Soil-plant Relationships of Magnesium in Selected Taranaki Yellow-brown Loams

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Abstract

The exchangeable Mg contents of soils in the Inglewood - New Plymouth area of Taranaki are primarily determined by Mg contents of parent materials. Inglewood coarse sandy loams, formed from Inglewood Tephra contained the lowest, and New Plymouth black loams formed from Oakura Tephra the highest, exchangeable Mg contents. Exchangeable Mg contents of soils formed from Inglewood and Oakura Tephras declined with increasing altitude. The exchangeable Mg contents of Taranaki yellow-brown loams formed from pumiceous parent materials under high rainfall conditions are more similar to those of yellow-brown pumice soils than of Central yellow-brown loams.

In a pot experiment, the Mg concentrations of ryegrass plants grown on Burrell gravelly sandy loam (0.24 m.e.% exchangeable Mg) or Inglewood coarse sandy loam (0.22 m.e.% exchangeable Mg) were lower than those of plants grown on Egmont black loam (1.22 m.e.% exchangeable Mg) or New Plymouth black loam (1.44 m.e.% exchangeable Mg). Only on the two soils of lower exchangeable Mg content did Mg additions of from 9 to 36 kg Mg ha^{-1} result in increased dry matter yields of ryegrass plants. Increases in ryegrass Mg concentrations and total Mg uptakes in response to Mg additions were also more marked on the soils of low exchangeable Mg content than on the soils of high exchangeable Mg content. Ryegrass dry matter yields increased with increasing temperature on all soils, as did plant Mg concentration and uptake, although the latter increases were greater on the soils of low Mg content and did not occur until after an apparent critical minimum temperature of ca. 14 C had been reached. Mg additions had no major effect on plant Ca or K concentrations.

The results of the field survey and the pot experiment are discussed in relation to the possible occurrence of Mg deficiency in plants and animals in Taranaki and the possibility of correcting these deficiencies using Mg-containing fertilizers.

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CHAPTER I

Introduction

Magnesium is an essential nutrient element for both plants and animals. In plants, Mg forms part of the chlorophyll molecule and is believed to participate in several other processes, which may include functioning as an enzyme co-factor in the processes of carbohydrate metabolism phosphate metabolism nitrogen metabolism and lipid metabolism (Gauch and Krauss, 1959); the regulation of cell osmotic potential (Sutcliffe, 1967) and the transport of phosphates within the plant (Jacob, 1958;Gauch and Krauss, 1959; Sutcliffe, 1967).

In animals, Mg is believed to act as an enzyme co-factor in many processes similar to those described above for plant cells. Further, the normal functioning of nerve cells is dependent upon the presence of adequate levels of Mg. When Mg is deficient, the nerve cells become more irritable, possibly resulting in the onset of a tetanic state in the affected animal. (Grunes et al, 1970). This disease is known as hypomagnasaemia (hypomagnasaemic tetany; grass staggers), and is of major practical importance, particularly in dairy or beef cows early in the post-parturition period. Over the July-September period, hypomagnasaemia may affect up to 2% of the cattle population in New Zealand. The economic importance of the disease arises from the fact that, in many cases, the affected animals die (Butler and Metson, 1967). It has been suggested that in order to ensure adequate animal intakes of Mg to prevent hypomagnasaemia, pasture herbage needs to contain at least 0.2% Mg (Kemp and T'Hart, 1957). Deficient levels for plants are commonly considered to be within the range of 0.1-0.15% Mg (McNaught, 1970). As there are few areas of soils in New Zealand which are Mg deficient with regard to plant requirements (Metson, 1974), the present Mg problem is more one of maintaining adequate contents in herbage to meet animal requirements. This problem is accentuated by seasonal fluctuations in plant Mg concentrations, with lowest contents generally occurring over the late winter-early spring period.

In the past, scant attention has been paid to the relationships between soil parent materials and soil types, and soil exchangeable Mg status, in Taranaki. In an early study, Grange and Taylor (1932) mapped the main soil series in Taranaki but presented what proved to be an over-simplification of the occurrence of different soil parent materials and the relationships between them and the various soil types. In a recent study, Neall (1972) mapped a large number of soil parent materials and thus enabled the relationships between soil parent materials and the various soil types in Taranaki to be better defined. This, in turn, has made possible this study of the relationships between soil parent materials, soil types, and soil exchangeable Mg contents in several areas of Taranaki. In this study, several factors known, or suspected, to affect the Mg content of soils, and the Mg supply to plants, were investigated.

Chapter II

Literature Review

2.1 Factors Affecting the Magnesium Content of Soils.

2.1.1 General.

The Mg content of an unfertilised soil is determined primarily by the Mg content of the parent material as modified by climate, relief, organisms and time. The effects of these various factors are summarised below.

i) Parent Material. For soils of similar age, developed under similar climatic conditions, initial total Mg contents generally relate closely to the Mg content of the parent rocks. In New Zealand, Chittenden and Hodgson (1953) demonstrated this relationship for soils of Waimea County. Many overseas workers, including Beeson (1959), Salmon (1963), Semb (1964), Reith (1967) and Mokwunye and Melsted (1972) have reported similar findings.

ii) Climate. The Mg contents of soils are affected by the intensity of weathering and leaching processes. In warm, humid climates the rate of weathering of primary minerals is rapid and Mg is readily released from primary minerals to exchangeable or secondary mineral forms. In cooler climates the rate of weathering is generally slower. The interaction between weathering and leaching is summarised as follows:

Weathering Intensity

Leaching intensity.	Low	High
Low	Slow release of Mg from primary mineral forms; Mg released in soluble form accumulates slowly as Mg exch as leaching losses are minimal.	Exchangeable Mg and secondary forms of Mg accumulate with time as leaching losses are minimal.
High	The Mg weathered out of primary minerals is rapidly leached out of the soil.	Secondary forms of Mg do not accumulate as primary forms are weathered due to high leaching losses.

(Adapted from Metson and Brooks, 1975)

iii) Relief. Soil Mg contents may increase or decrease as a result of soil erosion from steep slopes. In areas of low lying relief, soils may gain Mg in leaching waters from surrounding areas (Hanna, 1959; Alston, 1972).

iv) Organisms. Accumulation of Mg in the topsoil can occur when plant litter of a high base content, such as from a deciduous forest returns Mg to the soil surface. Podocarp forests, on the other hand, tend to produce an acid litter which causes accelerated leaching of Mg from topsoil. (Blakemore and Miller, 1968.)

v) Time. While time is not a factor controlling the initial Mg content of a soil, the time-span over which the agencies of soil formation have been operating on parent materials affects the Mg content of soils. As an example, recent soils formed on rhyolitic ash may possess similar exchangeable and reserve Mg contents to older soils formed on basaltic scoria even though basalts contain more Mg than rhyolite (Metson and Brooks, 1975). It is important, therefore, that to compare the effects of parent material, climate, relief and organisms on soil Mg contents, the soils should be of similar age.

2.1.2 Sources of Soil Mg.

(a) Mineral. The minerals which contribute most to the Mg content of soils are the primary ferromagnesian minerals - olivines, amphiboles, and pryoxenes (Metson, 1974) which are found in greatest abundance in ultrabasic and basic igneous rocks. The various ferromagnesian minerals crystallize during the solidification of magma and substitution of Mg for Fe in crystal lattice structures takes place. This substitution process is possible because Fe^{2+} and Mg^{2+} have similar ionic radii (Mg^{2+}, 0.78Å; Fe^{2+}, 0.83Å;) and the same charge. In the crystallization sequence Mg-rich minerals such as olivine crystallize first, followed in order of increasing Fe - enrichment, by pyroxenes, amphiboles and ferromagnesian micas (Goldschmidt 1958).

The ferromagnesian minerals that significantly contribute to soil Mg contents are only present in soils where weathering has been of short duration or low intensity (Salmon, 1963). However, such minerals may be preserved deep in the C-horizon of older soils (Wells, 1968). The important primary mineral sources of soil Mg are outlined in Table I.

Weathering of primary minerals may produce a number of Mg-rich secondary carbonate or silicate minerals. The carbonate minerals, dolomite, $MgCO_3.CaCO_3$, and magnesite, $MgCO_3$, are of little widespread significance as soil forming minerals, both usually occurring as massive local deposits (Goldschmidt, 1958). The silicate minerals of most widespread importance are serpentine, talc, chlorite and vermiculite. Serpentine, $Mg_3Si_2O_7 2H_2O$, derived by alteration of olivine, pyroxenes or amphiboles, and talc, $Mg_3Si_4O_{10}(OH)_2$, altered almost exclusively from Enstatite, are similar, both being 1:1 hydrosilicates with Mg substituting for Al in the octahedral layer (Goldschmidt, 1958). Chlorites have a 2:2 structure, the second octahedral layer comprising a brucite sheet (Fieldes and Weatherhead, 1968)

Table 1

Primary Mineral Sources of Soil Magnesium

Composition, Structure, Sources and ease of weathering.

Mineral:		
Olivine	$(Mg, Fe)_2 SiO_4$ (3)	Independent tetrahedral structure; Common in Basic and ultrabasic rocks. Readily weathered, and are not found in New Zealand soils as have weathered out of basalt-derived soils(2)
Pyroxenes:		
Enstatite	$Mg_2(SiO_3)_2$ (4)	Single-chain silicate structure.(4) Found in Andesitic and Basic igneous rocks. Readily weathered; where Augite contains less than usual amounts of Fe, Mg, weathering rate slower. May be present in mature soils due to accessions of volcanic material.(2)
Hypersthene	$(Mg, Fe)_2 (SiO_3)_2$	
Diopside	$CaMg (SiO_3)_2$	
Augite	$Ca (Mg, Fe Al) (Al Si_2)O$	
Amphiboles:		Double chain tetrahedral structure(4) found in a wide range of acidic to basic igneous rocks. Are readily weathered; where present in soils implies either recent origin or recent accessions of andesitic ash.
Anthophyllite	$(Mg, Fe) SiO_3$ (4)	
Hornblende	$(OH, F)_2 Ca_2 Na_2 (Mg,Fe)_5 (Al,Fe)_2Si_6O_{22}$	
Actinolite	$Ca (Fe, Mg)_3 (SiO_3)_4$	

Table 1 (cont..)

Mineral:		
Micas:		
Dioctahedral (Muscovite)	$K_xAl_2\ (SiAl)_4O_{10}(OH)_2$ (2)	2:1 layer silicate with Al^{3+} in 2 of 3 octahedral sites. Mg may substitute for up to half of octahedral Al (5). Found in schists, greywocke and granites. Relatively weathering resistant. (2) May contain up to 6% Mg (5) and may also form during weathering of feldspars. (2)
Trioctahedral (Biolite)	$K_x(Al,\ Fe,\ Mg)_2\ (Si,\ Al)_4O_{10}(OH)_2$	2:1 layer silicate structure with Mg occupying all octahedral positions, as a Brucite layer (5) Occurs in a wide range of rocks; is rare in rhyolite. Is readily weathered (2). Contains up to 17% Mg (5) and is an important source of Mg in early stages of soil development where present in parent rocks (4)
Fel spars:		
Acid (Ortho	) $K\ Al\ Si_3O_8$) $Na\ Al\ Si_3\ O_8$) $Ca\ Al_2\ Si_2O_8$)	Structure of frameworks of linked Si and Al tetrahedra; alkaline or alkaline-earth cations balance charge deficiencies due to substitution of Al for Si in the lattice. Contains small amounts of Mg (2) (1) Found in rhyolites (Orthoclases) and andesites (Plagioclases). Orthoclases

Table 1 (Cont..)

Mineral:		
		relatively weathering-resistant; Plagioclases weather easily.(2)
Volcanic Glasses	———	Structure of random chains of silicate tetrahedra interspersed with basic cations.(2) Susceptibility to weathering increases with increasing content of bases.(2) Some forms of intermediate and basic volcanic glass appear to be weathering resistant and would be poor sources of soil Mg.(2)

References:

(1) Fieldes and Swindale (1954)
(2) Fieldes and Weatherhead (1968)
(3) Goldschmidt (1958)
(4) Metson (1974)
(5) Salmon (1963)

Table 2

Magnesium accessions in rainwater (in kg Mg ha^{-1} yr^{-1}) estimated at various sites in New Zealand

Station	Location	Yearly average	Reference:
Ruakura	Hamilton	4.1	(1)
Wairakei	Taupo	3.6	(1)
Marton	———	3.4	(1)
Makara	Wellington	12.5	(1)
Broken River	Arthur's Pass	1.6	(1)
Winchmore	Canterbury Plains	1.5	(1)
Tara Hills	South Canterbury	1.1	(1)
Invesmay	Mosgiel	2.4	(1)
Soil Bureau	Taita	11.2	(2)
Soil Bureau	Taita	8.4	(3)
Soil Bureau	Taita	4.7	(4)

(1) D. M. Cooper, pers. comm. (1961-63 yearly average).

(2) Miller, R. B. (1961) The chemical composition of rainwater at Taita, (N.Z.). New Zealand Journal of Science 4: 844-53. (1956-58 yearly average).

(3) Blakemore, L. C. (1973). Element accessions in rainwater at Taita (N.Z.). New Zealand Soil Bureau Scientific Report 17: 16 pp. (1963-71 yearly average).

(4) Claridge, G.G.C. (1975). Element accessions in rainwater, catchment 4, Taita Experimental Station, 1969-74. New Zealand Soil Bureau Scientific Report 24: 56 pp.

and are soft and easily weathered (Kodama and Schnitzer, 1973). The vermiculites are similar to the chlorites but in place of the brucite layer is a layer of water and Ca and Mg ions. The Mg ions predominate and the water is in stable hexagonal closely packed layers around Mg^{2+} ions (Peterson et. al., 1965).

(b) Cyclic Salts.

In addition to primary mineral sources, cyclic salts originating from sea water and contributed in rainfall, are often an important source of Mg for soils. The amounts of Mg in rainfall accessions vary according to the proximity to the ocean and the direction of the prevailing winds (Table 2). Although Winchmore, Tara Hills, and Invermay are all located closer to the coast than Wairakei or Rukuhia, the prevailing winds at the former sites tend to be from an inland direction thus resulting in smaller additions of Mg by rainfall. It appears that coastal areas or elevated inland areas exposed to winds coming directly off the ocean may receive rainfall accessions of up to 10 Kg Mg $ha^{-1}yr^{-1}$ or more; for example, an area at Akatarawa, near Wellington, New Zealand, received average accessions of 13.4 kg Mg $ha^{-1}yr^{-1}$ (Miller, 1953). Data from other sources indicates a range of accessions from 0.28 - 34 kg Mg $ha^{-1}yr^{-1}$ (Salmon, 1963; Armitage and Low, 1970).

2.1.3 Transformations of Mg-bearing minerals in soils.

The transformation of primary minerals to secondary forms is thought to occur either as a result of structural decomposition of the mineral followed by the re-synthesis of residual products into secondary minerals or by substitutional changes in the chemical composition of a primary mineral but with concomitant preservation of the original structure of the mineral (Fieldes and Swindale, 1954). The two types of transformation are shown overleaf.

1. Olivines, Pyroxenes, Amphiboles, Feldspas, Glasses $\rightarrow$ Amorphous gels $\rightarrow$ 1:1 layer silicates upon recombination and recrystalization of alumina and silica; e.g. serpentine, talc, kaolinites. Mg may be lost via leaching.

2. Hornblende, Micas $\rightarrow$ Chlorites (2:2 silicates) $\xrightarrow[+H^+]{-Mg^{2+}}$ Vermiculites - 2:1 layer clays in which the brucite layer of chlorite has been lost. May be able to retain Mg from leaching solutions.

Olivines, pyroxenes and amphiboles undergo dissolution to form amorphous hydrons oxides which then re-crystallize with silica to form the hydrosilicate Serpentine which has a 1:1 kaolin type structute (Fieldes and Swindale, 1954). The feldspars and volcanic glasses weather to form amorphous clay minerals (allophane) or kaolin - type 1:1 clay minerals such as halloysite (Fieldes and Swindale, 1954).

As neither allophane nor halloysite contain appreciable amounts of Mg, the Mg content of the weathered glasses is either held at the exchange sites of the clay minerals, incorporated into the structure of other secondary minerals, or lost from the soil by leaching.

The first weathering stage for micas involves the loss of potassium followed by oxidation of octahedral iron and substitution of hydroxyl ions for oxygen. At the same time, Mg and Fe may be lost from octahedral positions (Wilson, 1975). Mg-rich micas may weather to form chlorites, which effectively conserves Mg in the soil system (Stephen, 1952), within the brucite layer of the chlorites. Vermiculite can form as the end result of the continued removal of Mg from both octahedral and interlayer sites (Barshad, 1960 a, b; Barshad and Foscolos, 1970; Kodama and Schnitzer, 1973). Vermiculite, which has a stable water and Mg^{2+} layer replacing the brucite layer of chlorites (Peterson et. al, 1965) is able to retain Mg from leaching solutions in preference to Ca and possibly Na (Peterson loc.cit.; Stephen, 1952).

The loss of Mg from other Mg-bearing primary and secondary minerals also occurs under acidic conditions. A large proportion of the Mg contained in olivines can be released in the presence of an acidic clay, whereas talc and hornblende release smaller proportions (Longstaff and Graham, 1951; Stahlberg, 1959, 1960). Mg may also be released from interlayer and octahedral sites of expanding clay minerals (Rice and Kamprath, 1968; Christenson and Doll, 1973).

With time, a large proportion of the Mg content of soil forming minerals is lost from the soil in leaching waters. The Mg content entering the sedimentation cycle may be re-precipitated as the carbonate minerals, magnesite or dolomite, or may finally reach the ocean as soluble Mg^{2+} (Goldschmidt, 1958).

2.1.4 Forms and Amounts of Mg in Soils.

Although Mg is present in all the soil separates (silt, sand and clay) (Kaila and Ryti, 1968) it has been shown that compared on a per-unit weight basis, the soil clay fraction can contain up to 95% of the total soil Mg (Mokwunye and Melsted, 1973b; Rice and Kamprath, 1968; Christenson and Doll, 1973; Protz and Riecken, 1968; Salmon, 1963). An increase in soil Mg content with increasing amounts of 2:1 layer lattice clays has been noted (Mokwunye and Melsted, loc. cit; Rice and Kamprath, loc.cit). The 2:1 clay minerals contain Mg either in octahedral positions (biotite and chlorite), in interlayer positions (vermiculite) or as a substitute for Al in lattice positions (illite and montmorillonite). With increasing weathering, many of these clay minerals degrade to form 1:1 clay minerals (kaolinite, halloysite), or secondary silica, of low Mg content (Fieldes and Weatherhead, 1968). Exceptions include soils formed on andesitic or basaltic parent materials containing unweathered reserves of ferromagnesian minerals (Metson and Brooks, 1975) or where conditions of impeded drainage have resulted in retention of Mg (Alston, 1972; Metson and Brooks, 1975).

Soil clays also retain Mg as exchangeable cations. The relative importance of exchangeable or structural Mg varies with soil types. Where large amounts of 2:1 clays are present, the amount of Mg present as a structural component is generally much greater than the Mg existing at cation exchange sites (Metson and Brooks, 1975). Soils such as yellow-brown loams derived from andesitic ash (Fieldes, 1968) may contain abundant Mg initially but can lose Mg relatively rapidly during the weathering process as the dominant allophane and halloysite clay constituents do not retain Mg as a structural component (Burrell and Fieldes, 1968; Metson and Brooks, 1975). The effect of weathering on Mg contents of volcanic soils has been investigated in comparative studies of exchangeable and boiling acid - extractable (Reserve) Mg contents in mature and immature Northern Red and Brown Loams and Northern and Central brown granular loams and clays (Table 3) derived from basaltic and andesitic parent materials, respectively. The immature members of both soil series contain far greater exchangeable and reserve Mg contents than the mature soils, which have lost Mg as a result of extended weathering (Metson and Brooks, 1975).

The sequence by which Mg is first transformed from primary mineral forms to secondary mineral forms and then lost from the soil can be expressed in terms of the forms and amounts of Mg in soils at different weathering stages. In this discussion, the following categories of soil Mg are referred to and defined as:

Total Mg - Mg extracted from a soil with a mixture of strong acids; includes all primary and secondary mineral Mg, Mg held on exchange sites and in interlayer spaces, and any organic Mg.

Reserve Mg - Mg extracted from a soil by hot or boiling dilute acids - often 1.0N HCl or HNO_3 (Stahlberg, 1960; Kaila and Ryti, 1968; Metson, 1968; Metson and Brooks, 1975). Considered to be Mg in finely-divided primary minerals susceptible to acid attack and Mg able to be displaced from octahedral and interlayer sites (Barshad, 1960 a,b).

Exchangeable Mg - Mg extracted from a soil by a salt solution,

Table 3

Exchangeable and Reserve Mg contents of Northern red and brown loams and Northern and Central brown granular clays.

Soil Group	Horizon	Exchangeable Mg	Reserve Mg
		m.e.%	
Immature N/R & B L	Topsoil	7.48 ± 5.88	24.5 ± 27.0
Immature N/R & B L	Subsoil	3.64 ± 3.08	13.0 ± 4.7
Mature N/R & B L	Topsoil	1.17 ± 0.51	1.3 ± 0.8
Mature N/R & B L	Subsoil	0.77 ± 0.49	0.8 ± 0.6
Immature N/C BGC	Topsoil	12.33 ± 1.03	63.3 ± 33.0
Immature N/C BGC	Subsoil	17.70 ± 4.00	95.0 ± 47.5
Mature N/C BGC	Topsoil	2.82 ± 1.14	1.8 ± 1.0
Mature N/C BGC	Subsoil	0.78 ± 0.45	2.1 ± 1.3

N / R & B L - Northern red and brown loams
N / C B G G - Northern and Central brown granular clays.
Source: - Metson and Brooks (1975)

> commonly either a dilute Ca salt (0.05 - 0.01 N) or an ammonium salt (IN) buffered at pH7. Dilute acids (0.01 N) are sometimes used. Includes Mg held at exchange sites and able to be displaced by the cations in the extractant, and also includes any water-soluble Mg or Mg held at organic exchange sites.

The amount of Mg held at organic exchange sites is unknown but is thought to constitute a large proportion of the total amount associated with the exchangeable fraction (Mokwunye and Melsted, 1972). True organic-complexed Mg is generally only present in small amounts (Mokwunye and Melsted, loc.cit).

Immature, or recent soils are characterised by the similarity of total Mg contents through the profile. The soil Mg content is primarily determined by the Mg content of the parent material, as shown in Table 4. These soils contain most of the minerals inherited from the parent material even if such minerals are easily weatherable (Fieldes and Weatherhead, 1968). The contents of reserve and exchangeable Mg have been shown (Metson and Brooks, 1975) to vary markedly between recent soil types presumably reflecting the ease with which the minerals present are weathered, and the Mg contents of these minerals. Therefore, recent soils from andestic ash may contain less reserve and exchangeable Mg than soils derived from hydothermally altered rhyolite, which although it initially contained less Mg, was more easily weathered.

Older soils show a different distribution of Mg in the various forms. Most of the Mg-bearing primary minerals are decomposed, except for larger sized particles, or the more resistant minerals, particularly if high pH conditions exist in a region of low leaching intensity. Thus biotite may persist for long periods in sands of pH > 6 (Fieldes and Weatherhead, 1968). Where 2:1 clay minerals have formed, Mg will have been incorporated into the clay mineral structures. Such soils are characterized by high reserve Mg levels (Metson and Brooks, 1975) when compared to soils formed on Mg-rich

Table 4 Total Mg contents in the various horizons of some recent New Zealand soils

Barrhill fine sandy loam (Southern recent on accumulating loess).		Ngauruhoe sand (Central recent, from andesitic ash).		Selwyn sandy loam (Weakly-leached southern recent).		Rotomahana sandy loam (Central recent, from andesitic ash).	
Horizon	Total Mg (%)	Horizon	Total Mg (%)	Horizon	Total Mg (%)	Horizon	Total Mg (%)
A_{11}	0.7	$A_{12}C$	4	A_{11}	0.6	A_1	1
A_{12}	1.1	C	4	A_{12}	0.65	C	1.2
(B)	1.1	IuC	4.5	C_{11}	0.7		
C_{11}	1			uA	0.8		

volcanic parent materials, which contain amorphous clays. Soils of high reserve Mg content are better able to replenish losses of Mg from exchange sites. The effects of more advanced weathering of topsoils with respect to subsoil horizons is typically reflected in the lower total Mg contents of the topsoil. Weathering and nutrient recycling effects generally result in higher exchangeable Mg contents in the topsoil than in the subsoil (Metson and Brooks, 1975).

The proportion of Mg in the total exchangeable bases generally increases with soil age. As Mg^{2+} is displaced from exchange sites by H^+ originating from rainwater or organic matter breakdown and brought into the soil in the leaching solution, it is able to be replenished from octahedral and interlayer positions in soil minerals (Barshad, 1960a; Barshad and Foscolas, 1970; Longstaff and Graham, 1951; Stephen, 1952a,b; Stahlberg, 1960). Other soil exchangeable cations especially Ca^{2+} and Na^+, are not commonly incorporated into secondary mineral structures, and once released (from primary minerals) are retained on exchange sites in the soil. Hence, leaching losses of these exchangeable cations may not be able to be replaced.

The relationship between pH and soil Mg levels is quite distinct and is also related to the stage of profile development, soil pH generally decreasing as soils age, and the base saturation, decreases under the influence of leaching (Wiklander, 1974). Low pH (older) soils tend to have low total Mg levels in the topsoil, while high pH younger or poorly drained soils have higher total Mg levels. The proportion of total Mg present as exchangeable Mg is greater in the low pH soils, possibly reflecting the effect of replacement of Mg by H^+ in the soil minerals resulting in the displacement of Mg and release on to exchange sites (table 5).

Once soils have reached the mature stage, they generally contain clays of 1:1 or amorphous structure, and/or iron oxides (Fieldes and Weatherhead, 1968). Most of the Mg present resides

Table 5: Topsoil (A Horizon) exchangeable and total Mg contents and pH of some New Zealand soils.

Soil type	Exch. Mg m.e.%	Total Mg %	pH
Okanto peaty loam	1.5	0.1	4.1
Tautuku silt loam	3.5	0.2	4.1
Wharekohe silt	2.3	0.08	4.3
Kaingaroa loamy sand	0.27	1.0	4.0
Patua loam	2.0	1.0	4.4
Otanomomo peat	14.8	0.3	4.3
Mean	4.06	0.5	4.2*
Manorburn sandy loam	2.2	0.3	6.2
Waikakahi clay loam	2.4	1.4	6.6
Waiareka clay	21.1	2.5	6.4
Ahuriri clay loam	5.6	0.9	7.0
Selwyn sandy loam	1.2	0.6	6.0
Mean	6.5	1.1	6.4**
Mean of 54 soils	-	0.8	5.5

* 9.9% of total Mg = exchangeable Mg

** 7.2% of total Mg = exchangeable Mg

in mineral forms which are not readily weathered (Mokwunye and Melsted, 1972). Mature soils generally contain smaller amounts of reserve, exchangeable and total Mg, and lower reserve and total, although not necessarily exchangeable Mg contents, than immature soils. In general, mature soils are depleted of most bases - Ca, K, Na, as well as Mg (Wells, 1968).

Under acid conditions, especially where low-fertility demanding plant species are present, organic matter breakdown is slow and a mor-type humus layer may form (Taylor and Pohlen, 1968). This results in a considerable accumulation of Mg in humus horizons above the topsoil. Thus weathering processes, soil erosion and movement of soil colloidal particles down the profile (Mokwunye and Melsted, 1973b) result in the depletion of Mg levels in the topsoils of highly weathered mature soils. This trend may be partly arrested by the action of plants in cycling some of the Mg back into the topsoil layer in the plant litter.

Published data on the Mg status of 5 soils formed on andesitic ash in Taranaki, including exchangeable reserve, and where available, total Mg contents are listed in Table 6. The topsoil exchangeable Mg contents are evidence for the effects of both the more advanced stage of weathering of the topsoils and, particularly in the case of Patua loam, the effects of nutrient cycling, as the subsoil of Patua loam has very low levels of exchangeable Mg. Reserve Mg contents of the recent soils probably reflect differences in composition of the parent materials (Metson and Brooks, 1975). Despite the appreciable contents of ferromagnesian minerals in the sand fraction of the yellow-brown loams, the reserve Mg contents are all low, as the clays probably do not contribute to the release of non-exchangeable Mg (Metson and Brooks, 1975). The decrease in the reserve Mg contents of both topsoils and subsoils of these yellow-brown loams is accompanied by the loss of some readily weathered ferromagnesian minerals particularly andesine (intermediate feldspars), volcanic glasses, biotite and hornblende from the sand fraction, which also decreases in abundance

Table 6: Exchangeable, reserve, and total magnesium contents (in m.e.%) of soils formed from andesitic volcanic ash in Taranaki

Soil Type	Classification	Exch. Mg		Reserve Mg		Total Mg		Mg as % CEC	
		T	S	T	S	T	S	T	S
Burrell gravelly sand(1)	Recent soil on Burrell andesitic ash	0.9	0.4	4.2					
Burrell gravelly sand(1)	Recent soil on Newall andesitic ash	1.1	1.6	1.5	4.7				
Stratford coarse sandy loam(2)	Moderately leached Central yellow-brown loam	1.4	0.9	4.9	4.3	82	82	5.0	4.0
Egmont black loam(2)	Moderately leached Central yellow-brown loam	5.4	3.9	4.9	-	74	148	15	13
Patua loam(2)	Very strongly leached Central yellow-brown loam	2.0	0.2	3.9	1.2	82	123	4.0	0.4

T - topsoil ; S - Subsoil

References: (1) Metson and Brooks (1975)

(2) New Zealand Soil Bureau (1968)

Table 7: Frequency of occurrence of fesromagnesian minerals in the sand fraction of Central yellow-brown loams from Taranaki

Minerals	Stratford coarse sandy loam		Egmont black loam		Patua loam	
	Topsoil	Subsoil	Topsoil	Subsoil	Topsoil	Subsoil
Sand % of soil	47	55	37	51	38	36
Feldspars (andesine)	A	a	A	A	a	A
Glass	A/s	A/s	a/S	c/c	C/c	C/c
Micas: Biotite	R	R	R	R	-	R
Muscovite	-	-	R	R	-	-
Hornblende A	-	-	C	C	S	C
Hornblende B	C	C	S	S	C	S
Augite	C	C	a	a	a	a
Hypersthene	R	R	s	R	-	S

with increased weathering (Table 7).

Total Mg contents in topsoils and subsoils show evidence for the effects of differential weathering of the different horizons in the representative Taranaki soils. Total Mg contents in the Stratford coarse sandy loam are the same in both topsoil and subsoil; with increasing weathering, total Mg contents in the topsoils are less than those in the subsoils on the Egmont and Patua loams (Table 6).

In the 5 representative soils Mg saturation of C.E.C. in topsoils and subsoils parallel the amount of exchangeable Mg present in the respective horizons, showing the effects of increased leaching. As the rate of leaching increases, so Mg is lost from exchange sites, and because of the nature of the soil clays, which are mainly allophane and hydrous feldspars (N.Z. Soil Bureau, 1968), there is insufficient reserve Mg available to replace these losses.

The soils from Taranaki are examples of soils formed from minerals that weather into amorphous secondary minerals (as described by Fieldes and Swindale, 1954) for which Mg content changes with increasing weathering in the following way:

i) Exchangeable Mg contents first increase and later, under the influence of increased leaching, decrease, particularly in the subsoil. Nutrient cycling may only partly counter this trend in topsoils.

ii) Reserve Mg contents decrease as the readily weatherable Mg-containing minerals are decomposed.

iii) The total Mg content of the topsoil decreases with respect to that of the subsoil.

iv) The Mg saturation of the CEC in the subsoil decreases relative to that in the topsoil.

2.1.5 Losses of Mg From soils.

a. As a result of leaching.

The replaceability of Mg with other cations is intermediate between K and Ca: $Na^{+} > K^{+} > Mg^{2+} > Ca^{2+}$ (Wiklander, 1974); Kurtz and Melsted, 1973). The rate of loss of Mg from the soil is governed not only by the ease of replacement of Mg by other cations, but also by several other factors, including:

i) Rainfall and Infiltration rate. Under high rainfall, especially when frequent heavy falls occur, the rate of leaching of Mg may initially be high from juvenile soils. Older soils have generally become impoverished of Mg under such a regime, and so the rate of leaching of Mg may be slow. High rainfall intensities tend to lead to rapid percolation of the leaching solution through well-drained soils, so that an equilibrium is not established between the soil and the solution (Wiklander, 1974). Accordingly, the Mg concentration in the leachate tends to decrease as rainfall intensity increases. In less well-drained soils, the percolation rate tends to remain relatively constant over a wide range of rainfall intensities and hence the Mg concentration in the leachate does not vary as widely as in well-drained soils. Also, coarse textured soils, besides being well-drained, usually have a lower CEC and exchangeable Mg contents than their finer-textured counterparts; thus the amounts of Mg lost from coarser-textured soils are usually less than those from finer textured soils due to differences in both drainage rates and exchangeable Mg present contents.

ii) Amount of Mg present in the soil. Under a constant leaching regime, the amounts of Mg leached from the soil will vary in proportion to the amounts of exchangeable Mg present in the soil. (Salmon, 1963; Kurtz and Melsted, 1973). All soils under a leaching regime, will tend to lose Mg (Wiklander, 1974); the rate of loss of Mg being partly determined by the capacity of the soil to buffer these losses. The importance of readily-weathered reserves of Mg in the soil lies in their ability to buffer leaching losses of exchangeable Mg (Stephen, 1952; Wilson, 1975).

iii) Composition of the Leaching Solution.

As the salt concentration of a leaching solution increases there is a greater tendency for the displacement of cations from the exchange complex of a soil by the process of ion exchange. The presence of Ca^{+2}, K^{+}, or NH_4^{+} in percolating solutions as a result of fertiliser applications or passage through upper horizons of higher content of these elements results in the displacement of Mg from soil exchange sites (Dixon and Taylor, 1942; Hogg, 1960, 1962; Kurtz and Melsted, 1973; Wiklander, 1974).

The presence of mobile anions tends to increase the displacement of Mg by cations in the soil solution. Thus application of chloride or nitrate salts to the soil can result in greater losses of Mg than application of bicarbonate, carbonate or phosphate salts (Hogg, 1962; Pratt and Harding, 1957). Nitrogenous fertilisers may therefore cause leaching losses of Mg by direct displacement of Mg from the exchange sites (NH_4^{+} -salts) or by providing ultimately, a mobile anion to the leaching solution (NO^{-}_{3}) Urea tends to be less effective than ammoniacal or nitrate salts in removing Mg from the soil (Pratt and Harding, loc. cit) probably because of the slower release of NH_4^{+} and NO^{-}_{3} from this fertiliser compared to that from the nitrate or ammonium salts.

Accelerated Mg loss resulting from urine applications (adding K^{+} and NH_4^{+} to the soil) was described by Hogg (1968). The loss of Mg from beneath dung patches was noted by During et al, (1973) who found that the under dung patches Mg was more susceptible to displacement by KCl fertilisers than that in the surrounding areas. Losses of Mg of up to 15 kg $ha^{-1} yr^{-1}$ were cited by Dixon and Taylor (1942) as the result of application of superphosphate to soils in the Waikato (N.Z.) over a 20 year period.

iv) Organic cycling. Mg uptake by plants, and the subsequent deposition of litter at the soil surface may retard the

the loss of Mg from soils (Jacob, 1958; Miller, 1963; Low and Armitage, 1970).

b. Removal of soil material from the profile. Mg may be removed from the soil as a result of erosion on sloping sites. The losses of Mg due to this process are difficult to evaluate; Hanna (1959) estimated that on such sites, the losses of Mg due to erosion were equivalent to approximately one-half of the leaching losses. Similarly, the downward movement of soil clays, which may contain a large proportion of the soil Mg may proceed in a manner analagous to the leaching of nutrient ions (Kurtz and Melsted, 1973), resulting in the depletion of Mg contents in the topsoil. This is considered to be one of the ways by which mature soils have become depleted of Mg (Mokwunye and Melsted, 1973b).

c. Through removal by plants and animals.

The amounts of Mg removed from the soil in crops varies very widely depending upon the Mg content and yield of the particular crop. Various estimates of the amounts of Mg in crops range from 4.5 to 29 kg ha^{-1} yr^{-1} (Salmon, 1963); or 3-109 kg ha^{-1} yr^{-1} (Fried and Broeshart, 1967). The amount of Mg removed in a hay crop has been estimated at between 7 and 12 kg Mg ha^{-1} (During, 1972). The probable loss of Mg in milk from dairy farms is estimated at approximately 2 kg Mg ha^{-1} yr^{-1}. Transfer of Mg from the soil to unproductive areas (sheds, races etc.) in dung may account for another loss of approximately 3 kg Mg ha^{-1} yr^{-1}. (During, loc.cit.).

On sheep farms, the main loss of Mg from the soil probably results from the transfer of Mg in dung from grazing areas to stock camps which may amount to approximately 20% of the total turnover of Mg under a sheep pasture (i.e. 4-6 Kg Mg ha^{-1} yr^{-1} where annual pasture production is 11,000 kg. D.M. ha^{-1} yr^{-1} containing 0.2-0.3% Mg.) (During, loc. cit.).

2.2 Factors affecting Mg Uptake by Plants.

2.2.1 Introduction.

The uptake of Mg from the soil by plants is dependent upon the interaction of a number of soil and plant factors. These include

i. Soil Mg content;

ii. Mg supply processes of diffusion, mass-flow and root interception;

iii. Cation-anion balance;

iv. Efficiency of uptake and translocation of Mg by plants;

v. Environmental factors.

vi. Ion antagonisms.

2.2.2 Soil Mg Content and Mg Availability to Plants.

Measurement of the activity of Mg or its concentration, in the soil solution, and especially indices which allow for the competitive effects of other cations (Ca^{2+}, K^+, H_3O^+) on Mg uptake, have generally been found to be the most successful for predicting the amounts of soil Mg available to plants (Salmon, 1964; Alston, 1972). These measurements are intensity measurements, however, and give no indication of the long-term Mg supplying power of a soil.

Measurements of the amounts of various categories of soil Mg including total Mg, acid-soluble Mg, and exchangeable Mg contents, have tended to be less successful in predicting the amounts of Mg taken up by plants due to the indirect relationship between these categories of Mg and the amounts present in the soil solution. These measurements are useful for identifying soils where Mg availability may be marginal. For example, soils with low total Mg contents are unlikely to contain large amounts of dilute acid-soluble or exchangeable Mg (Metson, 1974) and the potential of such soils to maintain an adequate supply of Mg for plant needs would be low. Similarly, soils with low levels of acid-soluble ("reserve") Mg are unlikely to be able to maintain adequate amounts of plant available Mg over the long term, (Metson and Brooks, 1975; Metson, 1974, 1968), as it is from this pool of soil Mg that losses of exchangeable Mg, by leaching or plant uptake, are replenished. However, as direct indicators of the amounts of Mg available to plants over a single growing season, measurements of reserve Mg are of limited use. Some investigators (Rice and Kamprath, 1968; Christenson and Doll, 1973; Kidson et al., 1975) have found releases of non-exchangeable Mg to plants over a period of months, but generally these releases have occurred only when soil reserve Mg levels were high (>15 m.e.%) due to the presence of unweathered ferromagnesian minerals or 2:1 and 2:2 layer clay minerals. It seems likely that in most situations the release of non-exchangeable Mg over a single growing season is too small to have any appreciable effect on the amounts of Mg available to plants (Salmon and Arnold, 1963).

Soil exchangeable Mg contents are directly related to, and in equilibrium with, the amounts of Mg present in the soil solution (Shone, 1967). Unfortunately, this relationship appears to be unique for different soil types, and depends upon a number of factors including soil CEC, amounts of Ca, K and other exchangeable cations present, and soil moisture content (Arnold, 1967), Thus as general predictors of the amounts of plant available Mg present in the soil, or the amounts needed for adequate plant nutrition, exchangeable Mg determinations have had limited success, as evidenced from reports by McNaught et al (1973 a); Salmon (1964) and Alston (1972). When individual soils and crops are considered, the utility of exchangeable Mg as a predictor of the amounts of plant available Mg improves (e.g. McNaught et al., 1973 b).

Attempts to improve the efficiency of exchangeable Mg as a general predictor of plant available Mg have had limited success. For a given amount of exchangeable Mg the concentration of Mg in the soil solution tends to decrease with increasing soil CEC (Arnold, 1967). Thus the relative saturation of the soil cation exchange complex with Mg has been employed (Bear and Toth, 1948; Price et.al., 1947; Felbeck, 1959) as an index of available soil Mg with a minimum value of 10% saturation proposed as an adequate supply of Mg for plants. Similarly, the use of other ratios such as exchangeable Mg/ exchangeable Ca, exchangeable Mg/ exchangeable K, exchangeable Mg/TEB have been advocated to allow for possible antagonistic effects of other ions on plant Mg uptake (Hooper, 1967; Hovland and Caldwell, 1960). Soil texture has also been used as an added criterion for relating the amounts of soil exchangeable Mg to plant requirements (Schachtsabel, 1954) with the amounts needed increasing for finer textured soils. This is in agreement with the concept of maintaining a constant Mg saturation of the soil CEC, as CEC generally also increases as soil texture becomes finer.

The data summarized by Metson (1974) indicate that on soils with low soil exchangeable contents, there is little difference in the amounts of exchangeable Mg extracted by a large range of neutral or weakly acidic extractants. Only where soils contain carbonates or easily-weathered Mg silicates do differences occur with dilute solutions of strong acids or salts buffered in the acid range extracting more Mg from such soils than dilute salts or weak acids.

With regard to the success of any of the above methods for a determination of the amounts of plant available Mg in a soil, Fried and Broeshart (1967) commented that the only reliable indicator in any given situation is the plants themselves. No single parameter is likely to be successful in defining the amounts of Mg available to plants in all soils (Metson, 1974). The use of ratios of exchangeable cations is subject to similar limitations, and as Felbeck (1959) pointed out, none of the ratios appear to be critical, and the values found can vary over wide ranges without necessarily affecting the health of the plants.

Perhaps the most comprehensive approach to the problem of determining amounts of plant available Mg in soils was suggested by Beckett (1972). This approach involves first characterising soil Quantity/Intensity relationships for the nutrient elements of concern; then, by considering the amounts of these elements likely to be withdrawn from the soil by the crop grown, probable changes in soil solution activity ratios over the course of the growing season could be calculated. If these activity ratios decreased below certain critical values which were tentatively established after a series of trials, then application of fertilisers would be indicated. For Mg, Beckett (loc. cit.) suggested that if a_{Mg}/a_{K} fell below a value of 50, then the application of Mg fertiliser would be likely to produce a crop response.

A summary of the findings of these various reports is given in Table 8 overleaf.

Table 8: Tabulated values of minimum required exchangeable and reserve Mg contents of soils quoted in the literature

a) Exchangeable Mg

i) A kg Mg ha^{-1}	Extractant	Comments	Reference
17-23	0.05N HCl	Horticultural crops	Prince (1941)
112	not indicated	Arable cropping	Felbeck (1959) citing Hester et al, (1947)
23-68	not indicated	Annual requirement for arable crops	Beeson (1959)
112	Georgia soil test procedures	Arable crops will respond to Mg additions below this soil content	Gallaher et al, (1975)
56	Dilute acids	Maize will respond to Mg additions when soil Mg content less than indicated level.	Hall and Hegwood (1975)
ii) As mg Mg per 100g soil			
3-5	IN NH_4OAc pH 7	Pasture plants	Reith (1964, 1967)
20	IN NH_4OAc pH 7	Provision of adequate Mg in pasture for animal health	Reith (1964)

Table 8 (Cont..)

a) Exchangeable Mg	Extractant	Comments	Reference
0.17	IN NH_4OAc pH 7	For clovers on pumice soil	Dorofaeff and McNaught (1962); data recalculated by Harrod and Caldwell (1967).
iii) As m.e.% Mg			
0.3	Not indicated	Agricultural and cropping soils	Welte and Werner (1963)
0.3	IN NH_4OAc pH 7	Agricultural and cropping soils	Metson (1968)
0.4)	IN NH_4OAc pH 7	Agricultural use of light	Schachtsabel (1954)
0.6)		medium	
1.0)		heavy textured soils	
0.15	IN NH_4OAc pH 7	For satisfactory clover growth on pumice soils.	Dorofaeff and McNaught (1962)
1.0	IN NH_4OAc pH 7	Pasture responses unlikely on medium-heavy textured soils	McNaught et al, (1968 a, b)

Table 8 (Cont..)

b) Acid-soluble ("reserve") Mg	Extractant		Comments	References
30 m.e.%	Boiling in HCI for 15 minutes	Very high	Soils with low or very low contents of reserve Mg likely to become Mg-deficient in near future	Meson and Brooks (1975)
15-30		High		
7-15		Medium		
3-7		Low		
3		Very Low		
5.0 m.e.%	Boiling 1N HCl, one hour	Minimum level for pasture requirements		Mayland and Grunes (1975) citing Broek and Van der Marel (1959)

2.2.3 Movement of Mg through the Soil to Plant Roots

There are three processes by which Mg may be brought into contact with plant roots for possible uptake:

Root interception,
Mass flow,
Diffusion (Corey, 1973).

Root Interception results from the occupation by growing roots of space formerly occupied by soil particles, which may hold nutrients adsorbed to their surfaces. As a result, the roots may take up some of these adsorbed nutrients. In a trial with corn on a well fertilised silt loam at pH6.8, 16 kg Mg ha^{-1} was considered to be made available to the crop by this process (Barber, 1966, cited in Corey, 1973).

Mass flow is the movement of Mg in solution in and with the soil water. Water movement in the soil occurs as a result of rainfall, water uptake by plants, or upward capilliary movement (Sutcliffe, 1967). The major factors which determine the amounts of Mg present in the soil solution have already been discussed in Section 1.1.4 (leaching of Mg) and include soil exchangeable Mg content, CEC, pH, amounts of other anions and cations in solution, soil texture and soil moisture content.

Water and nutrient uptake by roots are two separate processes; mass flow serves only to bring nutrients into close proximity with plant roots (Sutcliffe, loc.cit.). Nutrient uptake depends upon the state of the plant and its demands for nutrients, so that all of the Mg brought to the root surface may not necessarily be taken up. In some cases, when supply exceeds demand, it is possible to find an accumulation of Mg occurring at the root/soil interface (Fried and Broeshart, 1967).

Generally, mass flow is thought to be capable of providing adequate Mg for plant requirements throughout the growing season (Barber et.al., 1962; Fried and Broeshart, 1967; Corey, 1973).

The amounts of Mg moving by diffusion to the root surface are generally very small. This results from the low diffusion coefficient of Mg in the soil, e.g. the diffusion coefficient for Mg in a homionic soil was estimated to be 2.2x10^{-7} cm^{2} sec^{-1}, and in a heterionic soil, $1.0 \times 10^{-7} cm^2 sec^{-1}$ (Graham-Bryce, 1967), Thus the distances from which Mg can diffuse towards the root to satisfy plant requirements are very small being of the order of 10^{-4} to 10^{-6} cm (Fried and Broeshart, 1967), and the volume of soil (the Diffusion Volume) which can provide Mg via diffusion to plant roots is correspondingly small.

Diffusion and MassFlow are inter-related as the diffusion volume can be replenished by the influx of ions as a result of mass flow. A soil with a high content of exchangeable Mg may therefore supply Mg to the roots by diffusion for a longer period than a soil with a low exchangeable Mg content with the low Mg soil having to provide nutrients from a larger volume (via mass flow) to be able to meet plant needs.

The accessability of soil Mg to plants is also influenced by the type of root system present. The greater the penetration of the soil by plant roots, the shorter are the mean distances nutrients are required to travel to reach the plant root (Mengel, 1974). Plants with well-divided fibrous root systems are more likely to be able to extract sufficient Mg from a soil with low levels of plant available Mg than are those plants with less extensive root systems.

Thus, root interception may result in varying amounts of Mg being brought into contact with the root system for possible uptake, depending upon the type of crop and the amounts of adsorbed Mg contacted in this way. Mass flow usually provides the balance of plant Mg requirements throughout the growing season; only where soil Mg contents are low would diffusion play a significant role (Graham-Bryce, 1967).

2.2.4. Magnesium uptake by plants.

a. Uptake mechanisms and translocation of Mg.

The absorption of Mg by plant roots is an energy-requiring process (Brouwer, 1956; Sutcliffe, 1967; Hodges, 1973) probably involving a carrier mechanism to transport Mg^{2+} ions across the root-cell membrane (Epstein and Legget, 1954). The nature of the actual carrier has not been elucidated; however, work with phosphorylation uncouplers has suggested that the energy requirement for Mg uptake is provided by ATP (Sutcliffe, 1967; Hodges, 1973). Evidence for Mg uptake sites separate from those of other alkaline earth cations was found by Collander (1941) and Epstein and Legget (1954). However, in a recent review, Hodges (1973) presented evidence for a single carrier uptake mechanism for transporting cations across the root cell membrane with the relative amounts of different cations taken up being determined by their respective solution activities.

After absorption by roots, Mg is mobile within the plant, the proportions of total plant Mg in the different plant parts changing as the plant ages. The concentration of Mg in the roots exceeds that in the tops in seedling plants, but the situation is reversed as the plants mature (Brown, 1959). Mg may also be translocated from older to younger leaves (Gauch and Krauss, 1959), from vegetative to reproductive organs (Brown, 1959) or from stems and petioles into leaves (Sabbe and Mackenzie, 1973). The Mg concentration in pasture plants, particularly grasses, inceases as the plants mature (Grunes, 1973). An increase in the Mg content of grasses has commonly been observed over the late spring-autumn period (Grunes, 1973; McNaught et al, 1968a, 1973a; Mayland and Grunes, 1974, and Reith, 1963).

b. Plant Species Differences.

Plant species differ both in their requirements for Mg and in the relative efficiency with which Mg is taken up from the soil. Varietal differences in the efficiency with which Mg is absorbed from the soil and translocated within the plant have been found for a number of species including: sweetcorn (Clark, 1975); maize (Lutz et al, 1972); wheat (Ward et al, 1973); white clover (Snaydon and Bradshaw, 1969); and peanuts (Hallock et.al, 1971).

With regard to pasture species, Reith (1964) showed that perennial ryegrass (Lolium perenne), Cocksfoot (Dactylis glomerata) and Timothy (Phleum pratense) had similar requirements for Mg. Pasture grasses generally contained lower Mg concentrations in herbage than clovers (McNaught et al., 1968a; Rieth, 1963 , 1964). However, clovers are more sensitive to changes in soil Mg status, so that changes in the Mg content of mixed herbage in response to Mg fertiliser application are generally greater the higher the proportion of clover in the sward (Rieth, 1964). The magnitude of the seasonal changes in herbage Mg concentration is generally greater for grasses than for clover, so that by later summer, grasses and clover may both possess similar Mg concentrations (Rieth, 1964; McNaught et al.,1968(a); During, 1972).

Different grass species vary in their ability to extract Mg from the nonexchangeable pool of soil Mg. Ryegrass was unable to utilise nonexchangeable soil Mg during the course of a pot trial (Salmon and Arnold, 1963). Pangolagrass (Digitaria decumbens Stent), however, was found to be a very efficient user of Mg "fixed" in the clay fraction and it appears that most tropical grasses need very little Mg for optimal growth (Chesney, 1972).

c. Environmental Effects.

As plant Mg uptake is an energy-requiring process, it would be expected that Mg absorption would be affected by environmental conditions, particularly those of temperature, light, intensity and oxygen availability in the soil.

The relationship observed in many plant species between temperature and Mg uptake is related to the energy requirement for root Mg uptake; as temperature increases, so the rate of energy production is increased and plant roots become more efficient at absorbing Mg from the soil (Corey, 1973). Temperature dependence of the Mg concentration of ryegrass and other pasture species has been demonstrated in several experiments (Dijkshoorn and T'Hart, 1957 ; Hendricks and Grunes, 1966; Grunes et al., 1968; McNaught et al., 1968 a; Stuart et al., 1973). Herbage Mg content in these trials generally increased over the range 5 - 20°C. Similarly, increases in the concentrations of Mg in the grain of wheat (Labanauskas et.al., 1975) and other small grains (Ward et al, 1973) have been observed over the range 5-25°c.

As light intensity was decreased to about 25% of full daylight, Mg concentrations increased in the leaves of Crested wheatgrass (*Agropyron desertorum*), Basin Wildrye (*Elymus cinereus*) (Mayland and Grunes, 1974) and Coastal Bermudagrass (*Cynodon dactylon*) (Burton et al, 1959). This increase in leaf Mg content was thought to be the result of luxury consumption of Mg (Burton et.al., loc. cit.); i.e. total Mg uptake was reduced by the decrease in light intensity but not to the same extent as the decrease in total dry-matter production which also occurred. The findings of Deinum et al.(1968); and Hight et al.(1968) indicate that a similar phenominon occurs in Perennial Ryegrass, as, although herbage Mg concentration was not measured in these studies, total plant N, carbohydrate, and ash contents changed in a similar manner to those in the above studies. The results of McNaught et al (1968a) however, showed a positive correlation between incident radiation and Mg content of pasture grasses (mainly ryegrass).

As root respiration (and hence energy production) is dependent upon the presence of adequate oxygen in the soil atmosphere, it would be expected that Mg uptake by plant roots would be sensitive to soil aeration status (Corey, 1973). However, Mg uptake by barley did not appear to be affected by the soil aeration state (Ward et al, 1973), and in another study, Labanauskas et.al. (1975) showed that while the concentration of Mg in wheat grain was unaffected by soil aeration, Mg uptake was reduced, due to a reduction in wheat yield, by saturating the soil atmosphere with nitrogen.

d. Antagonisms.

i. K/Mg

The antagonism between the plant uptake of K and Mg has been long recognised. The first indications of this antagonism were found on acid sandy soils when application of K fertiliser resulted in the appearance of Mg deficiency symptoms in crops. Since then, the K/Mg antagonism has been recognised in a large number of crops, including some grown on soils with apparently adequate levels of exchangeable Mg (Metson, 1974). The K/Mg antagonism may not necessarily result in Mg deficiency but the application of K fertilizer may result in a depression of plant Mg content and, in some cases, crop yield.

In coarse textured soils K addition, whether as a fertiliser or in animal urine, may result in the displacement of Mg from the exchange complex with possible loss of Mg by leaching (Hogg, 1960,61,68; Welte and Werner, 1963; During et al., 1973). In this way, the availability of Mg would appear to have been reduced as a result of K fertiliser application. Such an effect may have occurred in an experiement by McNaught et al.(1968) on Whakarewarewa Sandy loam, where K fertiliser applications reduced herbage Mg concentrations only in the last 2 years of a 4-year trial. The application of K was also found to reduce the availability of Mg (expressed as $\frac{1}{2}$pMg-pK in soil saturation extracts) by Hovland and Caldwell (1960) as plant Mg concentrations also decreased.

Besides such "apparent" reductions in the availability of Mg, increasing K concentration in the soil solution can also directly reduce Mg uptake by plants. Salmon (1964) and Alston (1972) suggested that the antagonism between K and Mg was a mutual one for which concentration in the herbage was strongly correlated with the soil solution activity ratio $\sqrt{a_{Mg}} / \sqrt{a_{Ca} + a_{Mg} + Ba_{K}}$. Similarly, Prince (1951); Hansen (1972); and Fageria (1974) considered that the relative uptakes of Mg and K by plants were proportional to the ratios of their activities in the soil solution.

A K/Mg antagonism may be accentuated by the addition of nitrate to the soil which may result in an increased anion uptake by plants. Where adequate soil K is present, the anion uptake increase may be balanced by an increased uptake of K^+, as K^+ is more mobile in the soil than Mg^{2+} or Ca^{2+} (Dijkshoorn, 1957).

During the early spring period, when soil moisture content is higher than in late spring-summer, the K/Mg activity ratio will be higher in the soil solution than later in the season due to the greater relative desorption of monovalent cations and adsorption of divalent cations at the higher soil moisture contents (Schuffelin and Koenigs, 1962). Application of K fertiliser to the soil under these circumstances could further aggravate a situation in which the balance between plant K and Mg uptake may be already predisposed towards a low Mg content of pasture. McNaught (1964) observed that K fertiliser applications in spring could result in major depressions of herbage Mg content. The change from set stocking to rotational grazing on dairy and beef farms at the time of the spring flush of pasture growth could also contribute to the lowering of plant Mg contents at this time, due to a high rate of K^+ return in urine (Metson, 1974). When the combination of such effects occurs - high K/Mg ratio due to high soil moisture content, spring application of potassic fertilisers, high return of K^+ in urine, and a possible further decrease in the amounts of K^+ and Mg^{2+} taken up due to conversion of NH_4^+ to NO_3, for soils with marginal or low exchangeable Mg contents, it follows that significant major depressions in pasture Mg content could be expected.

The effect of the K/Mg antagonism is greater for grasses than for clovers (Reith, 1963, 64, 67; McNaught et al., 1973(a)). This may also to accentuate the effect of spring application of K fertilisers on pasture Mg content as pastures are generally grass dominant early in the growing season. It has also been noted that pasture Mg contents are decreased more in situations where K fertiliser is applied to correct a K deficiency than when applied to a soil of adequate K status. Where K fertilisers are required to be applied to achieve an increase in plant yield, then Mg should also be applied to offset the possible depressions in herbage Mg content (Welte and Werner, 1963).

It has been suggested that K/Mg antagonisms in pastures are probably only significant in situations where K fertilisers are applied in amounts in excess of plant requirements especially in early spring. Likewise, it is recommended that K fertilisers should not be withheld to avoid a possible K/Mg antagonism with consequent deleterious effects on stock health. Rather, the application of sufficient K to maintain pasture yields should be regarded as desirable (During, 1972) and where the possibility for serious reductions in herbage Mg exists, as for soils with low exchangeable Mg contents or a low Mg/K ratio (Mg/K 1.2; Hooper, 1967) then Mg fertilisers should be applied along with the K fertilisers.

ii. Ca/Mg.

Excessive calcium supply can compete with Mg for plant uptake in a similar manner to that found for potassium. However, reports of Ca/Mg antagonisms in the literature are not common (Metson, 1974).

The results of trials using soybeans and corn (Key et al., 1962) and German millet and alfalfa (McLean and Carbonell, 1972) grown on soils at different exchangeable Ca:Mg ratios suggested that the concentration and Mg in the herbage was dependent upon the amounts of exchangeable Ca or Mg present; as these two elements were varied simultaneously, it is difficult to ascribe changes in herbage Ca and Mg to a Ca/Mg antagonism. Key et al.(loc. cit) found that yields of soybeans and corn were not affected by the Ca:Mg ratio on the exchange complex provided Ca:Mg 1 and sufficient amounts of both Ca and Mg were present.

Indications of competitive effects of Ca on Mg uptake were found by Salmon (1964) and Alston (1972) who showed that, at a constant soil K content, ryegrass Mg concentrations in herbage were linearly related to the soil solution activity ratio $\sqrt{a_{Mg}} / \sqrt{a_{Mg+Ca}}$. Depressions in herbage Mg content as a result of Ca application, or vice-versa, in pasture have been reported by McNaught (1964); McNaught et al.(1973 b) and Mayland et al (1975).

Soil pH may enter into the interaction of Ca on plant Mg uptake. Thus Christenson et al.(1973) found that addition of lime resulted in both a soil pH increase and an increase in Mg uptake by oats whereas $CaSO_4$ application produced little change in either soil pH or Mg content and uptake. At high pH (6.8) and high soil Mg contents, addition of Ca depressed the Mg content of young corn seedlings (Hall and Hegwood, 1975) yet at lower soil Mg contents, at both high and low pH's, Ca application did not affect Mg contents. It thus appears that soil pH may influence the interaction between Ca and Mg, as well as the relative levels of Ca and Mg in the soil. Metson, 1974, summed up the Ca/Mg antagonism by observing that "..at high pH values (say >7.0) and at high levels of base saturation (say >90%) the probability of Mg deficiency at low levels of exchangeable Mg is higher than it would be at a lower level of pH or base saturation."

iii. N/Mg.

The interaction between N and Mg may occur either as the result of an enhancement of Mg uptake by NO_3^- - N or an antagonism by NH_4^+-N. As previously discussed, the effect of NO_3^- -N on Mg uptake may be influenced by the relative amounts of different cations present in the soil; addition of NO_3-N to the soil resulting in increased cation uptake by plants (Hansen, 1972; Dijkshoorn, 1957). Other reports are available for increases in plant Mg concentration resulting from N fertiliser application (Reith, 1967; Kershaw and Barton, 1965; Mayland and Grunes, 1974; Terman and Allen, 1974 (in corn.)). Mayland et al.(1975) found that a part of the increase in Mg uptake in pasture resulting from N fertiliser application was due to increased root proliferation. Alternatively, N fertiliser could have resulted in more efficient root uptake of Mg, or improved translocation of Mg within the plant. This latter point is supported by the evidence of Cain (1959) who found that N fertiliser application resulted in greater mobilization of Mg into the actively growing parts of the plant.

Reductions in Mg content of herbage following N fertiliser addition are most likely to result from growth dilution effects (Terman and Allen, 1974) or competitive effects between NH_4 and Mg (Hansen 1972 ; Kershaw and Barton, 1965).

Apparent reductions in Mg availability may also arise from N-induced leaching losses of Mg from soils when nitrogenous fertilisers are applied over a prolonged period, together with the reduction in soil pH especially where NH_4^+ containing fertilisers are used (Mulder 1956).

iv. Plant Mg uptake and soil pH.

Investigation of the relationships between soil pH and plant Mg uptake has been a difficult research area (Metson, 1974) due to:

(a) The difficulty in defining and measuring "exchangeable hydrogen";

(b) Strongly acid soils may have toxic levels of exchangeable Al;

(c) Acid soils usually have low base saturation levels, so that Mg may be deficient. Thus an apparent H^+/Mg^{2+} antagonism may in fact be equally an absolute Mg deficiency.

Evidence for an antagonism between Mg^{2+} and H^+ comes from the observations of Salmon (1964) who found that increasing H^+ activity in the soil (H^+ activity measured as the inverse of solution pH) resulted in a decrease in ryegrass Mg contents. Mg deficiency symptoms in oats were aggravated by low pH conditions (Ferrari and Sluijsmans, 1955), and Christenson et al.(1973) found that the liming effect of $CaCO_3$ additions had more effect on Mg uptake by oats than could be accounted for by changes in soil Ca level. There was a Mg uptake response in alfalfa when the soil pH was raised from 5.4 to 6.8 by liming (McLean and Carbonell, 1972). Lutz et.al.(1972) found that the Mg concentration in maize plants was increased as the soil pH was increased from pH 3.9 to 6.1.

In contrast, increasing soil Mg content at low soil pH (5.0) resulted in more efficient utilisation of the applied Mg by corn plants than when soil pH was increased to pH 6.3 (Hall and Hegwood, 1975). However, as the amounts of Mg applied differed at the two pH levels with more Mg being applied at the high pH, this result may be an artefact as plant dry-matter production was virtually identical at the low and high pH treatments.

2.3 Magnesium Fertiliser Applications to Pastures.

Magnesium deficiency is not generally a problem in New Zealand except for some areas of rhyolitic-ash derived soils in the Central Plateau region of the North Island. (Moody, 1962; McNaught and Ludecke, 1967). However, the maintenance of adequate Mg levels in pasture to prevent metabolic disorders particularly hypomagnasaemia, of lactating dairy and beef cattle, is a rather more widespread problem. Whilst the factors contributing to low plant Mg levels may not all be soil-derived, e.g., climate, and pasture management also affect pasture Mg levels (Metson, 1974), the problem of increasing herbage Mg concentrations to a minimum of 0.2% of dry matter or greater has received a great deal of attention both in New Zealand and overseas. The problem of hypomagnasaemia is accentuated by the seasonal variation in pasture Mg contents, these being lowest in the late winter to early spring period, which coincides with peak demand of beef and dairy cattle for dietary Mg supplies. Thus the problem is not only one of increasing herbage Mg content per se, but also of achieving this increase at a time when Mg concentrations tend to be at their lowest levels for the year.

The relationship between soil Mg levels and herbage Mg content, as defined by Salmon (1964), viz:

$$\text{herbage Mg} \propto \frac{\sqrt{a_{Mg}}}{\sqrt{a_{Mg} + Ca + Ba_{K} + Ca_{H}}}$$

is interpreted to mean that in order to double herbage Mg content, soil exchangeable Mg contents would have to be quadrupled. Therefore on soils with relatively low exchangeable Mg contents, significant increases in pasture Mg uptake and herbage Mg concentration can be achieved by the use of economic application rates of Mg fertilisers. However, on soils of higher exchangeable Mg content, smaller increases in plant Mg uptake would result from similar application rates. Results of Mg fertiliser trials in New Zealand have tended to confirm this viewpoint (Moody, 1962; Dorofaeff and McNaught, 1962; McNaught, 1964; McNaught and Dorofaeff, 1965;

Hogg and Karlovsky, 1966; Chittenden et.al., 1967; McNaught and Ludecke, 1967; McNaught et al.,1968a, b, 1973 a,b). McNaught et.al., (1968 a,b) showed that increases in herbage Mg content tended to conform to the square-root relationship as predicted by Salmon (1964), but in later work (Metson et al., 1973 a, b) it was suggested that the index $\log_{10}$ exchangeable Mg appeared to be a more efficient predictor of plant Mg concentration. A possible exception to the general consensus of response to Mg fertilisers would seem to be the results obtained by Every (1975). In this trial, large increases in pasture Mg levels occurred after the application of from 20 to 90 Kg Mg ha^{-1} (as MgO) to a soil testing 14 on the Advisory Test scale (c.f. the response-level of 4 generally recommended).

Results of Overseas experiments are in general agreement with those from New Zealand. In Scotland, large dressings of Mg (from 340 to 1200 kg Mg ha $^{-1}$) were required to achieve pasture dry matter Mg contents of 0.2% or more (Reith, 1963, '64, '67). It was suggested (Reith, 1964) that a soil content of 1.3 mg/100 g of exchangeable Mg was the minimum required to ensure an adequate supply of Mg to plants to prevent the occurrence of hypomagnasaemia. Large differences in plant response to fertiliser Mg were found between soils by Salmon and Arnold (1963) and Hooper (1967) in the U.K. Hooper (loc. cit.) concluded that a ratio of exchangeable Mg:K in the soil of 1.2 or greater was needed to ensure adequate Mg in the diet for stock health. On rangeland soils in U.S.A., an addition of 600 kg Mg ha^{-1} (as Mg $SO_4.7H_2O$) was needed to raise herbage Mg above 0.2% of dry matter (Mayland and Grunes, 1974). The same authors concluded that it was impractical to use Mg fertilisers to increase herbage Mg contents to offset problems of hypomagnasaemia. In an earlier paper (Grunes, 1973) it was asserted that Mg fertilisers may be useful on acid, sandy soils but on finer textured soils, the application of Mg fertilisers was often unsuccessful.

In terms of the effectiveness of various Mg fertilisers, Reith (1964) concluded that there was no difference between $MgSO_4.7H_2O$ kieserite ($MgSO_4.H_2O$), magnesite ($MgCO_3$), calcined magnesite (MgO) and magnesian limestone applied at equivalent rates of Mg. Kieserite, Serpentine superphosphate and finely-ground dolomite (80% passing a 120 mesh sieve) all produced greater pasture yield responses than did magnesian phosphate or coarsely-ground dolomite in an experiment on a Mg-deficient yellow-brown pumice soil (Hogg and Karlovsky, 1967). The particle size of calcined magnesite did not appear to affect Mg concentration increase in white clover, although the largest yield responses to Mg occurred when calcined magnesite of 0.5 mm or finer particle size was used (Hogg and Toxopeus, 1973.) The failure of talc-magnesite (20% Mg) to increase yield and plant Mg concentrations to the same extent as serpentine (21% Mg), dunite (28% Mg) or dolomite (11.5% Mg) in a trial on a Mg deficient gley-podzol was attributed to the coarse particle-size of the talc-magnesite since glasshouse experiments had shown talc-magnesite to be an effective Mg fertiliser (Chittenden et al, 1967).

Soil pH can determine the effectiveness of some Mg fertilisers. Heavy dressings of dolomite (1,000 to 4,000 kg ha^{-1}) have been shown to increase soil pH to such an extent that further dissolution of dolomite and hence supply of Mg is reduced. (McNaught et al, 1973 b); one effect of increasing the rate of dolomite applied was to increase the interval between application and the maximum effect of the fertiliser on soil exchangeable, and plant Mg, content. It was suspected that rapid decreases in the amounts of water-soluble Mg following application of $MgSO_4.7H_2O$ to two soils of high (7.0 and 7.6) pH were due to the formation of insoluble Mg carbonates (Mayland and Grunes, 1974). Likewise, the availability of Mg from basic slags may be reduced as the liming value of the slags increases (Heintze, 1963).

Magnesium fertiliser use on some soils may well be worth consideration for purposes of arresting the progressive decline in available soil Mg content which inevitably accompanies intensive land use (Dixon and Taylor, 1942; Metson, 1974). Within this category are those soils known to have low (< 7 m.e.%) reserve Mg contents (Metson and Brooks, 1975) including:

Northern podzols;

Northern yellow-brown sands;

Recent soils from pumice alluvium;
Yellow-brown pumice soils;
Central yellow-brown loams;
Northern and central brown granular loams and clays (mature)
Northern red and brown loams (mature).

Although many of these soils contain, at present, adequate contents of exchangeable Mg, over the long term, losses from the exchangeable Mg pool may not be replenished from soil reserves. For Horotiu sandy loam (a brown granular loam) it has been estimated that the yield of Mg in the pasture herbage over a three-year period was approximately equal to the quantity of Mg contained within the 0-7.5 cm topsoil layer, suggesting that the soil is of marginal Mg status for continued production (During et.al., 1973). Any additional losses of Mg from such a soil, as may be induced by the continual use of KCl fertiliser, could lead to reductions in available Mg supplies for pasture use with consequent adverse effects on animal, and later, plant health, unless Mg was replaced in fertiliser form.

Viewed from this perspective, the application of Mg fertilisers may be justified for reasons of preventing the development of a future deficiency. Overseas results (Reith, 1964) have shown that while applications of low rates of Mg (ca. 35 kg Mg $ha^{-1}yr^{-1}$) may have no immediate effect on pasture Mg concentration, long term benefits could include improved crop and animal performance. Areas in New Zealand where such a policy of Mg fertiliser application could be beneficial are the areas covered by the above soil types, especially where high annual rainfalls may lead to large leaching losses of Mg which may be further aggravated by spring applications of potassic and nitrogenous fertilisers (Hogg, 1960). Such areas could include parts of Northland, the Waikato-King Country area, the Volcanic Plateau (Taupo-Rotorua) and Taranaki.

Chapter III

Experimental Objectives and Design

There were two main objectives of this study:

A. To determine:

(1) the relative Mg-status of soils in the Inglewood - New Plymouth - Okato area of North Taranaki, and

(2) the relationship between soil Mg contents and areal distribution of soil forming tephras and lahar deposits.

B. To assess the relative Mg-supplying powers of a range of yellow-brown loams from Taranaki and the nature of plant responses to Mg fertilizer addition in a controlled-climate environment.

A. Field Sampling Programme

Over the period July 1974 - August 1975 soil samples were collected from sites located within the mapped area of Inglewood Tephra and analysed for exchangeable Mg contents. Additional samples were taken from soil formed on the Oakura Tephra (Neall, 1972), Burrell Lapilli, and un-named recent lahar deposits, to allow a comparison of the results of soil exchangeable Mg analyses for a range of soils formed under similar climatic conditions. Sites were sampled at different altitudes on Inglewood coarse sandy loam (formed from Inglewood Tephra) and Patua loam (formed from Oakura Tephra) to investigate the variation in soil Mg content with relation to:

(i) Increasing rainfall, and hence leaching intensity, with increasing altitude;

(ii) Increasing coarseness of soil parent materials with proximity to source (Mount Egmont).

B. Controlled-Climate Pot Experiment

Magnesium uptake by perennial ryegrass from four representative Taranaki yellow brown loams was assessed under a controlled climate regime using the climate control facilities at D.S.I.R., Palmerston North. This experiment was designed to investigate:

(i) The relative Mg supplying abilities of the four soils, using a perennial ryegrass (Lolium perenne L.) test crop in the absence of applied Mg fertilisers. Perennial ryegrass was used as the test crop because the critical period for hypomagnasaemia in Taranaki occurs during early spring in association with ryegrass-dominant pastures.

(ii) The effects of varying rates of Mg additions on Mg concentrations and dry-matter yields of ryegrass herbage. The rates of Mg added were chosen to cover a range of application-rates that would be feasible for inclusion as part of an annual topdressing programme.

(iii) The effects of small temperature increments, from 12°C (day)/5°C (night) to 14°C (day)/7°C (night) and then to 16°C (day)/9°C (night) on Mg concentration and uptake by ryegrass.

The climatic conditions for the experiment were designed to approximate the normal temperature conditions encountered during the eight-week period August - September in Taranaki, as indicated from data supplied by the New Zealand Meteorological Service. These climatic conditions are of special interest since it is in early spring when plant Mg contents are often insufficient to meet animal requirements. The temperature conditions selected also provided an opportunity for a comparison with the findings of

Kemp and T'Hart (1957) whereby increased Mg concentrations in ryegrass were only achieved at temperatures above 14°C.

Two cutting regimes were also investigated. In one regime, plants were harvested mid-way through the period between temperature changes, whereas in the other, harvests were taken at the conclusion of each temperature period. In this way it was possible to isolate effects due to temperature changes from effects of plant maturity.

Chapter IV

Materials and Methods

The values for soil exchangeable magnesium, calcium, or potassium contents are hereafter referred to for convenience, as "exchangeable Mg, Ca, or K contents" respectively. Soil reserve magnesium and soil total magnesium are hereafter referred to as "reserve Mg" and "total Mg". The values for total plant magnesium, calcium, or potassium contents are hereafter referred to as "plant Mg, Ca, or K" respectively. Soil type names are abbreviated as follows:

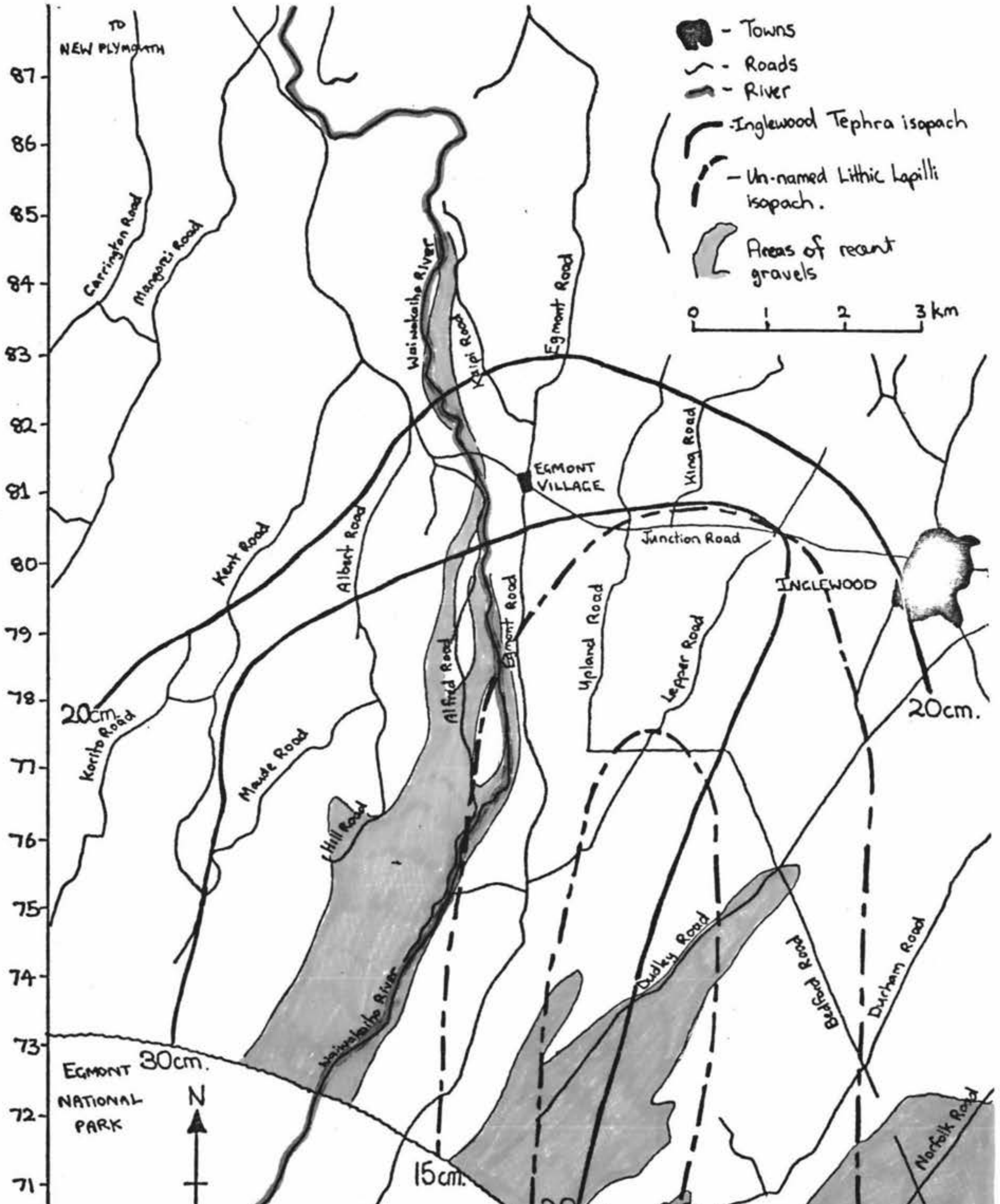
Burrell gravelly sandy loam - Burrell g.s.l.;
Egmont black loam - Egmont b.l.;
Inglewood coarse sandy loam - Inglewood c.s.l.;
New Plymouth black loam - New Plymouth b.l.

4.1. Soil Sampling Programme

4.1.1. Geology and Soils of the Sampling Areas

The soils chosen for this study were mainly Inglewood c.s.l., formed on Inglewood Tephra to the west and south-west of Inglewood township. Inglewood Tephra was erupted between 4 000-5 000 years B. P. (V. E. Neall, pers. comm.). Soils formed from Inglewood Tephra parent material extend over the area from Korito Road in the west to at least as far as Dudley Road in the east, and from the 500m contour near the Egmont National Park boundary to below the 150m contour near Egmont Village (Fig. 1.) (Neall, 1972). The area has a northerly aspect and is dissected by numerous sub-parallel streams, most of which form tributaries to the Waiwakaiho River. In the eastern part of this area, the Inglewood Tephra is overlain by a younger as yet un-named Lithic Lapilli (Fig. 1.) (V. E. Neall, pers. comm).

Fig.1. Distribution of soil parent materials in the Inglewood-New Plymouth sampling area.



The profile of Inglewood c.s.l. at a site near Inglewood township is 15cm of dark brown coarse sandy loam on brown, loamy, coarse sand and gravelly sand (Grange and Taylor, 1932). The soil may contain up to 33 percent by weight of partly pumiceous gravel (Gradwell, 1976). Soils of agricultural importance formed from Inglewood Tephra and classed as Inglewood c.s.l. were estimated to cover an area of ca. 10 000 ha (Grange and Taylor, 1932).

As the Inglewood Tephra thins to the north, the finer-textured New Plymouth black loams occur at altitudes of less than 150m on a more gently sloping land surface with a similar aspect to that upon which Inglewood c.s.l. occur. To the west, Patua loams occur on an area of similar physiography to that on which Inglewood Tephra was deposited, but with a westerly aspect. Patua loams and New Plymouth black loams were formed from Oakura Tephra, erupted<6 970 yr. B.P. (Neall, 1972). Additional soils from which samples were collected include a Stratford coarse sandy loam from near Stratford, and a Burrell g.s.l., formed from Burrell Lapilli, deposited ca, 1655 A. D. (Druce, 1966).

Within the area of mapped Inglewood c.s.l., the Newall, Norfolk, and Hangatahua soil series, formed on andesitic and laharic sands and gravels, occur along major stream and river channels. The texture of soils in these series varies widely, including loams, bouldery loams, sands, and gravelly sands (Grange and Taylor, 1932).

Rainfall

Rainfall over the range of soils investigated varies from 1 400mm at the coast near New Plymouth to ca. 3 800mm p.a. at the 500m altitude.

Land Use

The dominant land use on all soil types in the study area is dairy farming. At higher altitudes, on the Inglewood and Patua series, there are some larger sheep and beef breeding units. On some farms, hypomagnasaemia has occured in dairy herds, and prophylactic measures used have included the dusting of pastures with calcined magnesite prior to grazing, distributing Mg-containing stock licks and supplements and/or the application of serpentine or dolomite superphosphate.

4.1.2. Organisation of the Field Sampling Programme and Location of Sampling Sites

The soil sampling programme consisted of two surveys:

i) A reconnaissance survey was carried out between July and December, 1974, at which time soil samples were taken to investigate the range of exchangeable Mg contents in the soils formed on Inglewood Tephra and mapped as Inglewood c.s.l. Samples were also taken from the New Plymouth b.l., the Newall, Norfolk and Hangatahua bouldery sands, Burrell g.s.l., and Stratford coarse sandy loam in order to enable comparisons of the exchangeable Mg contents of a range of Taranaki yellow-brown loams. During the reconnaissance survey a total of 32 matching 0-10cm and 10-20cm topsoil samples were collected. The location of sites is given in Fig. 2, and a description of each site is contained in appendix 1.

ii) A detailed survey of exchangeable Mg contents was made for soils formed on Inglewood Tephra and the un-named Lithic Lapilli within the study area. In addition soils formed on Oakura Tephra to the west of the Kaitake Range at similar altitudes to the study area were sampled. This survey was carried out in August 1975 in order to examine:

a) the relationship between the areal distribution of Inglewood Tephra and the un-named Lithic Lapilli, and exchangeable Mg contents of the soils in the Inglewood - New Plymouth study area, and

b) the effects of increasing altitude, and hence rainfall and leaching intensity, on the exchangeable Mg contents of soils formed on Inglewood Tephra and the un-named Lithic Lapilli, and, for comparative purposes, soils formed on the Oakura Tephra. Forty-four matching 0-10cm and 10-20cm topsoil samples were collected from the Inglewood - New-Plymouth study area. The location of each site is shown

Fig. 2. Location of sampling sites-Reconnaissance survey.

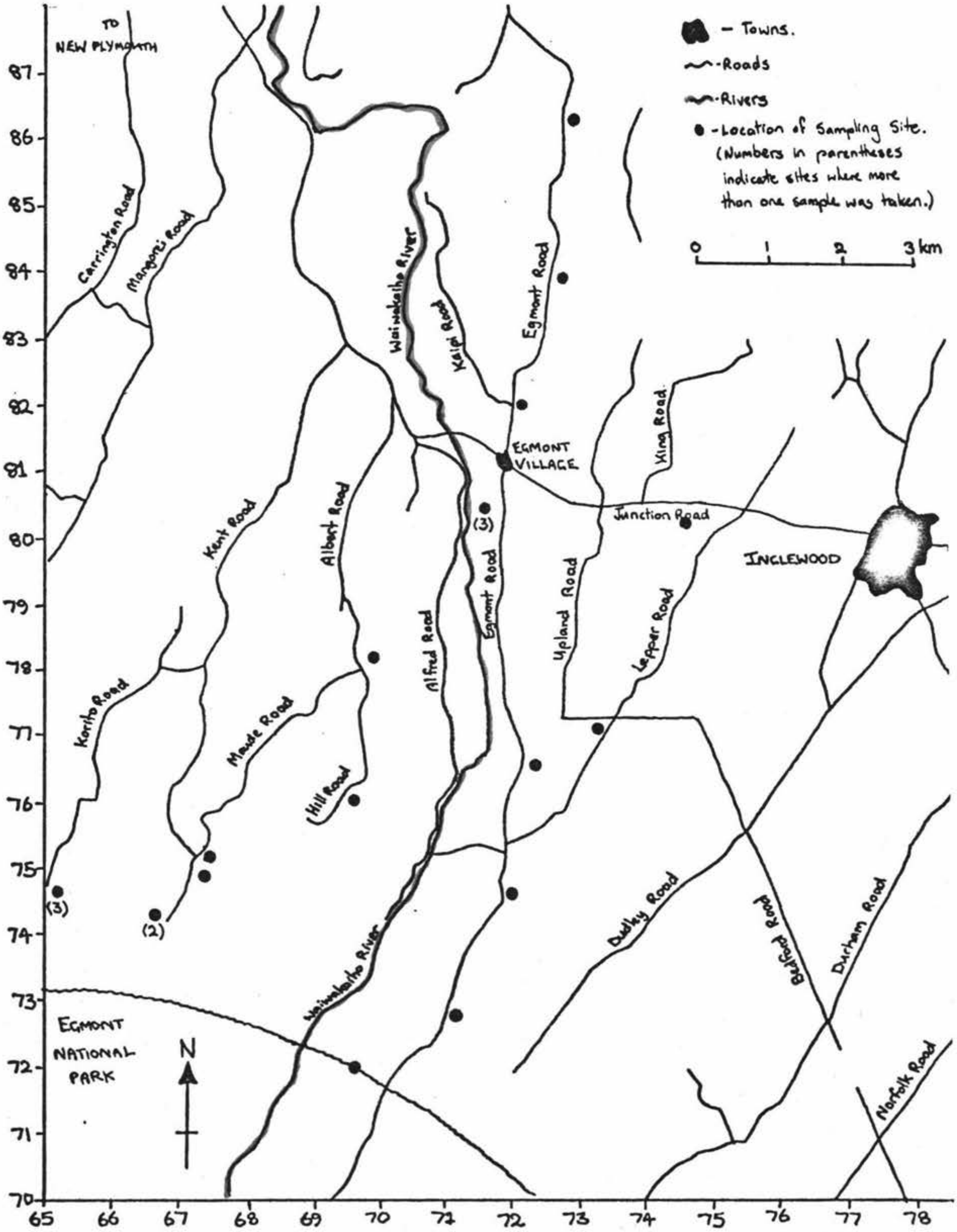
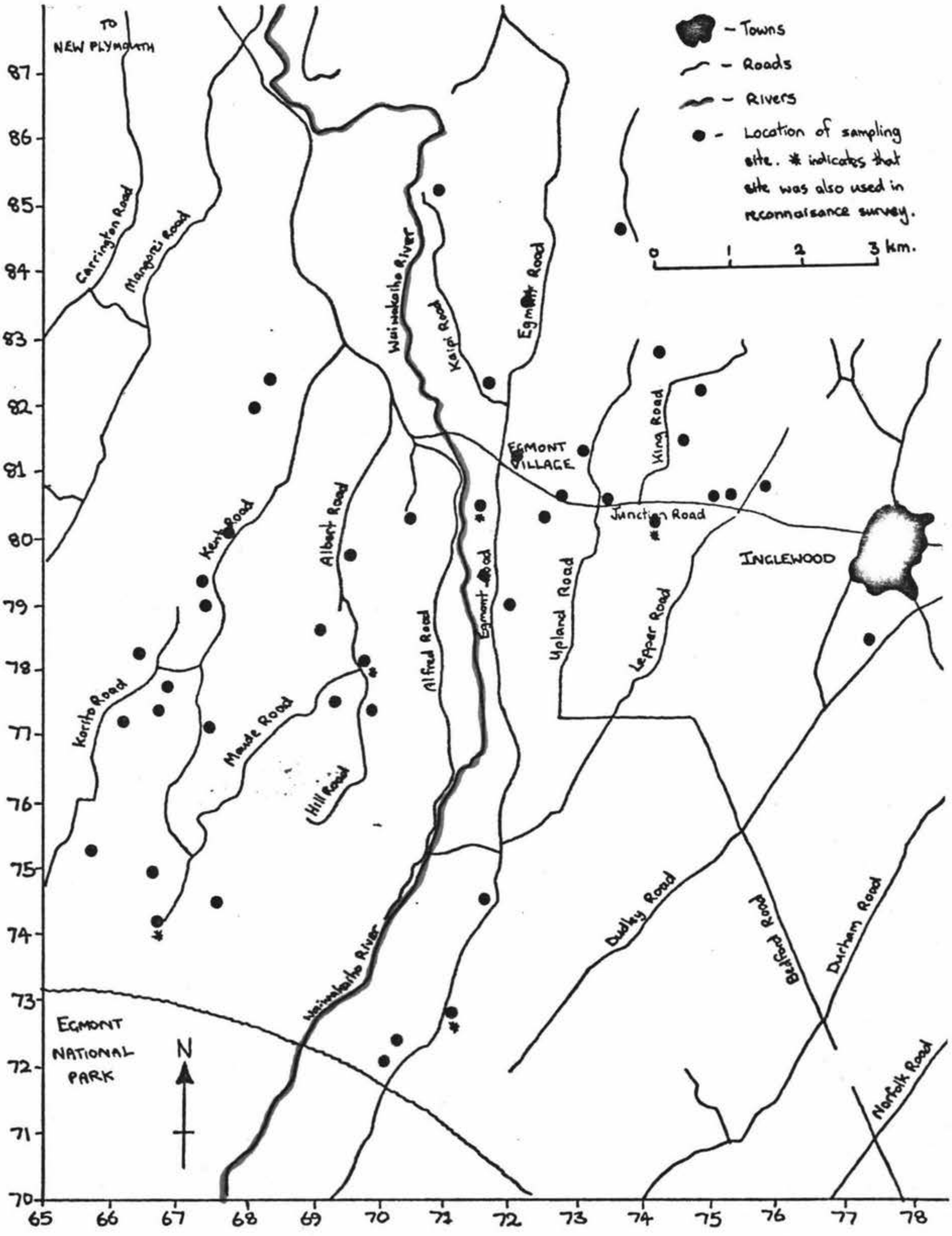


Fig. 3. Location of sampling sites - Detailed survey.



in Fig. 3.; details are given in appendix 1. Nine samples were collected from soils formed on the Oakura Tephra along Upper and Lower Pitone Roads.

4.1.3. Sampling Procedure

At each location, sampling sites were selected according to the following criteria:

i) no previous history of Mg fertilizer use;

and

ii) flat or gently rolling terrain distant from stream beds to avoid the influence of alluvial accretions in topsoils.

Ten random cores (0-20cm depth) were taken from an area of approximately 100 m^2 at each site. Obvious recent dung or urine patches were avoided. The upper 10cm of each core was taken as the upper topsoil sample, while the 10-20cm portion became the lower topsoil sample. The cores from similar depth layers at each sampling site were bulked together to form a composite sample for that site.

4.1.4. Sample Preparation for Analysis

Soil samples were air-dried in the laboratory, at ambient temperatures, and then crushed in a porcelain mortar and pestle to pass a 2mm sieve. In each case the 2mm portion which included large roots, pumice and lithic lapilli was discarded. The 2mm portion was retained for analyses of exchangeable Mg, Ca and K contents together with soil pH, cation exchange capacity, and total Mg as required, using procedures outlined in section 4.3

4.2. Pot Experiment

4.2.1. Soil Preparation

Four soils were used for the pot experiment with four rates of Mg fertilizer additions and two cutting regimes. There were four replicate pots of each soil type x fertilizer x cutting regime combination, making a total of 128 pots for the entire experiment. Locality details of the sites from which the four soils selected were taken are given below (Table 9). The soils were sampled at a depth of 2-15cm which avoided the dense root zone in the upper 2cm of the topsoil.

Soils were prepared for potting by passing through a soil shredder to break up large aggregates and then sieved through a 6.5cm wire mesh screen. Large stones and lapilli were discarded. After sieving, the soil was thoroughly mixed in a mechanical mixer prior to potting.

Square plastic pots of 2.2 litre capacity were ultimately filled with soil to within 2.5cm of the top. Allowing for variations in soil bulk densities, the actual final oven-dry (105 C) weights of soil used were:

Burrell gravelly sandy loam:	1470g
Inglewood coarse sandy loam:	1430g
Egmont black loam:	1435g
New Plymouth black loam	1235g

The procedure for potting was carried out in three steps:

(i) Sufficient soil was added to fill the pots to within 4.5cm of the top and was then lightly tamped down.

(ii) The extra soil required to fill the remaining 2cm of each pot was placed into a large plastic bag for mixing with the required of basal and treatment fertilizers (Table 10), together with 0.068g pot^{-1} of "Dasanit" insecticide to combat the effects of any insect pests present in the soil.

Table 9 Soils used for the Pot Experiment

Soil Type	Location (Grid reference, NZSM1 series)	Altitude (m.)
Burrell gravelly sandy loam	N108/766593 - adjacent to Barclay Road	510
New Plymouth black loam	N109/734945 - adjacent to Corbett Road	45
Inglewood coarse sandy loam	N109/658742 - 1 km East of Korito Road	450
Egmont black loam	N129/877255 - adjacent to Whareora Road	60

Table 10 Amounts of Fertilizers used

Treatment	Rate	Fertilizer	Amount per pot (g)
Basal*	400 kg ha^{-1}	30% K-super	0.675g
1	0 kg ha^{-1}	――――	
2	9 kg ha^{-1} Mg	$MgSO_4$ $7H_2O$	0.153g
3	18 kg ha^{-1} Mg	$MgSO_4$ $7H_2O$	0.306g
4	36 kg ha^{-1} Mg	$MgSO_4$ $7H_2O$	0.612g

* No basal fertilizer was added to Egmont Black Loam as the sampling site had been topdressed two weeks prior to sample collection with 375 kg ha^{-1} of 30% K-superphosphate.

Note:

0.068g "Dasanit" equivalent to 40 kg ha^{-1}, was added to each pot.

The fertilisers and insecticide were incorporated into the soil by thorough mixing within each plastic bag.

(iii) The amounts of soil required were weighed into each pot. The soil in each pot was then compacted down to within 2.5cm of the rim of the pot by dropping a 5kg weight from a height of 15cm above the soil surface on to the soil until the desired level was reached. The pots were then put aside to await planting.

Prior to the start of the experiment, the untreated soils were analysed for exchangeable Ca, K and Mg, soil pH, reserve Mg, and total Mg, according to the procedures outlined in section 4.3.

4.2.2. Planting

All pots were planted with 50 seeds of perennial ryegrass (Lolium perenne L.). The surface of the soil in each pot was loosened slightly, and the seeds were broadcast evenly over the surface of the soil and lightly tamped down.

4.2.3. Soil Moisture Contents

The soils were maintained throughout the experiment at a moisture content equal to that in a separate sub-sample of each soil which had been equilibrated at 60cm water tension. This tension was selected to ensure that adequate water was available for plant requirements and that the soil was sufficiently well aerated for vigorous root growth. To determine this moisture content, duplicate field-moist samples of each soil were placed in tension cups with porous ceramic bases, and thoroughly wet by capilliary action. This was achieved by raising the water level in the tension system slightly above the base of the cups. Subsequently, the soils were drained for 24 hours at 60cm tension using a hanging water column. After draining, the moisture content of the soil samples was determined by weighing each sample, oven-drying at 105°C for 24 hours, and re-weighing. The total weight for each pot was recorded, and used to replace daily water losses by evapotranspiration.

4.2.4. Growth Conditions and Harvesting

Details of the temperature ranges during growth periods and the timing of harvests in each cutting regime are summarised in Table 11 Plants were given a five-week establishment period in the glasshouse after which they were transferred to the controlled-climate room for an initial two-week acclimatisation period. Following this period, plants were assigned to one of two cutting regimes. The purpose of establishing the two cutting regimes was to investigate differences in ryegrass growth and Mg concentration and uptake under the alternative cutting regimes. Under cutting regime 1, the ryegrass grew between harvests under uniform temperature conditions; under cutting regime 2, the ryegrass grew through a temperature changeover.

For those pots assigned to cutting regime 1, (half of the pots in each soil type x Mg fertiliser treatment combination) herbage was trimmed to 2.5cm above the soil surface (first harvest) at the conclusion of the acclimatisation period. Two further harvests were taken at three week intervals corresponding with the end of the two imposed climate periods. For cutting regime 2, the first harvest was delayed until day 59, which coincided with mid-way through the 14°C (day)/7°C (night) period. The second harvest for this regime was taken three weeks later (day 81), i.e. mid-way through the 16°C (day)/ 9°C (night) period. The third harvest in cutting regime two was taken at the same time as that in cutting regime one, on day 92, at the conclusion of the experiment.

The herbage trimmed from the pots at each harvest was weighed, placed into a numbered container and dried overnight at 40°C in a "Cudden" vacuum-assisted drying oven with refrigerated moisture-extraction plates. After drying, each sample was re-weighed for dry-matter determination and then ground into a fine powder in a "Glen Creston" mill. Subsamples of ground herbage were analysed for total Ca, K, and Mg contents according to the procedures outlined in section 4.3.6.

Table 11 Temperature changes and harvest times during the pot trial

Period	Temp (^{o}C)	Cutting Regime 1 Planting	Time (days)	Cutting Regime 2 Planting
Establishment		50 seeds/pot	1	50 seeds/pot
	20 C day and night			
		Transferred to climate room	35	Transferred to climate room
Acclimatisation	12 C day 5 C night		36	
		First Harvest	48	
Climate-room experimental	14 C day 7 C night		49	First Harvest
		Second Harvest	70	
	16 C day 9 C night		71	
			81	Second Harvest
		Third Harvest	92	Third Harvest

4.2.5. Climate Room Growth Conditions

Full details of the environmental conditions in the controlled-climate room are shown in Table12 . Light intensity was measured with an Eppley pyranometer and Schott RG8 fitter system. Light was supplied by 4 x 1 000 watt Sylvania "metalarc" high-pressure discharge lamps together with 4 x 1 000 watt Philips tungsten iodide floodlamps. The light was directed down into the growth room through a screen. Water flowed over the screen to assist in temperature control within the room. The photoperiod was 12 hours with an abrupt light/dark change occurring half way through the two-hour changeover period from day temperature and humidity conditions to the night conditions. CO_2 level was uncontrolled.

4.3. Analytical Procedures

4.3.1. Soil Exchangeable Cations

Soil exchangeable Mg, Ca and K were determined according to the procedure of Salmon and Arnold (1963) in which 2g of air-dried soil was extracted by shaking with 50ml of neutral, 1N ammonium acetate in a polypropylene centrifuge tube on an end-over-end shaker (50 r.p.m.) for one hour. After removal from the shaker, the tubes were centrifuged for 10 minutes at 3 000 r.p.m. The supernatant solution was filtered (Whatman No. 44 filter paper) to remove suspended clay particles. An aliquot of the filtrate was diluted 10-fold with distilled, deionized water. To this was added an equal volume of 1.6% (w:v) $Sr(NO_3)_2$ to give an overall 20-fold dilution of the original solution and a final concentration of 0.8% $Sr(NO_3)_2$. Mg, Ca and K the final solution were determined according to the procedures outlined in section 4.3.7.

At the same time as soil subsamples were taken for exchangeable cation determination, a separate subsample was taken for estimation of the moisture contents of the air-dry samples, following oven drying for 24 hours at 105 C. All results were calculated on an oven-dry basis. Duplicate subsamples were used for estimation of exchangeable cation content and oven-dry weight.

Table 12: Environmental Conditions during Pot Experiment

Time (Days)	Temp. (^{o}C)		R.H.%		V.P.D. (mb)		Light Intensity
	Day	Night	Day	Night	Day	Night	
36-48	12	5	72	73	-5	-3	173 W m^{-2}
49-70	14	7	68	70	-5	-3	
71-92	16	9	64	65	-5	-3	

4.3.2. Soil pH

Soil pH was measured using 10g of air-dried soil and 25ml distilled water (Metson, 1956). The soil-water mixture was stirred thoroughly using a glass rod and left to stand overnight. The following day, the suspensions were stirred and immediately afterwards, the pH of the soil-water suspension was determined using an "Orion" pH meter and combination pH electrode.

4.3.3. Cation Exchange Capacity (CEC)

CEC was determined using the leaching method of Metson, (1956), in which 10g of air-dry soil where ammonium saturated by first leaching with neutral, 1 N ammonium acetate, and then with 90% ethyl alcohol to remove any excess ammonium acetate. The ammonium was removed from the soil by steam distillation in the presence of MgO, the distillate being collected in dilute (4.0%) boric acid containing a bromocresol green - methyl red mixed indicator. Ammonium was determined in the distillate by titrating against 0.1N HCl until the indicator changed to the neutral grey colour.

4.3.4. Reserve Mg

Reserve Mg was determined using a method adapted from that recommended by Metson (1968) in which 2.5g of air-dry soil was extracted by boiling for 15 minutes with 100ml of 1N HCl on a hot plate. After extraction and cooling, the mixture was filtered (Whatman No. 44) into a 500ml volumetric flask. The soil on the filter paper was rinsed three times with about 100ml of distilled-deionized water, and the washings collected and added to the filtrate which was then made up to volume with distilled-deionized water. The extract was diluted 10-fold with the final solution containing 0.8% $Sr(NO_3)_2$ (w:v). The concentration of Mg was determined according to the procedures outlined in section 4.3.7.

4.3.5. Total Soil Mg

Total soil Mg was determined using a wet acid digestion. A subsample of air-dry soil was ground in an agate mortar and pastle to pass a 125 M mesh. Duplicate 0.3g subsamples of the finely-ground soil were placed into separate 100ml polypropylene beakers with 10ml of a 1:1 mixture (v:v) of 40% HF and conc. HNO_3.

Digestion was carried out on a boiling water-bath by evaporating to dryness. This process was repeated at least three more times until a white residue remained. The residue was dissolved in 20ml of a dilute nitric acid solution (16ml of conc. HNO_3 in 500ml distilled-deionized water) by heating for 10 minutes at below boiling point on the water-bath. The solution was then filtered. The residue on the filter paper was rinsed several times with distilled-deionized water and the total volume made up with distilled-deionized water and $Sr(NO_3)_2$ to give a final solution concentration of 0.8% $Sr(NO_3)_2$ (w:v). Mg was determined according to the procedures outlined in section 4.3.7.

4.3.6. Total Herbage Mg, Ca and K contents

Samples of finely-ground herbage (0.2g) were weighed in duplicate, into 100ml "Pyrex" beakers and ashed for three hours in a muffle furnace at 475-500 C. After ashing and cooling, a few drops of distilled-deionized water were added to each beaker followed by 2ml of 2N HCl. The contents were then evaporated to dryness on a hot plate. The dry residue was dissolved in 10ml of 2N HCl by heating gently (without boiling) for 10 minutes on a hot plate.

The solution was filtered (Whatman No 44) into a 250ml volumetric flask and the residue washed with distilled-deionized water. The filtrate plus washings were made to volume with distilled-deionized water and 25ml of 8.0% (w:v) Sr $(NO_3)_2$ to give a final solution containing 0.8% Sr $(NO_3)_2$. Mg, Ca, and K were determined according to the procedures outlined in section 4.3.7.

4.3.7. Determination of Mg, Ca, and K in solution

Ca and Mg concentrations in the final solutions were determined using a Perkin-Elmer atomic absorption spectrophotometer. All final solutions contained 0.8% Sr $(NO_3)_2$ (w:v) as an interference suppressor. K concentrations were determined by flame emission procedures using either an E.E.L. flame photometer or a Perkin-Elmer 306A atomic absorption spectrophotometer. Standard curves for each set of determinations were prepared using standard solutions containing a range of Mg, Ca, and K, concentrations, in the appropriate matrix.

A summary of the analytical procedures used is given in Table13.

Table 13

Summary of analytical procedures used

Procedure	Soil Sampling Programme		Pot Trial		
	Reconnaissance Survey	Detailed Survey	Soils		Herbage
			pre-planting	after experiment	
Soil exch. Mg	x	x	x	x	
Soil exch. Ca, K	x		x	x	
Soil pH	x	x	x	x	
Soil C E C	x(1)		x		
Reserve Mg			x		
Soil Total Mg	x(1)		x		
Herbage Ca, K, Mg Contents					x

(1) Selected Samples Only

Chapter V

Results and Discussion

5.1. Field Sampling Programme

The results of this study are discussed in the order of exchangeable Mg contents and their relationship to soil parent materials, exchangeable Ca, K, and soil pH, and the variation of exchangeable Mg with increasing altitude. In this way the soils included in the study are compared, and major soil differences are isolated.

5.1.1. Soil Exchangeable Mg Contents

The results of analyses of samples taken from soils formed on the Inglewood Tephra from both the reconnaissance and detailed surveys show a similar range of exchangeable Mg values (Table 14, 15 and Appendix 2). The exchangeable Mg levels in the 0-10cm topsoil layer ranged between 0.20 to 2.71 m.e.% exchangeable Mg. The 10-20cm topsoil layer generally contained about one-third the amount of exchangeable Mg in the 0-10cm topsoil layer, the range being from 0.01 to 0.91 m.e.% exchangeable Mg. The exchangeable Mg in soil samples taken from other soil types (Table 16) indicate that there may be further areas of soils with similar exchangeable Mg contents in Taranaki, particularly soils of the Stratford, Burrell, Norfolk and Hangatahua series. The exchangeable Mg contents of New Plymouth black loams are higher than other soils sampled in the reconnaissance survey, being greater than 2.0 m.e.% exchangeable Mg at both of the sites sampled (Table 16).

The overall pattern of results in this survey was one in which younger soils on coarse-textured parent materials contain significantly less exchangeable Mg than older soils formed on fine-textured parent materials.

By inspection of the data presented by New Zealand Soil

Table 14 Soil exchangeable cation contents and soil pH of 26 samples from Inglewood coarse sandy loam (reconnaissance survey).

	0-10 cm		10-20 cm	
	Mean	Range	Mean	Range
Exch. Mg (m.e.%)	0.74 ± 0.56	0.20 - 2.71	0.26 ± 0.17	0.07 - 0.91
Exch. Ca (m.e.%)	5.66 ± 3.38	1.05 - 14.79	3.10 ± 2.32	0.40 - 8.52
Exch. K (m.e.%)	0.71 ± 0.77	0.20 - 3.95	0.34 ± 0.34	0.07 - 1.52
pH	5.7 ± 0.2	5.3 - 6.2	5.6 ± 0. 2	5.3 - 6.1

Table 15 Soil exchangeable Mg and soil pH of 44 samples from Inglewood coarse sandy loam (detailed survey)

	0-10 cm		10-20 cm	
	Mean	Range	Mean	Range
Exch. Mg (m.e.%)	0.68 ± 0.40	0.25 - 1.87	0.17 ± 0.12	0.01 - 0.64
pH	5.8 ± 0.2	5.2 - 6.2	5.8 ± 0.2	5.3 - 6.2

Table 16 **Results of soil exchangeable cation and pH determinations for a range of Soil types from Western Taranaki (reconnaissance survey)**

Soil Type (Sample Number)	Depth (cm)	Soil exchangeable Cations (m.e.%)			pH	Altitude (m)	Grid Reference (NZMS 1)
		Mg	Ca	K			
Stratford coarse	0-10	0,14	3.58	2,55	5,6	320	N119/842605
sandy loam (2)	10-20	0,14	1.97	3.43	5,3		
Burrell gravelly	0-10	0,35	3.57	1.35	5,7	490	N119/765599
sandy loam (1)	10-20	0,23	2,23	1.52	5.7		
(16)	0-10	1,84	6.05	0.60	5.7	425	N119/789598
	10-20	0.64	1.80	0.21	5.5		
New Plymouth	0-10	2,08	8.31	0.50	5.6	30	N109/701920
black loam (17)	10-20	0.51	4.12	0.17	5.4		
(18)	0-10	2,91	14.45	1.17	5.8	60	N109/710911
	10-20	0.35	2.08	0.59	5,2		

Table 16 (Cont..)

Soil Type (Sample Number)	Depth (cm)	Mg	Ca	K	pH	Altitude (m)	Grid Reference (NZMS 1)
Norfolk Bouldery	0-10	0.28	2.44	0.21	5.5	325	N109/697756
Sand (12)	10-20	0.16	1.61	0.14	5.6		
Newall Bouldery	0-10	1.38	5.82	0.44	5.6	455	N109/722723
Sand (14)	10-20	0.13	2.68	0.34	5.7		
Hangatahua	0-10	0.65	2.87	0.26	5.5	320	N118/534671
Bouldery sand (32)	10-20	0.38	1.97	0.26	5.7		
Patua loam (9)	0-10	0.53	5.43	0.60	5.6	395	N108/612763
	10-20	0.21	1.34	0.37	5.3		

Table 17: Soil exchangeable Mg, Ca, and K and soil pH of samples from previous broad surveys of Taranaki soils

Soil	Depth (cm)	Exch. Mg (m.e.%)	Exch. Ca (m.e.%)	Exch. K (m.e.%)	pH	Reference
Stratford coarse	0-7.5cm	1.4	9.3	0.62	5.0	1
Sandy loam	7.5-15cm	0.9	6.0	0.13	5.9	
Patua loam	0-7.5cm	2.0	6.9	0.41	4.4	1
Egmont black	0-7.5	5.4	12.6	0.62	5.7	1
loam	7.5-15cm	3.9	10.5	0.29	6.2	
Burrell gravelly	0-10cm	0.9				2 (On Burrell andesitic ash)
sand	15-25cm	0.4				
"	0-10cm	1.1				2 (On Newall andesitic ash)
C/YBL (and)*	0-15cm	2.44 ± 1.23				2
		1.04 ± 0.74				
C/YBL (rhy)**	0-15cm	1.32 ± 0.79				2
		0.75 ± 0.58				
YBPS$^+$	0-15cm	1.11 ± 0.98				2
		0.46 ± 0.46				

References: (1) New Zealand Soil Bureau, 1968

(2) Metson and Brooks, 1975

* Central Yellow-brown loams (andesitic)

** Central Yellow-brown loams (rhyolitic)

\+ Yellow-brown pumice soils.

Bureau (1968) and Metson and Brooks (1975), a similar trend can be found from previous broad surveys of the region (Table 17) However, in the present survey, exchangeable Mg contents were generally lower than previous measurements. This may be a reflection of the differences in criteria for sample-site selection. In the previous studies, samples were taken from soils in an unimproved state, whereas those in the present study were taken from agricultural land. As most of the sites from which samples were taken in this study had been farmed for periods in excess of 50 years, the continuing small removals of Mg from the soil as a result of their use for agriculture (During 1972) may have resulted in the differences between the present, and previous, studies.

The uptake of Mg from the soil by plants and its subsequent return to the soil surface in plant residues and animal wastes is known to result in increased exchangeable Mg contents in the upper layers of the soil with reference to those lower down (Metson 1968; 1974; During et al, 1973; Wiklander, 1974). This process of nutrient cycling is reflected in the greater contents of Mg in the 0-10cm topsoil layer compared to those of the 10-20cm layer at nearly all of the sampling sites (Tables 14-16; Appendix 2). This detailed pattern is also similar to that evident in the results of exchangeable Mg analyses reported in previous broad surveys (New Zealand Soil Bureau, 1968; Metson and Brooks, 1975) for Taranaki yellow-brown loams.

The exchangeable Mg content of the soils formed on the Inglewood Tephra and classed as Inglewood coarse sandy loam resembles more nearly the exchangeable Mg contents given for yellow-brown pumice soils (Metson and Brooks, 1975) than those of Central yellow-brown loams formed from either andesitic or rhyolitic parent materials (Table 17). This may be due to the coarse pumiceous nature of the Inglewood Tephra (Neall, 1972) which contains less Mg than many other soil forming tephras in Western Taranaki (Kohn and Neall, 1973). Thus, although the Inglewood coarse sandy loams are classified at present as Central yellow-brown loams, being formed on andesitic tephra, with reference to exchangeable Mg contents, the soils are more similar to yellow-brown pumice soils.

To examine the distribution pattern of exchangeable Mg, the data from the detailed survey were plotted at the site locations on a 1:63360 topographical map of the area, and contours constructed of equal exchangeable Mg content ("Iso-Mg contours"). For the 0-10cm topsoil samples, a general pattern of low exchangeable Mg contents is evident where Inglewood Tephra is preserved in the upper soil horizons (Fig. 4). In the eastern part of the survey area, where the Inglewood Tephra is overlain by the more recent un-named Lithic Lapilli, exchangeable Mg contents are higher. The high exchangeable Mg contents, from 1.6 to 1.9 m.e.% Mg, near Egmont Village are presumed to be due to the extensive use of Mg-containing fertilizers on some farms in this area. The pattern of exchangeable Mg contents for the 10-20cm layer is similar to that of the 0-10cm layer (Fig. 5), with the low exchangeable Mg contents extending further to the east. This suggests that the Inglewood Tephra influences the properties of the lower topsoil, being buried in the upper 10cm by the Lithic Lapilli. A transect (line A-A' on Fig. 5) demonstrates the relationship between the exchangeable Mg contents of the 0-10 and 10-20cm topsoil layers, and the occurrence of the Inglewood Tephra and the un-named Lithic Lapilli (Fig. 6). Although there are no reported analyses of the Mg content of the un-named Lithic Lapilli, the exchangeable Mg analyses in the present study indicate that it has a greater Mg content than the Inglewood Tephra.

5.1.2. Exchangeable Ca, K, and Soil pH.

The results suggest few relationships exist between exchangeable Ca or K contents and exchangeable Mg contents of soils formed on Inglewood Tephra (Table 14). Exchangeable Ca contents of the 0-10cm topsoil layer varied widely in soils formed on Inglewood Tephra, from 1.05 to 14.79 m.e.% exchangeable Ca. In the 10-20cm layer, exchangeable Ca contents were lower, ranging from 0.40 to 8.52 m.e.% Ca. Linear regression analysis did show that, in the 0-10cm topsoil layer, there was a trend for exchangeable Ca and Mg contents to increase together:

$$y = 0.10x + 0.19 \; ; \; r = 0.59^{**} \; (n = 26).$$

Fig.4."Iso-Mg" contours for 0-10cm topsoil layer.

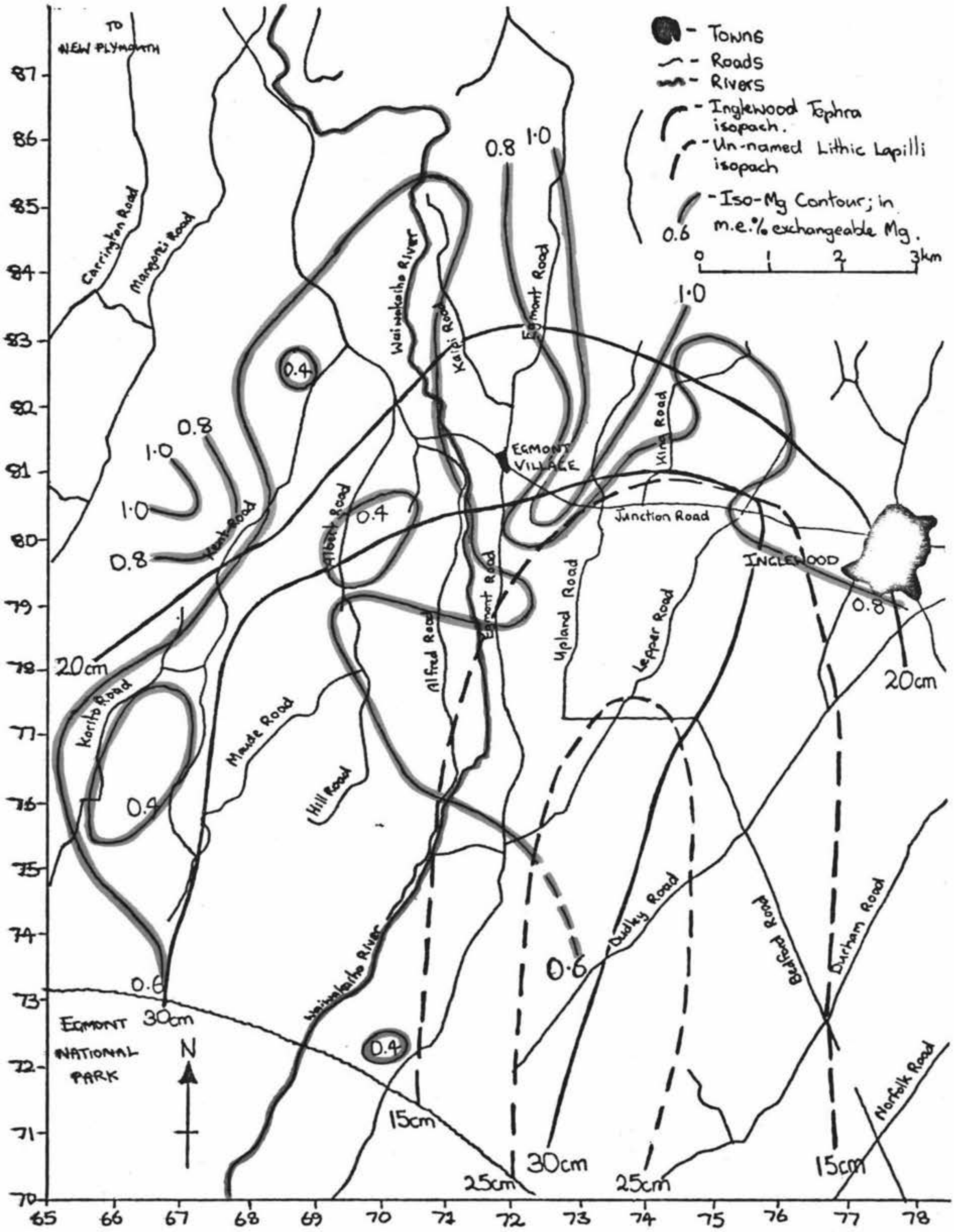
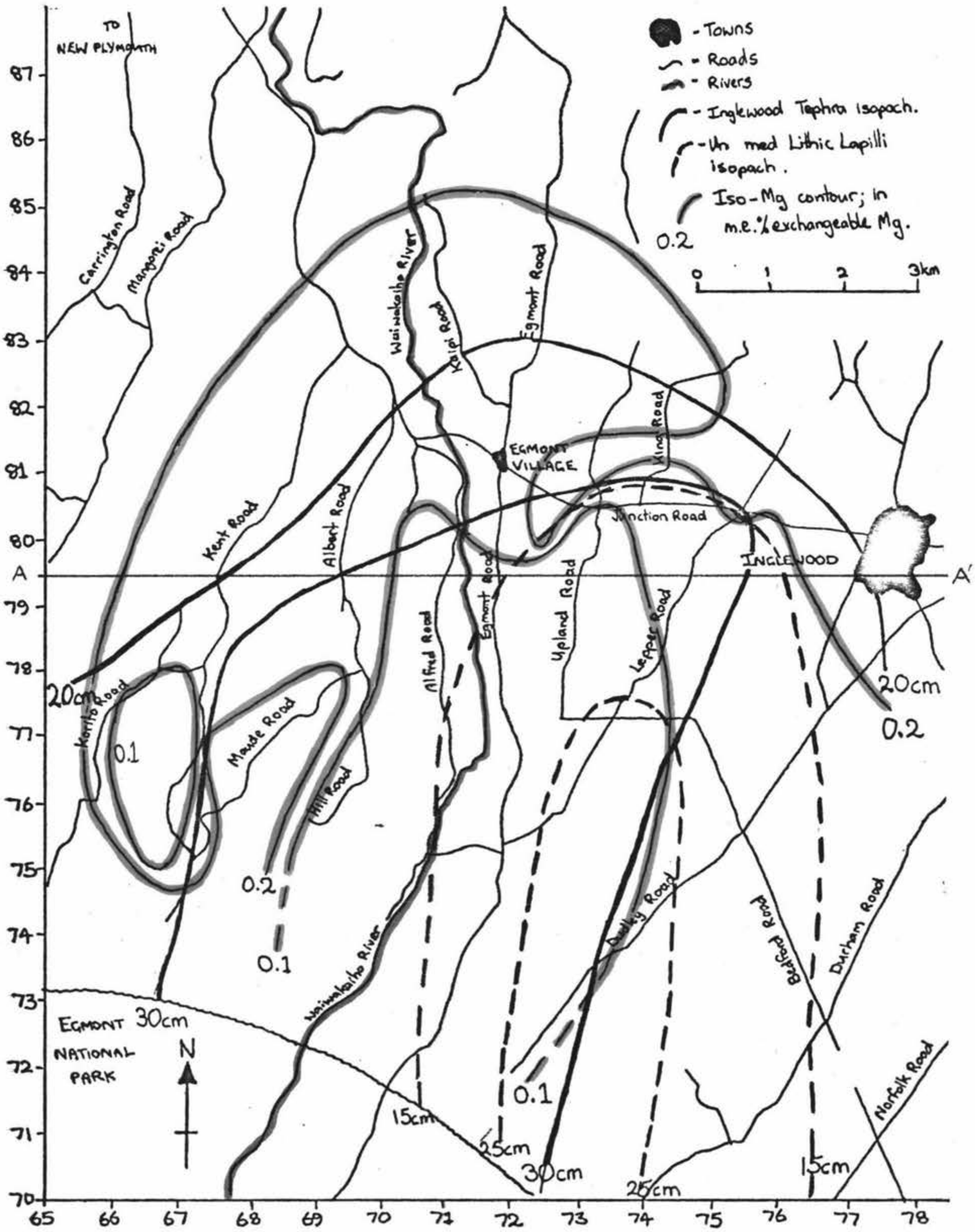


Fig. 5. "Iso-Mg" contours for 10-20cm topsoil layer.



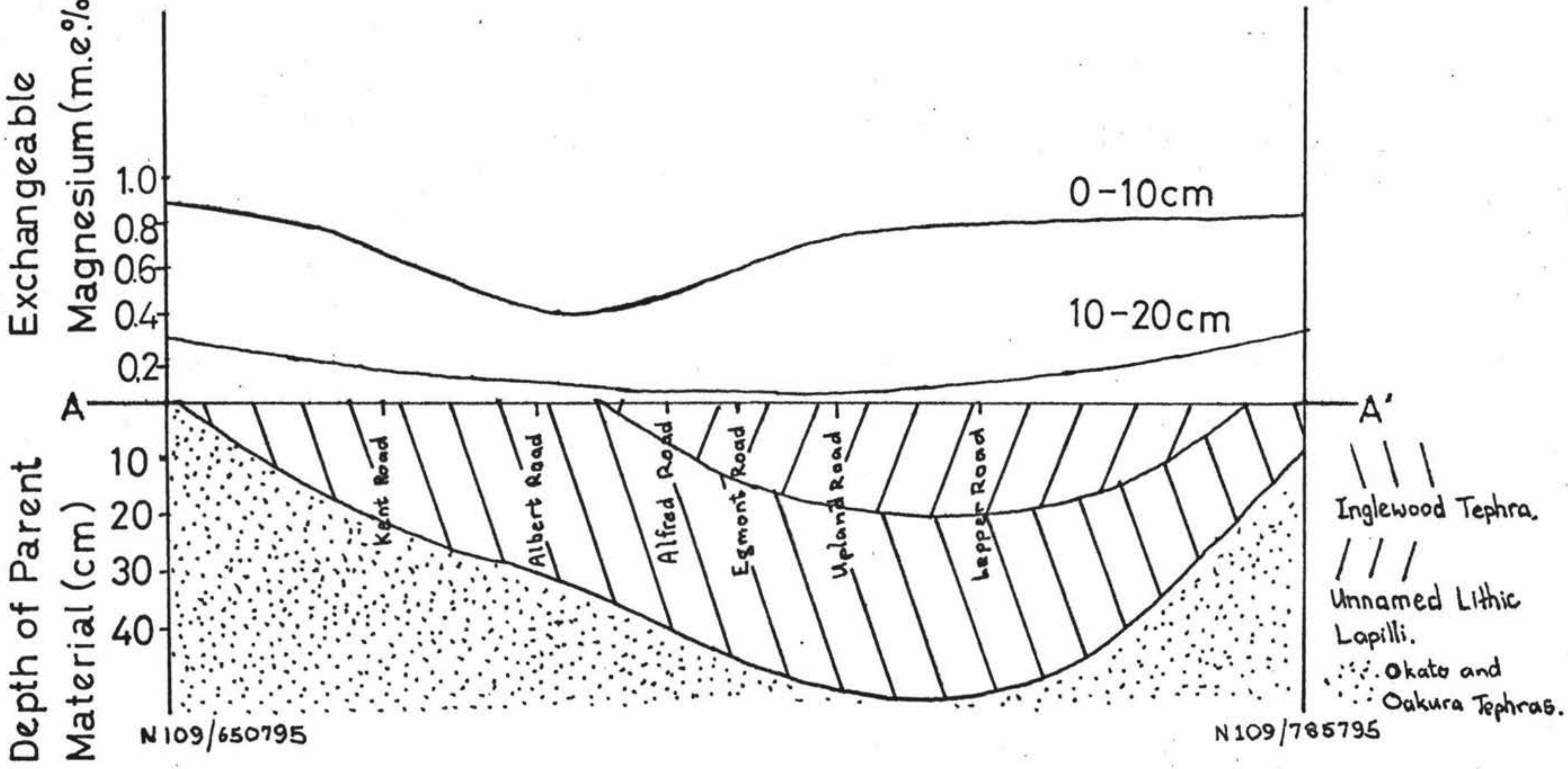


Fig.6. Changes in Soil exch. Mg (m.e.%) with Parent Material along transect A-A' (see Fig.5)

However in the 10-20cm layer, no relationship was evident:

$$y = 0.02x + 0.20 \; ; \; r = 0.20 \text{ n.s.} \; (n = 25).$$

(Where y = exchangeable Mg ; x = exchangeable Ca, in m.e.%)

This suggests that the relationship between exchangeable Mg and Ca in the 0-10cm topsoil layer may be related to the use of soil amendments, such as lime, which commonly contains small amounts of Mg. However as detailed fertiliser histories were not available for most of the sites visited, the possibility of recent and earlier use of mixed Ca/Mg fertilisers cannot be discounted.

Exchangeable K contents varied between 0.20 and 3.95 m.e.% K in the 0-10cm topsoil layer and 0.07-1.52 m.e.% K in the 10-20cm topsoil layer (Table 14). The absence of any relationship between exchangeable K and Mg in soils formed on Inglewood Tephra, viz;

$$\text{0-10cm: } y = -0.06x + 7.79 \; ; \; r = -0.08 \text{ n.s.} \; (n = 26)$$

$$\text{10-20cm: } y = -0.05x + 0.25 \; ; \; r = -0.10 \text{ n.s.} \; (n = 25)$$

(Where y = exchangeable Mg ; x = exchangeable K, in m.e.%)

is probably due to the widespread and varying use of K-containing fertilisers over the Inglewood - New Plymouth sampling area.

There was evidence for a positive relationship between exchangeable Mg and soil pH from the samples obtained in both surveys, but which only reached significance in the samples taken in the detailed survey:

$$\text{0-10cm : } y = 1.04x - 5.31 \; ; \; r = 0.53^{***} \; (n = 44)$$

$$\text{10-20cm : } y = 0.15x - 0.72 \; ; \; r = 0.27^{*} \; (n = 43)$$

(Where y = exchangeable Mg in m.e.% ; x = soil pH)

This effect may be partly attributed to the liming effect of Mg additions in the form of either dolomite or basic slag on the farms in the vicinity of Egmont Village, where soil pH was generally higher than elsewhere in the sampling area (Appendix 2) Over the rest of the sampling area, it appears that lime additions may have changed soil pH without any discernable changes in exchangeable Mg contents.

5.1.3. Variation of Soil Mg Content with Altitude

A summary of linear regression analyses of exchangeable Mg content vs. altitude for samples taken from soils formed on the Inglewood Tephra during both the reconnaissance and detailed surveys is as follows:

Reconnaissance survey:

0-10cm: $y = 1.28 - 0.002x$; $r = -0.36$ ($n = 26$)
10-20cm: $y = 0.48 - 0.001x$; $r = -0.44^{*}$ ($n = 25$)

Detailed survey:

0-10cm: $y = 1.20 - 0.002x$; $r = 0.42^{**}$ ($n = 44$)
10-20cm: $y = 0.26 - 0.006x$; $r = -0.23$ n.s. ($n = 43$)

(where y = exch. Mg in m.e.% ; x = altitude in metres)

This shows that exchangeable Mg contents tend to decrease with increasing altitude. The exchangeable Mg content results for the 0-10cm depth in the detailed survey best demonstrate this relationship (Fig 7.)

The wide variation in exchangeable Mg contents with increasing altitude is probably due in part to the exchangeable Mg contents being dependent upon the areal dispersion of the Inglewood Tephra. The exchangeable Mg content increases to the east as the Tephra thins, but it also increases to the north with decreasing altitude. Altitude transects of exchangeable Mg contents using the results of analyses of samples taken from along Egmont Road in both the reconnaissance and detailed surveys are plotted in Fig 8a, b. These transects lie close to the dispersal axis of the Inglewood Tephra, minimizing variations in the depth and grain-size of the parent material, and minimizing consequent effects on the exchangeable Mg contents of the soils. Linear regression analyses of exchangeable Mg content vs. altitude gave the following results:

Reconnaissance survey:

0-10cm: $y = 2.46 - 0.006x$; $r = -0.84^{*}$ ($n = 6$)
10-20cm: $y = 0.44 - 0.001x$; $r = -0.89^{*}$ ($n = 6$)

Detailed survey:

0-10cm: $y = 1.06 - 0.002x$; $r = 0.87^{**}$ ($n = 10$)
10-20cm: $y = 0.18 - 0.003x$; $r = -0.56$ n.s. ($n = 10$)

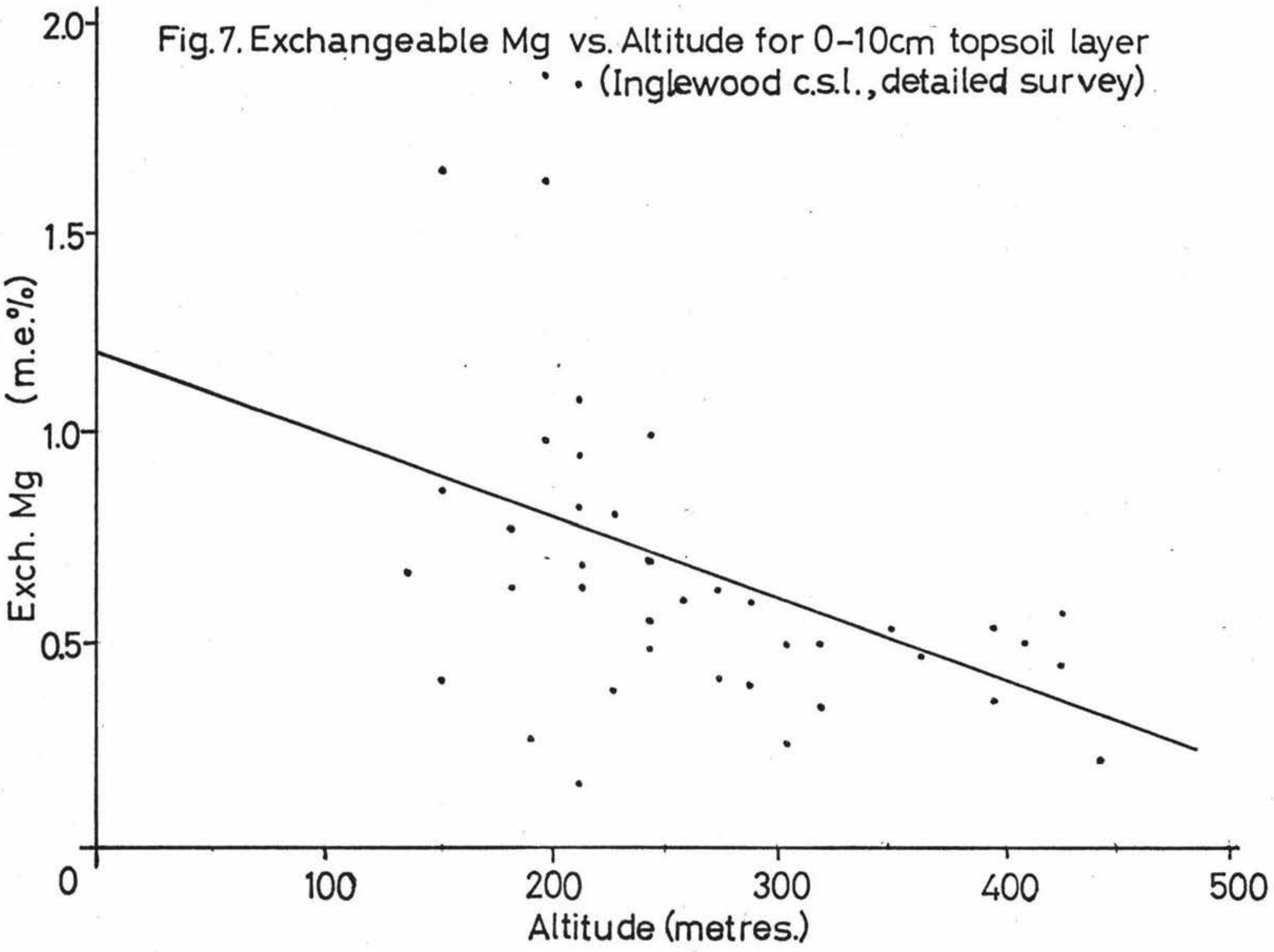
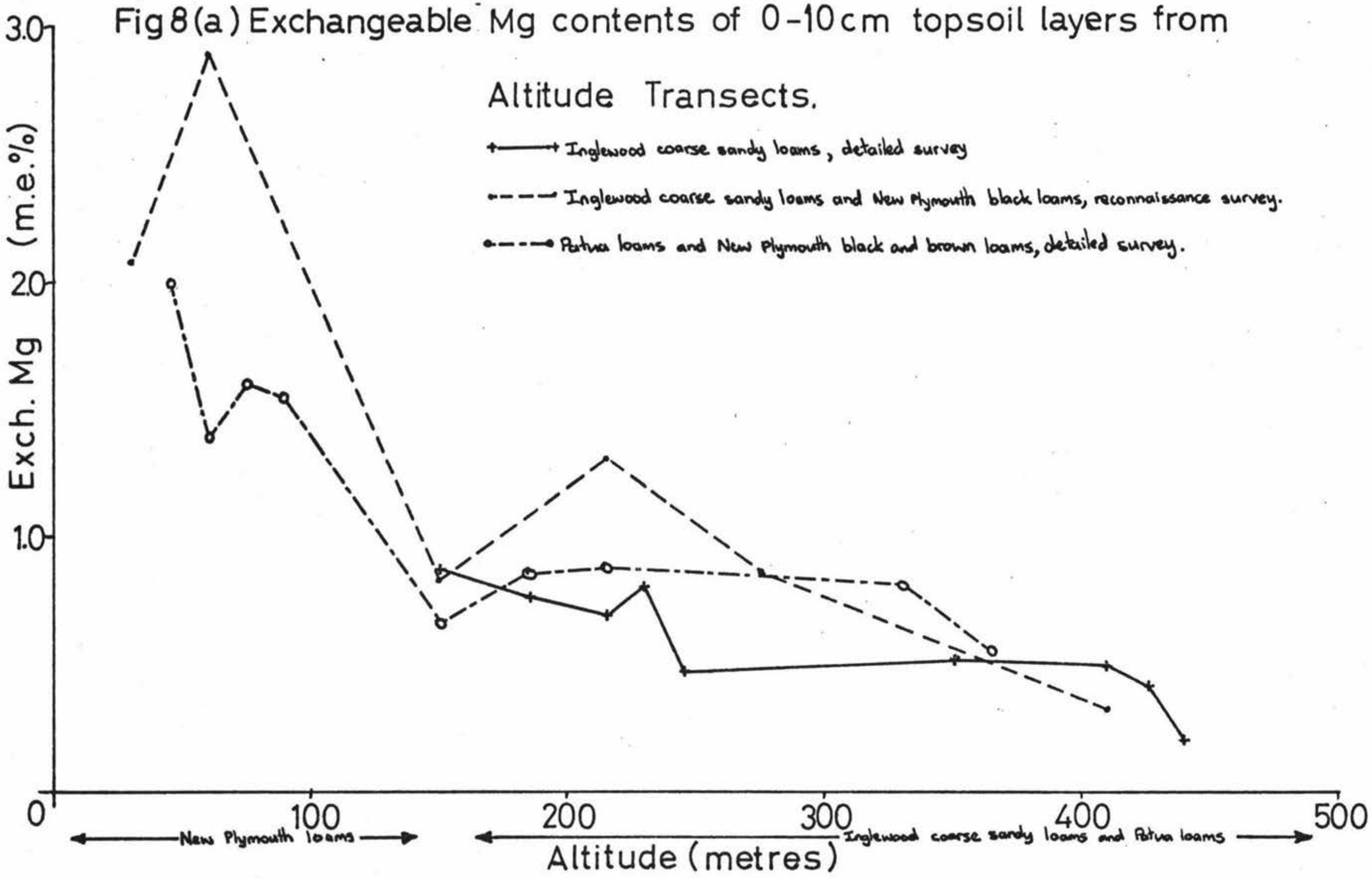


Fig. 7. Exchangeable Mg vs. Altitude for 0–10cm topsoil layer (Inglewood c.s.l., detailed survey)

Fig 8(a) Exchangeable Mg contents of 0-10cm topsoil layers from Altitude Transects.



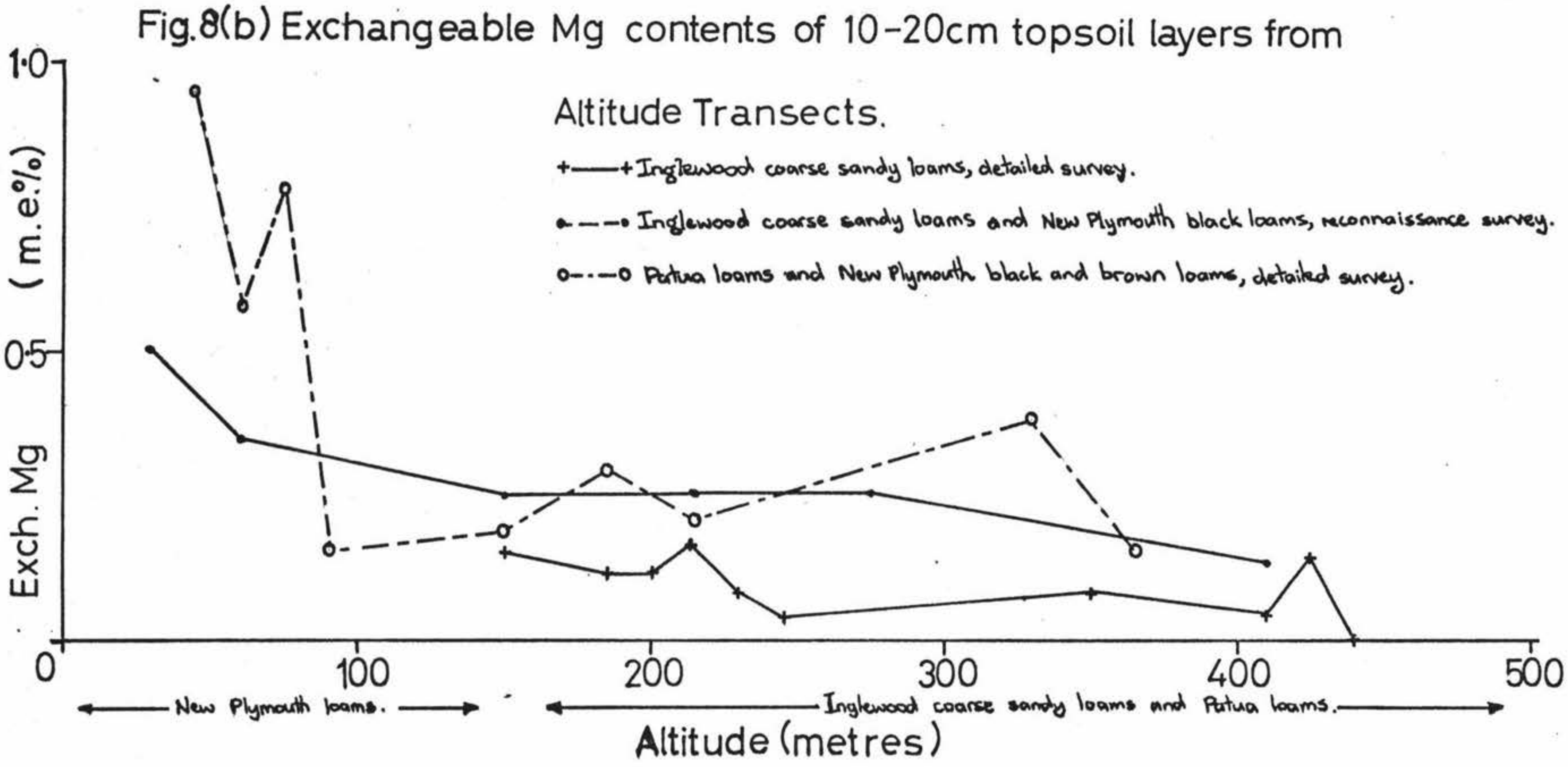


Fig. 8(b) Exchangeable Mg contents of 10-20cm topsoil layers from Altitude Transects.

To examine the effects of increasing altitude on the exchangeable Mg content of soils formed on a different parent material, an altitude transect of soils along Upper and Lower Pitone Roads was made. The soil types from which samples were taken vary from New Plymouth black and brown loams at lower altitudes to Patua loams at higher altitudes. Exchangeable Mg contents varied from 0.56 to 1.99 m.e.% Mg and from 0.16 to 0.95 m.e.% Mg in the 0-10cm and 10-20cm topsoil layers, respectively (Appendix 2). For both depths, exchangeable Mg content decreased with increasing altitude (Fig 8 a, b), although the decrease in the 10-20cm layer did not reach statistical significance:

0-10cm: $y = 1.74 - 0.004x$; $r = -0.82^{**}$ $(n = 9)$

10-20cm: $y = 0.66 - 0.002x$; $r = -0.59$ n.s. $(n = 9)$

There are marked discontinuities in the trend of exchangeable Mg contents with increasing altitude in the 0-10cm depths for both the New Plymouth b.l. - Inglewood c.s.l. transect of the reconnaissance survey and the New Plymouth b.l. - Patua loam altitude transect in the detailed survey (Fig 8a.) These discontinuities occur at approximately 150m altitude, coinciding with the change from New Plymouth brown loam to either Inglewood c.s.l. or Patua loam. A marked decline in exchangeable Mg content with increasing altitude also occurs at altitudes of 300-400m on both the Inglewood c.s.l. altitude transects and on the New Plymouth black and brown loams - Patua loam altitude transects. These two discontinuities occur at a similar altitude at which incipient iron mobilisation (150m) and the formation of thin iron pans (> 300m) have been observed (V. E. Neall, pers. comm). This suggests that the mobilisation of both Mg and Fe from primary soil forming minerals is occurring at similar altitudes and is possibly related to an increase in leaching intensity with increasing altitude. Similar discontinuities are evident, although less marked, in the 10-20cm depths (Fig 8b).

While total Mg contents are similar at all altitudes in soils formed on Inglewood Tephra (Table 18; V. E. Neall, pers. comm.) the ratio exchangeable Mg/total Mg decreases as altitude increases:

$y = 1.39 - 0.002x$; $r = -0.68^{*}$ $(n = 12)$

(where y = exchangeable Mg/total Mg ; x = altitude in metres)

Table 18 Exchangeable Mg, Total Mg, soil CEC, $\frac{\text{Exch. Mg}}{\text{total Mg}}$ and Mg saturation of CEC for selected sampling sites on Inglewood c.s.l.

Sample	Altitude	Exch. Mg	Total Mg	CEC	$\frac{\text{Exch. Mg}}{\text{Total Mg}}$	$\frac{\text{Mg}}{\text{CEC}}$
	(m)	———	m.e. %	--		(%)
19	151	0.84	72	31.7	0.012	2.7
20	213	1.31	87	36.4	0.012	3.6
27	213	0.89	81	-	0.010	-
7 a	213	0.57	96	-	0.006	-
7 b	213	0.24	156	-	0.002	-
28	244	1.29	86	26.0	0.015	5.0
22	351	0.47	80	-	0.006	-
30	396	0.20	135	26.5	0.002	0.8
13	411	0.33	90	24.3	0.003	1.4
4	503	0.29	107	-	0.003	-
10	503	0.28	98	21.8	0.003	1.3
31	503	0.37	94	28.3	0.004	1.3

This indicates that at higher altitudes, a smaller proportion of the total Mg present is in exchangeable form. Two possible sets of factors may contribute to the decrease in exchangeable Mg with increasing altitude:

i) Rainfall. Annual rainfall, and hence leaching intensity, increases with increasing altitude, over the area covered by the Inglewood Tephra. The range is from approximately 1 700mm p.a. at 150m of altitude to 3 800mm p.a. at 500m of altitude.

ii) Chemical weathering. Classically, the intensity of chemical weathering processes, especially the hydrolysis of primary silicates (Fitzpatrick 1971, pp 27) are thought to decrease with increasing altitude, although Ruxton (1968) has evidence for a reverse trend in weathering of tropical volcanic ash soils in Papua.

In this study, there is evidence for a decrease in soil CEC values with increasing altitude (Table 18):

$$y = 36.8 - 0.03x \; ; \; r = -0.71^{*} \; (n = 7),$$

(where y = soil CEC; x = altitude in metres).

which is probably indicative of a reduction in the intensity of chemical weathering processes at higher altitudes, because soil CEC is partly determined by clay minerals produced from the weathering of soil-forming minerals.

The Mg saturation of the soil CEC also decreases with increasing altitude (Table 18):

$$y = 5.12 - 0.01x \; ; \; r = -0.76^{*} \; (n = 7)$$

(where y = (exchangeable Mg/CEC) x 100 ; x = altitude in metres)

an effect which could be attributed to the increase in leaching intensity with increasing altitude. Previous studies (Beeson, 1959; Wiklander, 1974) confirm that where soils are formed from similar parent materials (eg sedimentary rocks or loess) the saturation of soil CEC with bases decreases with increasing leaching intensity.

At the higher altitudes, the combination of the reduced rates of Mg release from primary minerals, the lower soil CEC's

Table 19 Exchangeable Mg, total Mg, soil CEC, and indices of soil Mg status for a range of Taranaki yellow-brown loams

Soil Type	Altitude (m)	Exch. Mg	Total Mg m.e.%	CEC	Exch. Mg / Total Mg	Mg / CEC %
Burrell gravelly sandy loam	427	1.84	111	27.1	0.02	6.8
Hangatahua bouldery sand	320	0.65	63	18.1	0.01	3.6
Newall bouldery sand	396	1.38	79	28.4	0.02	4.9
Norfolk bouldery sand	335	0.28	82	26.5	0.003	1.1
Patua loam	426	0.53	-	31.3	-	1.7
Stratford course sandy loam	320	0.14	78	22.4	0.002	0.6
New Plymouth black loam	61	2.91	67	39.4	0.07	7.4

and the higher leaching intensity, would lead to a smaller pool of exchangeable Mg compared to soils at lower altitudes. The apparent similarity between the altitudes at which incipient iron mobilisation and iron pan formation occur and changes in the rate of decrease of exchangeable Mg content with increasing altitude in the 0-10cm topsoil layer suggests that leaching intensity may be the major factor influencing the size of the exchangeable Mg pool in soils formed on Inglewood Tephra. The decrease in the Mg saturation of soil CEC with increasing altitude would support this contention.

The decrease in exchangeable Mg content with increasing altitude in soils formed on the New Plymouth black and brown loams - Patua loam altitude transect suggests that similar factors to those discussed above also affect exchangeable Mg contents in these soils. The results of exchangeable and total Mg content and soil CEC determinations on soil samples collected from other soil types (Table 19) also indicate that the above factors influence exchangeable Mg contents of other soils in Taranaki. The percentage Mg saturation of soil CEC and the value of the ratio exchangeable Mg/total Mg are generally lower for soils at higher altitudes (Burrell gravelly sandy loam, Hangatahua bouldery sand, Newall bouldery sand, Norfolk bouldery sand, Patua loam, Stratford coarse sandy loam) than for soils at lower altitudes (New Plymouth black loam).

5.2 Pot Experiment

5.2.1. Initial Soil Magnesium Status

Exchangeable Mg, Ca, K, reserve and total Mg contents, soil pH and soil CEC for the unamended soils are given in Table 20 . It is apparent from these results and from experience working with these soils in the field and in the laboratory, that the soils used in the experiment could be grouped into two broad classes, viz: coarse textured soils of low exchangeable Mg content (Burrell g.s.l. and Inglewood c.s.l.) and finer textured soils with higher exchangeable Mg contents (New Plymouth and Egmont b.l.'s.). Exchangeable Ca, K, soil Cation exchange capacity (C.E.C.), and to a lesser degree, reserve Mg and soil pH also followed a similar pattern.

Table 20

Analyses of Untreated Soils used in Pot Experiment

Soil Type	Exchangeable Cations (m.e.%)					Percent Saturation of CEC with:			Reserve Mg (m.e.%)	Total Mg (m.e.%)
	Mg	Ca	K	pH	CEC (m.e.%)	Mg	Ca	K		
Burrell gravelly sandy loam	0.24	3.52	0.72	5.9	17.6	1.4	20	4.0	4.44	92.5
Inglewood coarse sandy loam	0.22	1.37	0.58	5.7	19.7	1.1	6.6	2.9	4.44	87.7
Egmont black loam	1.22	7.56	1.10	6.1	25.1	4.9	30	4.4	5.26	74.6
New Plymouth black loam	1.44	10.30	0.80	6.0	30.4	4.7	34	2.6	5.10	85.3

Table 21 Amounts of Mg in soils according to the categories of Metson and Brooks (1975)

Rating	Range (m.e.%) Exchangeable Mg	Reserve Mg
Very high	> 7	> 30
High	3-7	15-30
Medium	1-3	7-15
Low	0.5-1	3-7
Very Low	< 0.5	< 3

According to the criteria proposed by Metson and Brooks (1975), as shown in Table 21, the contents of exchangeable and reserve Mg contents in the Burrell g.s.l. and Inglewood c.s.l. would be considered to be in the very low and low categories respectively, in relation to other New Zealand soils. On the other hand, New Plymouth b.l. and Egmont b.l. would be considered to contain medium amounts of exchangeable Mg and low amounts of reserve Mg. Soils which contain low amounts of reserve Mg but medium to high exchangeable Mg contents would be expected to become depleted of exchangeable Mg with time, especially in areas of high rainfall (Metson and Brooks, loc.cit.)

According to the criteria proposed by Prince (1947), based on the percentage Mg saturation of the CEC, all four soils would be regarded as potentially Mg deficient and likely to respond to fertilizer Mg, as the percentage saturation of the CEC with Mg in each case was less than 6%. Allowing for variations in texture, Metson and Gibson (1974) stated that the minimum Mg saturation of the CEC should ideally range from 6 to 10%, with the higher figure pertaining to sandy soils of low CEC. On this basis, the heavier textured New Plymouth and Egmont b.l. would probably be classed as marginally Mg deficient in Mg, and the Inglewood c.s.l. and Burrell g.s.l., as extremely Mg deficient.

Not one of the soils used in the pot experiment approached the "ideal" percentage saturation of the CEC suggested by Bear and Toth (1948) of 65% Ca, 10% Mg and 5% K. In fact, in the two soils of lowest exchangeable Mg contents, the amounts of exchangeable K exceeded those of exchangeable Mg, which is the opposite situation to that commonly recommended (Bear and Toth, 1948; Graham, 1959; Hooper, 1967). Hooper (1967) considered it necessary for the exchangeable Mg/K ratio to exceed 1.2:1 to ensure that ryegrass herbage contained at least 0.2% Mg. This ratio was approached in the Egmont b.l. (Mg/K = 1.1:1) and exceeded only in the New Plymouth b.l. (Mg:K = 1.8:1). For the other two soils this ratio did not exceed 0.40:1.

These results could be interpreted to indicate that, of the four soils, Burrell g.s.l. and Inglewood c.s.l. which both contained extremely low contents of exchangeable Mg and percentage saturations of CEC with Mg would be expected to be the most responsive to Mg fertilizer additions in a similar way to that reported by Moody (1962) for the coarse-textured Te Rere sand. Smaller responses to Mg fertilizers on New Plymouth and Egmont b.l.'s would be expected on the basis of the above analyses and criteria and the finding that soils of similar exchangeable Mg contents have not generally tended to respond to the application of Mg fertilizers (McNaught et al., 1968b; McNaught et al., 1973 a, b.).

5.2.2. Dry Matter Yields

Ryegrass herbage yields and responses to Mg fertilizer addition and cutting regimes are summarized in table 22 . Yield responses were tested for significance using Yate's method for computing factorial effects. At the first harvest, ryegrass dry matter yields on the coarse textured Burrell g.s.l. and Inglewood c.s.l. were greater than those on the finer-textured New Plymouth b.l. and Egmont b.l. (Table 22). The relative yields obtained from the different soils changed during the course of the experiment so that by the third harvest, the yield ranking was New Plymouth b.l. = Egmont b.l.> Burrell g.s.l.> Inglewood c.s.l.

a) Dry Matter Yield Responses to Mg fertilizer additions

A significant ($p < 0.001$) yield response to Mg fertilizer additions occured at the first harvest (Table 23) over all soils. Although this effect persisted into the second and third harvest, the level of significance declined indicating that the response to Mg became less pronounced with successive harvests. The significant soils x rates of Mg interaction (Table 23), at all harvests, showed that the dry matter yield response to Mg additions varied between soil types.

For the two coarse-textured soils there was a trend for dry matter yields to increase with the addition of Mg at each harvest, which was reflected in the total D.M. yields (Table 22). The trend only reached significance ($p < 0.01$) for Burrell g.s.l. where large yield responses occurred at the first two harvests, and for total D.M. yields. On the finer textured soils there was generally no consistent yield response although at the third harvest a significant ($p < 0.05$) yield response occured

Table 22

Dry Matter Yield responses to Mg additions for each soil type and cutting regime

Treatment (kg Mg ha^{-1})	Cutting Regime	Harvest 1	Harvest 2	Harvest 3	Total
		g D.M. pot^{-1}			
		BURRELL GRAVELLY SANDY LOAM			
0	1	1.58	0.60	1.41	3.59
9	1	2.85	0.77	1.60	5.22
18	1	2.51	0.73	1.41	4.65
36	1	2.27	0.86	1.50	4.63
0	2	1.99	0.67	0.68	3.34
9	2	3.04	0.91	0.82	4.77
18	2	3.02	0.88	0.80	4.70
36	2	3.08	1.01	0.85	4.94
		INGLEWOOD COARSE SANDY LOAM			
0	1	1.17	0.42	0.55	2.14
9	1	1.33	0.41	0.54	2.28
18	1	1.56	0.40	0.59	2.55
36	1	1.33	0.41	0.62	2.36
0	2	1.52	0.40	0.33	2.25
9	2	1.74	0.42	0.35	2.51
18	2	1.67	0.49	0.32	2.48
36	2	1.49	0.48	0.51	2.48
		EGMONT BLACK LOAM			
0	1	1.09	0.83	1.38	3.30
9	1	1.06	0.95	1.96	3.97
18	1	0.91	0.90	1.64	3.45
36	1	1.00	0.93	1.86	3.79

Table 22 (Cont..)

Treatment (kg Mg ha^{-1})	Cutting Regime	Harvest 1	Harvest 2	Harvest 3	Total
		EGMONT BLACK LOAM			
0	2	1.45	1.08	0.89	3.42
9	2	1.37	1.07	0.79	3.23
18	2	1.44	1.30	0.77	3.51
36	2	1.50	1.09	0.81	3.40
		NEW PLYMOUTH BLACK LOAM			
0	1	0.86	0.68	1.72	3.26
9	1	0.78	0.59	1.42	2.79
18	1	0.75	0.63	1.33	2.71
36	1	0.88	0.61	1.63	3.12
0	2	1.12	0.87	0.85	2.84
9	2	1.05	0.81	0.80	2.66
18	2	0.90	0.82	0.83	2.55
36	2	1.10	0.92	0.93	2.95
LSD	5%	0.39	0.15	0.26	0.56
	1%	0.52	0.20	0.34	0.74

Table 23

Summary of Treatment Effects on Yields at each Harvest and for Total accumulated Yield

	Treatment Effects			Interactions			
	M	R	S	M x R	S x R	S x M	S x M x R
Harvest One	** ; +ve	*** 1 2	***	NS	NS	***	NS
Harvest Two	** ; +ve	*** 1 2	***	NS	**	**	NS
Harvest Three	* ; +ve	*** 1 2	***	NS	***	*	NS
Total DM Yield	***; +ve	*	***	*	NS	***	NS
Harvest Interaction	*	***	***	NS	***	***	NS

*; **; ***; Significant at $p < 0.05; < 0.01; < 0.001$. NS: Not Significant

M = Mg fertilizer

R = Cutting Regime

S = Soil Type

Effects tested for significance using the F-test on Egmont b.l. under cutting regime 1, but not under cutting regime 2. The differential results for the two cutting regimes are not readily explained. There were no total D.M. yield responses on New Plymouth b.l., and Egmont b.l. under cutting regime 2; the significant total D.M. yield response of Egmont b.l. under cutting regime 1 being due to the yield response at the third harvest.

b) Effects of Cutting Regimes

For all soil types significant ($p < 0.001$) dry matter yield differences occured between the two cutting regimes at all harvests (Table 23). At harvests 1 and 2, yields from cutting regime 2 exceeded those from cutting regime 1. At harvest 3 however, the reverse situation occured. These differences were probably due to the different growth periods at harvests 1 and 3 together with the different temperature conditions at harvests 1 and 2. For example, at harvest 1 the regrowth period was 11 days longer under cutting regime 2 than under cutting regime 1, and in addition a temperature increase (from 12C day/5 C (night) to 14 C (day)/7 C (night) also occured during this period (Table 11). At the second harvest, although the growth period was constant at 21 days, the yields from cutting regime 2 were again greater than those from cutting regime 1 (Table 22), as the plants grew through a temperature change, from 14 C (day)/ 7 C (night) to 16 C (day)/9 C (night) under the former regime, whereas those growing under the latter regime experienced constant temperatures of 14 C (day)/7 C (night) throughout. At the third harvest the differences in drymatter yields between the two cutting regimes reflected the different growth periods, viz:21 days under cutting regime 1 and 10 days under cutting regime 2. Temperature was constant over both regimes, at 16 C (day)/9 C (night).

c) Discussion

The pattern of dry-matter yield responses to Mg additions found for the four soils in this study agree in principle with the results previously obtained by other workers (Moody, 1962; Dorofaeff and McNaught, 1962; McNaught and Dorofaeff, 1965; McNaught and Ludecke, 1967; McNaught et al., 1968 a, b; Hogg and Karolvsky, 1968; Hogg and Toxopeus, 1973; McNaught et.al.,1973 a, b; Toxopeus and McNaught 1973; Metson, 1974), in which responses were commonly found on coarse textured soils of low pH and with soil exchangeable Mg contents of approximately 0.2 m.e.% or less. Few results of field or glasshouse experiments have been reported in New Zealand and fewer still have reported pasture yield responses to varying rates of Mg addition. Moody (1962) concluded that there was no significant difference in pasture yields on Te Rere sand between 250 and 500 kg ha^{-1} of $MgSO_4 \cdot 7H_2O$ (10% Mg). Later work has been mainly concerned with comparing pasture dry matter yields in the presence and absence of Mg additions. High rates of Mg addition (such as dolomite at 2 500 kg ha^{-1}) did not result in increased dry-matter yields over lower rates of Mg, but rather appeared to sustain the increases in yields over a longer period on responsive soils (McNaught et al., 1973a). The results of the present experiment, in which there was generally no significant difference between ryegrass yields from the 9 and 36 kg Mg ha^{-1} rates on the responsive soils (Table22) are in general agreement with these findings.

Yield responses to Mg addition on soils derived from rhyolitic Taupo pumice have been obtained at soil exchangeable Mg contents of from 0.15 to 0.20 m.e.% Mg (Moody, 1962; Hogg and Karlovsky, 1968). The results of the present experiment suggest that responses to Mg may also occur on soils derived from andesitic parent materials with similar exchangeable Mg contents. Yellow-brown loam soils derived from rhyolitic material with exchangeable Mg contents of ca. 1.0 m.e.% Mg have not shown yield responses to Mg fertilizer (McNaught and Ludecke, 1967; McNaught et.al., 1968; McNaught et.al., 1973 a, b) and other soil types of comparable or higher exchangeable Mg content have given similar results. The lack of a significant yield response to Mg additions for ryegrass on New Plymouth b.l. (exch. Mg 1.44 m.e.%) concurs with this general observation.

However, the indication of a response to Mg addition at the third harvest on Egmont b.l. (exch. Mg 1.22 m.e.%) indicates that this soil may contain a limited supply of plant available Mg. In an analysis of the Mg economy of pasture on a Horotiu sandy loam (1.5 m.e.% exch. Mg, 0.25cm, 0.6 m.e.% exch. Mg, 2.5-7.5cm), a soil of similar exchangeable Mg status to Egmont b.l., During et.al.,(1973) concluded that the soil was marginal in content of plant available Mg, and suggested that any loss of Mg from the soil-plant system could result in depressed plant Mg contents and also dry-matter yields. The results obtained in this present experiment, where herbage was removed at each harvest, coupled with the known low content of reserve Mg (Table 20 , and also Metson, 1968; Metson and Brooks, 1975) suggest that Egmont black loam may be very similar to Horotiu sandy loam with regard to the amounts of Mg available for plant uptake.

The lack of a significant yield response to Mg additions on Inglewood c.s.l. cannot be fully explained on the basis of soil Mg status, as the exchangeable Mg content of this soil was low enough to expect a yield response to follow Mg addition. However it is possible that ryegrass yields on Inglewood c.s.l. were limited by a deficiency of some other nutrient element, possibly one of the trace elements.

The differences in dry-matter yields produced at harvest 2 for the two cutting regimes appears to be related to the differences in the temperature conditions of the two regimes, as described previously. The ryegrass plants in cutting regime 2 grew at temperatures close to the optimum for ryegrass of between 15-16 C (Mitchell, 1956) for the latter half of this growth interval. Below this optimum temperature, a sharp decline in the rate of tiller dry-matter production has been found to occur (Mitchell, loc. cit.) and may explain the lower dry matter productionof ryegrass growing at the constant 14 C (day)/7 C (night) temperature conditions under cutting regime 1. A similar temperature effect may explain the differences in dry matter production obtained at harvest 2 and 3 in cutting regime 1, where a two-fold increase in dry matter production occured on three of the soils between the two harvests. Inglewood c.s.l. was again the exception.

A further factor that may have contributed to the increase dry matter yield between harvests 2 and 3 in cutting regime 1 could have been an increase in tiller numbers. Although no count of tiller numbers was taken during the experiment, tiller numbers probably did increase over the course of the experiment. The similarity in dry-matter yields between harvests 2 and 3 in cutting regime 2 could thus be attributed to both a temperature effect on growth and an increased rate of dry matter production due to increased numbers of tillers on each ryegrass plant compensating for the differences in the lengths of the regrowth periods for the two harvests.

5.2.3. Plant Magnesium

a) Plant Mg concentration

Ryegrass Mg concentrations generally increased with increasing rates of fertilizer Mg addition on all soils and for both cutting regimes (Table24). The largest main effects of Mg addition occured in Burrell g.s.l. and Inglewood c.s.l. where the mean plant Mg concentration averaged over all harvests increased from 0.16 to 0.22% and 0.13 to 0.21% respectively, for cutting regime 1, and from 0.17 to 0.25% and 0.13 to 0.22% respectively, for cutting regime 2. Smaller increases in mean plant Mg concentrations were found for New Plymouth b.l. and Egmont b.l., ranging from 0.24 to 0.28% and 0.22 to 0.25% respectively for cutting regime 1, and from 0.25 to 0.29% and 0.24 to 0.28% respectively, for cutting regime 2. All of the above increases were found to be statistically significant ($p < 0.001$). In most cases the minimum Mg concentrations occured in the untreated controls and the maximum concentrations for the highest rate of Mg addition (36 kg Mg ha^{-1}).

Linear regression analyses of plant Mg concentration and Mg fertilizer rates confirmed the above trends (Table25) for both mean Mg contents, calculated as the weighted means adjusted for dry matter yields at each harvest, and for plant Mg concentrations at each harvest. For each increment of Mg addition, the rate of increase of plant Mg concentration on Burrell g.s.l. and Inglewood c.s.l. was approximately double that occuring on New

Table 24

Ryegrass Mg concentrations in relation to soil type, Mg fertilizer addition, cutting regime, and Harvest period

Soil Type	Mg Rate (kg ha^{-1})	Cutting Regime	Harvest number: 1	2	3	Mean$^{(1)}$
				%Mg		
				± 0.01		
Burrell gravelly sandy loam	0	1	0.12	0.12	0.23	0.16
	9		0.14	0.16	0.28	0.18
	18		0.14	0.16	0.28	0.18
	36		0.16	0.19	0.33	0.22
				± 0.01		
	0	2	0.13	0.24	0.22	0.17
	9		0.14	0.29	0.29	0.20
	18		0.15	0.29	0.27	0.20
	36		0.18	0.36	0.36	0.25
				± 0.01		
Inglewood coarse sandy loam	0	1	0.12	0.11	0.15	0.13
	9		0.13	0.13	0.20	0.15
	18		0.16	0.16	0.22	0.17
	36		0.19	0.18	0.26	0.21
				± 0.01		
	0	2	0.11	0.14	0.23	0.13
	9		0.15	0.17	0.25	0.16
	18		0.18	0.20	0.26	0.19
	36		0.19	0.24	0.25	0.22

Table 24 (Cont..)

Soil Type	Mg Rate (kg ha^{-1})	Cutting Regime	Harvest number: 1	2	3	Mean(1)
			%Mg			
			± 0.01			
Egmont black loam	0	1	0.21	0.21	0.23	0.22
	9		0.23	0.22	0.25	0.22
	18		0.23	0.24	0.26	0.25
	36		0.25	0.25	0.25	0.25
			± 0.01			
	0	2	0.21	0.28	0.23	0.24
	9		0.24	0.29	0.25	0.26
	18		0.25	0.29	0.25	0.26
	36		0.27	0.31	0.25	0.28
			± 0.01			
New Plymouth black loam	0	1	0.21	0.20	0.27	0.24
	9		0.19	0.21	0.26	0.23
	18		0.23	0.21	0.28	0.25
	36		0.24	0.24	0.31	0.28
			± 0.01			
	0	2	0.21	0.30	0.26	0.25
	9		0.24	0.28	0.26	0.26
	18		0.23	0.27	0.27	0.26
	36		0.26	0.31	0.31	0.29

(1) Weighted mean; according to dry matter yields at each harvest.

Plymouth b.l. and Egmont b.l. The relative increases in plant Mg content found for the different soil types in this experiment are in general agreement with the results obtained from previous trials (Moody, 1962; Reith, 1963; Salmon and Arnold, 1963; McNaught and Ludecke, 1967; McNaught et.al., 1968 a, b; 1973 a, b) in which the largest responses generally occured on coarse-textured soils of low (Ca. 0.02-0.03 m.e.%) exchangeable Mg contents.

The different relative responses to Mg additions probably result from the fact that:

i) Ryegrass Mg content has been found to be linearly related to the activity ratio $\frac{A_{Mg}}{A_{Mg+Ca}}$ in the soil solution, for soils of similar K content (Salmon, 1964); and

ii) $\frac{A_{Mg}}{A_{Mg+Ca}}$ has been found to be directly related to soil exchangeable Mg contents within a single soil type (Arnold, 1967)

However, the rate of change of the activity ratio $\frac{A_{Mg+Ca}}{A_{Mg+Ca}}$ with increasing exchangeable Mg content differs between soil types. Arnold (1967) presented data (from Salmon, 1962) which indicated that the changes in this activity ratio for unit changes in soil exchangeable Mg content were larger in soils of low cation exchange capacity than in soils of high cation exchange capacity A similar relationship between soil exchangeable Mg and the same activity ratio for different soil types, was shown by Alston (1972) who concluded that the ability of any soil to buffer changes in the activity ratio varied in proportion to the soil exchangeable Mg content. It would be expected, therefore, that the activity ratio $\frac{A_{Mg}}{A_{Mg+Ca}}$ and hence the plant available Mg content of a soil would increase less rapidly in response to additions of fertilizer Mg, the higher the C.E.C. of a soil. The results of the linear regression analyses (Table25) are taken as evidence that similar relationships to those described above probably also hold for the soils used in this experiment.

There was a strong tendency for plant Mg concentrations to increase with successive harvests on all soils. This increase was significant ($p < 0.001$) for all soils except Egmont

Table 25

Results of Linear Regression Analyses of Herbage Mg conc. (% D.M.) (y) vs. adjusted treatment number (x)(1)

First Harvest	Cutting Regime	
Burrell	1	$y = 0.01x + 0.11$; $r = 0.83$ ***(2,3)
	2	$y = 0.01x + 0.11$; $r = 0.86$ ***
Inglewood	1	$y = 0.02x + 0.10$; $r = 0.92$ ***
	2	$y = 0.02x + 0.11$; $r = 0.87$ ***
Egmont	1	$y = 0.01x + 0.20$; $r = 0.73$ **
	2	$y = 0.01x + 0.20$; $r = 0.90$ ***
New Plymouth	1	$y = 0.01x + 0.18$; $r = 0.63$ **
	2	$y = 0.01x + 0.21$; $r = 0.76$ ***
Second Harvest		
Burrell	1	$y = 0.02x + 0.12$; $r = 0.87$ ***
	2	$y = 0.03x + 0.22$; $r = 0.87$ ***
Inglewood	1	$y = 0.02x + 0.09$; $r = 0.90$ ***
	2	$y = 0.03x + 0.20$; $r = 0.93$ ***
Egmont	1	$y = 0.01x + 0.20$; $r = 0.72$ **
	2	$y = 0.01x + 0.27$; $r = 0.73$ **
New Plymouth	1	$y = 0.01x + 0.19$; $r = 0.72$ **
	2	$y = 0.01x + 0.28$; $r = 0.29$ ns

Table 25 (Cont..)

Third Harvest	Cutting Regime	
Burrell	1	y = 0.022 + 0.22 ; r = 0.90 ***
	2	y = 0.03x + 0.20 ; r = 0.89 ***
Inglewood	1	y = 0.02x + 0.14 ; r = 0.81 ***
	2	y = 0.02x + 0.15 ; r = 0.76 ***
Egmont	1	y = 0.005x + 0.23 ; r = 0.39 ns
	2	y = 0.005x + 0.23 ; r = 0.39 ns
New Plymouth	1	y = 0.01x + 0.24 ; r = 0.79 ***
	2	y = 0.02x + 0.24 ; r = 0.83 ***
Overall		
Burrell	1	y = 0.02x + 0.15 ; r = 0.85 ***
	2	y = 0.02x + 0.15 ; r = 0.91 ***
Inglewood	1	y = 0.02x + 0.11 ; r = 0.95 ***
	2	y = 0.02x + 0.11 ; r = 0.93 ***
Egmont	1	y = 0.01x + 0.22 ; r = 0.72 **
	2	y = 0.01x + 0.23 ; r = 0.89 ***
New Plymouth	1	y = 0.01x + 0.22 ; r = 0.79 ***
	2	y = 0.01x + 0.23 ; r = 0.82 ***

Table 25 (Cont..)

Results of Linear Regression Analyses of Herbage Mg conc. (% D.M.) (y) vs. adjusted treatment number (x)(1)

(1) Treatments were numbered as control; 1: 9 kg Mg ha^{-1};
2: 18 kg Mg ha^{-1};
3: 36 kg Mg ha^{-1};
5: such that (adjusted trt. numbers -1) x 9 = rate of Mg applied in kg/ha.

(2) There were 14 d.f. for each regression.

(3) Significance is indicated by: ns - not significant
* - significant ($p<0.05$)
** - significant ($p<0.01$)
***- significant ($p<0.001$)

b.l., where the increase was less marked ($p<0.01$ for cutting regime 1). For cutting regime 1, the maximum plant Mg concentration occured at the final harvest on all soils. The largest overall increases (from 0.12 to 0.28% Mg) occured on Burrell g.s.l., with smaller increases occuring on Inglewood c.s.l. (from 0.15 to 0.21%Mg), New Plymouth b.l. (from 0.22 to 0.28% Mg) and Egmont b.l. (from 0.23 to 0.25% Mg). For cutting regime 2, the maximum plant Mg concentration was reached at harvest 2 for all soils except Inglewood c.s.l. Under this regime plant Mg concentrations at harvest 3 remained similar to those in the second harvest (Table 26) except for Inglewood c.s.l., where a further slight increase occured at the third harvest, and Egmont b.l., where Mg content of the herbage decreased at the third harvest. The largest increases in plant Mg concentration again occured on Burrell g.s.l. (from 0.15 to 0.29% Mg) with smaller increases on Inglewood c.s.l. (from 0.16 to 0.22% Mg), New Plymouth b.l. (from 0.23 to 0.29% Mg) and Egmont b.l. (from 0.24 to 0.29% Mg).

The differences in ryegrass Mg concentrations between the control (0 kg Mg ha^{-1}) and the highest rate of Mg addition (36 kg Mg ha^{-1}) are presented in Table 27 for each harvest. The data suggest that on the two soils of low (ca. 0.2 - 0.3 m.e.% Mg) exchangeable Mg content there was a greater increase in plant Mg concentration with additions of Mg and increasing temperature than on those of higher (ca. 1.2 - 1.4 m.e.% Mg) exchangeable Mg contents. This evidence for an increase in Mg content of ryegrass plants with increasing temperature regimes in good agreement with the results of previous work with a range of plant species (Dijkshoorn and T'Hart, 1957; Hendricks and Grunes, 1966; Grunes et. al., 1968; McNaught et. al., 1968 b) and more particularly for other grass species and for mixed pasture herbage (McNaught, 1964; Stuart et. al., 1973). It has been suggested (Kemp and T'Hart, 1957) that a critical minimum temperature appears to exist for perennial ryegrass below which Mg uptake responds only slightly to increases in soil and air temperature. Once this critical minimum temperature, of approximately 14 C is exceeded in the spring, Mg uptake by ryegrass increases rapidly. The results of the present study (Tables 24 and 27) indicate that for all soils the increases in plant Mg

Table 26 Average Ryegrass Mg concentrations for successive harvests (means of all treatments)

Soil type	Cutting Regime	Harvest 1	Harvest 2	Harvest 3	F (2/36 d.f.)
Burrell	1	0.14	0.16	0.28	451.3 ***
	2	0.15	0.29	0.28	349.8 ***
Inglewood	1	0.15	0.14	0.21	51.1 ***
	2	0.16	0.19	0.22	25.9 ***
Egmont	1	0.23	0.23	0.25	7.38 **
	2	0.24	0.29	0.25	78.5 ***
New Plymouth	1	0.22	0.21	0.28	80.3 ***
	2	0.23	0.29	0.28	45.2 ***

Table 27 Differences in plant Mg content between control (0 kg Mg ha^{-1}) and the highest (36 kg Mg ha^{-1}) Mg treatment rate.

Soil Type	Cutting Regime	Harvest 1	Harvest 2	Harvest 3
		% Mg		
Burrell g.s.l.	1	0.04	0.07	0.10
	2	0.05	0.12	0.14
Inglewood c.s.l.	1	0.07	0.07	0.11
	2	0.08	0.10	0.03
Egmont b.l.	1	0.04	0.04	0.02
	2	0.06	0.03	0.02
New Plymouth b.l.	1	0.03	0.04	0.04
	2	0.05	0.01	0.05

concentration between harvests 2 and 3 in cutting regime 1, and between harvests 1 and 2 under cutting regime 2 occured following the transition from a temperature environment of 14 C (day)/ 7 C (night) to one of 16 C (day)/9 C (night). It has already been shown (Dijkshoorn and T'Hart, 1957; Hendricks and Grunes, 1966; Grunes et al, 1968) that when temperature changes occur during a period of plant growth, temperature conditions at the conclusion of the growth period exert a stronger influence on ryegrass Mg concentrations than do those operating during the early part of the growth period. Thus, the higher temperatures at the conclusion of the second growth period under cutting regime 2, when day temperature increased from 14 C to 16 C midway through the period are reflected in the finding of an increase in Mg concentrations between harvests 1 and 2. Conversely the reduction in temperature when the plants were moved from the glasshouse (at 20 C) to the growth room (initially at 12 C day/ 5 C (night) may be responsible for the finding of lower plant Mg concentrations at the first harvest for all regimes. Again, the increase in temperature from 12 C (day) to 14 C (day) between harvests 1 and 2 in cutting regime 1 did not exceed the apparent critical minimum temperature of 14 C and so plant Mg concentrations were similar at each of these two harvests.

There appears to be no general consensus as to the physiological causes of this temperature effect on Mg uptake by plants. Since Mg uptake by plant roots is thought to be metabolically controlled (Collander, 1941; Epstein and Legget, 1954; Brouwer, 1956; Sutcliffe, 1967; Hodges, 1973) any increase in plant Mg concentration with increasing temperature may be explained in terms of increased rates of plant metabolism (Corey, 1973). Also, increasing temperature would be expected to stimulate root growth, and if the optimum temperature for ryegrass root growth is similar to that for ryegrass tillers, viz. 15 C (Mitchell, 1956) then increased exploration of the soil volume by roots may account for some of the increase in plant Mg uptake since the greater exploration of the soil volume by plant roots would decrease the mean distance for transport of nutrients from the soil to the plant root (Mengel, 1974). In addition, the interception of nutrients by plant roots growing through a soil has been shown to provide a significant proportion of plant Mg requirements (Barber, 1966) and any increase in root volume in response to temperature increases would be expected to result in increased Plant Mg uptake.

b) Plant Mg Uptake

Mg uptake at each harvest followed a similar pattern to that found for Mg concentrations (Table 28). A feature of the results was the similarity in total Mg uptake for the two cutting regimes, suggesting that the same total quantities of soil and fertilizer Mg were utilised within each regime. Hence in the following discussion concerning total Mg uptake the results used are the means of the two cutting regimes. The greatest relative uptake responses occured on the Burrell g.s.l. and Inglewood c.s.l., from 5.7 to 11 mg Mg/pot and from 2.9 to 5.4mg Mg/pot, respectively. For these two soils the highest rate of Mg application (36kg Mg ha^{-1}) produced an apparent two-fold increase in plant Mg uptake over the untreated controls. There were smaller increases in plant Mg uptake on the New Plymouth and Egmont b.l., where total Mg uptake increased from 7.5 to 8.7mg Mg/pot and 7.7 to 9.5mg Mg/pot, respectively.

At each separate harvest, Mg uptake responses occured as the result of dry matter yield and/or Mg concentration responses. Thus Mg uptake responses occured on Burrell g.s.l. (dry matter yield and Mg concentration responses) and Inglewood c.s.l. (Mg concentration responses) at the first two harvests, and on Egmont b.l. at harvest 3 in cutting regime 1 and harvest 2 in cutting regime 2 (dry matter yield responses). There were no Mg uptake responses at any single harvest on New Plymouth b.l.

The effect of increasing temperature on Mg uptake is shown by the differences between Mg uptakes in cutting regimes 1 and 2 at harvest 2 when Mg uptake was significantly greater ($p < 0.001$) under the higher temperature cutting regime 2, for all soils (Tables 28 and 29). This was due to concomitant differences in dry matter yields and plant Mg concentrations between the two regimes (regime 2 > regime 1). The effect of increasing temperature is again demonstrated by the large increases in Mg

Table 28

Mg uptake in relation to soil type, Mg fertilizer addition rate and cutting regime

Soil Type	Mg Rate ($kg\ ha^{-1}$)	Cutting Regime	Harvest Number 1	2	3	Total
			— mg pot^{-1} —			
Burrell gravelly sandy loam	0	1	1.9	0.8	3.2	5.9
	9		3.8	1.2	4.5	9.5
	18		3.6	1.3	4.0	8.9
	36		3.7	1.6	5.0	10.3
	0	2	2.5	1.6	1.5	5.6
	9		4.2	2.7	2.4	9.3
	18		4.5	2.5	2.1	9.1
	36		5.5	3.6	3.0	2.1
Inglewood coarse sandy loam	0	1	1.4	0.5	1.0	2.9
	9		1.7	0.6	1.1	3.4
	18		2.5	0.6	1.3	4.4
	36		2.5	0.8	1.6	4.9
	0	2	1.7	0.6	0.6	2.9
	9		2.6	0.7	0.7	2.0
	18		3.0	1.1	0.7	4.8
	36		2.9	1.2	1.4	5.5
LSD	0.05		0.8	0.4	0.8	1.4
	0.01		1.0	0.6	1.0	1.6

Table 28 (Cont..)

Soil Type	Mg Rate (kg ha^{-1})	Cutting Regime	Harvest Number			Total
			1	2	3	
			mg pot^{-1}			
Egmont black loam	0	1	2.2	1.7	3.2	7.1
	9		2.4	2.1	4.9	9.4
	18		2.0	2.2	4.3	8.5
	36		2.5	2.3	4.6	9.4
	0	2	3.1	3.1	2.0	8.2
	9		3.2	3.1	2.0	8.3
	18		3.6	3.8	1.9	9.3
	36		4.0	3.4	2.1	9.5
New Plymouth black loam	0	1	1.8	1.4	4.6	7.8
	9		1.5	1.3	3.6	6.4
	18		1.7	1.2	3.7	6.6
	36		2.1	1.5	5.0	8.6
	0	2	2.4	2.6	2.2	7.2
	9		2.5	2.3	2.1	6.9
	18		2.0	2.2	2.3	6.5
	36		2.9	2.9	2.9	6.7
LSD	0.05		0.8	0.4	0.8	1.4
	0.01		1.0	0.6	1.0	1.6

Table 29

Result of Analysis of Variance of Mg uptakes at harvests 1-3, and total Mg uptake

Classification	d.f.	Sum of Squares	Mean Square	F
First Harvest				
Soil Type	3	0.508	0.169	61.1***
Treatment	3	0.216	0.072	25.9***
Cutting Regime	1	0.21	0.217	78.2***
Soil type x treatment	9	0.160	0.018	6.44***
Soil type x cutting regime	3	0.021	0.007	2.58 n.s.
Cutting regime x treatment	3	0.011	0.004	1.27 n.s.
Remainder	105	0.291	0.003	
Total	127	1.424		RSD = 0.053
Second Harvest				
Soil Type	3	0.629	0.210	182.9***
Treatment	3	0.072	0.024	21.1***
Cutting Regime	1	0.330	0.330	287.6***
Soil type x treatment	9	0.053	0.006	5.15***
Soil type x cutting regime	3	0.060	0.020	17.4***
Cutting regime x treatment	3	0.006	0.002	1.62 n.s.
Remainder	105	0.120	0.001	
Total	127	1.270		RSD = 0.034
Third Harvest				
Soil Type	3	1.149	0.383	127.8***
Treatment	3	0.148	0.049	16.5***
Cutting Regime	1	0.808	0.808	269.7***
Soil type x treatment	9	0.085	0.009	3.17**
Soil type x cutting regime	3	0.170	0.057	18.9***
Cutting regime x treatment	3	0.006	0.002	0.66
Remainder	105	0.315	0.003	
Total	127	2.681		RSD = 0.055

Table 29 (Cont..)

Classification	d.f.	Sum of Squares	Mean Square	F
<u>Total Mg uptake</u>				
Soil type	3	4.78	1.59	164.9***
Treatment	3	1.19	0.40	41.2***
Cutting regime	1	0.02	0.02	2.05 n.s.
Soil type x treatment	9	0.69	0.08	7.94***
Treatment x cutting regime	3	0.02	0.007	0.70 n.s.
Remainder	109	1.04	0.01	RSD = 0.098
Total	127	7.74		

uptake between harvests 2 and 3 in cutting regime 1 for all soils as day temperature increased from 14 to 16 C between the two harvests. The increase in dry matter yields (Table 22) and plant Mg concentration (Table 24) which occured between the above two harvests contributed to the increases in plant Mg uptake.

c) Plant Mg Uptake and Changes in Exchangeable Mg Content

The apparent changes in exchangeable Mg content during the experiment (Table 30) were calculated by assuming that fertilizer Mg entered and remained in the exchangeable pool of soil Mg. This assumption is in line with the results of Mayland and Grunes (1974) who found that Mg applied as $Mg\ SO_4.7H_2O$ in a field experiment could be quantitatively recovered as soil exchangeable Mg, and Mokwunye and Melsted, (1973a) who found no evidence for Mg fixation in non-exchangeable form after incubating soils with various rates of fertilizer Mg. This assumption was necessary in the present experiment as Mg fertilizers were not uniformly distributed throughout the whole soil at the outset. The apparent changes in soil exchangeable Mg were calculated as the difference between the sum of exchangeable Mg content of the soil at the conclusion of the experiment, the Mg taken up by plants, and the estimated initial soil exchangeable Mg content(i.e., exchangeable Mg in untreated soils and fertilizer Mg added (in m.e. Mg)). In this calculation a negative result implied an unaccounted for nett loss of Mg from the exchangeable pool, whilst a positive result implied a nett gain of Mg to the exchangeable pool. Analysis of variance showed that the differences between soil types were significant ($p < 0.001$) as were differences between treatments (Table 31).

It appears that there was a loss of exchangeable Mg from the coarser-textured Burrell g.s.l. and Inglewood c.s.l. which tended to increase with increasing rates of Mg fertilizer. This result presumably indicates leaching losses of Mg, as there was some loss of water as drainage from the pots at each watering. The apparent gain in exchangeable Mg which occured on the New Plymouth b.l. and Egmont b.l. cannot be explained. The results of Kidson et al. (1975) indicated that only on soils of high (>30 m.e.%) reserve Mg content is there likely to be

Table 30

Changes in soil exch. Mg content over the experimental period for the various soil types, Mg fertilizer treatments and cutting regimes

Soil	Treatment ($kg\ ha^{-1} Mg$)	Cutting regime	exch. Mg Start	exch. Mg Finish	Total plant Mg uptake	Apparent change in exch. Mg
			mg pot^{-1}			
Burrell gravelly sandy loam	0	1	4.3	4.3	0.6	+0.6
	9		5.8	4.8	1.0	0.0
	18		7.4	4.6	0.9	-1.9
	36		10.4	9.5	1.0	+0.1
	0	2	4.3	3.6	0.6	-0.1
	9		5.8	4.8	0.9	-0.1
	18		7.4	5.2	0.9	-1.3
	36		10.4	9.3	1.2	+0.1

Table 30 (Cont..)

Soil	Treatment (kg ha^{-1}Mg)	Cutting regime	exch. Mg Start	exch. Mg Finish	Total plant Mg uptake	Apparent change in exch. Mg
			mg per pot			
Inglewood coarse sandy loam	0	1	3.8	4.5	0.3	+1.0
	9		5.3	3.7	0.3	-1.3
	18		6.9	4.2	0.4	-2.3
	36		9.9	8.3	0.5	-1.1
	0	2	3.8	5.2	0.3	+1.7
	9		5.3	4.3	0.2	-0.8
	18		6.9	4.0	0.5	-2.4
	36		9.9	7.1	0.6	-2.2

Table 30 (Cont..)

Soil Type	Treatment (kg ha^{-1}Mg)	Cutting regime	exch. Mg		Total plant Mg uptake	Apparent change in exch. Mg
			Start	Finish		
			mg pot^{-1}			
Egmont black loam	0	1	21.3	23.0	0.7	+2.4
	9		22.8	23.2	0.9	+1.3
	18		24.4	27.4	0.9	+3.9
	36		27.4	30.4	0.9	+3.9
	0	2	21.3	23.6	0.8	+3.1
	9		22.8	24.6	0.8	+2.6
	18		24.4	27.0	0.9	+3.5
	36		27.4	29.3	1.0	+2.9

Table 30 (Cont..)

Soil Type	Treatment (kg ha^{-1} Mg)	Cutting regime	exch. Mg Start	exch. Mg Finish	Total plant Mg uptake	Apparent change in exch. Mg
					mg pot^{-1}	
New Plymouth black loam	0	1	21.6	23.4	0.8	+2.6
	9		23.1	25.8	0.6	+3.3
	18		24.7	26.0	0.7	+2.0
	36		37.7	28.2	0.9	+1.4
	0	2	21.6	24.3	0.7	+3.4
	9		23.1	26.2	0.7	+3.8
	18		24.7	26.1	0.7	+2.1
	36		27.7	28.7	0.9	+1.9

Table 31 Results of analysis of variance of apparent changes in exchangeable Mg.

	d.f.	Sum of Squares	Mean Square	F
Soil type	3	0.310	0.437	59.9 ***
Treatment	3	0.095	0.032	4.35 **
Cutting Regime	1	0.0001	0.0001	0.01
Soil type x treatment	9	0.237	0.026	3.61 ***
Soil type x Cutting Regime	3	0.018	0.006	0.80
Cutting Regime x treatment	3	0.014	0.005	0.64
Remainder	105	0.765	0.007	
Total	127	2.439		RSD = 0.085

Table 32

Estimated recovery of fertilizer Mg by plants in relation to soil type, Mg fertilizer addition, and cutting regime

Mg treatment (kg Mg ha^{-1})	Amount Mg per pot (g)	Cutting Regime	Burrell g.s.l.	Inglewood c.s.l.	Egmont b.l.	New Plymouth b.l.
			% recovery of Mg fertilizer			
0	0.00	1	-	-	-	-
9	0.015		24	3	15	-9
18	0.031		10	5	4	-8
36	0.061		7	3	4	1
0	0.00	2	-	-	-	-
9	0.015		25	-6	1	-2
18	0.031		11	6	3	-2
36	0.061		11	4	2	2

an appreciable release of non-exchangeable Mg over a period of 30 months. Similarly, Salmon and Arnold (1963) found that very little non-exchangeable Mg was released to ryegrass plants during the course of a pot trial. Those trials which have shown utilisation of non-exchangeable Mg by growing plants have generally been conducted on soils containing expanding lattice clays containing high amounts of Mg, such as vermiculite (Rice and Kamprath, 1968; Christenson and Doll, 1973). As New Plymouth b.l. and Egmont b.l. contain low amounts of reserve Mg (5.26 and 5.10 m.e.%, respectively), and contain allophane and hydrous feldspars as the dominant clay minerals (New Zealand Soil Bureau, 1968) it is unlikely that the apparent increase in exchangeable Mg was due to any release of non-exchangeable Mg. However, it is apparent that in most cases the amount of nett loss or gain was a relatively small fraction of the soil exchangeable Mg pool.

The apparent recoveries of applied Mg were low on all soils ranging from essentially nil to a maximum of 25% (Table32). Such low recoveries are in general agreement with the findings of several other experiments in both New Zealand (McNaught et al., 1968b) and overseas (Mayland and Grunes, 1974).

5.2.4. Plant Calcium

Plant Ca values were similar for all soils except Inglewood c.s.l., over all treatments, being always within the range 0.42-0.71% Ca (Table33).

Ryegrass Ca concentrations on Inglewood c.s.l. were generally lower than those of the other three soils, ranging from 0.29 to 0.42% Ca and thereby reflecting the much lower exchangeable Ca content of this soil type (Table 33). However, even for this soil, plant Ca concentrations were always greater than the deficiency levels of 0.1 - 0.2% Ca for perennial ryegrass at the vegetative stage of growth (McNaught, 1970)

Data analysis using analysis of variance procedures showed that, for all soils except Inglewood c.s.l. only minor changes in plant Ca concentrations accompanied the addition of Mg fertilizers (Table 34). Although several of these treatment effects reached statistical significance the magnitude of the changes

Table 33

Ryegrass Ca concentration in relation to soil type, Mg fertilizer addition, cutting regime and Harvest period

Soil Type	Mg Rate ($kg\ ha^{-1}$)	Cutting Regime	Harvest number 1	2	3
			%Ca		
				±0.03	
Burrell gravelly sandy loam	0	1	0.50	0.63	0.68
	9		0.46	0.68	0.64
	18		0.47	0.71	0.67
	36		0.42	0.63	0.62
				±0.03	
	0	2	0.58	0.66	0.64
	9		0.59	0.76	0.69
	18		0.51	0.66	0.67
	36		0.51	0.71	0.66
				±0.01	
Inglewood coarse sandy loam	0	1	0.34	0.41	0.40
	9		0.30	0.42	0.41
	18		0.32	0.37	0.38
	36		0.29	0.33	0.34
				±0.03	
	0	2	0.37	0.38	0.40
	9		0.36	0.37	0.39
	18		0.30	0.38	0.34
	36		0.29	0.35	0.31

Table 33 (Cont..)

Soil Type	Mg Rate (kg ha^{-1})	Cutting Regime	Harvest number		
			1	2	3
			%Ca		
				±0.02	
Egmont black loam	0	1	0.64	0.51	0.49
	9		0.70	0.48	0.49
	18		0.62	0.51	0.50
	36		0.63	0.48	0.46
				±0.02	
	0	2	0.66	0.54	0.45
	9		0.67	0.53	0.45
	18		0.69	0.52	0.47
	36		0.60	0.51	0.43
				±0.02	
New Plymouth black loam	0	1	0.68	0.58	0.58
	9		0.58	0.60	0.57
	18		0.67	0.58	0.61
	36		0.61	0.60	0.63
				±0.02	
	0	2	0.62	0.61	0.54
	9		0.67	0.61	0.53
	18		0.60	0.54	0.53
	36		0.64	0.59	0.48

Table 34

Average ryegrass Ca concentrations in relation to soil type and cutting regime (mean of all harvests)

Soil : Type	Burrell g.s.l.	Inglewood c.s.l.	Egmont b.l.	New Plymouth b.l.
Cutting Regime 1				
Mg Rate	%Ca			
0 kg Mg ha^{-1}	0.60	0.61	0.38	0.55
9 " "	0.59	0.38	0.56	0.58
18 " "	0.62	0.36	0.54	0.62
36 " "	0.56	0.32	0.53	0.61
F_{calc}	2.27 n.s.	12.70***	1.06 n.s.	0.93 n.s.
Cutting Regime 2				
Mg Rate				
0 kg Mg ha^{-1}	0.63	0.38	0.55	0.59
9 " "	0.68	0.37	0.55	0.60
18 " "	0.62	0.34	0.56	0.55
36 " "	0.62	0.32	0.52	0.57
F_{calc}	4.03*	3.46*	3.37*	2.77 n.s.

involved was small and consequently would be likely to be of limited practical concern. For Inglewood c.s.l. significant decreases in plant Ca resulting from Mg addition were found at most harvests and at both cutting regimes. These results suggest that reductions in plant Ca concentrations resulting from Mg addition might be expected for soils similar to Inglewood c.s.l. which contain less than about 1 to 2 m.e.% exchangeable Ca.

These results are somewhat at variance with those of McNaught et al.(1968a, 1973b) who reported major depressions of plant Ca content resulting from the use of Mg fertilizers to Hamilton clay loam (exch. Mg 1.19 m.e.%, exch. Ca 9.5 m.e.%) and Horotiu sandy loam (exch. Ca 1.85 m.e.%, exch. Mg 12.8 m.e.%) However, the rates of Mg fertilizer used in their field experiments were much greater than those used in the present study. There are also several other reports in the literature which suggest that increasing rates of Mg addition can result in decreased plant Ca contents for a range of plant species (Key et. al., 1962; Salmon, 1964; Grunes et al., 1968; Martin and Page 1968; McLean and Carbonell, 1972; Cummins and Perkins, 1974; Clark, 1975).

When the correction of a plant nutrient deficiency on a soil deficient in more than one nutrient element results in increased plant dry-matter production, the concentration of other nutrient elements in the plant often decreases compared to those on the untreated soil (McNaught, 1970) by way of a simple dilution effect. This effect appears to account for the decrease in plant Ca concentration on Inglewood c.s.l., as plant Ca uptakes on this soil (Table 35) were not changed as a result of Mg addition to the soil. On soils where only a single nutrient is deficient, correction of that deficiency may not necessarily result in changes in the concentration of other nutrient elements in the herbage (McNaught, 1970) except where an antagonism between the element added and another nutrient, occurs as, eg. Mg and Ca, in this experiment. In the absence of any major depression in herbage Ca concentrations on soils other than Inglewood c.s.l. in this present experiment, plant Ca uptakes

Table 35

Ryegrass Ca uptake in relation to soil type, treatment cutting regime and harvest period

Soil Type	Mg Rate (kg ha^{-1})	Cutting Regime	Harvest Number 1	2	3	Total
			mg pot^{-1}			
Burrell gravelly sandy loam	0	1	7.8	3.7	9.5	21.0
	9		13.1	5.2	10.2	28.5
	18		11.8	5.2	9.4	26.4
	36		9.5	5.3	9.3	24.1
	0	2	11.5	4.4	4.5	20.4
	9		17.9	6.9	5.6	30.4
	18		15.4	6.0	5.4	26.8
	36		15.7	7.2	5.6	28.5
Inglewood coarse sandy loam	0	1	4.0	1.7	2.2	7.9
	9		4.0	1.7	2.2	7.9
	18		5.0	1.5	2.2	8.7
	36		3.9	1.4	2.1	7.4
	0	2	5.6	1.5	1.3	8.4
	9		6.3	1.6	1.4	9.3
	18		5.0	1.9	1.1	8.0
	36		4.3	1.7	1.6	7.6
LSD	0.05		2.1	0.9	1.6	3.9
	0.01		2.7	1.2	2.2	5.2

Table 35 (Cont..)

Soil Type	Mg Rate (kg ha^{-1})	Cutting Regime	Harvest Number 1	2	3	Total
			____ mg pot^{-1}		____	
Egmont black loam	0	1	7.0	4.2	6.8	18.0
	9		7.4	4.6	9.6	21.6
	18		5.6	4.6	8.2	18.4
	36		6.3	4.5	8.6	19.4
	0	2	9.6	5.8	4.0	19.4
	9		9.2	5.7	3.5	18.4
	18		9.9	6.8	3.6	20.3
	36		9.0	5.6	3.5	18.1
New Plymouth black loam	0	1	5.8	3.9	9.9	19.6
	9		4.5	3.5	8.1	16.1
	18		5.0	3.7	8.1	16.8
	36		5.4	3.7	10.3	19.4
	0	2	6.9	5.3	4.6	16.8
	9		7.0	4.9	4.2	16.1
	18		5.4	4.4	4.4	14.2
	36		7.0	5.4	4.5	16.9
LSD	0.05		2.1	0.9	1.6	3.9
	0.01		2.7	1.2	2.2	5.2

generally followed a similar pattern to that of dry matter yields on each soil type (Table 35). Accordingly, significant increases in plant Ca uptake only occured where dry matter yield responses to Mg fertilizer addition occured such as on Burrell g.s.l. and Egmont b.l.

As found for Mg, plant Ca concentrations tended to increase with successive harvests on Burrell g.s.l. and Inglewood c.s.l. (Table 33). A similar finding was reported by Dijkshoorn and T'Hart (1957), Hendriks and Grunes (1966), and McNaught et al. (1968a), who showed that Mg and Ca responded similarly to increasing temperature. However, on New Plymouth b.l. and Egmont b.l. plant Ca concentrations tended to remain constant or decrease with successive harvests (Table33). Within each soil type and at harvests 1 and 2, plant Ca concentrations were highest under cutting regime 2 than for cutting regime 1 indicating that Ca concentrations did tend to increase with increasing temperature.

For all soils Ca uptake increased between harvests 2 and 3 in cutting regime 1, as a result of the increase in dry matter yields which occurred between these two harvests (Table22). At harvest 2, Ca uptake in cutting regime 2 was greater than that in cutting regime 1 as was found for plant Mg uptake. However, as the increase in plant Ca uptake with increasing temperature was not generally as great as the increase in plant dry-matter production for New Plymouth b.l. and Egmont b.l. (Table 22), plant Ca concentration either declined or remained constant for these two soils. Therefore, it appeared that under the conditions of this experiment, plant Ca uptake was not as sensitive to increasing temperature as was the situation for plant Mg uptake.

5.2.5. Plant Potassium

There was no consistent effect of Mg application on plant K concentrations (Table36). For all soils and at all harvests there was a tendency for plant K concentration to increase with increasing additions of Mg. However only in some isolated cases did this trend reach significance.

Plant K concentrations declined with successive harvests

Table 36

Ryegrass K concentration in relation to soil type, Mg fertilizer addition cutting regime and harvest period

Soil Type	Mg Rate ($kg\ ha^{-1}$)	Cutting Regime	Harvest Number 1	2	3
				%K	
				± 0.12	
Burrell gravelly sandy loam	0	1	2.61	1.57	0.52
	9		2.09	1.32	0.54
	18		2.14	1.20	0.58
	36		2.26	1.61	0.80
				± 0.09	
	0	2	1.86	1.22	0.89
	9		1.67	1.16	0.83
	18		1.70	1.19	0.71
	36		1.64	1.08	0.74
				± 0.12	
Inglewood coarse sandy loam	0	1	2.45	2.36	2.13
	9		2.33	2.44	2.11
	18		2.45	2.36	2.22
	36		2.50	2.62	2.30
				± 0.10	
	0	2	2.12	2.38	1.58
	9		2.09	2.47	2.37
	18		2.20	2.56	2.38
	36		2.29	2.85	2.29

Table 36 (Cont..)

Soil Type	Mg	Cutting	Harvest Number		
	Rate	Regime	1	2	3
	(kg ha^{-1})			%K	
				± 0.10	
Egmont black loam	0	1	2.69	2.26	1.31
	9		2.78	2.30	1.21
	18		2.73	2.39	1.44
	36		2.78	2.44	1.36
				± 0.08	
	0	2	2.31	2.32	1.70
	9		2.42	2.18	1.81
	18		2.57	2.15	1.67
	36		2.41	2.24	1.75
				± 0.11	
New Plymouth black loam	0	1	2.47	2.52	1.45
	9		2.66	2.60	1.29
	18		2.70	2.58	1.43
	36		2.80	2.67	1.55
				± 0.10	
	0	2	2.39	2.35	1.38
	9		2.62	2.48	1.46
	18		2.57	2.38	1.40
	36		2.64	2.53	1.81

for all soils (Table 36). The extent of this decline was most marked on Burrell g.s.l., where plant K concentrations decreased from a maximum of 2.61% K to less than 0.9% K. For New Plymouth b.l. and Egmont b.l., plant K concentration declined from a maximum of 2.8% K to less than 1.80% K. The smallest decline occured on Inglewood c.s.l. where plant K concentrations generally remained above 2.0%.

Significant differences in K concentrations were found between cutting regimes, with concentrations for cutting regime 1 generally exceeding those for cutting regime 2 at harvests 1 ($p < 0.001$) and 2 ($p < 0.01$). At harvest 3 however, the reverse effect was found with plant K concentrations for cutting regime 2 generally exceeding those for cutting regime 1 ($p < 0.001$).

Plant K uptake varied greatly between soil types (Table37). At the first harvest, the order of plant K uptake was: Burrell g.s.l. > Inglewood c.s.l. > Egmont b.l. > New Plymouth b.l., paralleling the differences in dry matter production between soils at this harvest. The ranking of K uptake changed at the second harvest, to: Egmont b.l.> New Plymouth b.l.> Burrell g.s.l. > Inglewood c.s.l., due in the main to the large decreases in plant K concentrations on Burrell g.s.l., and reductions in dry matter yields for Inglewood c.s.l. By the third harvest, the continuing decline in plant K concentrations on Burrell g.s.l. caused a further decline in plant K uptakes on this soil relative to the other three soils so that the order then became Egmont b.l. > New Plymouth b.l. > Inglewood c.s.l.> Burrell g.s.l.

Differences in K uptake between the two cutting regimes at harvests 1 and 2 mainly reflected dry matter yield differences with K uptakes for cutting regime 2 generally exceeding those for cutting regime 1. The reverse situation occurred at harvest 3, due to the shorter growth period. Likewise, effects of Mg addition on plant K uptake were apparent where such additions resulted in dry-matter yield increases, i.e. for Burrell g.s.l. and Egmont b.l. For Inglewood c.s.l., a significant response in K uptake to Mg addition occurred at the first and third harvests ($p < 0.01$) due to the combined effects of the trends towards increasing dry matter yields with increasing Mg addition (Table 22) and the concomitant increase in plant K concentrations

Table 37

Ryegrass K uptake in relation to soil type, Mg fertilizer addition, cutting regime and harvest period

Soil Type	Mg Rate (kg ha^{-1})	Cutting Regime	Harvest Number 1 (g pot^{-1} x 10^{2})	2	3	Total
Burrell gravelly sandy loam	0	1	4.19	0.95	0.73	5.87
	9		5.96	1.02	0.86	7.84
	18		5.37	0.88	0.82	7.17
	36		5.13	1.37	1.20	7.70
	0	2	3.71	0.82	0.62	5.15
	9		5.08	1.06	0.68	6.82
	18		5.13	1.05	0.57	6.75
	36		5.05	1.09	0.63	6.77
Inglewood coarse sandy loam	0	1	2.86	0.99	1.17	5.02
	9		3.09	1.00	1.14	5.23
	18		3.82	0.94	1.31	6.07
	36		3.33	1.07	1.43	5.83
	0	2	3.22	0.95	0.52	4.69
	9		3.64	1.04	0.83	5.51
	18		3.67	1.25	0.76	5.68
	36		3.41	1.37	1.17	5.95
LSD	0.05		0.54	0.26	0.30	0.86
	0.01		0.72	0.35	0.40	1.13

Table 37 (Cont..)

Soil Type	Mg Rate (kg ha^{-1})	Cutting Regime	Harvest Number 1 (g pot^{-1} x 10^{2})	2	3	Total
Egmont black loam	0	1	2.93	1.88	1.81	6.62
	9		2.95	2.18	2.37	7.50
	18		2.48	2.15	2.36	6.99
	36		2.78	2.26	2.52	7.56
	0	2	3.35	2.51	1.51	7.37
	9		3.32	2.33	1.43	7.08
	18		3.70	2.80	1.29	7.79
	36		3.62	2.44	1.42	7.48
New Plymouth black loam	0	1	2,12	1,71	2,49	6,32
	9		2.07	1.53	1.83	5.43
	18		2,03	1.63	1.90	5.56
	36		2.46	1.63	2.53	6.62
	0	2	2.67	2.04	1.17	5.88
	9		2.75	2.01	1.17	5.93
	18		2.31	1.95	1.16	5.42
	36		2.90	2.32	1.68	6.90
LSD	0.05		0.54	0.26	0.30	0,86
	0.72		0.72	0.35	0.40	1.13

(Table 36).

Uptake of plant K did not always decline with successive harvests as found for plant K concentrations (Table 37). Under cutting regime 1, plant K uptakes generally increased between harvests 2 and 3, although not to the same extent as did dry matter yields (Table22). Except for Burrell g.s.l., plant K uptake was generally greater for cutting regime 2 than for cutting regime 1 at the second harvest, for all soils.

It appears therefore, from these results, that K uptake by ryegrass tends to increase with increasing temperature, a result which is in agreement with the findings of previous work (eg Dijkshoorn and T'Hart, 1957). However the amount of increase in K uptake achieved appears to have been partly masked by a decrease in the amounts of exchangeable K in the soil, as shown in Table 38. Allowing for the amounts of K taken up by the ryegrass plants (Table38), the data indicates that for each soil a large proportion of the initial exchangeable K content (calculated as the sum of the amounts of exchangeable K present in the untreated soil and the amounts of K fertilizer added) could not be accounted for at the conclusion of the experiment. Significant ($p < 0.001$) between-soil differences were found in the amounts of exchangeable K unaccounted for, which appear to be related to the initial soil exchangeable K status. A major potential source of this loss of K was as a result of leaching, since some drainage was inevitable over the duration of the experiment. Assuming that the loss of K was continuous throughout the experimental period, the decline in plant K concentration on these soils in which large dry-matter yield responses occurred as a result of increasing temperature may be due to the combined effects of:

i) A growth dilution effect, and

ii) A decrease in the size of the pool of available soil K as the experiment progressed, due to leaching and/or plant K uptake.

Differences in plant K concentration between cutting regimes at the third harvest could be due to differences in plant maturity, as plant K has been shown to decrease with increasing plant maturity under constant temperature (Dijkshoorn and T'Hart

Table 38

Changes in exchangeable K content over the experimental period for the various soil types, Mg fertilizer treatments, and cutting regimes

Soil Type	Mg Rate (kg ha^{-1})	Cutting Regime	K start	K finish	plant K uptake	K una/c for
			g pot^{-1}			
Burrell gravelly sandy loam	0	1	0.41	0.09	0.06	0.26
	9			0.08	0.08	0.25
	18			0.06	0.07	0.28
	36			0.07	0.08	0.26
	0	2	0.41	0.11	0.05	0.05
	9			0.10	0.07	0.24
	18			0.08	0.07	0.26
	36			0.10	0.07	0.24
Inglewood coarse sandy loam	0	1	0.32	0.17	0.05	0.10
	9			0.14	0.05	0.13
	18			0.14	0.06	0.12
	36			0.11	0.06	0.15
	0	2	0.32	0.15	0.05	0.12
	9			0.12	0.06	0.14
	18			0.12	0.06	0.14
	36			0.12	0.06	0.14

Table 38 (Cont..)

Soil Type	Mg Rate (kg ha^{-1})	Cutting Regime	K start	K finish	plant K uptake	K una/c for
			g pot^{-1}			
Egmont black loam	0	1	0,62	0.15	0.07	0.40
	9			0.16	0.08	0.38
	18			0.16	0.07	0.39
	36			0.16	0.08	0.38
	0	2	0.62	0.15	0.07	0.40
	9			0.13	0.07	0.42
	18			0.17	0.08	0.37
	36			0.19	0.07	0.36
New Plymouth black loam	0	1	0.39	0.14	0.06	0.19
	9			0.15	0.05	0.19
	18			0.15	0.06	0.18
	36			0.14	0.06	0.19
	0	2	0.39	0.15	0.06	0.18
	9			0.14	0.06	0.19
	18			0.15	0.05	0.19
	36			0.16	0.07	0.16

1957)

The ranking of total plant K uptakes was in the same order as the inital soil exchangeable K contents (Table 38), viz,: Egmont b.l. > Burrell g.s.l. > New Plymouth b.l. > Inglewood c.s.l. The differences in dry matter yields between soils resulted in a different trend for plant K concentrations, such that the apparent order of K supplying power to ryegrass plants was: Inglewood c.s.l. > New Plymouth b.l., > Egmont b.l. > Burrell g.s.l. Had dry matter yields on Inglewood c.s.l. been similar to dry matter yields on the other three soils, then it is possible that plant K on this soil would also have decreased with successive harvests.

The absence of any marked antagonism of Mg on plant K in the soils used in this experiment is in contrast to the results of previous experiments. It may be relevant to note, however, that in this present experiment, relatively low rates of Mg addition were used (maximum rate was 36 kg Mg ha^{-1}) compared with additions of greater than 100kg Mg ha^{-1} which have been used in previous trials (eg Reith, 1964; McNaught, 1973b; Mayland and Grunes, 1974).

It is of interest to note that the low plant K found at the final harvest on all soils except Inglewood c.s.l. would be considered deficient for ryegrass according to the criteria proposed by McNaught (1970), viz., 0.3 - 1.7% K, and yet dry matter yields did not appear to be adversely affected. It is not known whether dry matter yields would have been sustained at the same levels as those of the third harvest had the experiment been continued. These results would suggest that plant K of 1 - 2.0% K may well be adequate for perennial ryegrass at the vegetative stage (c.f. 2.0 - 2.5% K, McNaught, loc. cit).

5.3. General Discussion

In Taranaki, soils on Inglewood Tephra have been found to contain low to very low amounts of exchangeable Mg according to the criteria of Metson and Brooks (1975), and with Mg-saturations of the CEC of less than 10%. The value of 10% saturation is commonly considered to be the minimum saturation for ensuring an adequate supply of Mg to plants on coarse-textured soils (Prince, 1947; Metson, 1968, 1974; Metson and Gibson, 1974). These soils could easily become Mg deficient with intensive agricultural use, particularly as they are mainly used for dairy-farming.

In effect, the Mg status of Inglewood c.s.l.'s formed on Inglewood Tephra is more similar to many yellow-brown pumice soils than to typical Central yellow-brown loams. This similarity probably arises because:

i) Inglewood Tephra is pumiceous in nature, and although not composed of rhyolitic pumice and not floating in water, is very similar to pumice in grain size and vesicularity (Neall, 1972).

ii) The Inglewood Tephra is relatively young; recently being dated as between 4 000 - 5 000 years B.P. (V. E. Neall, pers. comm.)

iii) The soils are well-drained and are developed under a high rainfall, so that under the strong leaching regime exchangeable Mg is unlikely to accumulate in the topsoils.

These results show several chemical properties in common between coarse-textured yellow-brown loams and yellow-brown pumice soils. This is in agreement with the findings for certain physical properties, especially available water holding capacities (Gradwell, 1976).

Addition of Mg to Burrell g.s.l. resulted in dry matter yields and plant Mg responses similar to those reported by Moody (1962) for Te Rere sand, which is a yellow-brown pumice soil. Similar large plant Mg responses were obtained on Inglewood c.s.l. following Mg addition, although dry-matter yield responses were less marked.

This study also established that other soil series within the Inglewood-New Plymouth-Okato region of North Taranaki are potentially Mg deficient, including the Burrell, Hangatahua, Newall, Norfolk, and Stratford, series. Thus, Mg problems may be more common than is generally acknowledged for soils developed from andesitic parent materials from Mount Egmont.

The detailed survey of exchangeable Mg contents carried out in 1975 indicated that in the Inglewood - New Plymouth area, soil parent materials appear to be the primary factor determining the exchangeable Mg content of topsoils. This result is in general agreement with other studies of parent material effects including those both in New Zealand (Chittenden and Hodgson, 1953) and overseas (Beeson, 1959; Salmon, 1963; Semb, 1964).

Within the area covered by the Inglewood Tephra, additional secondary factors also appear to affect soil exchangeable Mg contents. These include:

i) Leaching intensity, which increases as rainfall and altitude increase, and

ii) Weathering intensity, which probably decreases with increasing coarseness of the soil parent material closer to source and with the cooler temperatures prevalent at higher altitudes. The decrease in exchangeable Mg content with increasing altitude found for the Patua and New Plymouth loams indicates that similar climate-related effects may also affect the exchangeable Mg contents of soils formed on other parent materials in Taranaki.

The relative Mg-supplying power to perennial ryegrass of the four soils used in the pot experiment was related to the exchangeable Mg contents of the four soils. The concentrations of Mg in the ryegrass plants grown on the control (0 kg Mg ha^{-1}) treatments were in the order of Burrell g.s.l. ≅ Inglewood c.s.l. < New Plymouth b.l. ≅ Egmont b.l., which was also the approximate order of the soil exchangeable Mg contents. Mg additions to Burrell g.s.l. and Inglewood c.s.l. produced greater changes in plant Mg than did the same additions to New Plymouth and Egmont b.l.'s. It is therefore apparent that for many of the Taranaki yellow-brown loams, as for soils elsewhere in New Zealand, exchangeable Mg contents and soil texture are the main factors determining the supply of plant-available soil Mg and the response of plants to applied Mg. Coarse-textured soils containing less than 0.2 - 0.3 m.e.% exchangeable Mg in Taranaki may be considered as likely to respond to applied Mg. This "critical" value for possible responses to Mg addition for Taranaki yellow-brown loams is similar to those found for other-soils of volcanic origin in New Zealand.

The different responses to applied Mg found for the soils used in the experiment may have practical implications for the control of hypomagnasaemia in grazing animals. The required Mg concentration in pasture plants for the provision of adequate dietary Mg for recently-calved dairy cows has been quoted as a minimum of 0.20% Mg (Kemp and T'Hart, 1957). Other reports indicate that a safe minimum plant Mg concentration may be around 0.25% Mg (Butler and Metson,1967). On the basis of the results of Kemp and T'Hart (loc. cit.) the ryegrass grown on the control treatments of New Plymouth b.l., and Egmont b.l. would be considered to contain adequate Mg for stock needs at all harvests throughout the experiment. For Burrell g.s.l., only after the day temperature exceeded 14 C did plant Mg increase above 0.2% Mg on the control treatments, while for Inglewood c.s.l. only at the third harvest under cutting regime 2, when day temperature was 16 C, did plant Mg exceed 0.2% Mg on the control treatments.

For both Burrell g.s.l. and Inglewood c.s.l. at the first harvest, the application of Mg at a rate equivalent to a field application of 36 kg Mg ha^{-1} resulted in increases of plant Mg level to close to 0.2% Mg. At later harvests, presumably as a result of the temperature effect on Mg uptake, the level of 0.2% Mg was exceeded even at lower rates of Mg addition for both soils. Therefore, the use of relatively low rates of Mg fertilizers might be expected to be a practical means of increasing plant Mg sufficiently to prevent the occurrence of hypomagnasaemia on Burrell g .s.l. and Inglewood c.s.l.

The temperature-dependence of Mg uptake by ryegrass was clearly demonstrated in this experiment. A critical minimum temperature of ca. 14 C,below which increasing temperature would not be expected to result in increased plant Mg was indicated, in agreement with the findings of Kemp and T'Hart (1957). A further feature of the plant Mg response to increasing temperature was the increase in the response to added Mg for Burrell g.s.l. and Inglewood c.s.l. after the temperature exceeded 14 C. For New Plymouth b.l. and Egmont b.l., the increase in plant Mg was much less than for the other two soils. Increasing the exchangeable Mg content of a soil by applying Mg fertilizer may therefore reduce the amplitude of seasonal fluctuations in plant Mg concentrations.

The problem of obtaining a sufficiently large increase in plant Mg by applying Mg fertilizer may be accentuated by the effect of temperature on plant Mg uptake. The temperature regimes used in this experiment were selected to approximate those operating in the field over the early spring period in North Taranaki, when hypomagnasaemia is most likely to occur in dairy cows. The results obtained indicate that not only are plant Mg concentrations likely to be low at this critical time, but that the response to added Mg is only minimal, increasing as temperatures increase and the danger period for hypomagnasaemia passes. There is no strong evidence for a Mg/Ca antagonism in any of the soils or treatments used in this experiment. Where Mg addition did result in a decrease in plant Ca, on Inglewood c.s.l., plant Ca was not depressed below the adequacy range for perennial ryegrass of from 0.25 to 0.30% Ca (McNaught, 1970). The results of the present experiment indicate that the application of Mg-containing fertilizers should not depress pastures Ca levels significantly and thereby affect dry-matter yields or complicate stock health problems.

While there was no evidence for an antagonistic affect of Mg on plant K in this experiment, the decrease in plant K which occurred as the experiment progressed is of interest. The susceptibility of dairy cattle to hypomagnasaemia has been postulated to increase as the herbage $\frac{K}{Ca + Mg}$ ratio increases, especially at low (ca. 0.2%) plant Mg concentrations. The maximum safe value for this ratio appears to be around 2.2 (Kemp and T'Hart, 1957). Obviously this ratio may be changed by additions of K and Mg fertilizers. If the use of fertilizer Mg proves impractical as a means of increasing plant Mg, which may prove to be the case on soils containing >1.0 m.e.% exchangeable Mg, then withholding K fertilizers until after the danger period for hypomagnasaemia may be a reasonable alternative proposal. Although withholding K may result in depressed levels of plant K, the results of this experiment indicate that this may not necessarily be detrimental to ryegrass yields. Even if dry matter yields are depressed, the improvement in feed quality could offset the reductions in the quantity of available feed. In situations where soils are deficient in plant-available K, and K fertilizer cannot be withheld, K addition may result in large depressions of plant Mg (Welte and Werner, 1963; McNaught et.al., 1973a). For such conditions the combined addition of Mg and K could help to overcome the problem of maintaining dry matter yields while avoiding low plant Mg concentrations (Welte and Werner, 1963).

The results of the field sampling programme showed that a large area of the soils formed on the Inglewood Tephra contain deficient, or potentially deficient Mg levels. Analyses of samples taken from other soil types indicate that there are probably other areas of soils in Taranaki with similar low contents of exchangeable Mg. These low Mg soils are commonly coarse textured and have formed on parent materials<5 000 years old under conditions of high rainfall, and include at least the Burrell, Norfolk, Newall, Hangatahua and Stratford series. The plant Mg levels found in ryegrass plants grown on the pot trial indicate that, while exchangeable Mg may be adequate for plant and animal requirements on the older soils, such as New Plymouth and Egmont b.l.'s, for the younger soils, such as Burrell g.s.l. and Inglewood c.s.l., it is probable that Mg deficiency, in terms of animal, if not plant, requirements, will soon become an increasing problem. This will make the application of Mg fertilizers to these soils an economic necessity in the future.

Chapter VI

Conclusions

i) Soils formed from Inglewood Tephra contain relatively low amounts of exchangeable Mg as compared with other soils in Taranaki and in New Zealand.

ii) Within the Inglewood - New Plymouth - Okato area of North Taranaki, soil parent materials appear to be the major factors determining exchangeable Mg contents. Within each soil series, exchangeable Mg contents decrease with increasing altitude due to the combined effect of increasing leaching intensity and decreasing weathering rate at higher altitudes.

iii) The low exchangeable Mg contents of soils formed on pumiceous andesitic parent materials in Taranaki are more similar to those of yellow-brown pumice soils rather than to those of other Central yellow-brown loams.

iv) The Mg supplying power of the Taranaki yellow-brown loams to perennial ryegrass increases with increasing exchangeable Mg contents.

v) Plant responses to added Mg varied with native exchangeable Mg contents. For soils containing less than 0.3 m.e.% exchangeable Mg, Mg fertilizer additions may result in increased plant dry matter and plant Mg concentration. For soils containing more than 1.0 m.e.% exchangeable Mg, dry matter yield and plant Mg concentration responses to Mg fertilizers are likely to be more difficult to achieve.

vi) Plant Mg concentration tended to increase with increasing temperature, within the range 12-16 C. A "critical" minimum temperature of ca. 14 C was indicated, below which increases in temperature did not result in increased plant Mg uptake.

vii) The use of Mg containing fertilizers on soils containing less than 0.3 m.e.% exchangeable Mg in Taranaki may be an effective method of raising animal intakes of Mg to prevent the occurrence of hypomagnasaemia. On soils containing more than 1.0 m.e.% Mg, plant Mg contents appear at present to be adequate for animal requirements.

viii) Many of the coarse-textured soils at high altitudes in Taranaki and with low exchangeable Mg contents are likely to be Mg deficient when used intensively for agricultural production, thereby making the use of Mg-containing fertilizers an economic necessity in the future.

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Appendix 1. Details of Individual Sampling Sites

i) Reconnaissance Survey

Date	Sample No.	Soil Type	Location (NZMS1)	Altitude (m)	Pasture	Fertilizers used (where known) and Comments.
7/74						
"	1*	BUR	N119/765599	488	RG, WC	
"	2	STR	N119/842605	320	RG, WC, FW	
"	3	ING	N109/734772	274	RG, WC	
"	4	ING	N109/65073 8	503	RG, BT, WC	Land under development. Lime, K-super used.
"	5*	ING	N109/673753	366	OG, RG, WC	
"	6*	ING	N109/698784	259	RG, WC	
"	7*	ING	N109/717806	213	BT, WC	Farm has not been topdressed in recent years.
"	8	ING	N109/744803	213	RG, WC	
8/74	9	PAT	N108/612763	396	RG, WC	K-super, Lime used.
"	10	ING	N109/650738	503	RG, OG, WC	Same site as sample 4.
"	11	ING	N109/668742	427	RG, WC	Lime, K-super. Recently oversown.
"	12	NOR	N109/697756	335	RG, WC	Superphosphate only.
"	13	ING	N109/710728	411	RG, WC	K-super only.
"	14	NEW	N109/722723	396	RG, OG, WC	Site infrequently fertilized; some crop mix which contains Mg used in past.
"	15	ING	N119/744658	427	RG, WC	K-super, lime used .
"	16	BUR	N119/789598	427	RG, WC	" " .

Date	Sample No.	Soil Type	Location (NZMS1)	Altitude (m)	Pasture	Fertilizers used (where known) and Comments.
8/74	17	NPL	N109/701920	34	RG, WC	Very little fertilizer in pasture over 4 months. prior to sampling, received "Ammophos" and K-super.
"	18	NPL	N109/710911	61	RG, WC	K-super,
"	19	ING	N109/727863	152	RG, WC	K-super.
"	20	ING	N109/717806	213	BT, WC	Same site as sample 7.
"	21	ING	N109/722770	274	RG, WC, FW	Ammophos and Osflow.
"	22	ING	N109/718746	351	RG, WC	K-super, Property has had severe hypomagnasaemia problem, and pastures have been dusted with MgO, but not at sampling site.
"	23	ING	N109/696720	457	OG	In native forest at boundary of Egmont National Park.
"	24	UNKN	N119/690694	588	OG	Sample site on roadside within Egmont National Park; 0-10cm sample only.
10/74	25	ING	N109/726831	152	RG, WC	Farmer had used Mg fertilizers.
"	26	ING	N109/721814	183	RG, WC	K-super.
"	27	ING	N109/717806	213	BT, WC	Same site as sample 7.
"	28	ING	N109/719792	244	RG, WC	

Date	Sample No.	Soil Type	Location (NZMS1)	Altitude (m)	Pasture	Fertilizers used (where known) and Comments
10/74	29	ING	N109/675755	366	RG, WC	K-super.
"	30	ING	N109/688742	427	RG, WC	Same site as sample 11.
"	31	ING	N109/650738	503	RG, OG, WC	Same site as sample 4.
"	32	HAN	N118/534671	320	RG, WC	

* Two separate samples (a) and (b) taken at these sites.

ii)

Detailed Survey (August 1975.)

Sample No.	Soil Type	Location	Altitude (m)	Pasture	Fertilizers used (where known) and comments.
33	ING	N109/684826	198	RG, WC	4 cwt/ac 30% K-super 2 x/yr.
34	ING	N109/681822	152	RG, WC	4 cwt/ac 50% K-super (spring); 4 cwt/ac 30% K-super (autumn); 1 cwt/ac $(NH_4)_2 SO_4$ (spring).
35	ING	N109/679′ 01	244	RG, WC	Fertilizer unknown.
36	ING	N109/675795	244	RG, WC	7 cwt K-super (50% Spring, 30% Autumn); farm has had hypomagnasaemia problem.
37	ING	N109/678796	244	RG, WC, FW	7 cwt 30% K-super/acre.
38	ING	N109/669779	305	RG, WC	3 cwt/ac 50% K-super (spring); 3 cwt/ac 30% K-super (autumn).
39	ING	N109/665784	274	RG, WC, CF	8 cwt/ac 50% K-super (4 Spring, 4 Autumn) and 1 cwt/ac $(NH_4)_2 SO_4$ (spring).
40	ING	N109/622744	320	RG, WC	8 cwt/ac 30% K-super (4 spring, 4 autumn); ¾ ton/ac lime spread two years before.
41	ING	N109/657754	396	BT	Undeveloped paddock on same property as sample 4. No fertilizer in recent years.

Sample No.	Soil Type	Location	Altitude (m)	Pasture	Fertilizers used (where known) and comments.
42	ING	N109/667776	305	RG, WC	8 cwt/ac 30% K-super (4 Spring; 4 Autumn);cwt/ac $(NH_4)_2$ SO_4 Spring. 1 ton lime/ac 3 years before. ½ ton/ac last year. Farm has had severe hypomagnasaemia problem.
43	ING	N109/674771	320	RG, WC, BT	5 cwt/ac 30% K-super in Spring.
44	ING	N109/667750	396	RG, WC, OG	On same property as sample 4; has had recent heavy dressings of lime (1ton/ac) and 30% K-super (15 cwt/ac).
45	ING	N109/668742	427	RG, WC	Same site as samples 11 and 30.
46	ING	N109/676746	366	RG, WC	Same property as sample 29.
47	ING	N109/693775	290	RG, WC, OG	1 ton/ac "Osflow"; 1 ton/ac lime; 1 cwt/ac $(NH_4)_2$ SO_4 - all recent. Discarded top 2cm to minimise contamination.
48	ING	N109/696782	274	RG, WC	3 cwt/ac 30% K-super and 1 cwt/ac KCl (spring); 4 cwt/ac 30% K-super (Autumn).
49	ING	N109/692787	259	RG, WC, FW	1½ cwt/ac "Ammophos" (spring); 3 cwt/ac 30% K-super (autumn).
51	ING	N109/696799	229	RG, WC	Fertilizer unknown.

Sample No.	Soil Type	Location	Altitude (m)	Pasture	Fertilizers used (where known) and comments.
52	ING	N109/705804	213	RG, WC, OG	5 cwt 30% K-super (spring) 1 cwt/ac $(NH_4)_2 SO_4$.
53	ING	N109/724835	152	BT, PA, RG, WC	3 cwt/ac 50% K-super (spring and autumn),and up to 2 cwt/ac KCl in spring .
54	ING	N109/711851	152	RG, BT, WC	3 cwt 30% K-super (spring); 3 cwt/ac 20% K-super (autumn). Pasture grazed by sheep.
55	ING	N109/717822	183	RG, OG, WC	4 cwt/ac 30% K-super (spring and autumn).
56	ING	N109/722813	198	RG, BT, WC	"Ammophos" fertilizer; amounts unknown .
57	ING	N109/719795	229	RG, WC	4 cwt/ac 50% K-super (spring and autumn). Same area.
58	ING	N109/721792	244	RG, OG, WC	Fertilizer unknown. Has used some serp. super.
59	ING	N109/701721	142	RG, BT, WC	3 cwt/ac 50% K-super. ½ ton/ac lime in last 2 years.
60	ING	N109/704723	427	BT, FW	Fertilizer unknown; very little in past 5 years.
61	ING	N109/710728	411	RG, WC	Same site as sample 13.
62	ING	N109/718746	351	RG, WC	Same site as sample 22.
63	ING	N109/717806	213	BT, WC	Same site as sample 7, 20, 27.
64	ING	N109/727804	213	RG, OG, WC FW	Previous autumn: 5 cwt serp. K-super; 3 cwt/ac Dolomite, Previous years: 3 cwt/ac super.

Sample No.	Soil Type	Location	Altitude (m)	Pasture	Fertilizers used (where known) and comments .
65	ING	N109/730807	213	RG, WC	Basic slag at 5 cwt/ac since 1937. Now used for beef-fattening; dairying until 13 years ago.
66	ING	N109/736851	152	RG, WC	3 cwt/ac 30% K-super (spring), 2 cwt super/ac autumn. ½ ton lime 6 years before.
67	ING	N109/744835	198	RG, WC, OG	New owner. Previous owners used "Osflow".
68	ING	N109/733815	198	RG, CF, WC	4 cwt/ac 50% K-super (spring), 4 cwt/ac serp. super (autumn) over past 2 years.
69	ING	N109/736806	213	RG, WC	4 cwt/ac 30% K-super (spring and autumn) Urea - 1 cwt/ac in spring.
70	ING	N109/749822	183	RG, WC, FW	4-5 cwt/ac 30% K-super and occasional dressings of blood and bone and crop-mix.
71	ING	N109/745816	198	RG, WC	5 cwt 30% K-super and blood and bone (unspec.).
72	ING	N109/744803	213		4 cwt/ac 30% K-super (spring and autumn) Same site as sample 8.
73	ING	N109/752805	213	BT, RG, WC	Fertilizer unknown.
74	ING	N109/759809	198	RG, BT, WC, FW	Fertilizer unknown (runoff area).

Sample No.	Soil Type	Location	Altitude (m)	Pasture	Fertilizers used (where known) and comments.
75	ING	N109/755804	213	BT, RG, WC, FW	4 cwt/ac 30% K-super last year. New owner. Previous owners allowed property to run down.
76	ING	N109/777785	213	RG, BT, WC, FW	4 cwt/ac 30% K-super (spring and autumn) Property used to graze horses.
77	NPL	N108/475803	46	RG, WC	In last year. Spring 3½ cwt dolomite, K-super (20%) Autumn: 3½ cwt dolomitic K-super. Previously, 6-7 cwt/yr 20% K-super.
78	NPL	N108/477796	61	RG, WC	3½ cwt/ac K-Serp. - Super (spring and autumn
79	NPL	N108/484786	76	RG, WC	3 cwt/ac 50% K-super (spring and autumn)
80	NPL	N108/489782	91	DG, WC, FW	Paddock largely unfertilized.
81	PAT	N108/513772	152	RG, WC	3 cwt/ac 30% K-super in autumn.
82	PAT	N108/514759	183	RG, WC, FW	4 cwt/ac 30% K-super (spring and autumn) Some N-fertilizer in spring.
83	PAT	N108/532740	244	RG, OG, WC	3-4 cwt/ac super. Sheepfarm.
84	PAT	N108/545730	335	RG, WC, FW	3 cwt/ac 30% K-super (spring); 4 cwt/ac aerial super (autumn).
85	PAT	N108/551727	366	RG, OG, WC	3 cwt/ac 30% K-super (spring); 3 cwt super (autumn). Samples 77-85 inclusive, taken along Upper and Lower Pitone Roads, to the East of the Kaitaki Range.

Code	Soil Types
BUR	Burrell gravelly sandy loam
HAN	Hangatahua bouldery sand
ING	Inglewood coarse sandy loam
NEW	Newall bouldery sand
NOR	Norfolk bouldery sand
NPL	New Plymouth black loam
PAT	Patua loam
STR	Stratford coarse sandy loam
UNKN	Unknown soil types.

Pasture Composition

BT	Browntop
CF	Cocksfoot
RG	Ryegrass
OG	Other grasses
WC	White clover
FW	Flatweeds

Given in order of dominant-minor sward components.

Appendix 2. Results of Soil Exchangeable Cation and Soil pH Analyses for Samples taken during the Field Sampling Programme

i) Reconnaisance Survey

			0-10cm				10-20cm			
Sample No.	Soil Type	Altitude (m)	Mg	Ca m.e.%	K	soil pH	Mg	Ca m.e.%	K	Soil pH
1a	BUR	488	0.35	3.57	1.35	5.7	-	-	-	
1b	BUR	488	0.23	2.23	1.52	5.7	-	-	-	
2	STR	320	0.14	3.58	2.55	5.6	0.14	1.97	3.43	5.3
3	ING	274	0.32	3.34	3.95	5.7	-	-	-	-
4	ING	503	0.29	5.20	2.02	5.9	0.18	8.52	1.52	5.8
5a	ING	366	0.36	12.13	0.35	5.7	0.11	6.71	0.14	5.9
5b	ING	366	0.21	5.53	0.22	5.9	0.07	6.78	0.38	6.0
6a	ING	259	0.67	6.05	0.20	5.9	0.16	1.78	-	5.7
6b	ING	259	0.34	4.30	0.46	5.5	0.11	1.62	0.11	5.5
7a	ING	213	0.57	3.84	0.74	5.7	0.33	5.98	1.08	5.8
7b	ING	213	0.24	2.78	0.21	5.6	0.12	1.42	0.21	5.5
8a	ING	213	1.15	8.31	1.15	5.6	0.54	4.59	0.85	5.3
8b	ING	213	0.74	8.51	0.92	5.3	0.36	3.33	0.23	5.5
9	PAT	396	0.53	5.43	0.60	5.6	0.21	1.34	0.37	5.3
10	ING	503	0.28	1.05	0.40	5.6	0.08	0.40	0.07	5.7

Sample No.	Soil Type	Altitude (m)	0 - 10cm Mg	Ca	K	soil pH	10 - 20cm Mg	Ca	K	Soil pH
			m.e.%	m.e.%	m.e.%		m.e.%	m.e.%	m.e.%	
11	ING	427	0.94	12.57	0.32	5.9	0.24	2.99	0.21	5.6
12	NOR	335	0.28	2.44	0.21	5.5	0.16	1.61	0.14	5.6
13	ING	411	0.33	1.97	0.33	5.4	0.13	0.91	0.17	5.3
14	NEW	396	1.38	5.82	0.44	5.6	0.13	2.68	0.34	5.7
15	ING	427	0.67	7.90	0.65	5.4	0.18	1.30	0.29	5.5
16	BUR	427	1.84	6.05	0.60	5.7	0.64	1.80	0.21	5.5
17	NPL	34	2.08	8.31	0.50	5.6	0.51	4.12	0.17	5.4
18	NPL	61	2.91	14.45	1.17	5.8	0.35	2.08	0.59	5.2
19	ING	152	0.84	6.00	0.29	5.7	0.25	2.94	0.13	5.7
20	ING	213	1.31	4.86	0.73	5.5	0.26	1.14	0.21	5.4
21	ING	274	0.87	4.90	1.44	6.0	0.26	1.97	0.38	5.4
22	ING	351	0.47	3.09	0.34	5.6	0.25	1.72	0.16	5.6
23	ING	457	1.59	5.37	0.56	5.3	0.37	1.02	0.25	5.3
24	UNKN	588	1.98	5.45	0.30	5.4	-	-	-	-
25	ING	152	2.71	14.79	0.55	6.2	0.91	6.43	0.20	6.1

Sample No.	Soil Type	Altitude (m)	0-10cm Mg m.e.%	0-10cm Ca m.e.%	0-10cm K m.e.%	0-10cm soil pH	10-20cm Mg m.e.%	10-20cm Ca m.e.%	10-20cm K m.e.%	10-20cm Soil pH
26	ING	183	0.51	5.56	0.36	5.8	0.26	5.24	0.16	5.9
27	ING	213	0.89	4.30	0.53	5.5	0.26	2.76	0.26	5.7
28	ING	244	1.29	6.41	0.51	5.7	0.41	4.46	0.30	5.8
29	ING	366	1.03	3.82	0.50	5.9	0.37	1.89	0.25	5.9
30	ING	427	0.20	1.38	0.34	5.6	0.17	0.73	0.34	5.6
31	ING	503	0.37	3.28	0.47	5.4	0.23	0.97	0.25	5.5
32	HAN	320	0.65	2.87	0.26	5.5	0.38	1.97	0.26	5.7

ii) Detailed Survey

Sample Number	Soil Type	Altitude (m)	0-10cm Exch. Mg (m.e.%)	0-10cm Soil pH	10-20cm Exch. Mg (m.e.%)	10-20cm Soil pH
33	ING	198	0.25	5.5	-	-
34	ING	152	0.41	5.7	0.12	5.8
35	ING	244	0.99	5.5	0.12	5.3
36	ING	244	0.70	5.7	0.12	5.9
37	ING	244	0.53	5.6	0.29	5.5
38	ING	305	0.47	5.8	0.04	5.8
39	ING	274	0.62	5.7	0.14	5.6
40	ING	320	0.33	5.8	0.04	5.8
41	ING	395	0.35	5.5	0.31	5.5
42	ING	305	0.25	5.8	0.04	5.4
43	ING	320	0.49	5.6	0.21	5.7
44	ING	396	0.53	5.7	0.08	5.9
45	ING	427	0.56	5.9	0.27	5.7
46	ING	366	0.46	5.7	0.27	5.6
47	ING	290	0.39	5.9	0.25	5.7
48	ING	274	0.41	5.5	0.21	5.4
49	ING	290	0.62	5.7	0.04	5.5

Sample Number	Soil Type	Altitude (m)	0-10cm Exch. Mg (m.e.%)	0-10cm Soil pH	10-20cm Exch. Mg (m.e.%)	10-20cm Soil pH
50	ING	259	0.62	5.7	0.12	6.2
51	ING	229	0.37	5.9	0.12	5.6
52	ING	213	0.25	5.6	0.04	5.7
53	ING	152	0.86	5.9	0.16	6.2
54	ING	152	0.41	5.9	0.17	6.0
55	ING	183	0.76	6.0	0.12	6.0
56	ING	198	0.70	5.8	0.12	5.8
57	ING	229	0.80	6.1	0.08	5.9
58	ING	244	0.47	5.7	0.04	5.7
59	ING	442	0.21	5.8	0.01	5.6
60	ING	427	0.43	5.2	0.14	5.4
61	ING	411	0.49	5.8	0.04	5.8
62	ING	351	0.52	5.6	0.08	5.7
63	ING	213	0.68	5.7	0.18	5.7
64	ING	213	1.85	6.0	0.39	5.9
65	ING	213	1.65	6.1	0.64	6.1

Sample Number	Soil Type	Altitude (m)	0-10cm Exch. Mg (m.e.%)	0-10cm Soil pH	10-20cm Exch. Mg (m.e.%)	10-20cm Soil pH
66	ING	152	1.87	6.2	0.49	6.2
67	ING	198	0.99	5.9	0.12	5.8
68	ING	198	0.95	5.9	0.20	5.6
69	ING	213	0.62	6.0	0.04	5.8
70	ING	183	0.66	5.8	0.16	5.8
71	ING	198	0.95	5.9	0.21	5.8
72x	ING	213	1.09	5.8	0.21	5.7
73x	ING	213	0.82	5.9	0.12	5.9
74	ING	198	1.62	6.0	0.21	5.7
75	ING	213	0.62	5.8	0.25	5.9
76	ING	213	0.62	6.3	0.23	6.1
77	NPL	45	1.99	6.1	0.95	5.9
78	NPL	61	1.42	5.8	0.58	5.9
79	NPL	76	1.62	6.0	0.78	6.1
80	NPL	91	1.54	5.7	0.16	5.3
81	PAT	152	0.63	6.2	0.19	6.4
82	PAT	183	0.86	5.9	0.29	5.4
83	PAT	244	0.88	5.8	0.21	5.8

			0-10cm		10-20cm	
Sample Number	Soil pH	Altitude (m)	Exch. Mg (m.e.%)	Soil pH	Exch. Mg (m.e.%)	Soil pH
84	PAT	335	0.82	5.7	0.38	5.7
85	PAT	366	0.56	5.7	0.16	5.8

BUR - Burrell gravelly sandy loam
HAN - Hangatahua bouldery sand
ING - Inglewood coarse sandy loam
NEW - Newall bouldery sand
NOR - Norfolk bouldery sand
NPL - New Plymouth black loam
PAT - Patua loam
STR - Stratford coarse sandy loam

Appendix III

Results of Analysis of Variance for:

i) ryegrass dry matter yields;
ii) ryegrass Mg concentration;
iii) ryegrass Mg uptake
iv) ryegrass Ca concentration;
v) ryegrass Ca uptake;
vi) ryegrass K concentration;
vii) ryegrass K uptake;

at each harvest.

Legend:

Soil type - Soil type effects
Treatment - Mg fertilizer addition effects
Cutting Regime - Cutting regime effects
Soil Type x Treatment - Soil type by Mg fertilizer addition interaction
Soil Type x Cutting Regime - Soil type by cutting regime interaction
Treatment x Cutting Regime - Mg fertilizer addition by Cutting Regime interaction.

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i) Ryegrass dry matter yields.

Harvest 1.

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CLASSIFICATION                              D.F.   SUM OF SQUARES   MEAN SQUARE        F              PROB

SOIL TYPE                                     3        47.46519       15.82173      203.134 ***     -0.0000
TREATMENT                                     3         1.72853        0.57618        7.397 ***      0.0002
CUTT REG                                      1         3.85101        3.85101       49.443 ***      0.0000
SOIL TYPE     X TREATMENT                     9         5.21798        0.57978        7.444 ***      0.0000
SOIL TYPE     X CUTT REG                      3         0.38086        0.12695        1.630          0.1869
TREATMENT     X CUTT REG                      3         0.07695        0.02565        0.329          0.8042
REMAINDER                                   105         8.17825        0.07789                RSD=   0.27908
TOTAL                                       127        66.89877
```

Harvest 2.

```
CLASSIFICATION                              D.F.   SUM OF SQUARES   MEAN SQUARE        F              PROB

SOIL TYPE                                     3         5.69533        1.89844      154.450 ***     -0.0000
TREATMENT                                     3         0.16306        0.05435        4.422 **       0.0057
CUTT REG                                      1         0.79254        0.79254       64.478 ***     -0.0000
SOIL TYPE     X TREATMENT                     9         0.33363        0.03707        3.016 **       0.0031
SOIL TYPE     X CUTT REG                      3         0.20850        0.06950        5.654 **       0.0012
TREATMENT     X CUTT REG                      3         0.04135        0.01378        1.121          0.3439
REMAINDER                                   105         1.29052        0.01229                RSD=   0.11087
TOTAL                                       127         8.52503
```

Harvest 3

```
  CLASSIFICATION                          D.F.   SUM OF SQUARES   MEAN SQUARE        F                PROB.

SOIL TYPE                                   3       12.66802        4.22267      113.707 ***       -0.0000
TREATMENT                                   3        0.33302        0.11101        2.989 *          0.0344
CUTT REG                                    1       12.04116       12.04116      324.241 ***       -0.0000
SOIL TYPE      X TREATMENT                  9        0.46329        0.05148        1.386            0.2037
SOIL TYPE      X CUTT REG                   3        2.09033        0.69678       18.763 ***        0.0000
TREATMENT      X CUTT REG                   3        0.07990        0.02666        0.718            0.5456
REMAINDER                                 105        3.89933        0.03714                  RSD=   0.19271
TOTAL                                     127       31.57515
```

Total Dry Matter yield.

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  CLASSIFICATION                          D.F.   SUM OF SQUARES   MEAN SQUARE        F                PROB.

SOIL TYPE                                   3       79.45637       26.48546      165.576 ***        0.0000
TREATMENT                                   3        3.89013        1.29671        8.117 ***        0.0001
CUTT REG                                    1        0.38117        0.38117        2.383            0.1256
SOIL TYPE      X TREATMENT                  9        9.23897        1.02655        6.416 **         0.0000
TREATMENT      X CUTT REG                   3        0.31626        0.10542        0.657            0.5790
REMAINDER                                 108       17.27626        0.15997                  RSD=   0.39996
TOTAL                                     127      110.56[illegible]
```

ii) Ryegrass Mg concentration

Harvest 1

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     CLASSIFICATION                         D.F.   SUM OF SQUARES   MEAN SQUARE        F             PROB

SOIL TYPE                                    3       0.21011         0.07004      352.381 ***     -0.0000
TREATMENT                                    3       0.05071         0.01690       85.043 ***     -0.0000
CUTT REG                                     1       0.00463         0.00463       23.305 ***      0.0000
SOIL TYPE      X TREATMENT                   9       0.00503         0.00056        2.818 **       0.0054
SOIL TYPE      X CUTT REG                    3       0.00048         0.00016        0.811          0.4905
TREATMENT      X CUTT REG                    3       0.00123         0.00041        2.056          0.1102
REMAINDER                                  105       0.02087         0.00020              RSD=     0.0141
TOTAL                                      127       0.29306
```

Harvest 2

```
     CLASSIFICATION                         D.F.   SUM OF SQUARES   MEAN SQUARE        F             PROB

SOIL TYPE                                    3       0.17352         0.05784      187.515 ***     -0.0000
TREATMENT                                    3       0.06609         0.02203       71.425 ***     -0.0000
CUTT REG                                     1       0.19845         0.19845      643.373 ***     -0.0000
SOIL TYPE      X TREATMENT                   9       0.02071         0.00230        7.461 ***      0.0000
SOIL TYPE      X CUTT REG                    3       0.03388         0.01129       36.614 ***     -0.0000
TREATMENT      X CUTT REG                    3       0.00151         0.00050        1.628          0.1874
REMAINDER                                  105       0.03239         0.00031              RSD=     0.0175
TOTAL                                      127       0.52655
```

Harvest 3

```
    CLASSIFICATION                       D.F.   SUM OF SQUARES   MEAN SQUARE        F            PROB

SOIL TYPE                                 3        0.10085        0.03362      83.619 ***      -0.0000
TREATMENT                                 3        0.08448        0.02816      70.047 ***      -0.0000
CUTT REG                                  1        0.00018        0.00018       0.437           0.5099
SOIL TYPE    X TREATMENT                  9        0.02973        0.00330       8.215 ***       0.0000
SOIL TYPE    X CUTT REG                   3        0.00041        0.00014       0.344           0.7936
TREATMENT    X CUTT REG                   3        0.00151        0.00050       1.251           0.2952
REMAINDER                               105        0.04221        0.00040               RSD=    0.02005
TOTAL                                   127        0.25937
```

iii) Ryegrass Mg uptake

Harvest 1

```
 CLASSIFICATION                        D.F.   SUM OF SQUARES  MEAN SQUARE        F              PROB

SOIL TYPE                                3      0,50811        0,16937       61,132 ***      -0,0000
TREATMENT                                3      0,21603        0,07201       25,991 ***      -0,0000
CUTT REG                                 1      0,21679        0,21679       78,249 ***      -0,0000
SOIL TYPE    X TREATMENT                 9      0,16046        0,01785        6,435 ***       0,0000
SOIL TYPE    X CUTT REG                  3      0,02142        0,00714        2,577 +         0,0577
TREATMENT    X CUTT REG                  3      0,01058        0,00353        1,273           0,2874
REMAINDER                              105      0,29091        0,00277                 RSD=    0,05264
TOTAL                                  127      1,42432
```

Harvest 2

```
 CLASSIFICATION                        D.F.   SUM OF SQUARES  MEAN SQUARE        F              PROB

SOIL TYPE                                3      0,62911        0,20970      182,940 ***      -0,0000
TREATMENT                                3      0,07246        0,02415       21,071 ***       0,0000
CUTT REG                                 1      0,32964        0,32964      287,571 ***      -0,0000
SOIL TYPE    X TREATMENT                 9      0,05309        0,00590        5,146 ***       0,0000
SOIL TYPE    X CUTT REG                  3      0,05973        0,01991       17,370 ***       0,0000
TREATMENT    X CUTT REG                  3      0,00554        0,00185        1,618           0,1897
REMAINDER                              105      0,12036        0,00115                 RSD=    0,03386
TOTAL                                  127      1,26996
```

Harvest 3

```
    CLASSIFICATION                                D.F.    SUM OF SQUARES   MEAN SQUARE          F                PROB

SOIL TYPE                                           3          1.14863          0.38288     127.787 ***         =0.0000
TREATMENT                                           3          0.14840          0.04947      16.509 ***          0.0000
CUTT REG                                            1          0.80809          0.80809     269.705 ***         =0.0000
SOIL TYPE      X TREATMENT                          9          0.08538          0.00949       3.166 **           0.0020
SOIL TYPE      X CUTT REG                           3          0.17004          0.05668      18.917 ***          0.0000
TREATMENT      X CUTT REG                           3          0.00589          0.00196       0.655              0.5814
REMAINDER                                         105          0.31460          0.00300               RSD=      0.05474
TOTAL                                             127          2.68102
```

Total Mg uptake

```
    CLASSIFICATION                                D.F.    SUM OF SQUARES   MEAN SQUARE          F                PROB

SOIL TYPE                                           3         .4.77721          1.59240     164.864 ***          0.0000
TREATMENT                                           3          1.19307          0.39769      41.174 ***          0.0000
CUTT REG                                            1          0.01981          0.01981       2.051              0.1550
SOIL TYPE      X TREATMENT                          9          0.68904          0.07655       7.935 ***          0.0000
TREATMENT      X CUTT REG                           3          0.02037          0.00679       0.703              0.5522
REMAINDER                                         108          1.04396          0.00966               RSD=      0.09828
TOTAL                                             127          7.74346
```

iv) Ryegrass Ca concentration

Harvest 1

```
   CLASSIFICATION                         D.F.   SUM OF SQUARES   MEAN SQUARE         F              PROB

SOIL  TYPE                                  3      2,20516        0.73505      303.815 ***       -0.0000
CUTT  REG                                   1      0,02284        0.02284        9.442 **         0.0027
TREATMENT                                   3      0,04552        0.01517        6.272 ***        0.0006
SOIL  TYPE     X  CUTT  REG                 3      0,03638        0.01213        5.012 **         0.0027
SOIL  TYPE     X  TREATMENT                 9      0,01933        0.00215        0.888            0.5388
CUTT  REG      X  TREATMENT                 3      0,01575        0.00525        2.170 +          0.0959
REMAINDER                                 105      0,25404        0.00242               RSQ=      0.04919
TOTAL                                     127      2,59902
```

Harvest 2

```
   CLASSIFICATION                         D.F.   SUM OF SQUARES   MEAN SQUARE         F              PROB

SOIL  TYPE                                  3      1,61732        0,53911      226,238 ***       -0,0000
CUTT  REG                                   1      0,00439        0,00439        1,844            0,1774
TREATMENT                                   3      0,01385        0,00462        1,938            0,1280
SOIL  TYPE     X  CUTT  REG                 3      0,01286        0,00429        1,800            0,1516
SOIL  TYPE     X  TREATMENT                 9      0,03894        0,00433        1,816 +          0,0738
CUTT  REG      X  TREATMENT                 3      0,00775        0,00258        1,084            0,3594
REMAINDER                                 105      0,25021        0,00238               RSQ=      0,04882
TOTAL                                     127      1,94532
```

Harvest 3

```
   CLASSIFICATION                      D.F.   SUM OF SQUARES   MEAN SQUARE        F              PROB

SOIL TYPE                                3       1,45806        0,48602      201,292 ***     -0,0000
CUTT REG                                 1       0,03188        0,03188       13,203 ***      0,0004
TREATMENT                                3       0,02001        0,00667        2,763 *        0,0457
SOIL TYPE    X CUTT REG                  3       0,03007        0,01002        4,151 **       0,0080
SOIL TYPE    X TREATMENT                 9       0,01852        0,00206        0,852          0,5702
CUTT REG     X TREATMENT                 3       0,00533        0,00178        0,736          0,5526
REMAINDER                              105       0,25352        0,00241               RSD=   0,04914
TOTAL                                  127       1,81739
```

v) Ryegrass Ca uptake

Harvest 1

```
    CLASSIFICATION                                      D.F.    SUM OF SQUARES    MEAN SQUARE        F                    PROB

SOIL TYPE                                                 3       12,12351          4,04117       184.816 ***          -0,0000
CUTT REG                                                  1        1,96515          1.96515        89.873 ***          -0,0000
TREATMENT                                                 3        0,34694          0,11565         5,289 **            0,0020
SOIL TYPE    Y CUTT REG                                   3        0,60600          0,20200         9,238 ***           0,0000
SOIL TYPE    X TREATMENT                                  9        1,24441          0,13827         6,323 ***           0,0000
CUTT REG     X TREATMENT                                  3        0,03628          0,01209         0,553               0,6472
REMAINDER                                               105        2,29593          0,02187                   RSD=     0,14787
TOTAL                                                   127       18,61823
```

Harvest 2

```
    CLASSIFICATION                                      D.F.    SUM OF SQUARES    MEAN SQUARE        F                    PROB

SOIL TYPE                                                 3        3,02092          1,00697       233,423 ***          -0,0000
CUTT REG                                                  1        0,33589          0,33589        77,862 ***          -0,0000
TREATMENT                                                 3        0,04985          0,01665         3,854 *             0,0116
SOIL TYPE    X CUTT REG                                   3        0,09224          0,03075         7,127 ***           0,0002
SOIL TYPE    X TREATMENT                                  9        0,22185          0,02465         5,714 ***           0,0000
CUTT REG     X TREATMENT                                  3        0,00668          0,00223         0.516               0,6722
REMAINDER                                               105        0,45294          0,00431                   RSD=     0,06568
TOTAL                                                   127        4,18042
```

Harvest 3

```
    CLASSIFICATION                        D.F.   SUM OF SQUARES   MEAN SQUARE        F              PROB

SOIL TYPE                                   3        6,23369        2.07790      151.109 ***     -0.0000
CUTT REG                                    1        4,28257        4.28257      311.437 ***     -0.0000
TREATMENT                                   3        0,03789        0,01263        0.919          0.4347
SOIL TYPE     X CUTT REG                    3        0,84705        0,28235       20.533 ***      0.0000
SOIL TYPE     X TREATMENT                   9        0,17013        0,01890        1.375          0.2089
CUTT REG      X TREATMENT                   3        0,00983        0.00328        0.238          0.8595
REMAINDER                                 105        1.44385        0.01375               RSD=    0.11726
TOTAL                                     127       13,02501
```

Total Ca uptake

```
    CLASSIFICATION                        D.F.   SUM OF SQUARES   MEAN SQUARE        F              PROB

SOIL TYPE                                   3       50.74177       16.91392      216.350 ***      0.0000
CUTT REG                                    1        0,00762        0.00762        0.097          0.7554
SOIL TYPE     X CUTT REG                    3        0.44670        0.14890        1.905          0.1325
REMAINDER                                 120        9,38144        0,07818               RSD=    0,27960
TOTAL                                     127       60,57754
```

vi) Rygrass K Concentration.

Harvest 1

```
    CLASSIFICATION                        D.F.   SUM OF SQUARES   MEAN SQUARE        F             PROB

SOIL TYPE                                  3       7.91770        2.63923       78.209 ***      -0.0000
CUTT REG                                   1       3.06281        3.06281       90.761 ***      -0.0000
TREATMENT                                  3       0.11295        0.03765        1.116           0.3462
SOIL TYPE     X CUTT REG                   3       0.86023        0.28674        8.497 ***       0.0000
SOIL TYPE     X TREATMENT                  9       1.11949        0.12439        3.686 ***       0.0005
CUTT REG      X TREATMENT                  3       0.10439        0.03480        1.031           0.3820
REMAINDER                                105       3.54351        0.03375               RSD=     0.18370
TOTAL                                    127      16.72090
```

Harvest 2

```
    CLASSIFICATION                        D.F.   SUM OF SQUARES   MEAN SQUARE        F             PROB

SOIL TYPE                                  3      32,24222       10,74741      258,837 ***      -0,0000
CUTT REG                                   1       0,36980        0,36980        8,906 **        0,0035
TREATMENT                                  3       0,48823        0,16274        3,919 *         0,0107
SOIL TYPE     X CUTT REG                   3       0,63319        0,21106        5,083 **        0,0025
SOIL TYPE     X TREATMENT                  9       0,48705        0,05412        1,303           0,2440
CUTT REG      X TREATMENT                  3       0,03939        0,01313        0,316           0,8137
REMAINDER                                105       4,35980        0,04152               RSD=     0,20377
TOTAL                                    127      38,61967
```

Harvest 3

```
    CLASSIFICATION                    D.F.   SUM OF SQUARES   MEAN SQUARE        F              PROB

SOIL TYPE                               3      34,83785       11,61262      218,252 ***     -0,0000
CUTT REG                                1       0,79853        0,79853       15,008 ***      0,0002
TREATMENT                               3       0,66279        0,22093        4,152 **       0,0080
SOIL TYPE    X CUTT REG                 3       0,81786        0,27262        5,124 **       0,0024
SOIL TYPE    X TREATMENT                9       0,96108        0,10679        2,007 *        0,0455
CUTT REG     X TREATMENT                3       0,36546        0,12182        2,290 +        0,0827
REMAINDER                             105       5,58678        0,05321                 RSD=  0,23067
TOTAL                                 127      44,03035
```

vii) Ryegrass K uptake

Harvest 1

```
   CLASSIFICATION                        D.F.   SUM OF SQUARES   MEAN SQUARE        F                 PROB

SOIL TYPE                                  3     103,50595       34,50132      114.481 ***        -0,0000
CUTT REG                                   1       2,05082        2,05082        6.805 *           0,0104
TREATMENT                                  3       5,34816        1,78272        5.915 ***         0,0009
SOIL TYPE     X CUTT REG                   3       5,25342        1,75114        5.811 **          0,0010
SOIL TYPE     X TREATMENT                  9      10,01132        1,11237        3.691 ***         0,0005
CUTT REG      X TREATMENT                  3       0,13128        0,04375        0.145             0,9325
REMAINDER                                105      31,64394        0,30137                  RSD=    0,54897
TOTAL                                    127     157,94489
```

Harvest 2

```
   CLASSIFICATION                        D.F.   SUM OF SQUARES   MEAN SQUARE        F                 PROB

SOIL TYPE                                  3      37,10385       12,36795      173.431 ***        -0,0000
CUTT REG                                   1       1,82859        1,82859       25.642 ***         0,0000
TREATMENT                                  3       0,88359        0,29520        4.139 **          0,0081
SOIL TYPE     X CUTT REG                   3       1,36725        0,45575        6.391 ***         0,0005
SOIL TYPE     X TREATMENT                  9       0,59322        0,06591        0.924             0,5073
CUTT REG      X TREATMENT                  3       0,15914        0,05305        0.744             0,5285
REMAINDER                                105       7,48791        0,07131                  RSD=    0,26705
TOTAL                                    127      49,42354
```

Harvest 3

```
 CLASSIFICATION                          D.F.   SUM OF SQUARES   MEAN SQUARE        F                 PROB

 SOIL TYPE                                3       26,40502        8,80167      94,293 ***       -0,0000
 CUTT REG                                 1       11,86210       11,86210     127,080 ***       -0,0000
 TREATMENT                                3        2,11442        0,70481       7,551 ***        0,0001
 SOIL TYPE     X CUTT REG                 3        2,18184        0,72728       7,791 ***        0,0001
 SOIL TYPE     X TREATMENT                9        1,25480        0,13942       1.494            0,1595
 CUTT REG      X TREATMENT                3        0,13387        0,04462       0.478            0,6982
 REMAINDER                              105        9,80106        0,09334                RSD=   0,30552
 TOTAL                                  127       53,75311
```

Total K uptake

```
 CLASSIFICATION                          D.F.   SUM OF SQUARES   MEAN SQUARE        F                 PROB

 SOIL TYPE                                3       60,05023       20,01674      26,752 ***       -0,0000
 CUTT REG                                 1        0,43409        0,43409       0.580            0,4477
 SOIL TYPE     X CUTT REG                 3        4,18203        1,39401       1.863            0,1395
 REMAINDER                              120       89,78886        0.74824                RSD=   0,86501
 TOTAL                                  127      154,45519
```

Appendix IV

Results of Analysis of variance for:

i) Ryegrass Mg concentration
ii) Ryegrass Ca concentration
iii) Ryegrass K concentration

for each soil type and cutting regime

Legend:

Treatment : Mg fertilizer addition effects

Cut : Harvest effects

Treatment x Cut: Mg fertilizer addition by harvest number interaction

oooOOOooo

i) Ryegrass Mg concentration

a) Burrell gravelly sandy loam

Cutting Regime 1

```
   CLASSIFICATION                       D.F.    SUM OF SQUARES   MEAN SQUARE        F                PROB

TREATMENT                                 3       0.03216         0.01072       53.041 ***          0.0000
CUT                                       2       0.18240         0.09120      451.309 ***          0.0000
TREATMENT     X CUT                       6       0.00344         0.00058        2.856 *            0.0225
REMAINDER                                36       0.00728         0.00020                  RSD=     0.01422
TOTAL                                    47       0.22528
```

Cutting Regime 2

```
   CLASSIFICATION                       D.F.    SUM OF SQUARES   MEAN SQUARE        F                PROB

TREATMENT                                 3       0.06695         0.02232       75.437 ***          0.0000
CUT                                       2       0.20698         0.10349      349.824 ***          0.0000
TREATMENT     X CUT                       6       0.00959         0.00160        5.401 ***          0.0005
REMAINDER                                36       0.01065         0.00030                  RSD=     0.0172
TOTAL                                    47       0.29417
```

b. Inglewood coarse sandy loam

Cutting Regime 1

```
   CLASSIFICATION                      D.F.   SUM OF SQUARES   MEAN SQUARE        F                PROB

TREATMENT                               3        0.04462        0.01487      38.456 ***         0.0000
CUT                                     2        0.03953        0.01976      51.081 ***         0.0000
TREATMENT    X CUT                      6        0.00223        0.00037       0.962             0.4643
REMAINDER                              36        0.01393        0.00039                  RSQ=   0.1967
TOTAL                                  47        0.10030
```

Cutting Regime 2

```
   CLASSIFICATION                      D.F.   SUM OF SQUARES   MEAN SQUARE        F                PROB

TREATMENT                               3        0.05501        0.01834      37.554 ***         0.0000
CUT                                     2        0.02533        0.01266      25.942 ***         0.0000
TREATMENT    X CUT                      6        0.00224        0.00037       0.764             0.6051
REMAINDER                              36        0.01757        0.00049                  RSQ=   0.8212
TOTAL                                  47        0.10015
```

c) Egmont black loam

Cutting Regime 1

```
   CLASSIFICATION                      D.F.   SUM OF SQUARES   MEAN SQUARE        F                 PROB

TREATMENT                               3        0.00887        0.00296       11.605 ***           0.0000
CUT                                     2        0.00376        0.00188        7.381 **            0.0021
TREATMENT     X CUT                     6        0.00257        0.00043        1.681               0.1539
REMAINDER                              36        0.00917        0.00025                   RSD=     0.01596
TOTAL                                  47        0.02437
```

Cutting Regime 2

```
   CLASSIFICATION                      D.F.   SUM OF SQUARES   MEAN SQUARE        F                 PROB

TREATMENT                               3        0.00746        0.00249       15.907 ***           0.0000
CUT                                     2        0.02454        0.01227       78.524 ***           0.0000
TREATMENT     X CUT                     6        0.00247        0.00041        2.627 *             0.0374
REMAINDER                              36        0.00563        0.00016                   RSD=     0.0125[illegible]
TOTAL                                  47        0.04008
```

d) New Plymouth black loam

Cutting Regime 1

```
    CLASSIFICATION                      D.F.   SUM OF SQUARES   MEAN SQUARE        F              PROB
 --------------------------------------------------------------------------------------------------------
   TREATMENT                              3        0.01446        0.00482      19.116 ***        0.0000
   CUT                                    2        0.04050        0.02025      80.339 ***        0.0000
   TREATMENT     X CUT                    6        0.00216        0.00036       1.430            0.2304
   REMAINDER                             36        0.00907        0.00025                RSQ=   0.01984
   TOTAL                                 47        0.06620
 --------------------------------------------------------------------------------------------------------
```

Cutting Regime 2

```
    CLASSIFICATION                      D.F.   SUM OF SQUARES   MEAN SQUARE        F              PROB
 --------------------------------------------------------------------------------------------------------
   TREATMENT                              3        0.01402        0.00467      15.877 ***        0.0000
   CUT                                    2        0.02660        0.01330      45.170 ***        0.0000
   TREATMENT     X CUT                    6        0.00430        0.00072       2.436 *          0.0445
   REMAINDER                             36        0.01060        0.00029                RSQ=   0.01707
   TOTAL                                 47        0.05553
 --------------------------------------------------------------------------------------------------------
```

ii) Ryegrass Ca concentration.

a) Burrell gravelly sandy loam

Cutting Regime 1

```
   CLASSIFICATION                      D.F.   SUM OF SQUARES   MEAN SQUARE        F              PROB
-----------------------------------------------------------------------------------------------------
TREATMENT                                3       0.02184        0.00728       2.265 +         0.0976
CUT                                      2       0.42215        0.21107      65.662 ***       0.0000
TREATMENT      X CUT                     6       0.01663        0.00277       0.862           0.5322
REMAINDER                               36       0.11572        0.00321                RSD=   0.05670
TOTAL                                   47       0.57633
-----------------------------------------------------------------------------------------------------
```

Cutting Regime 2

```
   CLASSIFICATION                      D.F.   SUM OF SQUARES   MEAN SQUARE        F              PROB

TREATMENT                                3       0.03154        0.01051       4.032 *         0.0145
CUT                                      2       0.21090        0.10545      40.440 ***       0.0000
TREATMENT      X CUT                     6       0.01988        0.00331       1.271           0.2952
REMAINDER                               36       0.09388        0.00261                RSD=   0.05107
TOTAL                                   47       0.35620
-----------------------------------------------------------------------------------------------------
```

b) Inglewood coarse sandy loam

Cutting Regime 1

```
   CLASSIFICATION                              D.F.   SUM OF SQUARES   MEAN SQUARE         F                  PROB

TREATMENT                                       3        0,02641         0.00880        12.701 ***           0.0000
CUT                                             2        0,04861         0.02431        35.071 ***           0.0000
TREATMENT    X CUT                              6        0,00855         0.00143         2.057 +             0.085[illegible]
REMAINDER                                      36        0,02495         0.00069                      RSQ=   0.7[illegible]
TOTAL                                          47        0,10853
```

Cutting Regime 2

```
   CLASSIFICATION                              D.F.   SUM OF SQUARES   MEAN SQUARE         F                  PROB

TREATMENT                                       5        0,03252         0,01084         3.462 *             0.0262
CUT                                             2        0,01295         0,00646         2,065               0,1417
TREATMENT    X CUT                              6        0,00953         0.00159         0.507               0,7986
REMAINDER                                      36        0,11272         0.00313                      RSQ=   0.[illegible]
TOTAL                                          47        0,16773
```

c) Egmont black loam

Cutting Regime 1

```
 CLASSIFICATION                       D.F.   SUM OF SQUARES   MEAN SQUARE        F                 PROB

TREATMENT                              3       0,00622          0,00207        1,058              0,3789
CUT                                    2       0,25959          0,12979       66,207 ***          0,0000
TREATMENT    X CUT                     6       0,01445          0,00241        1,228              0,3150
REMAINDER                             36       0,07057          0,00196                   RSD=    0,04427
TOTAL                                 47       0,35083
```

Cutting Regime 2

```
 CLASSIFICATION                       D.F.   SUM OF SQUARES   MEAN SQUARE        F                 PROB

TREATMENT                              3       0,01237          0,00412        3,373 *            0,0286
CUT                                    2       0,34355          0,17177      140,465 ***          0,0000
TREATMENT    X CUT                     6       0,00818          0,00136        1,115              0,3729
REMAINDER                             36       0,04402          0,00122                   RSD=    0,03497
TOTAL                                 47       0,40813
```

d) New Plymouth black loam

Cutting Regime 1

```
    CLASSIFICATION                          D.F.   SUM OF SQUARES   MEAN SQUARE        F                   PROB

TREATMENT                                    3        0,00914        0,00305        0.928                0.4371
CUT                                          2        0,01613        0,00806        2.456                0.1000
TREATMENT      X CUT                         6        0,03252        0,00542        1.651                0.1617
REMAINDER                                   36        0,11820        0,00328                     RSQ=   [illegible]
TOTAL                                       47        0,17599
```

Cutting Regime 2

```
    CLASSIFICATION                          D.F.   SUM OF SQUARES   MEAN SQUARE        F                   PROB

TREATMENT                                    3        0,01804        0,00601        2,769 +              0,0556
CUT                                          2        0,10396        0,05198       23,938 ***            0,0000
TREATMENT      X CUT                         6        0,01670        0,00278        1,282                [illegible]
REMAINDER                                   36        0,07812        0,00217                     RSQ=   [illegible]
TOTAL                                       47        0,21688
```

iii) Ryegrass K concentration

a) Burrell gravelly sandy loam

Cutting Regime 1

```
   CLASSIFICATION                    D.F.   SUM OF SQUARES   MEAN SQUARE        F                PROB
-----------------------------------------------------------------------------------------------------
TREATMENT                              3        0,74866        0,24955      4,609 **          0,0079
CUT                                    2       22,19760       11,09880    204,972 ***         0,0000
TREATMENT     X CUT                    6        0,58231        0,09705      1,792             0,1284
REMAINDER                             36        1,94932        0,05415                RSD=   0,23270
TOTAL                                 47       25,47790
-----------------------------------------------------------------------------------------------------
```

Cutting Regime 2

```
   CLASSIFICATION                    D.F.   SUM OF SQUARES   MEAN SQUARE        F                PROB
-----------------------------------------------------------------------------------------------------
TREATMENT                              3        0,19396        0,06465      2,055             0,1235
CUT                                    2        6,93382        3,46691    110,184 ***         0,0000
TREATMENT     X CUT                    6        0,05347        0,00891      0,283             0,9411
REMAINDER                             36        1,13277        0,03146                RSD=   0,17738
TOTAL                                 47        8,31395
-----------------------------------------------------------------------------------------------------
```

b) Inglewood coarse sandy loam

Cutting Regime 1

```
CLASSIFICATION                 D.F.   SUM OF SQUARES   MEAN SQUARE      F              PROB

TREATMENT                        3       0,23098         0.07699      1.383           0,2635
CUT                              2       0,65795         0.32896      5.911 **        0,0060
TREATMENT     X CUT              6       0,09493         0.01582      0.284           [illegible]
REMAINDER                       36       2,00376         0.05566                RSQ=  0,3293
TOTAL                           47       2,98762
```

Cutting Regime 2

```
CLASSIFICATION                 D.F.   SUM OF SQUARES   MEAN SQUARE      F              PROB

TREATMENT                        3       1,34781         0,44927     10,212 ***       0,0001
CUT                              2       1,70415         0,85208     19,360 ***       0,0000
TREATMENT     X CUT              6       1,01430         0,16905      3,843 **        0,0046
REMAINDER                       36       1,58377         0,04399                RSQ=  0,7197
TOTAL                           47       5,65003
```

c) Egmont black loam

Cutting Regime 1

```
     CLASSIFICATION                    D.F.   SUM OF SQUARES   MEAN SQUARE        F              PROB

TREATMENT                               3       0,12030         0,04010        1,103            0,3605
CUT                                     2      17,04671         8,52336      234,480 ***        0,0000
TREATMENT      X CUT                    6       0,09750         0,01625        0,447            0,8426
REMAINDER                              36       1,30866         0,03635                 RSD=    0,1906
TOTAL                                  47      18,5730[illegible]
```

Cutting Regime 2

```
     CLASSIFICATION                    D.F.   SUM OF SQUARES   MEAN SQUARE        F              PROB

TREATMENT                               3       0,00494         0,00165        0,062            0,9793
CUT                                     2       4,10112         2,05056       77,422 ***        0,0000
TREATMENT      X CUT                    6       0,23968         0,03995        1,508            0,2036
REMAINDER                              36       0,95348         0,02649                 RSD=    0,16274
TOTAL                                  47       5,29915
```

d) New Plymouth black loam

Cutting Regime 1

```
CLASSIFICATION                D.F.   SUM OF SQUARES   MEAN SQUARE        F              PROB

TREATMENT                       3       0,24996        0,08332        1.743             0,1756
CUT                             2      15,27338        7,63669      159.743 ***         0,0000
TREATMENT      X CUT            6       0,16086        0,02681        0.561             0,7588
REMAINDER                      36       1,72116        0.04781                [illegible]  0,21865
TOTAL                          47      17,40583
```

Cutting Regime 2

```
CLASSIFICATION                D.F.   SUM OF SQUARES   MEAN SQUARE        F              PROB

TREATMENT                       3       0,54045        0.18015        4,957 **          0,0056
CUT                             2      10,34882        5.17441      142,366 ***         0,0000
TREATMENT      X CUT            6       0,18975        0,03162        0.870             0,5262
REMAINDER                      36       1,30860        0,03635                [illegible]  0,19066
TOTAL                          47      12,38742
```