the same sequence had apparently reached a steady state in the oldest profiles. The results graphed in Fig 9 for Total Ca and K in the Kaiteriteri sequence show, in contrast, rather indeterminate trends with increasing soil development, although a general overall decline in both elements is apparent in going from the youngest to the oldest groundsurfaces. A feature of Fig 9 is the close similarity of the curves for both Total Ca and Total K. Simple regression of the data in Tables 8 and 10 was used to investigate this relationship. For the total amounts of each element in the profile:

\[ K = 0.799 \text{Ca} + 9.94 \times 10^4 \quad R^2 = 0.920^{**} \]

For percentages of each element:

\[ \%K = 0.571 (\% \text{Ca}) + 1.363 \quad R^2 = 0.354^{**} \]

The highly significant correlation between the profile totals (to 56 cm) of Ca and K is thought to be a reflection of the sand mineralogy of these soils. Sand mineralogical data in Table 26 shows the near absence of any mica fraction in the solum of even the youngest K 1 soil, although biotite is present to some extent in most C horizons. Such biotite, however, usually shows signs of extensive weathering. The principal sand fraction minerals present in the various solums are feldspars and quartz. Any Ca and K present in the solum must therefore be the result of partly-weathered feldspar. The close correlation between amounts of Ca and K in the profiles of the sequence may be an indication that these elements are weathering in the particular feldspars present and are being subsequently
leached from the system at about the same relative rates.

No significant correlations were found between Total Ca and Mg or Total K and Mg in the profile. Amounts of Mg in the solum do however show the steady decline found by Stevens (loc.cit.) in the Franz Josef sequence. Stevens ascribed this to leaching of magnesium weathered from moderately resistant minerals. The lack of significant correlation between Total Mg, K and Ca, may thus mean that Mg is being weathered and leached from the system at a rate rather different from that of Ca and K, or, alternatively, it may be a reflection of the possibility that Mg is being weathered from minerals other than feldspars.

Data for Total Al and Fe are tabulated in Tables 11, 12 and 13 and graphed in Fig 10. Depth functions for both elements show the effects of leaching in the upper horizons with a steady increase in percentages down the profile.

The accumulation of Total Al and Fe in the sequence is illustrated in Fig 10. Trends for both elements are very similar. The lower quantities of Total Fe present and the resulting smaller displacement between points when plotted on the same scale as Total Al tend to belie this statement, but an examination of the data in Table 13 will justify the observation. Amounts of both elements reach a peak on the K 3 ground-surface after a period of constancy between the K 1 and K 2 groundsurfaces with a subsequent almost linear decline to the oldest groundsurfaces. It may be that, up until the stage of soil development represented by the K 3 groundsurface, other elements are being lost from the profile by weathering and subsequent leaching faster than Al and Fe, but that subsequently, when only highly resistant mineral species such as quartz remain, the rate of loss of Al and Fe from the system becomes significant
in its own right.

The citrate-dithionite soluble iron (Fe\textsubscript{c}), was only measured in those horizons of maximum clay content subjected to clay mineralogical analysis. The G 6 site was not sampled for these analyses. Percentages of Fe\textsubscript{c} follow the Total Fe curve, with the maximum amount being extracted from the G 4 soil on the K 3 groundsurface.

Ellis (1969) has recently used the ratio Fe\textsubscript{c} to Total Fe (Fe\textsubscript{t}) as an index of weathering in a series of granite soils in Tasmania. He found values ranging from 0.05 in unweathered granite to 0.90 in strongly weathered granite and used these ratios to indicate differences in the age and degree of weathering of the profiles studied. The ratios calculated in Table 11 show a value of 0.27 on the youngest K 1 groundsurface rising rapidly to 0.50 on the K2 groundsurface and then continuing to slowly rise to a final value of 0.59 on the oldest K5 groundsurface. The only exception to this pattern is the G 5 (K 4) soil which has a rather lower ratio than expected of 0.38. One interpretation is that the K 1 groundsurface may be considerably younger than the other groundsurfaces which may be of a rather more uniform geological age. Alternatively, in a situation such as exists in the Kaiteriteri sequence, where even the youngest groundsurface overlies strongly weathered granite, small differences in the Fe\textsubscript{c}/Fe\textsubscript{t} ratio may be of much greater significance in the latter stages of weathering than observed by Ellis studying a situation covering a rather different range of granite weathering. If this is so, small changes in ratio may still signify considerable differences in age between the different groundsurfaces. The merit of discussing the Fe\textsubscript{c}/Fe\textsubscript{t} ratio in this sequence when only one horizon from each profile has been analysed is questionable. However, the results do suggest in a broad way that such
a ratio may have a place as an index of weathering at least on granite soils.
IV 2.4 Phosphorus analyses.

Results for organic phosphorus (Po) and Total phosphorus (Pt) in both stone and soil samples are tabulated in Table 14 and graphed in Fig 11. Results for Total P are summarised in Table 15. Organic P is calculated as Pt - \( \Sigma P_i \) where \( \Sigma P_i \) is the sum of the fractions in the inorganic phosphorus fractionation, the results of which are described later in this section. The use of this value, rather than that obtained by the ignition method of Walker and Adams (1958) requires some discussion. Williams and Walker (1967) found that ignition markedly increased the solubility in dilute acid of iron- and aluminium-bound phosphate in samples of weathered New Zealand greywacke rock. They conjectured that the magnitude of this increase in solubility was related to the degree of weathering of the sample. The results of Po determinations as measured by the ignition method are compared with organic P determined as Pt - \( \Sigma M \) in Table 16. This latter method was concluded by Williams et al (1970) to be the most accurate method of determining Po over a wide range of soil weathering. It can be seen from Table 16 that values for Po as determined by ignition are, in most cases, over-estimated, this result being presumably the consequence of increases in solubility of some phosphates in these strongly weathered and leached soils. Table 16 only includes data for soils in the granitic sequence but Mapua soils developed on the equally strongly weathered and leached Moutere gravels show similar characteristics. Fig 11 shows trends in both Pt and Po with increasing soil development. Pt shows a constant decline, with only the soils on the K 4 groundsurface disturbing the pattern. The decline in Pt, similar to that found in the older soils of the Franz Josef chronosequence by Stevens (1968) is an indication of the importance that
leaching plays in the P status of soils over the aeons of pedogenesis. Amounts of Po in the various profiles remain relatively constant throughout the sequence with the exception of the G 5 soil, until the oldest K 5 groundsurface which contains only 5.4% of organic phosphorus - a remarkably low value. If this value is accurate (see Section VI 2.), then it may be that, in the latter stages of soil development (such as on the K 5 groundsurface), a stage may be reached where quantities of elements important to plant nutrition reach such a low level, that plant growth in the system virtually ceases. The end-result of this would be an inevitable decline of organic matter in the system with a consequent lowering of the amount of Po present, together with changes in other soil characteristics dependent on soil O.M. content.

Inorganic phosphorus in soils of the sequence was fractionated into eight forms (Williams et al., 1967) which, in the following discussion, will be grouped as follows :-

\[
\begin{align*}
\text{NH}_4\text{Cl - soluble P} & \quad \text{NH}_4\text{F-P} \quad \text{1st NaOH-P} \quad \text{HCl-P} \\
\text{Red - sol. P} & \quad \text{2nd NaOH-P} \\
\text{Residual organic P} & \quad \text{Residual inorganic P}
\end{align*}
\]

The inclusion of HCl-P in the non-occluded P fraction, rather than in a separate category, is justified by the almost complete lack of this fraction in all soils of the sequence.
Concentrations of P in the various individual fractions are shown in Tables 17 and 18. The easily-soluble P fraction was found to be zero for all samples and consequently has not been included in any of the tables. Changes in the inorganic P fractions (ppm) within and between the soils on the different surfaces can be examined from Table 17. The youngest G 1 soil is the only one to contain any acid-extractable Ca-P (HCl-P), although amounts present in the solum are small. However, the cutting sample G 1.5 contains a considerable amount of this fraction, as does the stone sample from the G 1.2 horizon. Traces of acid-extractable Ca-P are found in some of the cutting samples from the older groundsurfaces. Non-occluded P shows evidence of accumulation in lower horizons of the G 1 profile, but in soils on older groundsurfaces, accumulation in surface horizons is apparent, although absolute amounts in the solum are very low (<20 ppm). A decline in the fraction from G 1 to G 7 also occurs. Occluded P remains relatively constant throughout all profiles as does residual P, although proportions of the residual organic and inorganic P fractions tend to vary between samples.

Weights of the various inorganic P fractions in the soil and stone fractions have been tabulated (Tables 19, 20 and 21) & plotted (Fig 12). The curve for $\Sigma$Pi bears a close relationship to that for Pt in Fig 11, showing a steady decline to a very low value on the oldest K5 groundsurface. Non-occluded P shows an initial sharp drop almost parallel to that in $\Sigma$Pi between the K 1 and K 2 groundsurfaces, followed by a smaller drop to an apparent steady-state on the three oldest groundsurfaces. This steady-state is probably similar to that discussed earlier (Section IV 2.2) with respect to carbon and nitrogen accumulation. Amounts of occluded inorganic P in the sequence show a linear decline between K 1 and K 5 but
residual P, after reaching a peak on the K 2 groundsurface, declines overall thereafter.

The behaviour of the various fractions is perhaps best illustrated in Table 22 and Figure 13 which show the proportions of $\Sigma P_i$ held in the various inorganic P fractions. The non-occluded P curve follows closely that in Fig. 12. From being 61% of $\Sigma P_i$ on the K 1 groundsurface, the fraction drops rapidly to an apparent steady state of about 12% of $\Sigma P_i$ on the oldest groundsurfaces. The final rise on the K 5 groundsurface is considered to lie within the error margin of the fractionation procedure and is not thought to be of significance. The percentage composition of the non-occluded P fraction on the K 1 groundsurface is of interest. The soil (<2 mm) and stone (>2 mm) fractions of the profile contain respectively 48% and 83% of their total inorganic P in the non-occluded fraction. Included in these percentages are 5.4% and 20% respectively of acid-extractable Ca-P (HCl-P). The stone fraction is therefore apparently less weathered than the surrounding soil matrix. Overall, 30% of the non-occluded P in the total inorganic P of the profile is contained in the >2 mm fraction and 31% in the <2 mm fraction. There is thus a considerable reservoir of P in the >2 mm fraction which has yet to be released by weathering processes. This is not the case in the soils developed on the older groundsurfaces (K 2 to K 5), where all material >2 mm has weathered and is now part of the solum. Another interesting feature of the non-occluded P data in Table 22 is the relative quantities of surface Al-P ($\text{NH}_4\text{F-P}$) and surface Fe-P (1st NaOH-P). Percentages of surface Al-P drop rapidly from a maximum of 30% on the K1 groundsurface to about 3-5% on all other groundsurfaces, while surface Fe-P remains relatively constant throughout the sequence. Occluded P, when expressed
as a percentage of $\Sigma Pi$ shows an almost linear increase, in contrast to the linear decline in absolute amount shown in Fig 12.

The curve for residual P (Fig 13) as a percentage of $\Sigma Pi$ shows a sharp rise from the K 1 to the K 2 groundsurface, followed by a nearly steady state on the next four groundsurfaces. The increase in residual P between K 1 and K 2 corresponds with the decrease in non-occluded P between the same two groundsurfaces. It thus appears as if the occluded P fraction is being transformed to residual P as fast as the non-occluded to occluded P transformation. However, the residual P fraction is mainly remarkable for the extremely large proportion of $\Sigma Pi$ it includes. Residual P on three of the groundsurfaces represents approximately 60% of the total inorganic P in the profile and on the K 4 groundsurface it represents over 70% of $\Sigma Pi$. Values of this magnitude for this fraction have not been reported previously.

The possible nature of this substantial fraction was investigated in a series of experiments involving two soil samples and samples of calcined "C - grade" rock phosphate from Christmas Island in the Indian Ocean. The soil samples selected for this further experimentation were G 3.3 and M. 5.5. Both contained large amounts of residual Po and residual Pi. The treatments that each of these soil samples was subjected to were as follows :

1. P fractionation as described by Williams et al (1967).
2. Williams' P fractionation, except that the residual Po fraction was determined using the method of Mehta et al (1954) as for the determination of organic P in soils.
3. Williams' P fractionation including determination of residual organic P by ignition at 550°C for 1 hour, followed by
extraction with 1.0 N HCl for 16 hours. This ignition/extraction determination of residual Po was repeated until no more residual Po was extracted. The sample was then analysed for residual Pi in the normal way. In both soils analysed, the ignition/extraction step was repeated 5 times before no more P was extracted.

(4) The samples were heated at 550°C for 2 hours and then subjected to P fractionation.

The results of this work for the G 3.3 sample are shown in Fig 14. Results for the M 5.5 sample are not given, but are very similar to those for G 3.3. The numbers of the histograms correspond to the experimental treatments enumerated above. A number of interesting facts emerge from Fig 14. The use of Mehta's alkaline extraction technique to determine residual Po (histogram number 2), gives a similar result to the ignition/extraction method of determining this fraction, shown in histogram number 1. The possibility of the Mehta method extracting inorganic forms of phosphate was investigated by heating a sample of non-calcined Christmas Island rock phosphate containing 16.2% of residual P with 0.5 N NaOH for 1 hour (Table 23). This sample was assumed to contain no organic P. The treatment extracted 61.1% of the total phosphorus. Even if it is assumed that such treatment would extract all fractions except HCl- and residual P as given in Table 23, it can be seen that only 56.6% of the total P would be extracted. The remaining 4.5% P that has been extracted must therefore come from the residual P fraction and is a minimum estimate, since the chances of all fractions except HCl-P and residual P being extracted by hot NaOH is rather doubtful, particularly with respect to reductant -
soluble P. The third histogram shows that continued ignition/extraction in the residual Po step removed some, but not all, of the residual inorganic P. This suggests that inorganic forms of residual P are being solubilised in the heating phase of the residual Po determination. Histogram number 4 shows the dramatic changes that occur when the sample is ignited prior to fractionation. Apart from the expected conversion of the organic P fraction to inorganic forms, the increase in the magnitude of NH₄F-P is almost entirely at the expense of the residual Po fraction. This discovery led to the work on calcined Christmas Island "C-grade" rock phosphate (CIRP) mentioned earlier.

It was known from previous work by Doak et al (1965) that heating of CIRP to about 450°C enhanced its solubility in citrate extractants. It was thought that this fact might have some relevance to the apparent increase in solubility of the residual Po fraction in these soils on heating to a similar temperature. It was therefore decided to subject to P fractionation a range of CIRP samples calcined at temperatures between 300°C and 1100°C. The results of this fractionation are given in Table 23 and graphed in Fig. 15.

The main features of Fig. 15 are the dramatic increase in the NH₄F-P fraction between 300°C and 500°C and the sharp drop in the same fraction after 700°C which is associated with a sharp increase in the HCl-P fraction. The increase in the NH₄F-P fraction between 300°C and 500°C is mainly at the expense of 1st NaOH-P, 2nd NaOH-P and residual P, which all decline from 15–25% of the Total P to less than 2% between 600°C and 1000°C. These changes in Al-bound phosphate (NH₄F-P) and acid-extractable Ca-P (HCl-P) are interesting when compared with work done at the Fertilizer Research Station, Otara, on mineralogical changes during calcination.
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(Dr. J. Rogers, pers. comm.). This shows the following changes:-

1. \( \text{CaO}^{3/2} \text{Al}_2\text{O}_3\cdot\text{P}_2\text{O}_5 \cdot 3\frac{1}{2} \text{H}_2\text{O} \xrightarrow{450^\circ\text{C}} \text{CaO}^{3/2} \text{Al}_2\text{O}_3\cdot\text{P}_2\text{O}_5 + 3\frac{1}{2} \text{H}_2\text{O} \)

   crandallite. 'meta' crandallite.

2. \( \text{CaO}^{3/2} \text{Al}_2\text{O}_3\cdot\text{P}_2\text{O}_5 \xrightarrow{800^\circ\text{C}} 4 \text{AlPO}_4 + 3\text{CaO}\cdot\text{P}_2\text{O}_5\cdot 2\frac{1}{2} \text{Al}_2\text{O}_3 \)

   'meta' crandallite cristobalite

3. \( 3\text{CaO}\cdot\text{P}_2\text{O}_5\cdot 2\frac{1}{2} \text{Al}_2\text{O}_3 \xrightarrow{900^\circ\text{C} - 1000^\circ\text{C}} \text{Ca}_3(\text{PO}_4)_2 + 2\frac{1}{2} \text{Al}_2\text{O}_3 \)

   cristobalite whitlockite corundum

The breakdown of crandallite through 'meta' crandallite to aluminium phosphate and cristobalite occurring between 450\(^\circ\) and 800\(^\circ\) agrees well with the increase in Al-bound phosphate found in the P fractionation over the same temperature range, while the subsequent dissociation of cristobalite to corundum and whitlockite between 900\(^\circ\) and 1000\(^\circ\)C corresponds to the increase in acid-extractable Ca-P between 800\(^\circ\) and 1000\(^\circ\)C. This close correspondence between fractionation and mineralogical chemical data is in itself a good advertisement for the fractionation procedure. However, the most interesting feature of Fig 15 from the point of view of the histograms in Fig 14 is the decline in residual P from being 16% of the total P in the unheated sample to zero in the sample heated to 600\(^\circ\)C. This confirms that some inorganic P fractions of a crandallite-type structure are solubilised on heating. The overall conclusion from the work pictured in Figs 14 and 15 is that the so-called residual organic P fraction in the Kaiteriteri and Mapua soils is composed of inorganic phosphates, possibly structurally similar to crandallite. These phosphates are almost certainly not organic in nature, contrary to the name of the fraction they are assigned. A better name for the fraction, if indeed it is to be distinguished separately at all, may be "residual P extracted by HCl after ignition."
These phosphates are apparently formed in the latter stages of soil development and must therefore be a product of soil weathering processes. Formation of such phosphates is presumably the main reason for the lack of success of Walker & Adams (loc. cit.) method for the determination of organic P in soils that are strongly weathered and leached.

A comparison of the data plotted in Figs 11, 12 and 13 with similar data plotted by Stevens (1968) for the Franz Josef chronosequence, shows that the portion of Stevens' curves covering the two oldest soils in the Franz Josef sequence corresponds well with the curves for the Kaiteriteri sequence. This applies particularly to Fig 13 where percentages of the various fractions of $\Sigma P_i$ are plotted. Stevens found, in his oldest soils, where acid-extractable Ca-P was nearly or completely removed from the system, that decreases in the percentage of non-occluded P and increases in the percentages of occluded and residual P occurred. This occurs in Fig 13. The maximum percentage of residual P in the Franz Josef soils was nearly 29% in the Okarito soil. This is comparable with the 24% found on the youngest K 1 groundsurface at Kaiteriteri. It would seem therefore, that, in terms of the P status of the Kaiteriteri soils, the youngest groundsurface in the Kaiteriteri sequence is approximately comparable with the oldest Okarito soil in the Franz Josef sequence.
IV 2.5 Mineralogical Analyses.

Mineralogical studies on samples of the Kaiteriteri sequence included clay mineralogical analyses and mineralogy of the sand fraction separated during mechanical analysis. Clay mineralogical data are given in Tables 24 and 25 and graphed as histograms in Figs 16 and 17. Due to lack of time, clay mineralogy was performed on only one horizon from each of the five groundsurfaces plus samples from the G 2 and G 8 profiles, results of which will be discussed separately (section IV 2.6). The horizon chosen in each case was that one containing the maximum clay content of the profile. The method used to determine the composition of the crystalline clay fraction is that described by Claridge (1969) and is somewhat similar to that used by Johnson et al (1963) with the basic difference that the magnesium/glycerol and potassium treatments are performed on separate slides which introduces errors due amongst other things, to preferred orientation of the clay particles. Consequently, the results given are not intended to be quantitative and should be regarded only as an indication of trends between the various groundsurfaces.

Both the fine and coarse clay fractions show similar trends in the sequence, although these trends are more pronounced in the coarse clay fraction. The fine clay fraction (\(<0.2\mu\)) shows vermiculite-1 decreasing from about a third of the clay fraction on the K 1 groundsurface to a common level of 5 to 15% on the K 2, K 4 and K 5 groundsurfaces. The kaolin content of these profiles shows a corresponding increase as the amount of vermiculite-1 decreases. The K 3 groundsurface presents an anomalous situation, containing entirely kaolin with no indication of either vermiculite-1 or the small, but significant, proportions of gibbsite
present on the other surfaces. The reason for this anomalous behaviour is uncertain. The K 3 groundsurface appears, from the clay mineralogy, to have undergone a period of more extensive weathering than either the K 4 or K 5 groundsurface, but other evidence, particularly the chemical data discussed in earlier sections, contradicts this. The possibility that the K 3 solum has developed from a pre-weathered PM appears unlikely in view of the mineralogy of the G 8 profile which will be discussed separately in Section IV 2.6. A similar anomaly appears in the coarse clay fraction (0.2 - 2.0 \( \mu \)), where the kaolin content of the K 3 sample is again significantly greater than on either of the older groundsurfaces. The trends apparent in the fine clay fraction are more definite in the coarse clay fraction. Small quantities of gibbsite and quartz are present in all samples. Vermiculite-1 is the predominant clay mineral on the youngest K 1 groundsurface but it drops to a relatively constant proportion on the older groundsurfaces, with the exception of K 3. Proportions of kaolin again increase with the declining vermiculite-1 content.

Kaolin, as a more advanced product of weathering than vermiculite-1 tends to predominate in the fine clay fraction, while the less weathered vermiculite-1 is of greater significance in the slightly coarser clay fraction. Overall, therefore, the sequence follows the latter stages of the micaeous weathering sequence in the zonal soils of New Zealand suggested by Fieldes (1968) for conditions of strong leaching at low pH values.

Fieldes (loc cit) has observed that soils high in kaolin are not necessarily deficient in potassium, since the weathering conditions producing kaolin are also capable of weathering potash feldspars.
This is confirmed in this sequence where no evidence of K deficiency in the vegetation has been found, even though soils on the older surfaces in particular contain kaolin as the predominate clay mineral.

The frequency of the heavy minerals of the sand fractions is shown in Table 26. Aegirine - augite is the predominant heavy mineral present with proportions of green hornblende decreasing from the youngest to the oldest groundsurface. Small quantities of zircon are present in all samples. Biotite, muscovite, ilmenite and garnet are present in very small quantities in some profiles while tourmaline, a boron containing mineral, is present on the K 2 groundsurface in very small amounts. The frequency of the lighter minerals of the sand fraction is not shown but is similar in all profiles. Samples from A horizons (G 1.1, G 3.1 etc.), contain predominantly feldspars and quartz with only traces of biotite. Cutting samples, however, contain up to 50% biotite together with feldspars and quartz. Much of the biotite and feldspar fractions on the older groundsurfaces shows signs of extensive weathering. Small amounts of muscovite are present in many cutting samples. Further differentiation of the feldspathic fraction was not attempted.
IV 2.6 Discussion of the G 2 and G 8 profiles

As was discussed earlier, the G 2 and G 8 sites were chosen for sampling as replicates of the G 1 and G 7 sampling positions respectively. Thus G 2 was selected as an example of a young soil developed on a steep-land landscape and G 8 as an example of the most strongly weathered soil in the area, being developed on an exposed ridge-top position. Unexpected differences in the G 2 profile when compared with other members of the sequence, were only noted after analyses had been completed, but it was recognised, even before the G 8 site had been sampled, that the soil-forming factors involved in this particular profile were probably different from those of other soils in the area. Reference to profile descriptions in Appendix I and a colour photograph of the site (Plate 2) shows that the B 2 horizon of this soil consists of a red, strongly weathered clay loam, the influence of which is apparent in the upper horizons of the profile. Similar areas of red weathering are found elsewhere in the study area, particularly on the more weathered portions of the landscape. Such areas, however, contain incomplete profiles compared with the G 8 site.

The G 8 profile is only found over one area of a few square chains and is not found elsewhere at Kaiteriteri to the best of the author's knowledge. It was thought that it would be of interest to sample the profile in an attempt to throw some light on its genesis. It was considered (Cutler, pers. comm.) that the profile was probably a remnant of an ancient landscape and that it may have formed from a preweathered P M. Consequently the profile was not expected to necessarily show similar characteristics to the other soils studied although it was thought that volume-weight data for nutrient elements in the profile would give even
lower values than that for the K5 groundsurface.

Quantities of Total Ca and Mg (Table 10) in the G 8 profile are similar to and Total K significantly lower than those found on the K 5 groundsurface, as might be expected. Mechanical analysis data (Table 4) also shows similarity to that from the K 5 groundsurface. However, the expected trend is not followed for other data. Thus oxid. C and N (Table 5) both show levels greater than those for all other profiles except G 3, while quantities of exchangeable Ca, Mg and K (Table 7) are greater than those for any of the profiles of the sequence. Levels of Total Al and Fe (Table 13) are also higher than trends in the sequence would indicate. Phosphorus data for the profile also does not follow expected trends in many instances, with quantities of total P, inorganic P fractions and total inorganic P being greater than in a number of the sites in the sequence (Tables 14 and 21). Percentages of the inorganic P fractions (Table 22) show similar trends to those for the more weathered members of the sequence, although reductant-soluble P tends to be a larger proportion than usual.

The main difference between the G 8 profile and the other sites in the sequence appears in the clay mineralogy of the G 8.3 horizon and, to a lesser extent, in the composition of the heavy mineral fraction. Tables 24 and 25 give the approximate composition of both clay fractions from the G 8.3 horizon. It was pointed out in the preceding section that values given in this table should not be considered quantitative and this particularly applies to the G 8.3 sample. Both fine and coarse clay X-ray diffraction traces show extremely low peak heights and apparently low-order crystallinity of clay minerals with the exception of gibbsite
which gave a very sharp peak on all slides. The possible amorphous nature of the soil clays demonstrated by the XRD patterns was refuted by IR patterns of the fine and coarse clay fractions of the G 8.3 sample. A Beckman IR 20 infrared spectrophotometer was used for these measurements. The IR traces showed considerable proportions of gibbsite and kaolin of a crystalline nature. It can be concluded therefore from the clay mineralogical analyses, that the G 8.3 horizon contains probably 50% gibbsite together with kaolin and some vermiculite-1 in the fine and coarse clay fractions. The reason for the very poor XRD patterns obtained with all treatments from the particular horizon sampled is presumably due to the non-random orientation of clay particles on the prepared slides. It is possible that the high gibbsite content of the sample may have affected particle orientation.

The relative abundance of the heavy minerals of the sand fraction tabulated in Table 26 shows a rather greater proportion of ilmenite than is present in the other soils of the sequence. The strongly weathered G 8.3 horizon also has a greater proportion of zircon crystals than any other sample.

The overall evidence, both chemical and mineralogical, confirms the likelihood of the groundsurface containing the G 8 profile being a residual pocket of the original landscape, with the profile being developed from a preweathered parent material. The high proportion of gibbsite in the G 8.3 horizon is strong evidence for this, as is the rather different chemical nature of the profile to that which would be expected if the G 8 profile were part of the overall Kaiteriteri sequence.
As was noted earlier in this section, the G2 site was originally chosen for sampling as an example of the youngest, least weathered soil of the area, developed on a steepland landscape. Consequently the profile was expected to show characteristics similar to those found in the G 1 profile on the youngest K 1 groundsurface. However, unexpected differences in the G 2 profile which emerged on analysis led to a further evaluation of the groundsurface on which the profile is situated and its position in the landscape. The observed differences, while possibly not as marked as those in the G 8 profile, are quite substantial and are apparent in much of the chemical volume-weight data.

Phosphorus data show considerable differences from expected trends. Quantities of both total P and total inorganic P (Tables 14 and 21) are lower than for all other sites except the most strongly weathered K 5 groundsurface. A stone sample from the G 2.2 horizon contained only 40 ppm of inorganic phosphorus (Table 18) compared with 484 ppm in a stone sample from the corresponding horizon of the G 1 profile. Percentages of inorganic P fractions in Table 22 show a lower proportion of non-occluded P than on the K1 groundsurface, while the percentage of residual P in the profile is considerably higher, being of a level similar to the more weathered groundsurfaces of the sequence. Although the C.E.C. of the profile is similar to that for the K 1 groundsurface (Table 7), the absolute quantities and depth functions of exchangeable Ca and Mg are very different (Tables 6 and 7). The quantity of exchangeable Ca in the G2 solum is twice that in the G 1 profile and exchangeable Mg, although similar in terms of absolute quantities in the profile, shows a markedly different depth function. Thus the G 1 profile shows maximum exchangeable Mg in the A horizon with a rapid decrease down the profile. In the G 2 solum, however,
exchangeable Mg increases down the profile, reaching a level in the B 2 horizon considerably greater than in any other sample. Profile totals (Tables 10 and 13) for Total Ca and K particularly and total Al to a lesser degree show a similarity to values for the G 1 profile indicating a similarly weathered feldspar content on both groundsurfaces. However, the very low quantities of Total Fe and Mg observed are thought to be an indication of a low level of ferromagnesium minerals in the G 2 profile.

Physical properties of the solum and the general area tend to place the G 2 profile as a soil developed on a K 1 groundsurface. Table 3 shows that the profile contains substantial proportions of material > 2 mm in the form of partly-weathered granite chips and granite boulders. Vegetation in the area of the sample site consists mainly of vigorous bracken and gorse similar to that found on the K1 groundsurface. Mechanical analysis data (Table 4) illustrate the youthfulness of the profile compared with others in the sequence with the overall clay content of the profile being of the order of 10%. If percentage clay content is taken as a criteria of the degree of weathering of a profile, the G2 solum has undergone less weathering than any other sampled Kaiteriteri profile. Clay mineralogical data (Tables 24 and 25) shows that the horizon of maximum clay content (G 2.4) contains similar proportions of kaolin and vermiculite-1 in both the fine and coarse clay fraction to those in the corresponding G 1.3 horizon.

While the physical properties of the profile indicate a young, rather weakly weathered solum, the chemical properties discussed above are rather more similar to those displayed by some of the more strongly weathered profiles in the sequence. Profile descriptions in Appendix I
show that, although the G 2 site is situated on a steep 37° slope, it is only about 40 feet below the ridge crest. Carter and Chorley (1961) and Schumm (1956) investigated hillslope development systems and concluded that a sequence of slope steepening, maintenance of a characteristic slope angle and a decline in angle during slope retreat could be identified with increasing stream incision and subsequent landscape dissection (Section II 3.2). It is apparent that, only during the final stages of this sequence, will the uppermost portions of a slope begin to be seriously affected by erosion. If this concept of slope formation is applied to the G 2 area of the Kaiteriteri landscape, it is possible that the parent material of the G 2 profile may have been influenced to some degree by the original preweathered ridge surface. This would explain the anomalous differences in the physical and chemical properties of the profile, with the solum showing characteristics of rather weak weathering due to its position on a steepland surface, but with its chemical nature being influenced to a large degree by a slightly different Parent Material from the other soils of the sequence. This argument presupposes that this part of the Kaiteriteri landscape has not yet reached a stage of declining slope angle. This, although difficult to substantiate, appears to be the case.

It has been shown in the preceding discussion, that both the G 2 and G 8 profiles are probably developed from a parent material of different composition to that of the other granite profiles studied. Consequently, neither of the profiles was considered as part of the Kaiteriteri sequence and have therefore been discussed separately. This variation in parent material, although not entirely unexpected in the case of the G 8 profile, was certainly not originally anticipated in the G 2 profile. However a
re-evaluation of the position of the G 2 groundsurface in the landscape has produced a satisfactory explanation for the observed differences. The case of the G 2 profile is considered to be a good example of the use of quantitative methods to discover differences in profile genesis not apparent in profile morphology and the need for a critical evaluation of the landscape prior to sampling in other sequential soil studies.
IV 3. MAPUA SEQUENCE

IV 3.1 "Physical" Parameters.

Horizon designations, and depths, weights of soil and stones in the profile, and results of pH measurements are shown in Table 27. Depth functions for soil pH show a tendency to increase slightly down the profile with relatively constant values of 4.1 - 4.8 being general throughout the profile. The one real exception is the M 1.5 sample with a pH of 5.6. This sample, taken from a cutting 1.8 m below the pit site, is probably the least weathered of all with a stone content of 82%. The very acid nature of all the profiles is probably partly a consequence of the vegetative cover of Pinus radiata in the study area. This species produces an acid litter and inevitably modifies the soil environment to produce an acid system.

Weights of soil plus stones per profile (Table 27) initially decline and then rise as one moves from steepland to ridge sites (Fig 18). The weight of soil in a tessera increases markedly between the steepland and midslope sites with a corresponding decrease in the weight of stones. The weight of soil then decreases slightly in the ridge sites but the weight of stones increases quite markedly. Not surprisingly, the same pattern emerges in the figures for the percentages of soil and stones in the various horizons, with the proportion of stones dropping from 43% of the total weight to only 5% on the midslope groundsurface and then increasing to 16% in the ridge profiles.

The nature of the stone fraction on each of the three groundsurfaces varies quite appreciably. The substantial stone fraction present in the M 1 profile consists of relatively unweathered greywacke gravels somewhat
similar in their degree of weathering to those found in profiles of the Spooner hill soils. This soil series occurs in the central region of the Moutere gravels formation and is generally considered to be considerably less weathered than the Mapua series. The stone fraction of the other steepland profile, (M 2) tends to be more weathered than that of the M 1 profile, but is still quite hard and will only break under a hammer blow. The gravels in the midslope sites, however, are so strongly weathered that the stone structure forms a virtually homogeneous matrix with the soil material. The gravels can be easily crushed in the hand and consequently were very difficult to separate during preparation of the soil for analysis. It was decided to include the crushable portion of the stone sample with the < 2mm soil material and thus the stone fraction included in Table 27 consists mainly of residual quartz and gravel fragments not broken up during soil preparation. Consequently, the stone fraction in the midslope sites is more substantial than appears from the data in Table 27. The ridge stone fraction consists mainly of concretionary pebbles, quartz pebbles and a small proportion of strongly weathered stones similar to those found on the midslope sites. These concretions contain higher percentages of iron (Table 36) and manganese than the surrounding soil matrix and are particularly prevalent in the B 1 horizon of both the ridge sites. Both the amount and nature of the steepland stone fraction is an indication of the less weathered nature of these profiles compared with the midslope and ridge profiles.

Results of mechanical analysis of soil material are tabulated and graphed in Table 28 and Fig. 19 respectively. Percentages of clay reach a maximum of 29% on midslope sites with steepland and ridge sites both containing about 22% clay. Rigg et al (1952) cite figures of
40 - 55% clay in Mapua clay loam subsoil samples while Kingston (1968), working in the same area as the present author, found clay contents in the upper B horizons of midslope ridge and gully sites of the order of 35 - 40% and 25 - 30% respectively. Similar differences are observable in Table 28 between the M 5 and M 6 midslope ridge sites and the M 3 and M 4 midslope gully sites. No loss of clay from the system through leaching is postulated in the Mapua sequence in contrast with the Kaiteriteri sequence where such a loss was suggested to explain a somewhat similar clay accumulation curve. Rather, it is suggested that the midslope area is a depositional groundsurface formed as a result of erosional processes operating on the ridge groundsurfaces. Such erosion from the ridges and deposition of finer size fractions on the midslope groundsurfaces would explain the greater proportion of clay on the latter landscape. Subsequent dissection of the midslope groundsurface is assumed to be the reason for the greater proportion of clay in the midslope ridge profiles compared with the midslope gully profiles. Silt contents of the solum remain constant on all groundsurfaces, being of the order of 17 - 19% in all profiles. Proportions of fine sand are slightly higher on ridge sites than on the other two groundsurfaces, while percentages of coarse sand decrease quite sharply from the steepland to the midslope and ridge sites, following the increase in profile weathering noted earlier on the two latter groundsurfaces.

Depth functions for all size fractions can be seen from Table 28. Clay contents reach a peak in the B 2 horizon of all profiles but insufficient evidence exists to differentiate between clay formed in situ, that illuviated from higher in the profile and clay transported from other
areas of the landscape. Maximum silt contents are found in the A horizons of all profiles with a general decline down the solum to a slightly higher value in the C horizon. Both coarse and fine sand fractions appear to follow somewhat similar trends to the silt fraction.
IV 3.2 "Organic" Parameters

Data illustrating the quantities of oxidisable carbon and nitrogen in the Mapua sequence are tabulated in Table 29 and graphed in Fig 20. Steepland and midslope sites show an apparent steady state with almost identical levels of both oxid. C and N in the solum with a decline to the ridge sites. A comparison of Fig 20 with the oxid. C and N accumulation curve in Fig 6 shows that the Mapua graph is virtually an extension of that for the Kaiteriteri sequence with extremely low levels of both oxid. C and N in all the Mapua profiles. Quantities of both elements in the vegetation are quite significant in the Mapua sequence but are approximately constant on all three groundsurfaces and are therefore inconsequential to the general shape of the graphs in Fig 20. The situation observed in this study again appears to be similar to the terminal steady-state ecosystem described by Jenny et al (1969), with gains and losses of both oxid. C and N being in a state of near equililrium.

Cation exchange data are given in Table 30. As in the Kaiteriteri sequence, percent base saturation (% B.S.) shows no consistent trends with increasing soil development, although horizons of the two steepland profiles give slightly higher values than the midslope sites particularly. Depth functions for all three groundsurfaces are substantially the same with 11-25 % B.S. in upper horizons and very low % B.S. in lower horizons. Exceptions to this are the cutting samples from the two steepland profiles (M 1.5 and M 2.6), which show % B.S. values of 109% and 82% respectively. The pH's of these two samples are 5.6 and 4.8 which are rather lower than would be expected for the observed % B.S. Although montmorillonite is the dominant clay mineral of the M 1.5 sample (and probably the M 2.6 sample
also), the main reason for these high values is thought to be the presence of soluble, acid-salts of calcium and magnesium which would cause the unusually high levels of exchangeable $\text{Ca}^{++}$ and $\text{Mg}^{++}$ in these two samples. Levels of exchangeable $\text{Ca}^{++}$, $\text{Mg}^{++}$ and $\text{Al}^{+++}$ in other horizons are slightly higher, particularly in B & C horizons, than in the Kaiteriteri sequence, while values of exchangeable $\text{K}^+$ tend to be very similar. Exchangeable $\text{Ca}^{++}$ and $\text{K}^+$ tend to decrease down the profile while exchangeable $\text{Mg}^{++}$ remains relatively constant in all horizons. Exchangeable $\text{Al}^{+++}$ increases quite markedly in many B and C horizons.

The data in Table 30 have been recalculated in Table 31 and graphed in Figs 21 and 22. Fig 21 shows an initial increase in C.E.C. between the steepland and midslope groundsurfaces, followed by a decline in the ridge profiles. T.E.B. values remain almost constant throughout the sequence. Neither curve shows any real resemblance to similar data from the Kaiteriteri sequence, but are again rather similar to the mechanical analysis data plotted in Fig 19. The results of multiple regression correlation analysis between oxid C, % clay, % silt and C.E.C. will be discussed later in section IV 4.

Fig 22 shows the profile changes in total exchangeable cations with increasing soil development. Exchangeable $\text{Ca}^{++}$ and $\text{K}^+$ both show a decline from the steepland to the ridge profiles while exchangeable $\text{Mg}^{++}$ remains relatively constant overall. The most marked change is that in exchangeable $\text{Al}^{+++}$ which increases substantially in the more weathered and leached profiles. Losses in exchangeable $\text{Ca}^{++}$ and $\text{K}^+$ are considered to be due to leaching losses following release of the ions during weathering, while the gain in exchangeable $\text{Al}^{+++}$ is an indication of the ability of soil colloids to retain aluminium ions released by weathering processes during pedogenesis.
"Total" Analyses

Tables 32, 33 and 34 detail Ca, Mg and K analyses on soil and stone samples of the Mapua sequence. Depth functions, especially of percentage values (Table 32), illustrate the influence of leaching in surface horizons with increasing percentages of both Mg and K in B and C horizons. Total Ca, however, remains relatively constant within the solum. Percentages of all three elements in the stone fraction (Table 33) tend to be rather similar to that of the corresponding soil value. The importance of the stone fraction in the steepland profiles can be appreciated from Table 34 which shows that nearly 50% of the Total Ca, Mg and K in these profiles is contained in this fraction. A large weatherable reserve of these three elements is therefore available on the steepland groundsurface while the midslope and ridge profiles have almost exhausted their original stone reserves.

Totals for profiles are summarised in Table 34 and trends with increasing soil development are graphed in Fig 23. Both Total Ca and K show a small overall decline between steepland and ridge groundsurfaces with Total Mg being almost identical on all three surfaces. As in the Kaiteriteri sequence, the curves for Total Ca and K exhibit a close similarity and simple regression of the data in Table 34 was again used to investigate this relationship. For the total amounts of each element in the profile:

\[ Ca = 0.775 \ K - 3.75 \times 10^4 \quad R^2 = 0.948^{**} \]

No significant correlations were found between Total Ca and Mg or Total K and Mg. Although the sand fraction of the Mapua soils contains predominantly quartz, the Ca and K present in the profiles is again
assumed to be the result of partly weathered feldspar with the close correlation between total amounts of Ca and K being due to similar relative weathering and leaching rates of the particular feldspars present. In contrast, Mg is apparently being weathered and leached from the system at a different rate from that for Ca and K.

Data for Total Al and Fe are tabulated in Tables 35, 36 and 37 and graphed in Fig 24. As in the Kaiteriteri sequence, depth functions for both elements show the effects of leaching in the upper horizons with a steady increase in percentages down the profile. Percentages of Al in the stone fraction (Table 36) are similar to those in the surrounding solum, but iron percentages on all groundsurfaces are greater than the corresponding soil values. This is further illustrated in Table 37 which summarises the profile data for both soil and stone fractions. In each profile, the proportion of iron held in the stone fraction exceeds that of aluminium with the difference in proportion becoming more marked with increasing weathering and leaching of the surface. From these results, it appears that iron is accumulating relative to aluminium in the stone fraction with aluminium being weathered and removed from the stone fraction at a faster rate than that for iron. This conclusion is reinforced by Fig 24 which illustrates the quantities of both Al and Fe on the groundsurfaces of the Mapua sequence. Total Al shows a constant decline with increasing soil development while Total Fe remains almost constant on all three groundsurfaces. This is rather different to the situation found in the Kaiteriteri sequence (Fig 10), where Total Al and Fe both decline from a peak value on the K3 groundsurface. It is uncertain whether these differences in the behaviour of Total Fe are a function of P M or a function of the differing degrees of soil development in the two sequences.
The use of the \( \text{Fe}_c/\text{Fe}_t \) ratio as an index of weathering by Ellis (1969) has been discussed with respect to the Kaiteriteri sequence (Section IV 2.3). As in that study, one horizon of maximum clay content on each of the three groundsurfaces of the Mapua sequence was analysed. Values of the \( \text{Fe}_c/\text{Fe}_t \) ratio range from 0.46 to 0.50 to 0.48 in the steep-land, midslope and ridge profiles respectively. The closeness of these values indicates rather less variation in the weathering undergone by the various Mapua groundsurfaces than was found in the Kaiteriteri sequence where values ranged from 0.27 on the K 1 groundsurface to 0.59 on the K 5 groundsurface.
IV 3.4 Phosphorus analyses.

Data showing organic phosphorus (Po) and total phosphorus (Pt) in both soil and stone fractions are presented in Table 38 and Fig 25 with results for Total P being summarised in Table 39. As in the Kaiteriteri sequence, Po is calculated as Pt-ΣPi, rather than as the value obtained from the ignition method for organic P. Although results are not shown, values for Po obtained by Walker and Adams' (1958) ignition method showed the same characteristics as in Table 16 for the Kaiteriteri sequence, being continually overestimated, presumably due to solubilisation of some inorganic phosphate during ignition.

Fig 25 shows a decline in Pt from 1600 Kg/ha in the steepleand profiles to 1060 Kg/ha on the midslope and ridge groundsurfaces. This initial decline is another illustration of the significance of leaching to the P status of soils during pedogenesis. The significance of the apparent steady state in solum phosphate content with increasing soil development, shown on the midslope and ridge groundsurfaces is not certain. The rate of loss of phosphorus from the soil system must inevitably decline with increasing soil development until it approaches a terminal steady state and it is possible that this is the situation pertaining in this study. Such a state would be reached when losses from the ecosystem equal the small gains of P from the atmosphere - possibly of the order of 0.1 Kg/ha/annum (Syers, Adams and Walker 1970). Organic P shows a similar decline to that for Pt declining from 28% of Pt to extremely low values of about 3% in the ridge profiles and only slightly higher proportions in the midslope sites. These latter values are very similar to the proportion of Po found on the K 5 groundsurface of the Kaiteriteri sequence. Possible
reasons for this have been discussed previously (Section IV 2.4) and are equally applicable to this sequence.

Inorganic P was fractionated into eight forms (Williams et al. 1967) which are grouped in the following discussion as for the Kaiteriteri sequence. (Section IV 2.4). The easily-soluble P fraction was again found to be zero in all samples and is therefore not included in any of the tables. Small amounts of acid-extractable Ca-P were found in the steepland sites only and are included in the non-occluded P fraction rather than considered separately.

Concentrations of inorganic P in the various individual fractions are shown in Table 40. Non-occluded P tends to be slightly higher in most surface horizons, this being due to an apparent accumulation of surface Al-P (NH$_4$F-P) in these horizons. Only very small amounts of surface Al-P are present in lower horizons. Absolute quantities of non-occluded P are very low in all samples, with the only appreciable quantities being in the steepland cutting sample (M 1.5) which also contains about 6% acid-extractable Ca-P. Occluded P increases down the profile as does residual P which, as in the Kaiteriteri samples, constitutes a large proportion of the inorganic P fraction. Concentrations of inorganic P fractions in stone samples from four of the profiles are shown in Table 41. These values were used in the compilation of Tables 42 and 43 which includes the phosphorus in the stone fractions. Values of ΣPi in all four samples tend to be slightly higher than in the corresponding soil sample, indicating a small, weatherable reserve of inorganic P in the stone fraction of the various horizons. The main features of the Mapua stone samples are the negligible or zero amounts of surface Al-P (NH$_4$F-P) in three of the samples and the large amount of reductant-soluble P in all four samples compared with any
of the corresponding soil samples. Both of these facts are an indication of the extent of weathering of the stone fractions of all profiles.

Weights of the various inorganic P fractions are tabulated in Table 44 and plotted in Fig 26. The curve for ΣPi closely parallels that for Pt in Fig 25, with a decline from the steepland profiles to an apparent steady state between the midslope and ridge sites. Non-occluded P shows a steady decline from 268 Kg/ha in the steepland profiles to 132 Kg/ha in the ridge profiles. This decline is not unexpected in view of the increased weathering and leaching which the ridge profiles are assumed to have undergone. Occluded and residual P however, remain almost constant on each of the three groundsurfaces.

Proportions of ΣPi held in the various inorganic P fractions are presented in Table 45 and Fig 27. A decline in the fraction of non-occluded P is evident with increasing soil development, but the decline is not nearly as marked as that observed in the Kaiteriteri sequence (Fig 13). Relative proportions of surface Al-P (NH₄F-P) and surface Fe-P (1st NaOH-P) are very similar to those in the more weathered profiles of the Kaiteriteri sequence, with percentages of surface Al-P being in the range 1.9 - 6.5% in all except the M 1 profile, while surface Fe-P remains relatively constant throughout the sequence. Occluded P falls and then rises, with no overall change in proportion between the steepland and ridge surfaces. Residual P rises from being 50% of ΣPi in the steepland profiles to nearly 60% in the midslope and ridge profiles. These proportions, although not quite as high as in the more weathered members of the Kaiteriteri sequence, are still unusually large compared with other N.Z. soils. Thus Stevens (1968) found 28.7% residual P in the oldest, most strongly weathered and leached
member of the Franz Josef chronosequence, while Williams (1965) found up
to 25% residual P in strongly weathered and leached basaltic soils in the
North Auckland sequence. Investigations into the nature of the residual P
fraction similar to those described for the Kaiteriteri sequence (Fig 14)
were carried out with identical results, which are not presented here.
The conclusions expressed in Section IV 2.4 are therefore equally applic­
able to the residual P fraction of the Mapua hill soils.

The rather insignificant variations in the nature of the inorganic
P fractions and the total and organic P between the three groundsurfaces
of the Mapua sequence is considered to be a reflection of the extremely
weathered and leached nature of even the most youthful steepland profiles
in the sequence. A comparison of the data plotted in Figs 25, 26 and 27
with similar data for the Kaiteriteri sequence (Figs 11, 12 and 13) there­
fore shows some correspondence with that portion of the Kaiteriteri curves
covering the most strongly weathered and leached profiles of the Kaiteri­
teri sequence.
IV 3.5 Mineralogical Analyses.

Mineralogical studies on samples of the Mapua sequence consisted of clay mineralogy on samples from the steepland, midslope and ridge ground-surfaces. Data from these analyses are given in Tables 46 and 47. The method used to determine the percentage composition of the crystalline clay fraction was that employed for the Kaiteriteri sequence (Section IV 2.5). As was noted in that section values given are only intended to be approximate.

The clay composition of the Mapua soils is rather more complex than that in the Kaiteriteri sequence. Clay mineralogical data are best considered in two groups. The first comprises the M 1.3, M 5.3 and M 8.4 samples being the horizons of maximum clay content in the steepland, midslope and ridge profiles respectively. The second group consists of the M 1.5 cutting sample and the horizons of the complete M 8 profile.

The fine clay fraction of the first group (Table 46) shows an increase in the metahalloysite content from 49% in the M 1 profile to 79% and 70% in the M 5 and M 8 profiles. Associated with this increase is a decrease in the proportions of montmorillonite and interlayered hydrous mica to zero in the M 8 profile. These changes are to be expected with increasing soil development. The M 8.4 horizon also contains small but significant proportions of illite and vermiculite - 2. This finding will be discussed later in this section.

The approximate composition of the coarse clay fraction is shown in Table 47. The M 1.3 and M 5.3 samples contain similar proportions of clay minerals with the dominant constituent in each being vermiculite-1. Confirmation of the more extensive weathering of the M 5 profile is shown in the slight decline in the illitic component and the slight increase in the
metahalloysite fraction in the midslope profile compared with the steep-land sample. The M 8.4 ridge sample is notable in that while containing similar proportions of illites, metahalloysite and quartz to the M 1 and M 5 samples, it contains no vermiculite-1 but considerable vermiculite-2. In addition it contains a larger proportion of interstratified montmorillonite-illite. The presence of vermiculite-2 in the profile considered to be the most strongly weathered in the Mapua sequence directly contradicts the usual weathering sequence of micaceous clay minerals formulated by Fieldes. It is possible that the strong acidity of these soils is causing losses of Al\textsuperscript{+++} from the system and that the normal course of micaceous clay mineral weathering is being reversed with increasing soil development, leading to formation of the "less-weathered" vermiculite-2 rather than the expected vermiculite-1.

A study of the second group of data originally distinguished shows that the clay fraction of the M 1.5 cutting sample consists principally of montmorillonite and illite with montmorillonite predominating in the fine clay fraction. This can be regarded as an approximation to the clay composition of the P M of these soils.

Investigation of the clay mineralogy of the M 8 profile has revealed a number of interesting features. Among those mentioned previously is the presence of vermiculite-2 rather than the expected vermiculite-1. The proportion of vermiculite-2 shows a steady increase down the profile in both the coarse and fine clay fractions. The large fraction of illite in the fine clay of the M 8 profile is most interesting. The A horizon contains approximately equal proportions of illite and metahalloysite with illite dropping to zero in the B 3 horizon. Two questions arise from this:
(a) the reason for the decline in illite with depth and
(b) the reason for illite being present at all in such a strongly weathered
and leached profile. An obvious explanation for both the presence and
observed depth gradient of illite is that it is present as the result of
loessial accumulation. The possibility of late Pleistocene loessial
deposition from the then-exposed floor of Tasman Bay has been mentioned by
Kingston (1968). Assuming this deposition to be a source of illite, one
would still expect that the illitic fraction would have disappeared in the
intervening period through its conversion to later clay minerals of the
micaceous weathering sequence. Another explanation is that the crushing
of strongly weathered stones during sample preparation (III 4.2) may have
released an illitic component. However, if this was the case, the
proportion of illite would be expected to increase down the profile.

The presence of illite in this strongly developed Mapua soil is of
particular interest in that A.S. Campbell (pers.comm.) has found sub-
stantial proportions of illite in the Okarito gley podzol, the final
member of Stevens' Franz Josef chronosequence and the most strongly
developed soil on the West Coast of the South Island. The Okarito
profile shows an increase in illite with depth. As was stated earlier,
it appears feasible that the normal weathering sequence of micaceous
clay minerals could be reversed as far as vermiculite-2 under the cond-
itions pertaining in both the Okarito and Mapua soils. However, reversion
from vermiculite-2 to illite would require a new source of potassium. It
is possible that the source of potassium in the Mapua sequence is the
K-cycle. Litter fall will be continually adding substantial amounts of
quite freely soluble K to the soil system, part of which may be acting as a
reactant in the formation of illite. The potassium source at Okarito is more likely to be the weathering of residual mica of large particle size in the bottom of the profile. However, this latter argument appears improbable in the case of the M 8 profile. Although the basic idea of reversal of the usual clay weathering sequence is perhaps the most likely explanation for the presence of illite in both the Mapua and Okarito profiles.

The other interesting feature of the coarse clay fraction of the M 8 profile is the presence of a component tentatively identified as interstratified montmorillonite-illite. This clay mineral, which forms the dominant proportion of the A horizon coarse clay fraction, shows a strong 28 Å peak with Mg/glycerol treatment collapsing to 10 Å upon K⁺ treatment. A more complete clay mineralogical study of the Mapua sequence would be extremely interesting in following the distribution of both illite and interstratified montmorillonite-illite in profiles on the midslope and steepland groundsurfaces.
IV 4. MULTIPLE REGRESSION ANALYSIS

IV 4.1 Multiple regression analysis between C.E.C., organic matter, clay and silt for the Kaiteriteri and Mapua sequences.

Multiple regression analysis has recently been used as a means of investigating the effect of O M and clay on C.E.C. (Yuan et al., 1967, Syers et al., 1970). The method, although useful in many ways, has its limitations. One of these is the assumption that the dependent variable bears a linear relationship to the contributing independent variables which should not interract in any way. In some cases clay - O M complex formation has been suggested with a reduction in the C.E.C. of the clay fraction occurring through a blocking of the negative charge of the clay particle by O M (Syers et al., loc cit).

In this study, the soils from the two sequences were considered separately, with % silt being added to % oxid. C and % clay as the independent variables. Table 48 presents the range and means of data for both sequences with simple correlation coefficients between the four variables being listed in Table 49. Samples from the granite sequence show highly significant (1%) positive correlations between both % clay and % oxid. C and C.E.C. with a significant (5%) positive correlation between % silt and C.E.C. The Mapua sequence, however, shows a highly significant negative correlation between both % silt and % oxid. C with C.E.C., while % clay shows a highly significant positive correlation with C.E.C. In addition, % oxid. C shows a highly significant positive and a significant negative correlation with % silt and % clay respectively. The latter correlation is considered to be an indication of the existence of clay - O M complexes in these soils.
The multiple regression equations for both the soil types are shown in Table 50. The $R^2$ values show that both these equations are significant at the 1% level. Partial regression coefficient t-tests on soils of the granite sequence gave a highly significant value for the $b_1$ (% clay) coefficient, a very highly significant value for the $b_2$ (% oxid.C) coefficient, and a non-significant value for the $b_3$ (% silt) coefficient. Taken together with the $R^2$ value, this indicates that the C.E.C. of the Kaiteriteri soils may be predicted from their multiple regression equation with % oxid. C and % clay being the most important factors in determining C.E.C.

The regression equation for the soils of the Mapua sequence shows a number of unexpected characteristics. The $R^2$ value, although significant at the 1% level, only explains 47.9% of the variation in C.E.C. which is rather lower than might be expected. Partial regression coefficient t-tests showed a significant value for the $b_1$ coefficient only. However elimination of the % oxid. C term from the regression equation raises the t-test value for the $b_1$ and $b_3$ coefficients to the 0.01% and 0.1% significance levels respectively. In addition, the form of the equation is most unusual, with negative coefficients for both oxid. C and silt and an extremely large constant value. The $R^2$ and t-test values indicate that the C.E.C. of the Mapua soils can only be predicted with a limited degree of accuracy from the calculated multiple regression equation. Reasons for this include the possibility of one or more of the three independent variables being non-linearly related to the C.E.C. and the likelihood of interaction effects, particularly the formation of clay-O M complexes.
The equations show that each percentile of oxidisable C contributes 1.21 meq to the C.E.C. of the Kaiteriteri soils with the C.E.C. of the predominantly kaolinitic clay fraction being 6 meq/100g.
RESULTS - FOLIAGE
V 1. **INTRODUCTION**

The results reported in this section cover the results of foliage analyses from samples in both the Kaiteriteri and Mapua toposequences. To aid discussion, the results are divided into the following groups:

V 2. **Critical foliage levels**: a discussion of possible nutrient deficiencies as suggested by foliar analyses.

V 3. **Foliage nutrient-tree volume correlations**: results of multiple regression and simple correlation analysis between foliage nutrients and tree volume.

V 4. **Soil-foliage correlations**: results of simple correlations between soil properties and foliage nutrient levels.

Soil data not presented earlier in this thesis are presented in Tables 62 and 63. These include results of Bray No. 2 and Olsen phosphorus tests (Table 62) plus easily-reducible manganese and hot-water soluble boron (Table 63). These analyses were performed on A horizon samples only.
V 2. FOLIAGE ANALYSES.

V 2.1 Critical foliage levels.

The use of foliage analysis as an indication of the nutrient requirements of forest stands has been discussed in Section II 4.2. The following table is intended only as a guide to critical foliar levels in *P. radiata*. At this point, the author must express his thanks to Dr. G.M. Will, N.Z.F.R.I., Rotorua and Mr. F.R. Humphreys, N.S.W. Forestry Commission, Sydney, for their co-operation in making available the information included in this table.

Critical foliar levels for the growth of Pinus radiata in N.Z. and N.S.W.

<table>
<thead>
<tr>
<th></th>
<th>Will</th>
<th>Humphreys</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>1.4 - 1.6%</td>
<td>1.25%</td>
</tr>
<tr>
<td>P</td>
<td>1000 ppm</td>
<td>1000 - 1200 ppm</td>
</tr>
<tr>
<td>B</td>
<td>8 ppm</td>
<td>7 - 10 ppm</td>
</tr>
<tr>
<td>Ca</td>
<td>-</td>
<td>1000 ppm - preferably 1500 ppm</td>
</tr>
<tr>
<td>Mg</td>
<td>600 - 800 ppm</td>
<td>500 - 600 ppm</td>
</tr>
<tr>
<td>K</td>
<td>3000 - 4000 ppm</td>
<td>4000 ppm</td>
</tr>
<tr>
<td>Fe</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Al</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Mn</td>
<td>&gt; 700 ppm toxic*</td>
<td>&gt; 700 ppm toxic</td>
</tr>
<tr>
<td>Zn</td>
<td>5 ppm</td>
<td>-</td>
</tr>
</tbody>
</table>

* Lamuza (1966)

Both sets of values have been formulated as a result of culture trials and extensive field experimentation. Will and Humphreys have both
stressed that values cited should not be considered unequivocal or absolute, because taken out of their association with other elements and the manner and position of sampling, conclusions reached from them may be misleading. However, the present author feels that with the consistent sampling technique employed in this study and the close similarity of this technique to that employed by Humphreys in particular (Section III 4.3), comparisons with such tables are useful.
Nutrient levels in Kaiteriteri Foliage.

Foliage nutrient data for the elements N, P, B, Ca, Mg, K, Fe, Al, Mn and Zn in individual sampled trees at Kaiteriteri are presented in Table 51 with average values of each element at each sampling site being given in Table 52. These Kaiteriteri results can be grouped into two sections. Trees on the two steepland groundsurfaces (G1 and G2) contain satisfactory levels of most elements although nitrogen levels tend to be rather low in some samples. Trees on both surfaces are noticeably chlorotic, but this is almost certainly due to competition from the ubiquitous gorse and bracken causing a lowering in the optimum rate of photosynthesis rather than any soil nitrogen deficiency. Recent release cutting should alleviate this chlorosis. Boron values are probably satisfactory although not particularly high, while magnesium levels are rather low in a number of the sampled trees.

Trees sampled from the other five groundsurfaces (G 3 to G 7) show a number of nutrient deficiencies. Nitrogen values tend to be marginal and all sites are quite seriously deficient in phosphorus. This is highlighted by considering average foliar N : P ratios from trees on those groundsurfaces subject to P deficiency. Values range from 16.0 to 23.3, which Raupach's (1967a) data would suggest are unsatisfactory for tree growth. In contrast, trees on the two steepland groundsurfaces have N : P ratios within the 5 to 16 range suggested by Raupach as being necessary for satisfactory growth. Severe boron deficiency is apparent on all sites with the exception of G 5. Trees at this site were sampled just outside a pegged trial area and J. Slow (pers. comm.) has recently informed the author that the trial area was left untreated, while borax was mistakenly applied to the area surrounding it.
All trees sampled have therefore actually been treated with boron, a treatment which is apparent in the foliage data. These results confirm both visual observations of boron deficiency on all these sites and previously reported boron deficiency in the area (Stone and Will 1965a, Appleton and Slow 1966). No visual signs of boron deficiency were noted on the two steepland groundsurfaces sampled, confirming the value of about 8 ppm given by Stone and Will (loc cit) as a critical foliage level for this element in the Kaiteriteri area. In addition, phosphorus deficiency reported by Appleton and Slow (loc cit) has been confirmed by these results. Reference to Table 51 which presents foliage analyses for individual sampled trees shows that a very noticeable feature of the data is the substantial variation in calcium and magnesium levels between individual samples taken within a specific area. This is apparent in all sites but is probably best demonstrated in the G 7 samples where calcium and magnesium levels range from 539 ppm to 1923 ppm and 505 ppm to 1292 ppm respectively. Calcium values indicate a deficiency of this element on all except steepland sites with magnesium values also being close to deficiency levels. Although uptake of individual cations varies widely, total cation uptake remains relatively constant, particularly within and also between the sampled sites. Thus although the G 7.6 and G 7.7 foliage samples contain widely differing amounts of Ca, Mg and K (Table 51), the sum of Ca + Mg + K remains very similar for both; viz., 29.6 meq/100g and 27.2 meq/100g respectively. The inherent calcium and magnesium deficiency of these soils is therefore apparently being accentuated in the plant by the preferential uptake of potassium.
Nutrient levels in Mapua Foliage

Foliage nutrient levels in *P. radiata* growing on the various sampling sites in the Tasman forest are given in Table 53 with average values for each site being presented in Table 54. Comparison of these results with the critical foliar levels listed previously shows the possibility of nitrogen deficiency on both the main and midslope ridge sites with a likelihood of manganese toxicity also affecting tree growth on these surfaces. These symptoms of nitrogen deficiency agree with previous reported work in the same area which suggested that nitrogen is the limiting element for growth on hard ridge sites (Stone and Will 1965b, Appleton and Slow 1966). Some individual trees on all surfaces have values suggesting other deficiencies, particularly boron and calcium. However, the average values at any site exceed critical foliar levels. Phosphorus and magnesium levels appear satisfactory in all cases, although values of both are sometimes rather low in *P. radiata* on ridge sites. Midslope gully and steepland sites show satisfactory levels of all elements with the possible exception of calcium levels in both sets of gully samples. The relationship between foliar Ca, Mg and K discussed in the previous section for the Kaiteriteri sequence also applies on the Mapua soils where substantial variation in calcium and magnesium levels is apparently often associated with varying potassium uptake. Thus total cation uptake remains relatively constant even though individual cation uptake may vary considerably from tree to tree. However, the likelihood of any induced calcium deficiency appears to be considerably less than at Kaiteriteri. Nitrogen values are satisfactory in ridge and steepland sites, although not at particularly high levels.
Comparison of average foliage nutrient levels in Table 54 with data illustrating differences in tree volume on the different surfaces (Table 55) shows that poor tree growth in Tasman forest is generally associated with lower nitrogen and phosphorus levels and higher calcium and manganese levels than that for good tree growth. These relationships will be considered in more detail in VII 2. when the results of simple correlation analysis and multiple regression analysis between foliar nutrient levels and tree volume will be discussed.
V 3. FOLIAGE NUTRIENT - TREE VOLUME CORRELATIONS

V 3.1 Foliage nutrient - tree volume correlation - Mapua.

Some of the results of simple correlation analysis and stepwise linear multiple regression analysis are given in Tables 56 and 57. All foliage data used in these statistical analyses were expressed as ppm in the interests of uniformity. A measure of tree volume was used as the dependent variable rather than site index. This measure was obtained by taking the product of \((\text{diameter breast height})^2\) and tree height. This gives a value which is easy to calculate and which is directly proportional to the volume of a cone which is essentially the equivalent of tree form. In the following pages, the value of \((\text{dbh})^2 \times \text{height}\) will be called tree volume. A discussion on the merits of using tree volume rather than site index as a measure of tree growth will be left until VII 2. All statistical data were calculated on an IBM 1620 computer using an IBM library program which enabled both simple correlation analysis and stepwise linear multiple regression analyses to be performed. It was explained earlier that although trees sampled on the Mapua ridge, gully, and top ridge surfaces were of uniform age, it was not possible to find any areas of a similar vintage on the two Mapua steepland sites. It was decided to include only those trees of similar age in the statistical analyses which meant the exclusion of foliage data from both steepland sites. In the Kaiteriteri area, a combination of the widespread incidence of B deficiency causing deformed trees and the general youthfulness of the planted trees meant that a meaningful analysis of the situation in a manner similar to that in the Tasman forest was not feasible. Multiple regression analysis was therefore not performed on Kaiteriteri data.
Simple linear correlation analysis (Table 56) shows that six of the ten foliage nutrients measured are significantly related to tree volume with foliar N, P, Ca, Fe and Mn being significant at the 1% level and foliar Al being significant at the 5% level. Of these six elements, foliar N, P, and Fe are positively correlated with tree volume while foliar Ca, Al and Mn are negatively correlated. The best correlation is with foliar P (0.703), followed by foliar Mn (-0.663), Ca (-0.615), Fe (0.394), N (0.378) and Al (-0.352).

The IBM program used for this work assumes linear relationships between independent and dependent variables. To check this assumption, foliar nutrients were separately plotted against tree volume. Relationships were linear, with the exception of foliar Mn and Ca versus tree volume, both of which showed distinctly hyperbolic functions. To correct for these hyperbolic relationships, reciprocal values for foliar Mn and Ca were used in the regression analysis instead of foliar Mn and Ca. Inclusion of Mn\(^{-1}\) and Ca\(^{-1}\) increased the simple correlation coefficient between Mn and tree volume from -0.663 to 0.780 and between Ca and tree volume from -0.615 to 0.819, indicating a better fit to a hyperbolic rather than a linear function in each case.

The results of stepwise linear multiple regression analyses are shown in Tables 57, 58 and 59. In each case, dependent variables are placed in the order of significance in which each is entered into the regression equation. Table 57 shows the equation developed using all ten dependent variables. The 'best' equation is that including Ca\(^{-1}\), Zn, P, Mg and Mn\(^{-1}\) viz.
Tree volume = \(-92.79 + \frac{69814}{\text{Ca}} + 0.4472 \text{ Zn} + 0.0104 \text{ P}^* + 0.0112 \text{ Mg}^* + \frac{7684}{\text{Mn}}\)  

\[ R = 0.850 \]

*** significant at the 0.1% level  
** significant at the 1% level  
* significant at the 5% level

This equation explains 85% of the variation in tree volume. It should be noted that foliar Zn, when introduced into the regression equation is significant at the 0.1% level, but the addition of the extra terms reduces it to an insignificant level. The equation suggests that the factor most influencing tree volume is the foliar Ca level, with large trees having a low Ca content and poor trees a higher foliage Ca content. Two possible explanations exist for this result. One is that the poor growth of \textit{P. radiata} is being caused by a higher uptake of calcium resulting in higher foliar Ca levels. Calcium levels in the needles of poor trees are certainly high relative to the best trees but the same levels are by no means high when compared with other values for \textit{P. radiata}. In addition, the low levels of calcium found in the Mapua soils means that Ca toxicity is out of the question. The most likely explanation for the behaviour of foliar Ca is that it is merely a dilution effect caused by the differences in tree volume. Thus a relatively constant Ca uptake in all trees would give a higher concentration in the poor trees and a lower concentration in good trees. A similar explanation to that for foliar Ca can be advanced to explain the nature of the foliar Mn effect on tree growth. However, the possibility of Mn toxicity is not so unlikely in this case. Both Will and Humphreys (pers.comm.) cite a critical level of 700 ppm for Mn in \textit{P. radiata}.
foliage, a level established from pot and culture trials (See Section V 2.1). This value, although surprisingly low when compared with many pasture plants and in view of the acid soils which \textit{P. radiata} appears to prefer, agrees well with the data in this study. All of the 16 trees in this study with foliage Mn contents $>700$ ppm can be classed as poor trees. If Mn toxicity is accepted as a possible explanation of Mn$^{-1}$ appearing in equation (1), then this may be a consequence of the strongly acidic soils on those sites carrying poor \textit{P. radiata}. The appearance of Zn in the regression equation is inexplicable. Foliar Zn levels range from 35 ppm to 98 ppm, an expected range and not one which indicates Zn deficiency. The simple correlation coefficient between foliar Zn and tree volume is only 0.140 and the correlation between foliar Ca$^{-1}$ and foliar Zn only -0.236. Zn deficiency must therefore be discounted as a contributor to differences in tree growth. The significant dependence of tree volume on foliar P and Mg is not unexpected and suggests that a deficiency of both elements may be limiting tree growth on poor sites. Field trials on these soils have already shown both of these elements to be necessary for satisfactory tree growth. However nitrogen, which has also been shown to give significant growth responses in field trials, does not appear as a significant factor in the calculated regression equation.

The possibility that foliar calcium levels may be an indication of an effect rather than a cause of growth differences led to the calculation of the regression equation in Table 58 from which foliar Ca has been omitted. The best equation is now :-
Tree volume = - 80.97 + \frac{22342}{Mn} *** + 0.0181 P **
+ 0.0030 N *
\[ R^2 = 0.738 \] (2)

This equation, which explains 73.8% of the variation in tree volume, can be interpreted in terms of growth being affected by toxic levels of Mn and deficiencies of P and N. As has previously been mentioned, each of these factors appears a possible cause of the observed growth differences. Although tree volume is probably being influenced by Mn toxicity, it is possible that differences in foliar Mn levels may be due to a dilution effect as are foliar Ca levels. For this reason, a third regression equation was calculated (Table 59) which contained neither foliar Mn nor foliar Ca terms. The 'best' equation is now:

Tree volume = 1.34 + 0.0323 P *** - 0.0718 Al **
+ 0.4679 Fe *
\[ R^2 = 0.608 \] (3)

This equation explains 60.8% of the variation in the dependent variable and can be interpreted in terms of a phosphorus deficiency causing the major differences in tree volume. The negative correlation of tree volume with foliar Al is a further indication of the unsatisfactory acidity of these soils. However the positive correlation of tree volume with foliar Fe is difficult to attribute to acidity unless high aluminium uptake is reducing iron uptake. Iron deficiency symptoms frequently appear on acid soils where heavy metal toxicity occurs in plants. The inclusion of foliar Al in equation 3 when foliar Mn is excluded tends to confirm the validity of an acidity problem which is apparently likely to be present as a heavy mineral toxicity rather than as a calcium deficiency.
V 4. SOIL-FOLIAGE CORRELATIONS

V 4.1 Soil-Foliage Correlation - Kaiteriteri

The usual and best method of investigating soil-foliage correlations in *Pinus radiata* is to sample the particular tree concerned and also the soil adjacent to each sample tree to a standard depth. Because this study was part of a wider project and time was limited, this approach could not be used. To avoid taking the average foliage value from 7 to 11 trees and correlating this with the corresponding soil data, a method which would only have enabled seven observations to be made, foliage data from each tree was correlated individually with the corresponding soil data from the one sampling site near the tree position. By this means an increase in the error degrees of freedom was obtained. The method used is rather artificial however, and correlations thus obtained should not be considered unequivocal. However they are useful when considered in conjunction with other data involving the observed growth differences.

Relevant data for the Kaiteriteri sequence are presented in Table 60. Highly significant relationships between soil and foliage phosphorus, calcium and potassium are indicated. The observed correlations between soil and foliar manganese and boron are not considered to indicate real relationships. It is interesting to compare these correlations with the nutrient deficiencies known and predicted to exist on the Kaiteriteri soils. Boron, phosphorus and calcium deficiencies were predicted as limiting growth when critical foliage levels were previously examined (V 2.2). Magnesium values were also considered to be close to critical levels. Both foliar Ca and P levels are strongly correlated with soil calcium and phosphorus, while hot-water-soluble boron shows no real correlation with foliar boron. This latter result is not really surprising as Humphreys (pers.comm.) has stated
that no such correlation has ever been observed on boron-deficient soils in Australia. No correlation is found between soil and foliar magnesium. Correlations between soil and foliar Ca have been discussed by Humphreys (1964) in connection with *P. radiata* growing on Ca-deficient soils in New South Wales. Humphreys concluded that the absolute minimum level of exchangeable calcium necessary for satisfactory growth was 0.2 meq/100g, a level which is not exceeded in many of the A horizons of the granite soils. Similarly, Ballard (1969) showed a correlation between soil P tests and foliage P in an area of phosphorus-deficient *P. radiata* in Riverhead forest, Auckland. Ballard found that soil tests which extract the 'available' P from the soil provide a better correlation with foliar levels than do tests which remove the total phosphate. The Bray No. 2 and Olsen tests were shown to give the best results. In the present study, both of these methods were shown to correlate satisfactorily with foliar P levels. In addition, the level of non-occluded P (calculated from the P fractionation data) is also a useful indicator of soil P levels, although unsatisfactory for use in routine determinations.

Generally speaking, it can be seen that differences in the foliar content of a deficient element are mirrored by differences in the soil content of that same element. This occurs particularly when the soil content of that element is expressed in a form relatively 'available' to plants.
Soil-Foliage Correlation - Mapua

The criticism of the method of sampling used in obtaining soil-foliage correlations in the Kaiteriteri soils also applies to the Mapua sequence. The consequences outlined previously should therefore be borne in mind in the present discussion.

The results of simple correlation analysis between soil and foliage data for the Mapua sequence are presented in Table 61. Highly significant correlations for nitrogen, phosphorus and manganese are indicated, with the correlation coefficients for all measures of soil phosphorus being considerably higher than those for the other two elements. These high soil-foliage P correlations confirm the earlier finding that each of the methods used gives a satisfactory indication of the phosphorus nutrition available on a particular site. The comparatively high correlation between soil and foliage nitrogen is not particularly surprising as total N, the soil variable used, could be expected to give a good indication of nitrogen availability for tree growth over a limited range of soil types in the same climate. The fact that easily-reducible manganese was measured on samples that had been air-dried and stored for a considerable length of time also must have affected the analyses to some extent. Consequently, the value of the correlation coefficient obtained may well have been higher if the analyses had been performed on fresh soil samples.

It is again noticeable that the correlations obtained involve the three elements which are known or have been predicted to be present in unsatisfactory amounts. Unlike the Kaiteriteri soils, the level of exchangeable Ca$^{++}$ in the A horizon of all the Mapua profiles is well above the minimum suggested level of 0.2 meq/100g (Humphreys, 1964). In this
connection, it may be noted that foliage calcium is not correlated with either total or exchangeable calcium, indicating that soil calcium levels are probably not directly related to differences in growth.
VI

DISCUSSION - SOILS
VI 1. CONSTANCY OF SOIL-FORMING FACTORS OTHER THAN RELIEF

VI 1.1 KAITERITERI GRANITE SEQUENCE

VI 1.1.1 Parent material

The landscape on which the soils of the Kaiteriteri granite sequence have formed is derived from Separation Point granite (Section III 2.1.1). Although a particular granite formation might be considered to be a fairly uniform parent material, a number of factors likely to cause inconstancy must be considered. These include contamination by loessial material, inconstancy of mineral suites in soils of the sequence, and variation in chemical and physical properties of the parent material throughout the sequence.

Because of its unique geography, the Nelson province is one of the areas within New Zealand least affected by recent loessial additions. Some additions of alluvium to the Kaiteriteri landscape from the Motueka river valley are possible, but the mainly granitic nature of any such alluvium means that any depositions would be of minimal significance.

The range of granitic composition in the Separation Point formation (Grindley, 1961) suggests that inconstant mineral suites might be expected. Sand mineralogy of C horizon samples from all profiles (Table 26) showed that this was not the case with fairly uniform heavy mineral composition being found on all surfaces.

Possible variations in chemical and physical properties of the parent material are best considered with respect to the effects of previous surfaces on the present soils. Besides the profile sampled as G 8, numerous patches of red weathering occur in profiles on the older surfaces of the area. The rather different nature of the chemical and mineralogical
properties of the G 8 solum have already been discussed in some detail (IV 2.6). It is reasonable to expect that profiles containing patches of red weathering will have their chemical and mineralogical composition affected to some degree. Such areas were in fact avoided during sampling. However, an alternative situation which is rather more difficult to predict may occur in certain situations. This is exemplified by the case of the G 2 profile (IV 2.6). Unexpected chemical differences in the solum led to a re-evaluation of the surface on which the profile is situated. The observed differences (which could not be anticipated in the profile morphology) are attributed to a parent material influenced to some degree by the previous pre-weathered ridge surface. Such an effect may well occur in other parts of the Kaiteriteri landscape and it would seem that chemical investigation of the profile is the only conclusive way of identifying such areas.

It is therefore concluded that areas of slightly different parent material are present in the Kaiteriteri sequence. Differences in parent material composition are almost entirely attributable to the effects of previous pre-weathered surfaces which may, or may not, be visible as patches of red weathering. In cases where red weathering is not visible chemical analyses of the profile may be the only way of positively identifying such an area. One such site has been found in the present study (G 2) and has subsequently been omitted from the sequence.
VI 1.1.2 Vegetation

It is always difficult to delineate the Biotic Factor and its resultant effect as an independent soil forming factor. Crocker (1952) has discussed in detail the possibility that the actual effective biota or Effective Disseminule Factor is the independent plant factor in pedogenesis rather than the Total Disseminule Factor or available biota postulated by Jenny.

The existence of patches of red weathering throughout the Kaiteriteri sequence indicates that the area may have experienced a previous warmer climate than that of the moment (Te Punga, 1964). Whether the different biotic factor associated with this climate cycle had any effect on the present cycle of soil formation is uncertain. However, if one assumes that the present period of soil formation began subsequent to the removal by erosion of the previous red weathered surface, then little effect would be anticipated. In the absence of any evidence to the contrary it can only be assumed that the frequency and composition of the available biota has remained uniform over the restricted area of this sequence throughout the period of soil formation.

Wild pigs are quite common in the dense scrub of the steeper surfaces and excreta was occasionally noticed on these surfaces during site reconnaissance. Such areas were avoided during sampling. No marked differences in earthworm population were noticed between the different profiles studied. The animal population of the various groundsurfaces sampled are considered unlikely to have had differential effects on the corresponding soils.
Jenny's Fundamental Equation of Soil-Forming Factors defines time as the period of soil formation. However, the time factor in soil sequence studies is always difficult to quantitatively define. In this study, any accurate assessment of the age of surfaces is impossible due to the lack of any convenient materials for dating purposes.

It is probable that the present Kaiteriteri landscape is the result of discrete erosion cycles or a long period of erosion including continued downcutting and stream incision (II 3.3). The obvious interpretation of this hypothesis is that the respective surfaces and their associated soils are of different ages. In terms of Jenny's (1946) definition, the time factor is therefore apparently inconstant in the profiles of the sequence.

This interpretation raises the interesting question of whether it is ever possible to separate relief from time as an independent soil-forming factor in a situation such as exists in the Kaiteriteri sequence. The only way in which this could occur would be if the landscape was completely developed during the period of one discrete erosion cycle, giving a uniform period of soil development on all ground surfaces. This possibility appears most unlikely in the present case.

However, the concept of time as a soil-forming factor can be approached in another way which is particularly applicable to the present case. It is postulated that the zero time of soil formation for the whole sequence should be that time when the oldest K 5 surface entered a period of stability and began undergoing the processes of soil development. The surfaces formed since zero time have been formed as a result of one or more erosion cycles causing variations in the relief
factor in the form of changes in degree of slope. With the time factor being considered in this context of being the age of the system as a whole rather than the age of its individual components, it can be seen that the time factor is constant within the sequence. Further argument on this suggestion will be left until VI 4. when the sequence as a whole will be discussed.
VI 1.1.4 Climate

There are few published data concerning past climates in the Nelson region. While the depression of snowlines during the period of Pleistocene glaciation undoubtedly had an effect on ecological succession (Willett, 1951), no definite consequences to soil formation have been postulated. Thorp (1965) has observed that since climate and biological activity are known to have varied significantly since late Pleistocene time, most soils which are more than a few thousand years old have been affected to a greater or lesser degree by changes in climate and corresponding biological activity.

Evidence of previous climatic cycles in the Kaiteriteri area is seen in the patches of red weathering present in a number of profiles throughout the area, particularly those on the oldest groundsurfaces. Te Punga (1964) considers that similar areas of red weathering in the Wellington district were formed during a seasonally humid climate with a hot, dry, period, with a mean annual temperature above 60°F and an annual rainfall in excess of 40". Such a mean temperature is at least 5°F greater than the present day mean. One or more such periods of red weathering may have occurred. However, the likelihood that the present landscape has formed since this period means that its significance to the present study is probably minimal.

In the absence of reliable data concerning even gross climatic changes, it must be assumed for the purposes of this study, that any such changes have occurred with similar effects upon all portions of the landscape studied.
Bidwell and Hole (1965) have discussed the anthropic influences of Man on the five soil-forming factors. It would appear most unlikely that any occupation of the Kaiteriteri area by Maori or Pakeha has ever occurred. It is probable that the area was felled in the middle to late 19th century. Some burning may have occurred during this period but its effects may have been similar at all sites. Extensive burning by the N.Z. Forest Service preceded recent planting of the area in *P. radiata*. Effects of this burn could be seen on some sites where a charcoal layer overlaid the solum. On such sites, this layer was carefully removed and analysed separately. The recent burn, however, would have had little effect on long-term soil processes.
VI 1.2 MAPUA SEQUENCE

VI 1.2.1 Parent Material

The two factors most likely to cause variations in the parent material of the Mapua soils are contamination by loessial material and differences in the chemical and physical properties of the parent material.

The possibility of Pleistocene loessial deposition has been discussed by Kingston (1968) who suggested that the characteristic fine sandy loam topsoil of the Mapua Hill soils may have been deposited at the close of the Pleistocene as strongly weathered loess blown up from the then-exposed floor of Tasman Bay. Any recent additions of loess could only have come from the southern portion of the Moutere gravels and would therefore be of little significance to soil development.

The situation described in the Kaiteriteri sequence where differences in parent material composition are ascribed to the influence of previous preweathered surfaces has not been identified in the Mapua sequence. However, Taylor and Pohlen (1962) cite the Mapua sandy loam as an example of a soil formed at least in part from a pre-argillised parent material so that a similar situation could exist in this sequence.

The strongly weathered Moutere gravels forming the parent material of the Mapua sequence would therefore seem to be a relatively uniform material with the occasional variability observed in the Kaiteriteri sequence apparently being absent.
VI 1.2.2  Vegetation:

With the exception of the two steepland sites, all sampled surfaces have carried _P. radiata_ for about the last 45 years. Whether this has significantly affected the processes of soil development on these surfaces compared with the two steepland sites which have only carried _P. radiata_ for the last 7 to 10 years is unknown. Any differences, however, would probably be unimportant over this relatively short period. Otherwise, it must be assumed that the frequency and composition of the available biota has remained uniform over the restricted area of the sequence throughout the period of soil formation.
The arguments advanced in section VI 1.1.3 regarding the time factor must also be advanced for the Mapua sequence where a similar mode of landscape development is postulated. Further comment on this suggestion will be left until VI 4.
VI 1.2.4 Climate

As in the case of the Kaiteriteri sequence, the effects of past climatic cycles on the soils of the Mapua sequence are impossible to ascertain. Again, in the absence of any reliable data, it must be assumed that any climatic changes have had similar effects on all surfaces in the sequence.
The influence of Man on the soils of the Mapua sequence has been very marked in many areas. Burning associated with early farming in the area undoubtedly accelerated erosion from the ridges although the situation on the Mapua soils is not nearly as bad as that on the adjacent Rosedale soils. Planting of *P. radiata* probably stabilised eroded surfaces to some extent but the effects of logging can be very severe particularly on ridge areas. The A horizon may often be destroyed by the haulage methods used to remove timber from felling area to mill. Such ridge sites were carefully avoided during sampling.

The prevalence of erosion in the Mapua sequence means that depositional surfaces are quite common, particularly in gullies. The midslope gully sites sampled fall into this category, although neither show the extremely deep A horizons found in some gully profiles.
VI 2. THE METHOD OF INVESTIGATION

VI 2.1 The soil sequence studies.

The method of investigation used in this study is similar to that employed by Stevens (1968). The following discussion deals with the problems encountered during the present study and provides suggestions as to how it could have been improved.

The difficulties associated with sampling have been mentioned earlier. In particular, the errors associated with the use of volume-weight sampling tins in a number of the Kaiteriteri sites were considered. It was suggested that such errors were of minimal importance being of a similar magnitude in all cases. This was confirmed by a later sampling which checked some of the horizons previously sampled. It was found that the expected errors were considerably less than anticipated and in fact were within the limits of experimental error.

It was thought unnecessary to conduct a preliminary sampling within either of the sequences in view of the 1964 soil survey of the Kaiteriteri block and the apparent similarity of the Mapua area. As has been stated earlier, the original intention in the Kaiteriteri granite sequence was to sample two sites on each of the four postulated groundsurfaces. However, subsequent work showed that five groundsurfaces had been sampled and that two of the sample sites showed evidence of a slightly different P M due to the influence of a previous, strongly argillised landscape. Consequently, of the five groundsurfaces actually sampled the results from four were based on only one profile. It appears that a preliminary sampling would have been advantageous and that a greater area of the landscape should have been sampled. Results obtained could then have
been assessed with far more certainty.

The same argument can be applied to the Mapua sequence, in which all profiles, although rather different morphologically, were found to be chemically similar. Results from this sequence are consequently of limited value. A preliminary sampling may have confirmed this lack of variability and enabled more emphasis to be placed on the Kaiteriteri sequence.

Another problem lies in the very poor chemical status of nearly all the sampled soils. Analytical methods were often being employed at the lower limits of their precision. This could not be overcome and consequently some results, particularly those in the inorganic phosphorus fractionation contain quite large percentage errors. However these should be considered in the context of their low absolute values rather than as an indication of poor analytical technique.

Aided by hindsight one can conclude that more would have been gained from the toposequence studies by concentrating on the Kaiteriteri sequence and adopting a more extensive sampling procedure. Although considerable analytical work has been carried out, concentration on one sequence would have meant that samples could have been studied in greater depth. In particular, mineralogical studies could have been greatly expanded. An investigation of the weathering processes occurring in the stone fraction between the K1 and K2 groundsurfaces would also be very interesting.
As in the soil sequence studies, the investigation of nutritional problems in *Pinus radiata* growing on both the Kaiteriteri and Mapua soils has been affected by the limited amount of sampling that was possible. This particularly applies to the lack of sufficient soil data to correlate with foliar nutrient levels and has meant that the small amount of data that was available has been expanded rather artificially to cover this deficiency. The unexpected problems encountered in the application of multiple regression analysis to tree nutrition problems in Tasman forest meant that large-scale soil-foliage correlations would have been invaluable as an aid to establishing the causes of the observed growth variation. It would have been preferable to have sampled a considerably larger number of trees (say 200-300) over a far wider area of the Tasman forest and to have taken soil samples from the vicinity of each sampled tree. The method employed by Humphreys (1964) which consists of taking two soil samples from 0-3 inches and 12-15 inches under each tree appears to be a suitable technique in this respect.

Some thought should also be given to a simple method for sampling foliage on mature and near-mature trees. Unfortunately not all foliage sampling is done on young trees although this is the most common situation. It is preferable that foliage samples should be collected from new season's growth in the active crown. Climbing to these positions is impractical and dangerous owing to the very thin crowns and flimsy trunk structure at these heights. The alternative is felling of the required sample tree which besides often smashing the tree-top is rather a drastic method when a large number of trees are to be sampled.
Although the multiple regression technique employed in this study has its problems, it is clear that the method is extremely valuable particularly if used on a large scale and in conjunction with soil data and foliage analyses. In this context the possibility of adopting a similar procedure in fertiliser trial work could be considered. The present use of foliage analyses alone as a method of following and assessing trials is also very desirable and should be used wherever possible.
VI 3. SOIL DEVELOPMENT

VI 3.1 Behaviour of Soil Phosphorus

It is not intended to discuss in this section the phosphorus fractionation procedure used in this work or the merits of the various methods of determining $P_o$, other than to repeat the observation that the ignition method was found to be unsatisfactory in these strongly weathered and leached soils. Williams (1965) extensively reviewed the literature on soil phosphorus and fully examined the fractionation scheme he adapted from earlier procedures. The determination of organic P has been discussed by Syers (1966) and Williams and Walker (1967). Some discussion of the soil phosphorus data has already appeared in IV 2.4 and IV 3.4. This section will examine the changes in soil phosphorus with increasing soil development in more detail.

It is considered that the soil-forming processes exemplified in the Mapua sequence are included within the range of soil development covered in the Kaiteriteri sequence. Consequently the following discussion will be based mainly on results from the Kaiteriteri sequence. Essentially this sequence is one of increasing soil development and as such it bears a close relationship to Stevens' (1968) study of the soils of the Franz Josef chronosequence. As both studies were conducted in the same department, the approach and methods used in each are very similar. Comparison of the present study with that of Stevens should therefore provide an interesting view of the behaviour of soil phosphorus with increasing soil development.

Comparison of phosphorus data from the Franz Josef and Kaiteriteri sequences shows that the total phosphorus content of the K 1 groundsurface of 2622 Kg/ha is approximately comparable to that of the Mapourika profile at Franz Josef with 2288 Kg/ha. Relative proportions of the
inorganic P fractions in Table 22 places the K 1 groundsurface between the Mapourika and Okarito profiles in terms of degree of development (see Stevens, Fig 25). The period of soil formation at these two sites was assessed by Stevens at 12,000 and 22,000 years respectively. Physical properties of the Franz Josef and K 1 profiles further confirm this hypothesis. Stone material >2 mm constitutes 36% of the Mapourika profile while the Okarito profile contains only 16% stones. In comparison, the G 1 profile contains about 20% of stone material. This, plus similar evidence, shows that the K 1 groundsurface in the Kaiteriteri sequence has apparently reached a stage in soil development similar to the oldest, most developed profiles of the Franz Josef chronosequence. Consequently the soils on the oldest groundsurfaces of the toposequence have reached a point considerably more advanced than in any of Stevens' sites. The two studies can therefore be considered complementary in the sense that they will illustrate changes in individual properties over a longer period of soil development than does each individually.

The large quantity of P lost from the system during pedogenesis is evident in Figs 11 and 12. This loss is similar to that found by Stevens (loc cit), corroborates work by Wild (1961) and tends to refute Beadle (1962). Arguments advanced by Beadle to refute Wild's work are not really applicable to most New Zealand studies. The parent material of the Kaiteriteri soils is not very low in P, but erosion has obviously removed areas of surface horizon from the older more than the younger groundsurfaces. However, the fact that each erosion cycle might be expected to cut into fresh mineral material of higher P content than the preceding surface contradicts Beadle's hypothesis. Total P in the ecosystem was not measured in this...
study but the fact that the vegetation density decreases markedly from the K 1 to the K 5 groundsurface means that trends at present observed would be magnified, not reduced, if this factor was included. The decline in the P content of the soil system is therefore attributed to leaching losses, rather than to the factors outlined by Beadle (loc cit). The loss of these large amounts of P is primarily due to the decrease in the non-occluded P fraction, although the occluded, residual and organic P fractions also show an overall decline in absolute amounts particularly in the later stages of the sequence.

Stevens (loc cit) showed that the hypothesis of Chang and Jackson (1957) was generally valid for soils of the Franz Josef chronosequence. Chang and Jackson suggested that "Ca-P" was initially transformed into "Al-P" which then reverts to "Fe-P". They then suggested that the development of concretions and iron coatings during soil development may later convert non-occluded forms into occluded forms of inorganic P. The validity of this hypothesis is generally confirmed in the Kaiteriteri sequence. Amounts of acid-extractable Ca-P are nil on all except the K 1 groundsurface where a small proportion still remains. Some evidence for the postulated conversion of "Al-P" to"Fe-P" can be found in that the proportion of NH₄F-P drops from 30% on the K 1 groundsurface to about 3-5% on all other groundsurfaces while 1st NaOH-P remains relatively constant throughout the sequence at 7-13% of ΣPi. The present study goes considerably beyond the final point of the Chang and Jackson hypothesis. Fig 13 shows a considerable loss of non-occluded P between the K 1 and K 2 groundsurfaces, a decline which is paralleled by a sharp increase in the proportions of residual P. The majority of this non-occluded fraction is
being lost from the soil system with the loss paralleling the loss in $\Sigma P_i$ (Fig 12). However, some of the non-occluded P fraction is apparently being converted to other forms of inorganic P. The evidence of Figs 12 and 13 would suggest that occluded P is being transformed to residual P at a rate faster than the non-occluded to occluded P transformation. Work with Christmas Island rock phosphate (IV 2.4) has shown that part of the residual P fraction is possibly an individual crystalline form similar to crandallite ($\text{CaO} \cdot \frac{3}{2} \text{Al}_2\text{O}_3 \cdot \text{P}_2\text{O}_5 \cdot \frac{3}{2} \text{H}_2\text{O}$) in structure. After the stage of development represented by the profile on the K 2 groundsurface, the amounts and proportions of non-occluded P remain almost constant, particularly on the three oldest groundsurfaces. Losses of P from the system are now from the occluded, residual and organic P fractions. It would appear therefore, that Chang and Jackson's hypothesis should be extended to include the possibility that occluded forms of inorganic P may be further converted into secondary mineral forms with increasing soil development.

The present study plus that of Stevens (loc cit) has shown that all postulated inorganic P fractions may decline in the soil system if soil-forming processes continue for a sufficient length of time. The rate of decline of these inorganic fractions is considered to be in the order: acid-extractable Ca-P $\gg$ non-occluded P $\gg$ occluded P > residual P. Whether these declines are directly attributable to leaching or occur via conversion to organic phosphorus which is subsequently mineralised and leached is uncertain.

Only a few studies have discussed soil P content in connection with other soil parameters and in relation to environmental conditions. Walker and Adams (1959) developed a hypothesis relating changes in total
and organic P to differences in soil development. This was restated by Walker (1965). The present study supports the hypothesis, particularly that part dealing with changes in the ecosystem in the later stages of soil development.

Stevens (loc cit) found that there was little evidence in the Franz Josef chronosequence to support that part of Walker's hypothesis regarding the elimination of N-fixing plants from the plant succession when all the acid-extractable Ca-P and plant-available forms of non-occluded inorganic P within root range have been converted to organic P or occluded forms of inorganic P. However, competition for light rather than an inadequate phosphorus supply is probably the dominant factor in the elimination of nitrogen-fixing species at Franz Josef. Plant succession on the ground-surfaces studied in this sequence follows the hypothesis almost perfectly. Thus the three oldest groundsurfaces containing no acid-extractable Ca-P and a very low, constant amount of non-occluded P carry a heath vegetation, while the least developed K 1 groundsurface which still contains a small amount of acid-extractable Ca-P supports a vigorous legume cover of gorse (Ulex sp.) plus broom (Cytisus sp.). The K 2 groundsurface, which is at a stage in soil development where C and N are still being accumulated due to the small reserve of "plant-available" non-occluded P which is still present in the profile, carries a rather stunted gorse cover. Walker (loc cit) indicated that, once nitrogen-fixing plants are replaced in the plant succession by those with lower nutritional requirements, a decline in the carbon and organic nitrogen, sulphur and phosphorus contents of the profile should increasingly occur. This happens in the Kaiteriteri sequence. Oxidisable C and N both reach a peak on the K 2 groundsurface and then
decline reaching an apparent steady state between the K 4 and K 5 ground-surface. Po after remaining fairly steady shows a marked decline to an extremely low level on the most developed K 5 groundsurface. Stevens (loc cit) observed that once all weathering of coarse fractions in the solum is finished, the previous balance between formation and mineralisation of Po is shifted towards loss of Po because (i) less non-occluded P is available for plants; (ii) less plant tissue is formed, and so less Po is formed, (iii) lower growth rates and absolute amounts of plant tissue require less P. At this stage, mineralised P in excess of plant requirements is leached or converted to occluded forms. Absolute losses of organic P by leaching, perhaps within colloidal OM may also occur. All of these mechanisms may be operating within the Kaiteriteri sequence. No evidence has been found in this study to indicate at what point inorganic P in the system will stop declining. Whether a stage in soil development can be reached where no phosphorus remains in the soil system is unknown, but it appears most likely that declining phosphorus in the ecosystem will follow an asymptotic curve approaching but never reaching zero.
Further Aspects of Soil Development.

This study has basically attempted to investigate gains, losses and transformations of certain elements within and between the members of a sequence of increasing soil development. Some of these changes have been discussed previously, including changes in soil phosphorus which have been dealt with in some detail in the previous section. Due to the basic similarity in soil development of the Kaiteriteri and Mapua sequences the following discussion will be based mainly on the results of the Kaiteriteri toposquence. As was mentioned earlier, comparison of this work with that of Stevens (1968) should prove interesting in that considered together they cover an extremely wide range of soil development. Comparison with other sequence studies is impossible since the few of these which have been investigated are concerned with far less weathered and leached soils than are found in the Kaiteriteri sequence.

At least four indices of weathering have been employed in soil sequence studies: index mineral determinations, optical and clay mineralogy, estimation of the ratio of extractable iron to total iron ($\frac{Fe_c}{Fe_t}$ ratio) (Ellis, 1969) and changes in the forms of inorganic P (Chang and Jackson, 1957). No attempt was made to use index minerals in this study. Clay mineralogy of the Kaiteriteri sequence followed the general pattern of decreasing vermiculite-1 and increasing kaolinite as soil development increased, with the oldest soils of the sequence containing mainly kaolin in both the fine and coarse clay fractions. Investigation of the $\frac{Fe_c}{Fe_t}$ ratio was only performed on one horizon from each profile and results have been discussed in detail earlier (IV 2.3). The absence of acid-extractable Ca-P on all but one of the groundsurfaces
sampled and the large proportion of 'residual' forms of inorganic P give a good indication of the degree of soil development undergone by the profiles studied.

A number of interesting features have been noted. The influence of weathering in reducing particle size is confirmed in the Kaiteriteri and Mapua sequences. The inability of the system to continue supplying some nutrients, particularly P, once all weatherable rock material has been reduced to smaller size fractions, means that an inevitable decline in nutrient status occurs. Stevens (loc cit) showed that soil degradation could occur after a long period of apparent steady state but the present study goes further than this and shows that nutrient losses following this period are probably asymptotic approaching but never reaching zero.

Perhaps the most interesting observation of the present study is the apparent decline in the contents of both silt and clay together with total Al and Fe with increasing soil development. Increasing soil development is usually associated with increasing clay content. However, it appears possible that finer size particles may be lost from the soil system either by eluviation or by conversion to secondary mineral forms. This situation is most likely to become significant at a stage when the course of micaceous weathering is nearing completion and when the organic matter content of the system has or is beginning to decline. The decline in both total Al and Fe is not really surprising. Both elements must be continually weathering from coarser size fractions and at a stage in soil development when the majority of the more rapidly weathered elements have been lost from the solum, the rate of loss of both Al and Fe may become significant in its own right. Unfortunately, Stevens' Franz Josef study
did not include any iron or aluminium analyses so no comparisons with the present study are possible. Comparison of the two studies shows that the relative rates of loss of a number of elements from the soil system during the processes of soil development are in the order:

\[ P, Ca, Mg, K \gg Al, Fe \gg SiO_2. \]

Finally, mention should also be made of the nature of the possible profile which would finally develop at Kaiteriteri assuming soil-forming processes were allowed to continue naturally under the present temperate climate for an indefinite period of time. The dominant soil-forming processes of the Franz Josef chronosequence are gleying and podzolisation. The dominant process of the Kaiteriteri sequence, developed under considerably different weathering conditions is more likely to be strong argillisation with the end-product a very strongly argillised profile containing a higher proportion of quartz than was present in the original profile.
VI 4. CONCLUSIONS

This study has shown that all elements present in the soil system may be lost over sufficiently long periods of pedogenesis. In addition, it is possible that both silt and clay may be lost from the soil system in the later stages of soil development. Rode (1961) in addition to categorising all sequential soil studies as comparative geography, divided the irreversible processes of pedogenesis into two phases. The first, during which soil changes occur rapidly, is followed by a period of indeterminate length in which apparent steady-states or dynamic equilibria of many soil parameters may be observed. Stevens' (1968) study of the Franz Josef chronosequence was probably the first which covered periods of dynamic equilibrium as well as demonstrating soil degradation after-equilibrium. The present study supports Stevens' conclusions that Rode's hypothesis is basically correct, but that only a few soil parameters demonstrate apparent steady-states. It appears that those parameters which do are most often those having some connection with the organic cycle eg. org C, N, CEC.

The present study has been based on the sequential approach to the study of soils first outlined by Jenny (1941.) A complaint often levelled at Jenny's fundamental equation of soil-forming factors is that its definitions of the five state factors are unreal when referred to many natural situations. Consequently, if one strictly obeys Jenny's definitions, monofunctional soil sequences are considered virtually impossible to locate in nature. Jenny (1946) realised this limitation and suggested that the problem could be overcome in a situation where the amount of change of a soil property conditioned by one factor greatly
exceeded the changes conditioned by all of the others. It may be that
this argument needs to be extended to cover the point that no two soil
sequences are exactly alike in terms of the five soil-forming factors.
For this reason each sequence should be considered in its own right as
part of its own environment. Consequently Jenny's definitions of the
five state factors should be used as a guide rather than as a definitive
statement of the place of a particular factor in soil development.

The present study could well be construed as illustrating a
bifunctional soil sequence with both time and relief factors varying
significantly within the sequence. However the dominant factor in soil
development is undoubtedly the variation in the relief factor and more
particularly the slope factor. Time and parent material, while varying
according to Jenny's classical definitions are both doing so as a con­
sequence of variations in the relief factors. Thus a sequence has been
identified which is essentially monofunctional. In terms of Jenny's
nomenclature, the Kaiteriteri sequence can be described as a toposequence
or more accurately as a clinosequence. The same arguments apply to the
Mapua sequence which can also be classed as a toposequence. Although
morphological differences between the three groundsurfaces identified in
the Mapua toposequence are quite marked, very little variation in chemical
properties is found between the three areas. It would seem that the
substantial age of the system is obscuring any differences in chemical
properties which may once have been present.

It is obvious from Jenny's original treatise (1941) that he hoped to
develop pedology as a truly quantitative science with the help of consid­
erable data gained from a large number of varied sequences. That this
objective has not been realised is an indication of the inherent suspicion with which most pedologists have, until recently, regarded any attempts at introducing mathematical language into pedology. To say that the subject is too complex to be considered in a quantitative manner is only avoiding the issue, not attacking it. No subject is so complex that it cannot be interpreted quantitatively with at least some degree of precision. Jenny's approach to soil development, although clearly over-simplified, was the first very necessary step in this direction. One of the most astonishing features of the 30 years since Jenny's original work appeared is the limited amount of progress made by other workers in furthering or constructively modifying his ideas. Advancements have been attempted by Jenny himself but these have probably only achieved complication of the simplified situation described in his first two papers (1941, 1946). These remain the best description of his ideals and the methods he hoped would be used to attain them. Very few attempts have been made to investigate monofunctional soil sequences, a fact which has undoubtedly hindered further development of Jenny's theories. The main problem is the lack of appreciation of what is involved in such a sequence. Many sequences which purport to be monofunctional turn out to be bi- or even tri-functional on close examination. In addition, no two sequences are ever studied in the same way with each study reporting differing soil parameters, often determined by varying analytical methods.

The distrust of the quantitative approach is found in other fields of soil science besides pedology. In this context, the present widespread use of statistics should not be confused with the formulation of mathematical laws. If some of the chemists now involved in pure
chemical research could be convinced of the tremendous challenges awaiting them in the general field of soil science there is no doubt that tremendous advances would occur. Until this happens or until soil scientists are prepared to get down to an intensive study of the detailed kinetics and mechanisms of the various soil processes, the subject will undoubtedly remain in an essentially static phase.
VII

DISCUSSION - FOLIAGE DATA
Study of soil-foliage correlations and foliage nutrient data has elucidated some of the probable nutrient deficiencies causing retarded growth of *P. radiata* in parts of the Kaiteriteri area. For the purposes of this discussion, the soils of the study area need to be divided into two groups.

The soils of the steepland areas are mapped as variants of the Pokororo soil type (Fig 3), and foliage nutrient data shows that this soil contains sufficient nutrients for satisfactory growth of *P. radiata* once the dense gorse has been penetrated. Pokororo soils cover perhaps half of the planted area (Cutler, pers comm), and application of fertilisers to this area would seem to be unnecessary at this stage, with the possible exception of boron. Foliage boron contents, while satisfactory for normal growth, are fairly close to the critical level and it would probably be advisable for any future boron fertilisation programme to include the steepland areas.

The remainder of the planted area is mapped as either Kaiteriteri hill soil or Kaiteriteri sandy loam. *Pinus radiata* growing on both these soils shows symptoms of a number of nutrient deficiencies. These include P and B, both of which are severely deficient, as well as Ca and Mg, which also appear to be quite seriously deficient. Deficiencies of Ca and Mg are probably being accentuated by preferential potassium uptake in some cases. Appleton and Slow (1966) have observed that fertilisers have no appreciable effect on tree growth at Kaiteriteri unless boron deficiency is corrected first. Boron must therefore be added in conjunction with other treatments. In discussing the comprehensive fertiliser trials
established in the area, Appleton and Slow observed that magnesium ammonium phosphate with boron appeared very promising. This would agree with the observations above. The extremely low level of exchangeable calcium in these soils has already been noted and considerable additions of calcium are needed to bring exchangeable calcium up to a reasonable value. It would seem therefore that a fertiliser such as borated serpentine superphosphate or a Thermophos type with borate added should be used in routine fertilisation of the deficient areas. Such a fertilizer programme should have as a secondary aim the establishment of an N : P foliage ratio of approximately 10, rather than the ratios of 16-23 found at the moment.

Increased tree growth brought about by correction of phosphorus and boron deficiencies in particular, could place a severe strain on the nitrogen status of many of these soils. The possibility of induced nitrogen deficiency should be considered when planning any future fertilisation programmes. The continued use of borated magnesium ammonium phosphate will certainly prevent this inherent problem. However, some form of calcium would still need to be added in order to raise soil calcium to a satisfactory level. As can be seen from the soil data the Kaiteriteri soils contain very low amounts of several nutrients. Elimination of the deficiencies mentioned above by means of suitable fertiliser programmes may well induce other deficiencies, particularly those of plant micronutrients. Such deficiencies will need to be corrected if and when they become apparent.
VII 2. MAPUA

The history and nature of the nutritional problem in *P. radiata* growing on Moutere gravel soils have been discussed earlier (Section II 6.2). Of the two problems mentioned there, the second, involving the relative rates of growth of first and second rotation stands, does not concern the present study. The present work has rather been aimed at establishing the underlying causes of the widespread areas showing symptoms of nutrient deficiencies in both first and second rotation stands. This problem has tended to be ignored in preference to the debatable point of whether the differences in growth rate between first and second rotation are real or merely a consequence of different establishment practices.

Suggested fertiliser programmes to alleviate deficiencies have been developed from the results of poorly designed field trials using treatments based on the results of limited foliar analyses and the presence of similar visual deficiency symptoms to those described in the literature. Both visual diagnosis and the use of critical foliar levels independently of other data are recognised as being of doubtful value in predictive diagnosis of nutrient deficiencies (Gentle & Humphreys 1968).

The present study has used the technique of stepwise multiple regression as described by Draper and Smith (1966) to investigate relationships between foliar nutrient levels and tree volume. In addition, studies of critical foliage nutrient levels and soil-foliage correlations have been used to support the multiple regression analyses. Gentle and Humphreys (loc cit) have found that where plantings which cover a range of site qualities are available, this method provides the most reliable diagnostic guideline.
The question of whether to use tree volume or tree height as the measure of tree growth in the regression analyses requires amplification. Whyte (1969) has stressed the importance of trunk basal area (and hence diameter) rather than tree height to the volume of timber in a forest stand and therefore also to the volume of a single tree. Reference to Table 55 shows that, as in the case of Gentle and Humphreys (loc cit), the range in tree height is limited, covering a range of only 2-3 times, whereas measures of tree volume cover a range of values from 3 to 181, a 60 fold difference. Such a variation in the range of the dependent variable must have a considerable effect on the establishment of a predictive relationship between it and foliar nutrient levels. The importance of using the best possible data in statistical problems is often stressed. In particular, the range of the data analysed is particularly important in regression analyses. The use of site index and other measures of tree height rather than tree volume as a measure of tree growth is a characteristic of almost all statistical studies involving tree growth. Gentle and Humphreys (loc cit) have used an almost identical approach to that employed in the present study with the exception that site index was used as the dependent variable. Similarly, Kingston (1968) used site index in the correlation of tree growth with soil physical parameters and landform parameters in the same area as the present study. Numerous other examples abound in the literature. The reasons for this are difficult to establish. Except for those cases involving dense stocking rates, the only argument advanced appears to be that of practicality (Ralston, 1964). It seems to be felt that the added measurements needed to obtain volume measurements make it an unsatisfactory alternative to height. The only
added figure required is that of diameter breast height which can be measured in considerably less time and with far less trouble than it takes to assess tree height. The use of volume rather than height as a measure of tree size would therefore seem to be preferable with the advantages gained in the statistical analyses far outweighing the slight extra time involved.

The results of the multiple regression analyses are somewhat puzzling and perhaps indicate that a knowledge of plant physiology and soils is needed to make the statistics intelligible. In section V 3.1, the three calculated regression equations are presented and discussed. Of the three equations calculated, equation 2 would appear to be the most realistic. However, equation 1, which predicts foliar Ca as being the most significant factor causing variations in tree growth, produces by far the highest multiple correlation coefficient (0.850). As was previously stated the most logical explanation for the measured foliar Ca contents is that they are the results of a dilution effect caused by the differences in tree size. All the evidence is strongly against calcium being a factor contributing directly to the variations in growth. Absolute foliage levels of Ca preclude any possibility of Ca toxicity and the absence of any correlation between exchangeable or total soil calcium and foliar calcium prevents its consideration as a direct contributory factor. In the Kaiteriteri soils where calcium deficiency is present, such a correlation is observed. It is probable that, if calcium was a direct cause of the observed growth variations, such a correlation between soil and foliar calcium would have been found. However if the variations in foliar Ca are the results of a dilution effect, it would be expected that the simple correlation coefficient between foliar Ca and tree volume would be lower than that for the elements causing the variations in tree size. This is because a deficient or toxic
element should be correlated with tree size to a higher degree than an element whose concentration only mirrors the effects of that deficiency and which is more likely to be affected by interaction with other foliar nutrients.

Multiple regression procedures are employed in order to distinguish between factors which contribute directly to the variations in growth and those that contribute by virtue of their relationship with direct factors. One can therefore conclude in this particular case that the stepwise multiple regression procedure has been unable to separate these two groups of factors. This is a serious criticism of stepwise regression, which is generally acknowledged as being the most useful of all multiple regression techniques. Its widespread use supports its place in regression analysis.

Reasons for this apparent failure must therefore be examined. It is possible that insufficient observations have led to the apparently unreal conclusions predicted by the regression analyses. 48 data sets were used, a total which although not large, covered a satisfactory range and should have been sufficient to ensure a true result. Alternatively, the fact that measures of tree nutrition such as foliar nutrient levels are being employed as an indirect measure of soil conditions may have had some effect. In this case the differences in the foliar nutrient levels are merely reflecting differing soil properties on the various sample sites. Whether this indirect approach to the investigation of tree nutritional problems has led to a breakdown in the stepwise regression procedure in this particular case is uncertain. The only other explanation seems to be that the result was obtained by chance. Although this explanation may appear rather unlikely, it seems to be the most probable one to explain the
conflicting statistical and plant physiological views inherent in equation 1. Some evidence for it does exist. The simple correlation coefficient between foliar Ca and tree volume (-0.615) is the third highest of the 10 elements measured. Multiple regression using foliar Ca (rather than foliar Ca$^{-1}$) shows that calcium is of no significance to tree volume, being the eighth variable entered at the very low t value of 0.2131. In this case the stepwise regression is obviously distinguishing foliar Ca as being insignificant to tree growth but with a high simple correlation coefficient with tree volume because of its interaction with other more significant factors. On taking the reciprocal of foliar Ca, one has apparently obtained by chance a simple correlation coefficient higher than for any of the other elements. This causes foliar Ca$^{-1}$ to be entered first in the regression equation and leads to the subsequent development of equation 1. It is therefore concluded that equation 1 should be discarded from consideration as a real representation of the causes of the observed growth variations.

As was stated earlier, equation 2 appears to be the most realistic of the three calculated regression equations. This equation can be interpreted in terms of tree growth being affected by toxic levels of Mn and deficiencies of P and N. Each of these factors is supported by other evidence. Foliar contents of both P and N correlate significantly with soil measures with P showing the higher correlation. Field experimentation has also predicted both to be deficient (Appleton and Slow, 1966). It is a little more difficult to vindicate the inclusion of manganese if calcium is excluded. However, the possibility of manganese toxicity
cannot be reasonably excluded, particularly since a majority of the poor trees contain levels of manganese in the needles considerably above the supposed critical level of 700 ppm. This conclusion is reinforced by the observed correlation between easily-reducible Mn and foliar Mn content. If manganese toxicity is conceded as being a more likely cause rather than result of the variations in tree growth, equation 3 must be discarded from consideration. It is concluded therefore that equation 2 gives the best predictive relationship for tree volume.

It is worth noting that in all three calculated equations, phosphorus is inserted into the regression equation at a t-test value considerably higher than that for nitrogen suggesting that phosphorus is of more importance than nitrogen in the nutrition of *P. radiata* in the Tasman forest. This is at variance with the conclusions of a number of workers (Stone and Will, 1965b, Appleton and Slow, loc cit) that nitrogen is the principal deficient element affecting tree growth on the Mapua soils. This latter view has been based primarily on the results of field trials which have generally shown that additions of P alone produce no response whereas N alone or N + P produces an appreciable increase in tree growth. No work has been done to find whether any free-living N-fixers are present in the Tasman forest soils. It is possible that if such organisms are present, their effectiveness may be severely limited by soil acidity as well as a lack of phosphorus. This would explain the observations cited above. Additions of P alone or P + lime would take some time to correct the incipient nitrogen deficiency, whereas N alone or N + P would be expected to give an immediate response. However, it seems likely that continuing additions of phosphorus and perhaps lime may eventually lead to
an improvement in the nitrogen economy of the system to a point where no further additions of nitrogen are needed. The close relationship existing between the two elements can be seen from the sharp reduction in the t-test value of phosphorus when nitrogen is entered into equation 2. Thus the t-test value for the phosphorus coefficient drops from 4.0364 to 2.9199 upon the introduction of nitrogen, while the corresponding t-test value for the Mn⁻¹ coefficient increases from 5.8503 to 6.2793 showing that Mn⁻¹ is independent of both phosphorus and nitrogen. It appears therefore that although phosphorus is the main deficiency limiting growth, nitrogen will need to be added for some time in order to get the organic cycle moving at a more reasonable rate. However the results of the multiple regression analysis have shown that before maximum responses can be expected an increase in the pH of the soils concerned is required to overcome the significant effect that manganese toxicity is apparently having on tree volume. It is therefore suggested that an investigation should be made of the effects of lime together with added phosphorus and nitrogen on tree size. An economic alternative to lime in the Nelson area could be dolomite. Liming on these very acid soils should not cause any problems due to release of ammonia from nitrogenous fertilisers particularly if the two treatments are applied separately. An added advantage of liming would be to prevent an incipient calcium deficiency which could eventually occur on these soils. Noonan (1970) has concluded that there is sufficient nitrogen available in Tasman forest soil to allow decomposition of residues after clear-felling. However, mineralization is so slow that insufficient nutrients become available to supply the needs of dense regeneration. It is suggested that this slow mineralization may well be caused by the acidity of the system or
a deficiency of phosphorus or by a combination of these two factors. Liming together with addition of phosphorus may therefore also improve the rate of mineralization with a consequent increase in the quantity of nutrients available for tree nutrition.

The present study contains insufficient soil data to enable definite conclusions to be drawn on the use of soil analyses to determine future tree growth. Ballard (1969) found that the quantity of Bray No. 2 extractable phosphate corresponding to a volume production of 12,000 cu ft/acre and a height of 120 feet at 40 years of age in *P. radiata* at Riverhead forest, Auckland, was approximately 5 ppm with a corresponding Olsen value of approx. 3.5 ppm. These values, which approximately correspond to the difference between good and poor growth of *Pinus radiata* are generally obeyed in the present study (Table 62). However, it can be seen that the difference in levels of extractable soil P on the different soils growing *P. radiata* ranging from very good to very poor is very slender.

Although difficulties have been encountered in the application of multiple regression techniques to this investigation of nutrient deficiencies in *Pinus radiata*, this author agrees with the view of Gentle and Humphreys (loc cit) expressed earlier in this section that the method provides the most reliable diagnostic guideline to nutrient deficiencies. The method has its disadvantages, notably that it can only be used really satisfactorily in areas carrying *P. radiata* of a uniform age and of a range of site qualities within that one age-class. Further if tree volume is used as the measure of tree size in the regression analysis, a procedure which would appear to be preferable to using site index, the age of the tree must be such that a useful measurement of tree volume can be achieved. For this reason,
the sampled trees would need to be at least 10 years old and preferably older. The main advantage of the method lies in the ability of the computerised multiple regression program to cross-correlate the nutritional evidence, thus investigating any interactions which may be present and thereby allowing interpretation to proceed much further than is possible with the usual sort of mensurational evidence derived from field trials. However, it is obvious that a number of factors should be considered in the use of the multiple regression procedure as outlined in this study. The largest possible amount of data should be used, covering the widest possible range in tree size within the one age-class. In addition the concentrations of as many foliar elements as possible should be measured. In the case where a linear regression program is to be used all of these foliage concentrations should be investigated for possible curvilinear relationships with the dependent variable and any such relationships discovered should be corrected for. It is obviously preferable that soil chemical data should be available if possible in order to compare with the predictions of the regression equations. Whether or not such data are available the results of multiple regression analysis should be considered in conjunction with all available data, particularly that involving tree physiology and critical foliar levels. As a final conclusion, it may be apposite to quote Gentle and Humphreys (loc cit) regarding approaches to the diagnosis of nutrient deficiencies.

"The key to avoiding repetitious experimentation, of a type which is really a succession of corrections of previous errors of diagnosis, is to expend time generously gathering initial diagnostic data. As a rule of thumb a year spent in this way is worth about five years spent filling-in data deficiencies later in the life of the field experiment."
VIII SUMMARY

1. A clinosequence of soils developed on an old, strongly weathered granite landscape at Kaiteriteri was recognised, described and studied.

2. A toposequence of Mapua soils developed on the strongly weathered alluvial, Moutere gravels was tentatively identified and studied.

3. An investigation into the causes of poor growth of Pinus radiata on both the Kaiteriteri and Mapua soils was undertaken.

4. An extensive survey of the literature reviewed a number of studies on catenary sequences and toposequences. The influence of relief as a soil-forming factor and the theoretical aspects of hillslope evolution have also been reviewed.

5. An extensive survey of the literature reviewed the various methods used in the determination of the nutrient requirements of forest stands with particular reference to Pinus radiata. The evidence for a productivity decline between the first and second crops of P. radiata in both Australia and New Zealand (particularly Nelson) was reviewed.

6. The development of the Kaiteriteri landscape is postulated in terms of five K cycles with profile development occurring subsequent to each erosion cycle on a groundsurface formed during that cycle.

7. The vegetation, climate and parent material of both the Kaiteriteri and Mapua sequences were described.

8. The sampling methods and analytical techniques used in the study were described.

9. Soil morphogenesis was illustrated by detailed profile descriptions.
The end-product of development in both sequences is a strongly argillised profile.

10. Changes in measured soil parameters between the different ground-surfaces of the Mapua toposequence were generally small and were similar to those found in the later stages of the Kaiteriteri clinosequence. These small changes were in contrast to the morphological differences between the profiles of the sequence and were attributed to the vast age of the system obscuring any differences which may once have been present.

11. A decline in profile clay content with increasing soil development was noted in the Kaiteriteri clinosequence.

12. Oxidisable carbon and nitrogen initially increased in the system but then declined asymptotically to a near steady-state between the K 4 and K 5 groundsurfaces.

13. Cation exchange capacity increased to the K 3 groundsurface and then decreased whereas total exchangeable bases remained relatively constant throughout the sequence. Low base saturation was common in many of the soils of the Kaiteriteri clinosequence.

14. Total calcium, magnesium and potassium all showed an overall decline with increasing soil development but only magnesium showed a relatively regular decrease.

15. Total aluminium and iron in the profile showed an initial increase to the K 3 groundsurface and then decreased. It was suggested that at a certain point in soil development where the easily weatherable minerals have been lost from the system, the rate of loss of aluminium
and iron becomes significant in its own right.

16. Over 80% of the phosphorus in the soil tessera was lost from the system during the stage of soil development encompassed in the Kaiteriteri clinosequence.

17. Amounts of organic phosphorus remained relatively constant between the K 1 and K 4 groundsurfaces but then declined sharply on the K 5 groundsurface where only 5.4% of the total phosphorus in the profile was in the organic form.

18. Non-occluded and occluded phosphorus both show a regular decline in absolute profile quantity. Residual phosphorus shows an irregular decline in absolute profile quantity.

19. The proportion of non-occluded phosphorus in the profile shows an asymptotic decline with increasing soil development. Occluded phosphorus becomes an increasing proportion of the total inorganic phosphorus while residual phosphorus follows an inverted asymptotic curve reaching proportions ranging from 58% to 72% of $\Sigma P_i$ between the K 2 and K 5 groundsurfaces.

20. Comparison of the behaviour of the inorganic phosphorus fraction of two soil samples with that of calcined "C" grade Christmas Island rock phosphate led to the conclusion that the residual organic phosphorus fraction of these strongly weathered and leached soils could be a phosphate mineral of crandallite-like structure.

21. X-ray diffraction studies on samples from the Kaiteriteri clinosequence showed a declining vermiculite-I and increasing kaolin content with increasing soil development. The Mapua toposequence exhibited a number of unexpected features including the presence of a
substantial proportion of illite in the most strongly developed profile of the sequence. A number of possible explanations for this result were put forward.

22. A lengthy discussion first commented upon the extent to which the four soil-forming factors other than relief had been held constant or ineffectively varying in both sequences. It was suggested that Jenny's definitions of the five soil-forming factors should be used as a guideline to deciding their constancy in a particular sequence rather than as strict, definitive, statements.

23. A discussion on the method of investigation used in the study concluded that it would have been preferable to have undertaken a more extensive sampling within the Kaiteriteri clinosequence and to have ignored the Mapua toposequence.

24. The latter part of the discussion centred around soil formation under the headings of behaviour of soil phosphorus, further aspects of soil development and conclusions. Important points included:

(i) An hypothesis proposed by Walker linking the amounts and forms of phosphorus with declining nitrogen in the ecosystem was confirmed.

(ii) It was suggested that all forms of phosphorus may decline in the soil system with increasing soil development. The rate of decline is in the order:

acid-extractable Ca-P >> non-occluded P >> occluded P >> residual P.

(iii) Rates of loss of total elements were found to be in the order:

Ca, Mg, K, P >> Al, Fe >> SiO₂
(iv) Continued soil degradation was observed for all parameters in the sequence. Thus declines in total soil nitrogen, oxidisable carbon, C.E.C., calcium, magnesium, potassium, aluminium, iron, phosphorus and profile clay content plus organic, non-occluded, occluded and residual phosphorus were noted. These declines were suggested as being due to the completion of the physical weathering of stones and gravels whereupon no further minerals from freshly weathered rock could enter the pedogenetic process. Comparison with Stevens' study of the Franz Josef chronosequence showed that nearly all soil degradation patterns follow an asymptotic path. The profiles developed on the K 4 and K 5 groundsurfaces were considered to be examples of the terminal steady-state ecosystem described by Jenny.

25. A combination of foliage analyses and soil-foliage correlations were used to investigate the causes of nutrient deficiencies in Pinus radiata in the Kaiteriteri area. It was concluded that with the exception of the soils of the steeplands, Pinus radiata growing on the Kaiteriteri soils were deficient in phosphorus, boron, calcium and magnesium. The possibility of other induced deficiencies appearing when these four major elements are added was discussed. Borated serpentine superphosphate or thermophos with added borate were suggested as suitable remedial fertiliser mixtures.

26. A combination of foliage analyses, soil-foliage correlations and in particular multiple regression analysis between tree size and
foliage nutrient levels were used to investigate the reasons for the areas of _Pinus radiata_ on the Mapua soils in Tasman forest showing poor growth and symptoms of nutrient deficiencies. Equations relating tree volume to foliar nutrient levels were derived and their implications examined. Reasons for the partial failure of the multiple regression analysis to conclusively identify the cause of the problem were discussed. It was concluded that low levels of soil phosphorus were an important factor in limiting growth and that nitrogen deficiency was of rather less importance. In addition, manganese toxicity was an important contributor to low tree volume. It was suggested that the effect of liming should be examined in conjunction with alleviation of the phosphorus and nitrogen deficiencies in order to improve conditions for tree growth.
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