The Yield and Chemical Composition of Barley as Influenced by High Levels of Ca and Mg in the Growth Medium

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Cynthia Ann Grant

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ABSTRACT

Studies were conducted in solution and soil culture to examine the effect of high concentrations of Mg and Ca in the medium on the growth and nutrition of barley. Uptake of K by excised roots was decreased slightly by increasing concentration of Mg. Efflux of K from intact barley plants was increased when either Ca or Mg was increased above 8 mM. Yield of barley in hydroponic culture decreased when Ca or Mg was increased above 8 mM. Yield of barley in soil studies also decreased with increasing levels of either Ca or Mg. Concentration of Ca and Mg in the soil solution of unamended soils was generally lower than 8 mM but application of NH_4NO_3 increased soil solution concentration of Ca and Mg to potentially toxic levels. Concentration of the nutrients in the tissue generally reflected concentration of the nutrients in the growth medium and there was no indication that Ca or Mg restricted uptake of K. Concentration of Zn and Mn in the soil and tissue decreased with increasing Ca and Mg content of the soil. Reduced yield of barley on soils high in Mg and/or Ca may therefore be due either to direct Ca or Mg toxicity or reduced availability of Mn and/or Zn associated with soils high in Mg and/or Ca.

Addition of $CaSO_4$ and/or KCl to soils high in Mg generally did not increase barley yield. On the Assiniboine complex soil, however, application of broadcast KCl increased grain yield. Application of 6000 kg ha^{-1} of Ca as $CaSO_4$ or $CaCl_2$ increased Ca:Mg ratio in the soil solution, but concentrations of Ca and Mg were increased to levels

potentially deleterious to crop yield. Therefore, it is unlikely that application of Ca as $CaSO_4$ or $CaCl_2$ would be of economic advantage on soils high in Mg.

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1.0 Introduction

Soils in arid regions usually have a cation exchange system dominated by Ca and Mg. Ca saturation of montmorillonitic soils should comprise about 60 to 80% of the exchange, in order to ensure flocculation of soil particles for formation of stable aggregates with clay minerals. Mg normally constitutes about 4 to 20% of the exchange capacity of soils, with chernozems generally containing about 14% Mg. However, the level of Mg may be much higher in soils formed in depressional sites where leached nutrients accumulate, in lightly leached soils, and in soils formed from Mg-rich parent materials such as dolomite (Mengel and Kirkby 1979).

Most Manitoba soils were developed on glacial materials. Many of the soils in the eastern portion of the province formed from tills and alluvial deposits derived from iceflows which passed over dolomitic outcrops (Klassen 1974). These soils tend to have high levels of exchangeable Mg. In some cases, as much as 50% of the exchange may be occupied by Mg (Smith and Ehrlich 1967).

Mg has been observed to interact with the other nutrient cations both in the soil system and the nutrition of the plant (Mengel and Kirkby 1979). Therefore, both the absolute level of Mg in the soil system and its abundance relative to other plant nutrients such as Ca, K, Mn and Zn will be important in influencing crop productivity.

Although numerous studies have been conducted on interactions of Mg with other cations, the emphasis has generally been placed on the investigation of Mg deficiency rather than Mg excess. The effect

of high levels of Mg and low Ca:Mg ratios in soils on crop production has not been fully examined.

High concentrations of Mg could have direct chemical effects on plant growth. It has been suggested that Mg could interfere with the uptake of other cations, most notably K, resulting in an induced nutrient deficiency. Mg could interfere with Ca utilization by the plant, possibly replacing Ca on membrane binding sites, leading to impaired membrane integrity. Mg could also possibly interfere with uptake and utilization of micronutrient cations such as Mn and Zn.

Alternately, high concentrations of Mg could influence crop growth indirectly. High levels of Mg tend to be associated with heavy clay soils and often with soil structural problems which could reduce crop yield. The pH of soils high in Mg tends to be high, which could lead to problems in micronutrient availability.

The objectives of this research project were therefore to:

(1) Determine the effect of varying concentrations of Mg and Ca on the uptake of K by excised roots and to determine if Mg interfered with the transport of K across the plasma membrane into the root cells.

(2) Determine the effect of high concentrations of Ca and Mg on root membrane integrity as indicated by leakage of electrolytes and K from intact barley plants.

(3) Determine the chemical effects of high concentrations of Mg and Ca on the growth and K, Ca, Mg, Mn and Zn content of barley grown in hydroponic culture.

(4) Determine yield and K, Ca, Mg, Mn and Zn content of barley grown in soils varying in Ca and Mg content and ratio of Ca:Mg.

(5) Determine the effects of additions of Ca or K on yield, K, Ca, Mg, Mn and Zn content of barley, grown on a variety of soils.

(6) Determine (a) the relationships between NH_4 acetate-extractable K, Ca and Mg and soil solution concentrations and activities of these ions (b) uptake of these ions by barley plants as related to content of these cations in the soil and (c) the soil solution concentrations of Ca and Mg in relation to critical concentrations as determined by hydroponic culture.

2.0 Review of the Literature

2.1 Ca, Mg, K, Mn and Zn in the Soil System

Cations in the soil system are generally involved in a dynamic equilibrium between nonexchangeable, exchangeable and solution forms. The nonexchangeable cations normally include cations in primary minerals and most of those in the secondary minerals and nonexchangeable cations are generally only sparingly available for plant growth. In contrast, exchangeable cations are held on the cation exchange system and move readily into solution for plant uptake in response to a decrease in concentration in the soil solution. Cations in the soil solution are the immediate source of nutrient uptake by plants. The concentration of the cation in the soil solution (intensity factor) and the ability of a soil to replenish the soil solution when nutrients are removed by plants (buffer capacity) determine the plant availability of a particular cation in the soil.

Ca in the soil occurs in primary minerals such as feldspars and amphiboles, in carbonates and sulfates, as exchangeable Ca and as soluble Ca salts. Soils in Manitoba often contain high levels of carbonates as calcite or dolomite. Normally, in arid soils, Ca is the dominant cation on the cation exchange system, comprising about 60 to 80% of the exchange of montmorillonitic soils. Ca saturation of the exchange promotes flocculation of soil colloids, improving soil structure (Mengel and Kirkby 1979). Ca is strongly adsorbed on the cation exchange system due to its divalent charge and relatively small hydrated radius (Talibudeen 1981).

Concentration of Ca in the soil solution of calcareous soils is primarily a function of the solubility of the carbonate salt and the partial pressure or concentration of CO_2 in the soil system. Increases in CO_2 result in increasing concentration of Ca in the soil solution. For example, increasing the CO_2 of the system from 0.033 KPa, the pressure of CO_2 in air, to 10.1 KPa, the pressure of CO_2 in flooded soil, increased the Ca concentration in the solution from 1.26 mM to 1.92 mM, in a calcareous clay suspension (Russell 1973).

Ca concentration in the soil solution of noncarbonated soils is a function of the amount of Ca on the exchange complex, since the soil solution concentration is in equilibrium with cations on the exchange. Soluble salts and moderately soluble salts such as $CaSO_4$ also affect soil solution concentration of Ca. In addition, the concentration of Ca in the soil solution is a function of the anion concentration (Hansen 1972). For example, as mineralization of N or nitrification occurs, the anion concentration of the soil solution increases. This results in an increase in the cation concentration of the soil solution since electroneutrality is maintained. Addition of salts such as KCl also increases Ca concentration or concentration of other cations in the soil solution since the cation associated with the salt added displaces some of the cations on the exchange complex. Concentration of Ca in nonsaline, neutral soils normally is in the order of 3 to 10 mM (Russell 1979).

Mg occurs in a number of primary minerals such as biotite and serpentine and in secondary clay minerals such as vermiculite, illite and montmorillonite. Soils in Manitoba may contain Mg as $MgCO_3$,

dolomite and soluble Mg salts such as $MgSO_4$. Nonexchangeable Mg includes that in the primary minerals and most of that in the secondary minerals. Exchangeable Mg usually composes 5 to 20% of the cation exchange capacity, (Mengel and Kirkby 1979) although in some soils, derived from dolomitic deposits, the proportion of Mg on the exchange may be over 50% (Smith and Ehrlich 1967). Magnesium tends to be less strongly adsorbed to the cation exchange than Ca due to the larger hydrated radius of Mg (Talibudeen 1981).

Concentration of Mg in the soil solution generally ranges between 2 and 5 mM, although concentrations as high as 150 mM have been reported. As with Ca, concentration in the solution will increase with increasing concentration of NO_3^- and other anions in the solution (Mengel and Kirkby 1979).

Most K is bound in primary minerals such as feldspars or in secondary clay minerals such as illite. Therefore, clay soils tend to be very high in total K. The major sources of K for plant uptake are exchangeable and soil solution K. Fixation of K can occur in interlayer sites of 2:1 clay minerals such as illite and vermiculite (Nommik and Vahtras 1982). Fixed K is only sparingly available for plant growth.

K adsorbed on the cation exchange is held less tightly than Mg (Talibudeen 1981). K typically constitutes approximately 5% of the exchangeable cations. Concentration of K in the soil solution tends to be substantially lower than the concentration of either Ca or Mg. In unfertilized soils, the concentration of K in the soil solution is

normally in the range of 0.1 to 1.0 mM (Russell 1973). The concentration of K in the solution is important in determining the availability for plant growth, as it controls the K diffusion rate towards the plant root. The buffering capacity of the soil for K is also important, as it determines the ability of the nonexchangeable and exchangeable K to replenish the solution concentration of K after plant removal (Mengel and Kirkby 1979).

Mn is generally present in the soil in much lower amounts than Ca, Mg or K. The most important forms of Mn in the soil are Mn^{2+} and the Mn oxides which contain trivalent or tetravalent Mn. Mn^{2+} is adsorbed on the cation exchange and is present in the soil solution at very low concentrations. Mn^{2+} in the soil solution and the easily-reducible Mn are called "active Mn" and are the forms available for plant growth. Since the form of Mn present in the soil system is controlled by reduction-oxidation processes, factors which influence redox reactions will influence Mn supply to the plant. Therefore, soil pH, organic matter content, microbial activity and soil moisture content will influence Mn availability. Mn availability decreases with increasing soil pH (Mortvedt et al 1972) and may increase to toxic levels if soils are waterlogged (Olomu and Racz 1974). Concentration of total divalent Mn in acid and neutral soils is in the range of 0.001 to 0.1 mM. In calcareous soils the concentration is somewhat lower (Russell 1973).

Zn in the lithosphere occurs primarily as sphalerite and can substitute to some extent for Mg in silicate minerals. Weathering of

of Zn minerals gives Zn^{++} in solution. Common Zn compounds such as the hydroxides, carbonates and phosphates are relatively soluble, and are not present in soils except as reaction products of highly soluble zinc fertilizer (Kalbasi et al. 1978). Native forms of soil zinc, which control the concentrations of Zn in soil solution, are Zn^{++} ions adsorbed on clay minerals, hydrous oxides of Fe and Al and organic matter. (Hodgson 1963; Nair and Cottenie 1971; Kalbasi and Racz 1978). The level of Zn in the solution is low, in the range of 10 to 300 ug g^{-1} of Zn. Solubility of Zn decreases as pH increases, particularly in the presence of $CaCO_3$. Also, intensity of Zn adsorption increases as pH increases and, so availability of Zn tends to decrease with increasing pH (Mortvedt et al. 1972).

2.2 Roles of Ca, Mg, K, Mn and Zn in Plant Nutrition

Ca, Mg and K are macronutrient cations in plant nutrition while Mn and Zn are micronutrient cations. Each of these cations performs specific functions in the physiology of the plant.

Mg is utilized by plants in smaller quantities than K or Ca, composing in the order of 0.1 to 0.5% of the dry weight of plants. Mg tends to move upward in the plant in the transpiration stream but it is also phloem mobile. Mg plays a critical role in the structure of the chlorophyll molecule. However, only 15 to 20% of total plant Mg is used in this manner. Most of the total Mg in the tissue is diffusible and associated with inorganic anions and with organic anions such as malate and citrate (Mengel and Kirkby 1979). Mg is also associated

with nondiffusible anions such as oxalate and pectate (Mengel and Kirkby 1976).

Mg is a cofactor in almost all enzymes activating phosphorylation and serves to form a bridge between the pyrophosphate structure of ATP or ADP and the enzyme molecule. Since energy transfer reactions are fundamental steps in most aspects of anabolism and catabolism, Mg is of importance throughout the physiology of the plant. As well, light induced uptake of Mg from the inner spaces of the thylakoids to the stroma appears to be important in increasing the affinity of RuBP carboxylase for CO_2 so that CO_2 fixation can proceed at a maximum rate (Mengel and Kirkby 1979). Mg also appears to be involved in the stabilization of ribosomal particles into the formation required for protein synthesis (Bidwell 1979).

Unlike Mg, Ca plays only a minor catalytic function, being involved as an activator of a few enzymes. Its primary importance lies in its structural functions and in the detoxification of other substances. Ca is often present in plants in high amounts. Plants seem to be able to grow well at much lower concentrations than are normally found, as long as the concentrations of other divalent ions are also at low concentrations. Therefore, it is suggested that the high levels of Ca normally found in plants are necessary to detoxify other divalent metal cations (Bidwell 1979). In particular, calcicoles, plants which are adapted to soils high in Ca, suffer from heavy metal toxicity, especially from Al, Fe and Mn, if grown on acid soils low in Ca. In contrast, calcifuges, plants which are

adapted to soils low in Ca, develop lime-induced chlorosis due to deficiency of Fe if grown on soils high in Ca (Hanson 1984). Ca also appears important in the detoxification of oxalic acid, by the formation of Ca-oxalate crystals (Bidwell 1979).

Ca is required for cell elongation and cell division and appears to play an essential role in biological membranes. Removal of Ca from membranes by EDTA treatment increases permeability to a great extent, leading to diffusion of organic and inorganic components in and out of the cell (van Steveninck 1965). Therefore, Ca influences uptake and efflux of other ions (Marschner 1983).

Uptake of Ca is primarily a passive process. Ca movement into the root appears to be restricted to the root tips, to areas where the casparian strip has not formed. Therefore, Ca apparently moves essentially via the apoplast. The downward movement of Ca is very limited due to low concentrations present in the phloem sap, so translocation within the plant is primarily restricted to the transpiration stream. Intensity of transpiration is the major controlling factor in Ca movement. However, Ca translocation appears to be mediated to some extent by hormones as well (Mengel and Kirkby 1979). The number of available binding sites for Ca also appears important in determining the movement of Ca. Ca moves towards available binding sites within the plant tissue. Therefore increasing the cation exchange capacity (CEC) of the tissue increases the movement of Ca to the tissue by increasing the sink capacity for Ca storage. Dicots have a much greater CEC and a greater demand for Ca than

monocots (Marschner 1983).

External Ca, such as that in the soil solution, is important in membrane structure and function, reducing passive ion fluxes and making the membranes more hydrophobic (Hanson 1984). Ca deficiency leads to increased membrane permeability and as the deficiency becomes more severe, there is a general disintegration of membrane structure. Due to the limited remobilization of Ca after initial deposition within tissue, Ca deficiency symptoms will occur initially in younger tissue. Meristematic tissues are severely affected, because a shortage of Ca prevents the formation of new cell walls, preventing cell division. Chlorosis of margins of younger leaves and the production of stunted, discolored leaves are among the symptoms of Ca deficiency (Bidwell 1979).

K is taken up actively by the plant and is extremely mobile within the plant. It is transported toward meristematic areas and redistributed from older to younger tissue if a deficiency occurs (Mengel and Kirkby 1979). K is generally present in plant tissue at the highest concentration of all cations. K is unevenly distributed between the vacuole and the cytoplasm and, so the average concentration measured in bulk tissue is not necessarily a reflection of the concentration of K in each of these compartments. Because the vacuole occupies a large proportion of the cell volume, the K concentration in the cell is generally similar to that in the vacuole (Leigh and Wyn Jones 1984). Concentration of K in the cytoplasm is normally in the range of 100 to 200 mM. Concentration of K in the vacuole is more variable, but the

lower limit of concentration of K may be 10 to 20 mM. Concentration of K in the cytoplasm appears to be regulated independently of external concentration of K, while concentration of K in the vacuole appears to be more dependent on K supply (Glass and Siddiqi 1984).

Within the cytoplasm, K plays a major role in enzyme activation. More than 60 different enzymes are activated by K. K appears to influence enzyme activity by altering protein conformation. Enzymes activated by K include synthetases, oxidoreductases, dehydrogenases, transferases and kinases (Mengel and Kirkby 1979). K is important in protein synthesis. Uptake and assimilation of NO_3 into amino acids is unaffected by low concentrations of K, but the incorporation of N into protein is reduced. In vitro protein synthesis requires 100 to 150 mM K and a high K:Na ratio. Therefore, the cytoplasmic requirement for high concentration of K and a high K:Na ratio may reflect the necessity of these conditions for protein synthesis. High concentrations of K may also be required within the cytoplasm for maximum photosynthesis, for folding of proteins into their active forms and for control of membrane potential and cytoplasmic pH (Leigh and Wyn Jones 1984).

Concentration of K within the vacuole is not regulated as precisely as within the cytoplasm. No biochemical functions have been found for K in the vacuole and it is believed to play a biophysical role. K within the vacuole is present as simple salts such as KNO_3, KCl and K malate. These salts are important in controlling the osmotic potential of the vacuole and so maintaining turgor presssure (Leigh and Wyn Jones 1984). Plants that are well supplied with K require less

water than plants which have a restricted K supply, apparently due to a reduction in transpiration rate due to the lower osmotic potential of the mesophyll cells and regulated opening and closing of the stomata by the guard cells. K plays a key role in guard cell function, through its influence on the osmotic potential of the cells (Mengel and Kirkby 1979). K mediated changes in turgor are directly related to such phytochrome controlled movements as straightening of the hypocotyl arch in mung beans and leaf movement of mimosa (Marschner 1983).

K salts are the most common substances used by the plant to influence osmotic potential in the vacuole, however other solutes such as Na salts, sugars and amino acids can substitute for K in this function. Plants with restricted K supply often increase concentration of Na, Mg and Ca, which presumably substitute for K in the vacuole to maintain turgor pressure. The lower limit for K concentration in the vacuole appears to be 10 to 20 mM K, even in barley roots grown without K (Leigh and Wyn Jones 1984).

Assimilate translocation is enhanced by K, an effect that is likely related to K influence on photophosphorylation. K also enhances CO_2 assimilation directly, and leads to an increase in ATP production (Mengel and Kirkby 1979). In the phloem sap, K composes 80% of the total cations. Ben-Zioni et al. (1970) suggested that the high concentration of K in the phloem is related to K involvement in malate cycling in nitrate metabolism.

K deficiency symptoms tend to begin in the older leaves with mottled chlorosis and necrosis of leaf tips and margins. A decrease in

turgor may occur as well as a decrease in resistance to drought, frost, salinity and fungal attack (Mengel and Kirkby 1979). K deficiency may induce bushy growth and a reduction in stem growth (Bidwell 1979). Lodging may increase due to decreased lignification of vascular bundles (Mengel and Kirkby 1979).

Mn is a micronutrient cation, considered deficient at tissue levels below 20 ug g^{-1} (Mortvedt et al 1972). Uptake of Mn is considered to be an active process. Mobility of Mn in the plant is low but Mn is preferentially translocated to meristematic tissue (Mengel and Kirkby 1979).

Mn can bridge ATP enzyme complexes in phosphokinases and phosphotransferases and can also activate decarboxylases and dehydrogenases in the TCA cycle. Mg can substitute for Mn in these reactions, but Mn is specifically required for the oxidation of indoleacetic acid (IAA) by IAA oxidases (Mengel and Kirkby 1979). Mn is also required for function of the electron transport system in the water splitting reactions of photosynthesis. Mn may also have a structural role in chloroplasts, which lose their structural integrity if Mn is extremely deficient (Bidwell 1979).

Deficiency symptoms of Mn in cereals occur first in younger leaves, as grey spots and stripes at the leaf base. Turgor of plants is reduced and the upper portions of the plant leaf may break over (Mengel and Kirkby 1979). Grey speck of oats is caused by Mn deficiency.

Zn is required by plants in very small quantities, with tissue concentrations of 25 to 150 ug g^{-1} considered adequate for plant growth

(Mortvedt et al 1972). Uptake of Zn by the plant is believed to be an active process (Mengel and Kirkby 1979). Mobility of Zn within plants is low (Mengel and Kirkby 1979), but deficiency symptoms generally appear initially in older tissue (Bidwell 1979).

Zn functions in the activation of numerous enzymes, serving to bind and orient the enzyme and substrate to facilitate reaction. Carbonic anhydrase and a number of dehydrogenases, proteinases and peptidases are activated by Zn. Deficiency of Zn results in a decrease in RNA levels and ribosome content of cells, leading to a reduction in protein synthesis and an increase in nonprotein N (Mengel and Kirkby 1979). Zn is also involved in the synthesis of indoleacetic acid, an important growth hormone. Zn deficiency can therefore lead to short, stunted plants with impaired apical dominance (Bidwell 1979). Zn deficiency symptoms in cereals include chlorotic bands on either side of the midrib of the leaf, stunting and yield reduction.

2.3 Cation Interactions in Ion Uptake

Uptake of Mg is believed to be essentially a passive process, although there may be some active component (Mengel and Kirkby 1979). Uptake of Ca is also primarily passive, however uptake of K is almost certainly an active process (Mengel and Kirkby 1979).

The precise mechanism of uptake of K is still under investigation. Although mechanisms have been proposed such as diffusion exchange coupled with Donnan phenomena (Hiatt 1968) and passive diffusion due to an electrochemical gradient (Higinbotham 1973), until recently the most

widely accepted theory of K accumulation was the carrier theory, as proposed by Epstein (Epstein and Hagen 1952; Epstein 1953). Briefly, the biological membrane was believed to contain specific carrier molecules which were able to transport ions across the membrane. The carrier molecules were believed to possess binding sites specific for particular ion species, which enabled selective ion transport across the membrane (Mengel and Kirkby 1979).

A general scheme for carrier mediated ion transport proposed that the active carrier, a phosphorylated compound, was diffusible in the membrane. At the outer membrane boundary, it formed a carrier-ion complex with the specific ion for which it had affinity. The diffusible complex moved across the membrane to the internal boundary where a phosphatase enzyme split off a phosphate group from the carrier complex, reducing the affinity of the carrier for the transported ion. The ion was released into the cytoplasm. A carrier ATP kinase at the inner membrane phosphorylated the carrier with the breakdown of ATP, restoring the affinity of the carrier for the ion. The carrier moved back through the membrane to the outer membrane boundary by diffusion to repeat the ion transport process. Transfer of the ion through the membrane was accomplished with the breakdown of one ATP molecule (Mengel and Kirkby 1979).

The idea of an ion dependent ATPase acting as a carrier was supported by the close correlation between ATP and plasmalemma influxes of K (Petraglia and Poole 1980). However, recently the idea of the carrier being an ion dependent ATPase has been replaced by the concept

of an electrogenic pump which acts to create an electrochemical gradient which facilitates the movement of K across the membrane (Clarkson 1985; Leonard 1985; Mengel 1985). ATP produced in the mitochondria is broken down by a plasma membrane associated ATPase, leading to the active extrusion of H^+ from the cell. The extrusion of H^+ results in the creation of a free energy gradient across the plasma membrane in accordance with the Nernst equation (Sze 1985).

$$w = [RT/zF] \ln \left[[H]o/[H]i\right]$$

where w = membrane potential

R = molar gas constant

T = temperature in degrees Kelvin

z = valence of ion

F = Faraday constant

[H]o, [H]i = external and internal concentration, respectively.

The free energy gradient for H could be coupled to K influx. The movement of K through the membrane could be facilitated by a K carrier, although the carrier would not directly utilize ATP, but rather utilize the energy of the electrogenic gradient created by the electrogenic pump (Leonard 1985; Mengel 1985). The carrier proteins could be pores specific for the passage of the particular ion, which provide a gated aqueous channel through the hydrophobic lipid bilayer.

The tonoplast membrane of the cell also appears to contain ATPase which functions in the active transport of H into the vacuole. The

energy conserved in the H gradient may be used to accumulate inorganic and organic solutes in the vacuole. Preliminary research indicates that the tonoplast ATPase may be structurally and mechanistically different from that of the plasma membrane (Leonard 1984).

Whether uptake of K occurs by the action of a K coupled ATPase or through a gated channel through the plasma membrane in response to an electrochemical gradient, the observed maintenance of cytoplasmic K concentration within narrow limits indicates that some form of transport regulation is in effect to control the rate of uptake of K. Early discussions of transport regulation compared ion uptake to enzyme mediated catalysis of a substrate, since both involve the temporary occupation of a limited number of active sites by substrates, with potential for saturation at high substrate concentrations. Ion transport should logically follow Michaelis-Menten kinetics, as described for enzymes, where:

$$V=Vmax\ [S]/(Km+[S])$$

Vmax=Maximal rate of transport

[S]=Concentration of substrate in the medium

Km=Michaelis constant, equal to substrate concentration at 1/2 Vmax.

The Michaelis-Menten relationship can be transformed to the Lineweaver-Burke equation by taking the reciprocal of both sides of the equation, resulting in a linear relationship. The y-intercept of the Lineweaver-Burke equation is equal to 1/Vmax while the x-intercept is

equal to -1/Km (Lehninger 1975).

Recent investigations of ion uptake have utilized the Michaelis-Menten and Lineweaver-Burke equations to examine characteristics of the carrier system. Investigations have been conducted both with excised roots (Overstreet et al. 1952; Zsoldos and Erdei 1981) and with intact plants (Claassen and Barber 1974; Claassen and Barber 1977; Rosen and Carlson 1984). Initial studies indicated dual kinetics, implying the existence of two separate uptake systems at low and high substrate concentrations (Epstein and Leggett 1954). Other researchers concluded that kinetics were more complex, with multiple slopes to the uptake curves (Glass 1976; Pettersson and Jensen 1979; Nissen 1980). The characteristics of the uptake curves are used to attempt to determine the number of carrier systems in operation and their methods of regulation.

K influx appears to be regulated by the cytoplasmic concentration of K, possibly by an allosteric feedback mechanism. A decrease in the cytoplasmic concentration of K would feed back to K transport mechanisms on the plasmalemma and tonoplast, adjusting their activity to restore the concentration of K in the cytoplasm to an optimal level. The regulation of influx may be due to the binding of cytoplasmic K to an allosteric binding site, discrete from the external site (Glass and Siddiqi 1984). Calculations by Glass (1976) led to the proposal of a tetrameric allosteric system located on the inner surface of the plasmalemma. Conformational changes in the transport system would be induced by binding of cytoplasmic K, altering the kinetic

properties of transport.

If external supply of K is restricted, mobilization of K from the vacuole may occur to maintain cytoplasmic K at adequate concentrations. Charge balance and osmotic functions of K in the vacuole may be met by a replacement of K by alternate solutes such as organic solutes, Ca, Mg or Na. An overall decrease in tissue concentration of K would occur, coupled to an increase in the concentration of the substituting cations. Further restriction in K supply could lead to a decrease in cytoplasmic K concentration and a decrease in plant growth (Glass and Siddiqi 1984).

Although the kinetics of K absorption appear to be complex, they support the concept that uptake of K is facilitated by a gated channel or a proteinaceous carrier that possesses a limited number of K binding sites. At high concentration of K, the sites are filled, corresponding to saturation in the rate of absorption.

The concept of a transport system displaying saturation kinetics provides a reasonable framework for the discussion of ionic antagonisms and interactions.

Two major effects of the other cations on the uptake of K have been observed:

1. Interference of uptake by ions such as Na.
2. Enhancement of uptake by ions such as Ca.

Jacobson et al. (1961) found evidence of interference of uptake of K by Na at 5.0 mM K. They also observed that Ca tended to decrease absorption of Na and increase absorption of K, even if the Ca was

present in low amounts. From a mixed solution of Na and K, the sum of the absorbed cations was essentially equal, with Ca merely shifting the ratio. They suggested that Na and K compete for a common carrier. Epstein (1961) also observed competition between Na and uptake of K, with Ca reducing the inhibitory effect of Na. Rb also competed with K for uptake and this competition was not influenced by Ca. Mg was ineffective in reducing Na interference. Epstein concluded that Ca was essential for the selectivity of uptake of K over Na. He proposed that two species of carrier transport K and Rb. One of these has a low affinity for K and Rb and is inhibited by Na. Ca could reduce the inhibition of K-Rb transport at this site. The other site has a higher affinity for K and is essentially unaffected by Na in the presence of Ca. The operation of these two systems would produce the dual kinetics observed.

The high affinity system (System I) would be of primary importance in the uptake of K from the soil system, where concentration of K tends to be low. However, K must also move within the plant, from the cortical cells to the transpiration stream and from the transpiration stream to the cells in the stems and leaves (Leonard 1984). Since the concentration of K in the transpiration stream is high, the low affinity-high capacity system II transport system may function effectively in the movement of ions from the transpiration stream to the target cells.

Elzam and Hodges (1967) observed that uptake of K from a 0.1 mM solution by excised corn roots was decreased by the addition of Ca, and

to a greater extent by the addition of Mg, at concentrations between 0.005 and 2.0 mM. In contrast, uptake of K by excised barley roots was not influenced by Ca. The effect of Mg on K uptake by excised barley roots was not examined.

Kawasaki and Hori (1968) found that the rate of uptake of Rb decreased in the presence of divalent cations at the lower concentration range of the monovalent cations and increased at higher concentration in the presence of Ca. Their observations are in contrast with the results of Epstein (1961), although both studies showed Na uptake was inhibited in the presence of Ca at all concentrations. Kawasaki and Hori concluded that the stimulating effect of Ca on uptake of Rb might be located in the metabolic process of ion uptake. Kawasaki and Hori (1973) observed an increase in uptake of Rb in the presence of Ca at 25 C but no change at 2 C, indicating a metabolic process was responsible. Kawasaki et al. (1973a) demonstrated that metabolic inhibitors such as cyanide and DNP decreased uptake of Rb and eliminated the effect of Ca, reinforcing the importance of energy supply on Rb uptake. In the same series of experiments, Kawasaki et al. (1973b) studied the effects of Mg and found that its effects were similar to those of Ca. Welte and Werner (1963) had previously reported that Mg tended to competitively interfere with uptake of K.

A number of field studies have examined the effect of high concentration of Mg in the soil on concentrations of K and other cations in the tissue. Aulakh and Pasricha (1978) found an antagonistic effect of Mg on concentration of K in the tissue and

uptake by the plant. They attributed this to competition for the same binding site or reactive centre. They also found reduced yield of rapeseed due to this effect.

Liebhardt (1979) found no effect of Mg, applied in liming treatments, on K concentration of corn tissue. High Mg additions decreased Mn, Cu and Zn concentration of tissue. Liebhardt suggested that high Mg created a nutritional imbalance and a deficiency of Mn, resulting in decreased yield.

Martini and Mutters (1985) found that dolomitic limestone had no effect on concentration of K in the shoot in soybeans, but application of the recommended rate of lime, 3000 kg ha^{-1}, produced the highest total uptake of K. Liming had no influence on concentration of Zn or Fe or total shoot content of these cations. Total shoot content of Cu was higher in limed than unlimed plants.

Kumar et al. (1981) stated that increasing levels of Mg applied as $MgCl_2$ to soils in pot studies decreased concentration of Zn in the shoot in wheat and the magnitude of the decrease depended on Mg and Zn levels. High levels of Mg antagonistically affected K absorption. Increasing levels of Mg increased the concentration of Cu and Fe in the plants.

Narwal et al. (1985), working with cowpea in sand culture, found that Mg had a synergistic effect on root concentrations of K up to 20 ug g^{-1} Mg and an antagonistic effect on concentration of K in all plant parts at 40 ug g^{-1} Mg.

Carter et al. (1979a) commented that in order to prevent low

uptake of K due to N competition, one had to supply an adequate proportion of Ca in the solution. They suggested that K deficiency on solonetzic soils could be a result of low Ca:Mg ratios.

Physical properties of ions will influence their interactions with other ions and with carrier sites. Charge and hyrated radii are the most important of these properties. Mutual inhibition is more pronounced between ions of similar hydrated radii. Univalent ions having similar hydrated radii, such as K, NH_4, Rb, and Cs appear to interact with the same absorption site and interfere with the absorption of the others (Hiatt and Leggett 1974). Plant roots were selective, however in absorption of K over Na if Ca was present.

Ca tends to enhance absorption of ions with small hydrated radii such as Rb and K and decrease the absorption of ions with large hydrated radii such as Li and Na. Ca appears to play an essential role in biological membranes and its removal results in increased membrane permeability (Mengel and Kirkby 1979), a factor that may be important is its effect on ion selectivity. The differing effects of Mg on uptake of K may relate to a competition of Mg and Ca, leading indirectly to a breakdown in selectivity of the transport system for K.

2.4 Effect of High Magnesium Levels on Crop Yields

Most of the research reported in the literature discussed the effects of Mg deficiencies on crop yield and quality. Magnesium fertilization has often been reported to increase crop yield on soils containing low concentrations of Mg (Salmon 1963; Welte and Werner

1963; Bolton and Penny 1968). The influence of high soil Mg levels on crop yield and quality has been examined by only a few researchers.

Generally, high Mg levels and low Ca:Mg ratios have not been found to greatly influence crop yield. Halstead et al. (1958), examined the growth of alfalfa on soils treated with either Mg or Ca carbonate. They found that variations in the ratio of Ca:Mg on the exchange from 0.4 to 13.4 caused by carbonate applications did not generally influence the yield of alfalfa. However, on a sandy loam soil, when the amount of carbonate applied was slightly in excess of that required to neutralize the soil, yields of alfalfa grown with K or P singly were considerably lower with Mg carbonate than with Ca carbonate.

Yoshida (1964) found no correlation between Mg content of roots or shoots and the yield of oats. However, the emphasis of this study was examination of Mg deficiency. The lowest solution Ca:Mg ratio used was 2:1 while the lowest solution K:Mg ratio used was 1:1.

Fox and Piekielek (1984) found no yield response of corn to ratios of Ca:Mg on the exchange between 1.8 and 36.9. No response to addi-additions of Ca, Mg or K occurred on the soils highest in Mg. However, the lowest ratio of Ca:Mg on the exchange was 1.8, which was not excessively low. They stated that it was unlikely that corn would show a negative yield response to exchangeable Ca:Mg ratios of 1.0 or higher.

Ohno and Grunes (1985) grew wheat in solution cultures containing Mg concentrations of 0.1 to 4.5 mM and concentrations of K of 0.1 to

6.0 mM. They found no effect of Mg on yield of shoots or roots.

In contrast to the studies cited above, other studies have shown an effect of Mg and Ca:Mg ratio on yield and on nutrient content of various crops.

Vlamis (1949) examined the production of lettuce and barley on serpentine soils high in Mg and showed that yield was increased on these soils when Ca was added. Vlamis also found that plants grown on Mg-saturated cation-exchange Amberlite produced smaller plants than Amberlite saturated with Ca, K or Sr. Vlamis (1949) suggested that the primary cause of poor yield on the serpentine soils was the low saturation of Ca on the cation exchange. If the Ca saturation of the exchange was decreased by increasing K saturation, symptoms and yield depression were similar to those obtained when Mg levels were high. When normally fertile soils were leached with $CaCl_2$ or $MgCl_2$ to alter the percentage saturation of Ca or Mg, the yield of both lettuce and barley declined when the degree of Ca-saturation fell below 20%.

Elgabaly (1955) utilized sand culture to examine the effects of Na, Ca and Mg on the growth of barley seedlings. Cations were added as Ca+Mg, Ca+Na and Na+Mg with the two cations summing to 10 meq of adsorbed cations per 300 g of sand plus resin (0.333 mM of univalent cation per kg of soil and resin). Systems with Na and Mg had poorer growth than systems with Na and Ca. Roots were influenced to the greatest extent. Roots grown with 100% Mg were thick, short, brown, had few branches and were similar to those grown in a pure Na system. Leaves of plants grown in pure Mg showed burning to a greater extent

than did those in a pure Ca system. In systems with Mg and Ca, any combination of the two ions showed better growth than that in a homoionic system. Maximum shoot growth occurred at a Ca:Mg ratio of 7:3. Chlorosis increased as Mg saturation increased. The level of K in plants did not change greatly with Ca:Mg ratio in the medium. Elgabaly (1955) concluded that Mg and Na had greater deletereous effects on barley growth than did Ca when provided to the plants in the absence of other ions. When Ca and Mg were applied together, plant growth was stimulated over a fairly wide range of cation ratios.

Key et al. (1962) grew soybeans and corn in soils that had been leached with Ca or Mg solutions to give varying Ca:Mg ratios. They found that the amount of Mg appeared to be more important to plant growth than the Ca:Mg ratio. The yield decreased if the Ca:Mg ratio fell below 1:1. They attributed the decrease in yield to a Ca deficiency. Martin and Page (1965) found a similar response with citrus plants. Provided that the exchangeable Mg did not exceed Ca, the growth of the plant was not influenced. Seedling growth was decreased when Mg exceeded 50% of the exchange. Leaf Mg levels above 0.9% were associated with decreased yield. Absorption of K was not affected by Mg except at the highest rates. They suggested that the plant Ca and Mg values were closely related to the soil exchangeable Ca and Mg percentages.

Unpublished data collected by Spratt (Brandon Research Station files) from a 5-year Manitoba survey of corn nutrient relations showed that Mg levels in both the ear leaf and the soils were inversely

related to silage yield. Mg and K in the ear leaves were negatively correlated even though Mg and K in the soils were positively correlated.

Benko and Fecenko (1979) found that where the sum of K + Mg was kept at 10 meq per litre (10 mM univalent ion), decreasing the ratio of K:Mg led to symptoms of K deficiency in barley. Yield was highest where the meq ratio of K:Mg was 1:7 (1:3.5 in terms of mM) and decreased as the ratio decreased.

Fageria (1973) found that maximum yield of groundnuts in a hydroponic system was obtained at about 40 uM Mg, when concentrations of Ca and K were 125 and 204 uM, respectively. Yield decreased when concentration of Mg increased above 75 uM. Increasing concentration of Mg decreased the uptake of K and Ca. The author suggested that if high levels of Mg were present in the soil, one would have to apply higher rates of K and Ca to satisfy plant requirements. Working with rice in dilute solutions, Fageria (1973) found that yield decreased above a Mg concentration of 33 uM, while yield increased up to a concentration of Ca of 250 uM. Fageria (1983) also reported that increasing the concentration of Mg in the medium decreased K and Ca absorption by rice.

Liebhardt (1979) found that when the pH of a poorly buffered acid soil was increased from 5.6 to 6.4 by application of dolomite, yield of corn was lower than when the pH was adjusted with either calcite or a mixture of calcite and dolomite. Yield of corn was negatively related to soil Mg. The high soil Mg was also associated with a decrease in plant Mn, suggesting that high soil Mg may cause a deficiency of Mn

resulting in reduced yield.

Carter et al. (1979a) working with both saline and non-saline soils, found that levels of Ca which were adequate under non-saline conditions became limiting when salinity increased, due to the greater amount of Ca required to safeguard the selective permeability of the plasmalemma against the toxic effect of other ions in the solution. They also indicated that other ions in the solution could reduce uptake of Ca and cause salinity-induced Ca deficiency. They found that the growth of barley at the seedling stage was reduced at a Ca:Mg ratio between 0.77 and 0.40 and a Ca:total cations ratio of 0.17 to 0.11. In solutions of these formulations, Ca deficiency symptoms were apparent. As the plants grew out of the seedling stage, a greater resistance to low Ca:Mg ratios was apparent and the final dry weights were reduced only when the Ca:Mg ratio was less than 0.77 to 0.40. Growth of plants in soil was similar to growth in the solution culture.Soils with a low Ca:Mg ratio showed Ca deficiency symptoms. Adding gypsum increased barley yield. From this study, the researchers concluded that the concentration of Ca per se in the soil was not as important as the ratio of Ca:Mg or the ratio of Ca:total cations.

Carter et al. (1979b) found that in soils which contained appreciable amounts of salts, precipitation of salts at low moisture contents tended to reduce the ratio of free ionic Ca to Mg. This effect was due to the higher solubility of Mg as compared to Ca salts. The decrease in the Ca:Mg ratio was be most pronounced in saline soils. A decrease in the Ca:Mg ratio occurred as the moisture content decreased

from saturated paste extract to -1500 KPa. Therefore, saline or near saline soils which have Ca:Mg ratio near unity in the saturated paste extract may develop an adverse Ca:Mg ratio especially under an arid moisture regime.

Schulte et al. (1981) stated that the optimum range in percent saturation of the exchange sites depended on the cation exchange capacity of the soil. The amount of cation present was considered more important than the percent CEC saturation. As an example, the authors point out that a soil with a CEC of 0.03 mol kg^{-1} would contain only 59 mg kg^{-1} of K at the 5% saturation, while a soil with a CEC of 0.60 mol kg^{-1} would contain 1175 mg kg^{-1} of K at 5% saturation. Therefore, the authors state that higher CEC soils would not require as high a saturation of Ca or K to ensure an adequate supply to the plant as a soil with a lower CEC. Very high levels of Mg in the soil would suppress the uptake of Ca and K by plants. The deficiency of Ca or K could be corrected by addition of these nutrients rather than by changing the supply of Mg.

2.5 Effects of High Calcium Levels on Crop Yields

Limited information is available on the effect of high levels of Ca on crop yields. Studies examining high Ca levels have generally dealt with "overliming" effects, rather than effects of Ca per se. York et al. (1954) examined the influence of lime applications as high as 22420 kg ha^{-1} on yield and tissue nutrient content of alfalfa, corn, Sudan grass and sericea grown on initially acid soils. Maximum yield

of sericea occurred where no lime was applied and yield decreased significantly with each increment of lime added. Maximum yield of corn, Sudangrass and alfalfa were obtained at 2240 kg ha^{-1} of lime. Yield of corn and Sudangrass decreased with higher lime applications. Yield of alfalfa remained essentially constant with additions of lime as high as 22420 kg ha^{-1}. The deleterious effects of overliming on yield of crops other than alfalfa were not due to a deficiency of potassium or magnesium. The authors suggested that the injury could have been due to a deficiency of Fe, Mn or both.

Racz and Haluschak (1974) examined the influence of phosphorus fertilization on Cu, Zn, Fe and Mn utilization by wheat on calcareous and noncalcareous soils. They determined that yield of wheat on the calcareous soils was lower than on the noncalcareous soils. Plants grown on the calcareous and noncalcareous soils had comparable concentrations of Fe, Mn and Cu. However, concentration of Zn in plants grown on the calcareous soils tended to be lower than in the plants grown on the noncalcareous soils.

Liebhardt (1979) found that corn and barley yields were depressed by lime applications of 8960 kg ha^{-1}. Tissue analysis showed Mn and Zn levels were in the deficiency range. Liebhardt suggested that overliming decreased yields by inducing a deficiency of Mn or Zn. At high rates of lime, both exchangeable Ca and Mg were negatively related to yield, but Ca was less negative in its effect on yield compared to Mg.

2.6 Summary

The literature indicates that Mg is involved in complex interactions with other macro- and micro-nutrient cations in the soil system. There is some information indicating that high levels of Mg could interfere with the uptake of K, Ca and certain micronutrients. However, there is little or no information on the effects of additions of K on plant growth and yield on soils high in Mg. It is also not clear whether Mg interferes with uptake of other cations at concentrations found in the soil solution, whether interference occurs in soil systems or whether such interference leads to a constraint on yield. Information on whether or not the ratio of cations in soil solution or the concentration per se is important in determining uptake of nutrients and plant growth is also lacking.

3.0 General Materials and Methods

The experimental methods used for the individual studies reported in this manuscript are described prior to the results and discussions in the appropriate subsections. The analytical methods utilized in the experimentation and in characterizing the soils are outlined below.

3.1 Plant Tissue Analysis

(a) Nitric-perchloric acid digest of plant tissue .

A 1-g sample of plant material was weighed directly into a 75 mL graduated test tube, 7 mL of 70% HNO_3 was added to the tube, the tube shaken and the sample left to digest overnight. Tubes were shaken and 3 mL of 70% $HClO_4$ were added and samples shaken. Boiling chips were added to the test tubes and the tubes placed on a cold digestion block. The block was heated to 100 C and samples digested for 1 h. The temperature was increased to 220 to 230 C and samples digested for 1.5 to 2 h. Tubes were removed from the digestor and cooled for 5 min. A 5-mL aliquot of 1 M HCl was then added to prevent K precipitation as $KClO_4$ crystals. Samples were cooled, diluted to near the graduation mark with distilled deionized water, cooled again and brought to volume. Tubes were then stoppered and shaken to mix the solution. Solutions were allowed to settle until clear. A 20-mL sample of solution was transferred to plastic scintillation vials for analysis.

(b) Atomic absorption spectrophotometer analysis for K, Na, Ca, Mg, Zn and Mn (Steckel amd Flannery 1966).

Nutrient content of plant tissue digests was determined using a

Varian AA-5 atomic absorption spectrophotometer. Parameter guidelines for the nutrients analyzed are given in Table 3.1.

Table 3.1: Parameter guidelines for Atomic Absorption Unit AA-5

Element	Slit Width	Wavelength	Lamp Current
----	-um--	----nM----	--mA---
K	300	7664	0.5
Na	200	5890	2.5
Ca	100	4227	5.0
Mg	100	2852	1.5
Zn	100	2138	6.0
Cu	100	3247	3.0
Fe	50	2483	5.0
Mn	50	2795	5.0

Lithium was used in the diluent for both standards and samples of K and Na to act as an ionization buffer and to suppress ionization of K and Na. Lanthanum was used in the diluent in both standards and samples of Ca and Mg to preferentially combine with interfering anions, thereby releasing Ca and Mg.

3.2 SOIL ANALYSES

Soil samples were air dried and ground to pass a 2 mm sieve, unless

otherwise stated.

(a) pH and conductivity using 1:2 soil:water ratio

A 25-g sample of soil was placed into an erlenmeyer flask and 50 mL deionized water added. Samples were shaken for 0.5 h. pH was measured immediately with a Fisher Accumet 805 MP pH meter. Conductivity of the solution was measured using a Yellowsprings Instruments Model 31 Conductivity Bridge.

(b) NH_4 acetate-extractable (exchangeable) K, Ca and Mg

A 2.5-g sample of soil was placed into a 125 mL erlenmeyer flask, 25 mL of 1 N ammonium acetate solution buffered to pH 7.0 added and the sample shaken on a reciprocating shaker for 0.5 h. A 20-mL portion was filtered through Whatman No. 42 filter paper into a plastic scintillation vial. Samples were analyzed for K, Ca and Mg by atomic absorption spectrophotometry as previously outlined.

(c) DTPA Extractable Zn and Mn

A 10-g sample of soil was placed into a 125 mL erlenmeyer flask, 20 mL of extracting solution (0.005 M DTPA (diethylenetriamine pentacetic acid), 0.1 M TEA (triethanolamine) and 0.01 M $CaCl_2$ added, and the flask capped and shaken on a reciprocating shaker for 2 h. The solution was filtered through Whatman No. 42 filter paper into a 20 mL plastic scintillation vial. Samples were stored at 3 C and analyzed as soon as possible by atomic absorption spectrophotometry.

(d) Field Capacity

Soil samples were air dried and sieved to pass an 8 mm sieve. Soil was then added to a 5-cm diameter plexiglass tube with the bottom covered by 4 thicknesses of cheesecloth. Soil was packed by tapping the tube lightly on the bench surface. 150 mL of distilled water was added to the soil surface and the top of the tube was sealed with parafilm. After 48 h, a 25-g sample of soil was removed from immediately above the wetting surface and dried at 105 C for 24 h. Moisture content was then calculated by mass:

$$\% \text{ water} = 100 \times \left[\frac{\text{mass of moist soil}}{\text{mass of dry soil}} - 1 \right]$$

(McKeague 1981)

(e) Extraction of Soil Solution Ca, Mg, K, Na and S by centrifugation

A 35-g sample of air dry soil was placed into a 46 mL polypropylene centrifuge tube. The soil was wetted to field capacity by the addition of distilled water. Tubes were covered by plastic film and incubated at room temperature for 7 d to allow equilibrium between phases.

After incubation, tubes were adjusted to a common weight by removal of soil from the heavier tubes to ensure that the centrifuge remained balanced. Tubes were centrifuged at 15,000 RPM (30,000 G) for 40 min. The supernatant was quickly decanted to reduce back-leakage. Samples were returned to the centrifuge, centrifuged for an additional

Samples were returned to the centrifuge, centrifuged for an additional 20 min and the supernatant removed and combined with the first extraction.

Samples were stored for a minimum of 24 h to allow the sediment to settle. Aliquots for analysis were carefully pipetted from the vials to avoid contamination with sediment. Samples were analyzed for Ca, Mg, K and Na by atomic absorption spectrophotometry. SO_4-S was measured by colorimetry on a Technicon AA-II. The SO_4^- was reacted with $BaCl_2$ to form $BaSO_4$. Excess Ba was assessed by complexing it with methylthymol blue. The uncomplexed methylthymol blue, measured at 460 nm, was equal to the SO_4-S present in the sample (Technicon Industrial Systems 1972).

(f) Calculation of ionic activities

Ionic activities of the various ions in the soil solution were calculated as outlined by Adams (1971). This method employs correction for "ion pair" formation between various cations and anions and results in calculation of the activity of the free ion in solution. Activity coefficients were calculated using the Debye-Huckel equation after calculation of the ionic strength of the solution. Ionic strength was calculated from the measured concentrations of Ca, Mg, K, Na and SO_4. HCO_3 was assumed to be present at concentrations required to maintain electroneutrality of solutions. The ionic activities were calculated by a series of successive approximations, first assuming no association (ion pairing) of ions in solution and then correcting for association of ions until a constant value for the ion activity was obtained.

4.0 Ca and Mg Effects on Uptake and Efflux of K and Leakage of Solutes by Barley Plants

Net uptake of K by a plant involves the balance between K moved into the root across the plasma membrane, presumably by an active uptake system of some type, and the passive efflux of K from the root. Ca is known to influence membrane permeability and the action of the active uptake system, presumably due to its effect on maintenance of membrane integrity (Epstein 1961; van Stevaninck 1965; Kawasaki and Hori 1973; Marschner 1983). High concentrations of Mg have been observed to reduce the accumulation of K by plants (Welte and Werner 1963; Elzam and Hodges 1967; Kawasaki and Hori 1968). Mg could influence K accumulation by the plant by directly competing for K at an uptake site or by competing for Ca on membrane binding sites and reducing membrane integrity. Alternately, Mg could substitute for K in the vacuole of the plant, reducing the cell requirement for K for osmotic functions.

In natural soil systems, Mg and Ca occur together in solution. However, studies on the effect of Mg on nutrient flux have generally examined the effect of Mg in the absence of Ca. The following studies were therefore designed to evaluate the effects of various concentrations of Ca and Mg in solution on the uptake of K and the efflux of solutes from barley plants. Short term uptake studies were designed to determine if high concentrations of Mg in the presence of Ca would lead to any reduction in the transport of K across the plasmalemma. Leakage studies were designed to determine if high

concentrations of Mg in the presence of Ca could influence membrane permeability.

4.1 The Effect of Varying Concentrations and Ratios of Ca and Mg on K Uptake by Barley Seedlings

4.1.1 Introduction

Uptake of K is regarded as an active process (Mengel and Kirkby 1979) and is believed to occur by the action of a carrier system (Epstein and Hagen 1952; Epstein 1953) or gated pore linked to an electrochemical gradient generated by ATPase (Leonard 1985). The influence of Ca and Mg on the uptake of K has been investigated by a number of researchers. Epstein (1961) and Jacobson et al. (1961) found that Ca enhanced uptake of K whereas Elzam and Hodges (1967) reported that Ca interfered with uptake of K. Pomeroy and Andrews (1985) also found that high concentrations of Ca (10 mM) interfered with uptake of Rb by isolated winter wheat cells for the first 6 h of uptake. Kawasaki and Hori (1968) showed that Ca decreased the rate of uptake of Rb at low Rb concentrations and increased the rate at high Rb concentrations. Elzam and Hodges (1967) found that Mg decreased uptake of K to a greater extent than did Ca. Kawasaki and Hori (1968) reported that Mg was similar to Ca in its influence on uptake of K. These studies examined the effect of Mg and Ca on uptake of K in isolation. But, Mg and Ca are both present in the soil system. Rosen and Carlson (1984) examined the effect of varying ratios of Mg:Ca on

the uptake of K by plum rootstalks at moderate concentrations but found no effect.

Welte and Werner (1963) suggested that Mg may competitively interfere with K uptake. In a competitive system, the effect would tend to increase with increasing concentration of the divalent ion. High concentrations of Mg would conceivably restrict crop yield by interfering with uptake and utilization of K.

Excised roots are frequently used to study the uptake of nutrients by plants (Glass and Dunlop 1979; Kawasaki et al. 1984; Lynch and Lauchli 1984). However, excision generally leads to an initial reduction in net uptake, as compared to that observed in intact plants. With time, roots recover from the effects of excision and uptake returns to normal rates (Glass 1978). Although the rate of uptake is influenced substantially by excision, the relative effects of specific ions on the short term uptake of nutrients by plants should not differ between excised and intact roots. Therefore, use of excised roots should provide an adequate qualitative measurement of the effect of Mg and Ca on the transport of K across the plasmalemma, over a short period of time.

The objective of the following study was therefore to examine the influence of varying concentrations and ratios of Ca and Mg on the short term uptake of K by excised barley roots.

4.1.2 Materials and Methods

Two separate experiments were conducted. In each experiment,

barley seeds (Hordeum vulgare cv. Bonanza) were soaked in aerated distilled water for 24 hours. Germinating seedlings were then transferred to aerated solutions of 0.5 mM $CaSO_4$ and grown in the dark at 21 C for 8 d to produce roots low in K. Roots were excised from the 8 d old plants, rinsed once in 0.5 mM $CaCl_2$ and held in 0.5 mM $CaCl_2$ until used, within 1 h.

Excised roots were mixed gently and 0.75 g fresh weight of root was blotted on paper towels. The sample was transferred to a 20 cm x 20 cm single layer of cheesecloth and the edges gathered together using white cotton thread to form a "teabag". The teabag was placed in 4 L of 0.5 mM $CaCl_2$ for temporary storage until all teabags for that replicate were prepared. Roots for each replicate were prepared immediately prior to use in the cation uptake study. Uptake of K by excised roots was evaluated using 500 mL of solution. In the first experiment 16 treatment solutions were used, consisting of a full factorial combination of K at 0.08 or 8.0 mM, Ca at 0.08 or 0.16 mM and Mg at 0.08, 0.16, 0.32 or 0.64 mM. Solutions were labelled with 6.6×10^5 Bq ^{86}Rb per mM K. In the second experiment, 16 treatment solutions were used, consisting of a full factorial combination of Ca and Mg at 0.08, 0.16, 0.32 or 0.64 mM. All solutions also contained K and Na at 0.08 mM. Solutions in the second experiment were labelled with 7.4×10^5 Bq ^{86}Rb per mM K. A control treatment of pure distilled water was included for comparison. In both experiments solutions were adjusted to a pH of 5.5 and a temperature of 21 C. Solutions were aerated during the absorption period. Treatments were replicated 3 times in a

randomized complete block design.

The uptake period was initiated by removing a teabag from the holding solution, rinsing it in two successive 1 L aliquots of 0.5 mM $CaCl_2$, spinning it in the air to remove excess liquid, and immersing it in the aerated uptake solution. To facilitate handling, the uptake procedure was initiated with successive samples at 2 min intervals.

After the completion of the 15 min uptake period, the roots were removed from the solution and placed in 250 mL of unlabelled solution of the same composition as the uptake solution for 2 min. The roots were then placed for 10 min in a second 250 mL aliquot of unlabelled solution held in an icebath. The teabags were then removed and roots separated from the cheesecloth. The roots were dried at 70 C, weighed, and then digested in a 70% nitric acid 30% perchloric acid mixture. After digestion, the samples were diluted to 25 mL with distilled water and 15 mL aliquots counted using the Cerenkov technique (Gelsema et al. 1975; Lauchli 1969). A quench curve was constructed using food coloring mixed to give a brown color and the counts corrected for quenching using the sample channels ratio technique (Lang 1976).

Statistical analyses were conducted using regression analysis (Steel and Torrie 1980). Only parameters with p 0.05 were included in the regression equations.

4.1.3 Results

Uptake of K from solutions of 0.08 mM concentration of K decreased with increasing concentration of Mg (Fig. 4.1.1). Concentration of Ca

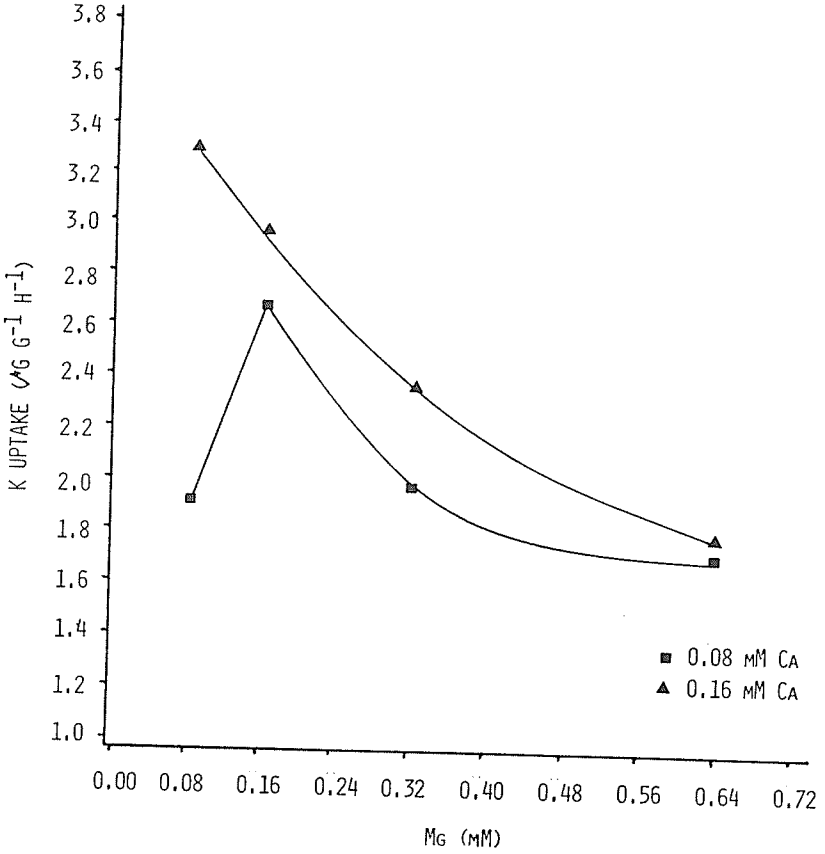

FIG. 4.1.1: K UPTAKE BY EXCISED BARLEY ROOTS AS A FUNCTION OF CA AND MG CONCENTRATION OF THE SOLUTION. EXPERIMENT 1.

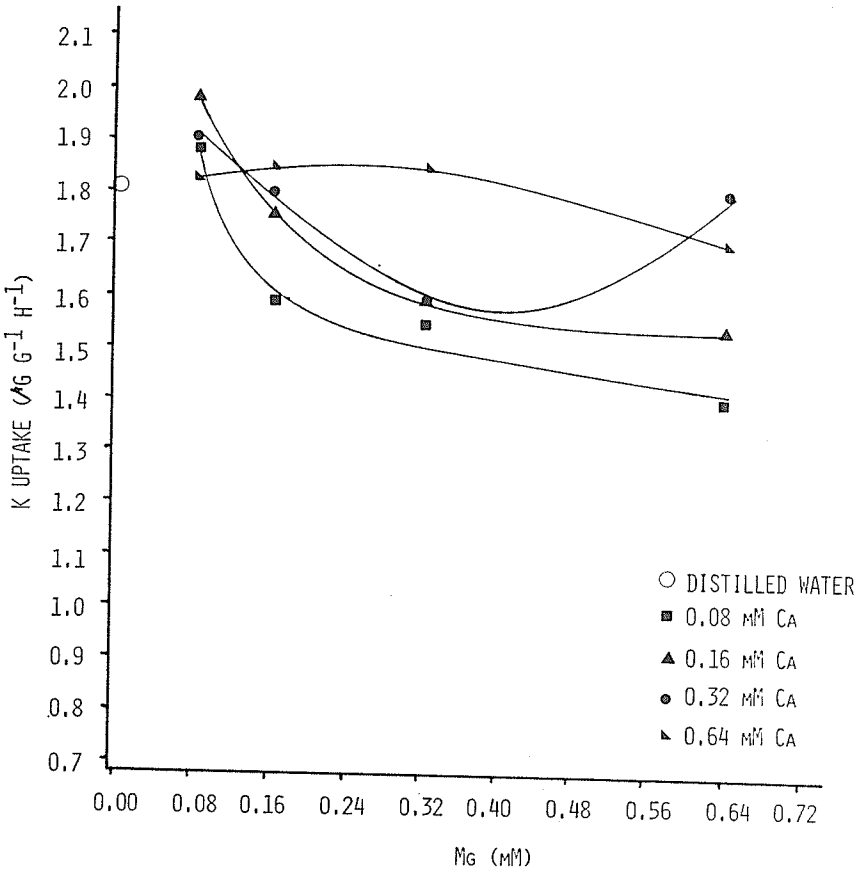

FIG. 4.1.2: K UPTAKE BY EXCISED BARLEY ROOTS AS A FUNCTION OF CA AND MG CONCENTRATION OF THE SOLUTION. EXPERIMENT 2.

had no significant effect on uptake of K. However, there was a consistent tendency for uptake to be slightly higher at a Ca concentration of 0.16 mM than at a Ca concentration of 0.08 mM (Fig. 4.1.1). Uptake of K was best described by the following regression equation:

$Y = 2.87 - 1.76\ Mg$

where Y = uptake of K in u mol gm^{-1} hr^{-1}, Mg in mM ($p=0.0030$, $r^2 = 0.42$).

In contrast, at the 8.0 mM K level, Mg had no effect on uptake of K at either high or low concentration of Ca (data not presented).

Results from experiment 2 showed similar trends to those observed in experiment 1 although the magnitude of uptake was slightly higher in experiment 1 than experiment 2 (Fig 4.1.2). Differences in magnitude of uptake between the two experiments may relate to slight differences in constancy of temperature and degree of aeration during root culture in the two experiments. Uptake of K decreased as concentration of Mg increased but uptake of K increased significantly as concentration of Ca increased. The reduction in uptake of K at high concentration of Mg was most marked at the lower concentrations of Ca. As the concentration of Ca increased, the deleterious effect of concentration of Mg on uptake of K decreased. At 0.32 and 0.64 mM Ca, concentration of Mg had no effect on uptake of K. Uptake of K in experiment 2 was was best described by the following regression equation:

$Y = 1.86 + 1.10\ Ca - 1.95\ Mg + 0.84\ CaxMg - 1.41\ Ca^2 + 1.72\ Mg^2$

where Y = uptake of K in u mol gm^{-1} hr^{-1}, Mg and Ca in mM ($p=0.0001$, $R^2=0.59$).

4.1.4 Discussion

Neither Ca nor Mg significantly affected uptake of K by excised roots when concentration of K was maintained at 8.0 mM. In contrast, uptake of K in 0.08 mM concentration decreased with increasing concentration of Mg and increased with increasing concentration of Ca to 0.32 mM. The difference in response at the high and low concentration range apparently reflects the action of two different methods of uptake. A passive influx at the high concentration of K range was unaffected by the relatively low concentrations of Mg and Ca used, while an active uptake system at the low concentration of K range was affected by Ca and Mg. The concentration of K in soil solutions in unfertilized soils is closer to the low rather than the high concentration range used. These results agree with those of Kawasaki and Hori (1968) who found that the rate of uptake of Rb from solutions of 1.0 mM Rb increased in the presence of Ca and Mg, but the effect of Ca was greater than that of Mg in promoting increased uptake. They found that the effect of Ca was greater if Na was present in the absorption solution. Bange and Schaminee-Dellaert (1968) found that in a mix of Rb and Na, Rb absorption was stimulated by the presence of Ca, but not by that of Mg. Earlier work by Epstein (1961) had demonstrated competition between uptake of Na and K, with Ca reducing the inhibitory effect of Na. He found Mg to be ineffective in reducing the interference. Epstein concluded that Ca was essential for the selectivity of uptake of K over Na. Overstreet et al. (1959) also observed that uptake of K increased with concentration of Ca at concentrations of K greater than 0.1 mM.

The increase in net uptake of K with Ca may relate to the effect of Ca on cell membrane integrity. Ca is known to be essential for membrane integrity (Steveninck 1965; Mengel and Kirkby 1979). Function of a selective ion uptake system would require the existence of a differentially permeable membrane, to exclude undesirable ions while allowing for the controlled passage and retention of required nutrients. Ca promotion of membrane integrity could increase net uptake of K by decreasing K efflux, as suggested by Mengel and Kirkby (1979). Replacement of Ca by Mg could lead to a decrease in membrane integrity resulting in higher efflux and lower net influx.

4.1.5 Conclusion

Ca and Mg at concentrations between 0.08 and 0.64 mM had no influence on uptake of K by excised barley roots when concentration of K in solution was 8.0 mM. In contrast, at low concentrations of K in the solution (0.08 mM), uptake of K by excised barley roots increased with increasing concentration of Ca from 0.08 to 0.32 mM and decreased with increasing concentration of Mg from 0.08 to 0.64 mM. Since concentrations of K in the soil solution of unfertilized soils are closer to the lower rather than the higher concentration range used, it is possible that a restriction on uptake of K by Mg could exist in high Mg soils. However, in the presence of an adequate concentration of Ca, the effect would likely be small.

4.2 The Effect of Varying Concentrations and Ratios of Ca and Mg on Solute Leakage from Barley Roots

4.2.1 Introduction

Ca and Mg are closely interrelated in plant physiology and may compete with one another for anion equivalents and binding sites in the plant tissue. One of the important functions of Ca in plant physiology is in the maintenance of membrane integrity (Bisson 1984; Mengel and Kirkby 1979; Steveninck 1965; Welch and Epstein 1969). The maintenance of properly functioning semipermeable membranes within the cell is critical to life. Interference with proper membrane function could interfere with ion absorption and plant growth.

The plasmalemma is generally believed to be the seat of the ion absorption mechanism and standard procedure for experiments to examine the uptake of ions is the inclusion of a low concentration of Ca in treatment solutions to ensure proper membrane function. Damage to membranes and transport mechanisms occurs within a short time period when Ca is not present in the solution (Lauchli and Epstein 1970).

Mengel and Kirkby (1979) suggested that the commonly observed Viets effect (Viets 1944), in which Ca and other divalent ions in the external medium were observed to increase the uptake of K and Br, was due to decreased membrane leakage promoted by Ca. The decreased permeability would enhance retention of absorbed monovalent ions.

Numerous studies have examined the effects of Ca on the uptake of

K (Bange and Schaminee-Dellaert 1968; Elzam and Hodges 1967; Overstreet et al. 1952). Pomeroy and Andrews (1985) examined the effect of Ca on the uptake and efflux of Rb by isolated winter wheat cells, and found that high concentrations of Ca decreased initial uptake of Rb but did not influence Rb efflux. But there is little information available on the effect of concentration of Mg and Ca on the leakage of solutes from intact plant roots, particularly at high cation concentrations.

The objective of these studies was to examine the influence of external Ca and Mg on the efflux of electrolytes from the roots of intact barley plants. Changes in electrical conductance of the solution were used to evaluate leakage of all electrolytes from the root into distilled water, while ^{86}Rb was used to simulate the movement of K out of the root into solutions containing varying concentrations of Ca and Mg. Rb was substituted for K since a suitable isotope of K was not available.

4.2.2 Methods and Materials

1. Electrolyte Leakage Studies

Electrolyte leakage from intact barley roots was evaluated after roots were treated with various concentrations of Ca and Mg.

Barley seeds (cv. Bonanza) were washed in distilled water, then soaked in aerated distilled water for 24 h. Seeds were then transferred to flats of vermiculite for 6 d, until seedlings were in the early 2-leaf stage. Seedlings were then transferred in groups of 3 to aerated full strength Hoaglands California #1 solution (Hoagland and

Arnon 1950). Twenty-four groups of 3 seedlings were grown in 10 L of solution, adjusted to pH 6.5 and changed every 4 d and on the d before use of the seedlings. Seedlings were grown for 10 d in a growth chamber with relative humidity of approximately 60% and a 16 h light and 8 h dark cycle with light period temperature of 23 C and dark period temperature of 16 C.

Groups of seedlings were randomly selected and rinsed in distilled, deionized water. Seedling groups were then transferred to beakers containing 500 ml of the aerated experimental solutions, which sisted of all combinations of 2, 4 and 8 mM Ca and Mg plus a istilled water check. Ca and Mg were added as nitrate salts. All treatment solutions were adjusted to pH 6.0.

Seedlings were maintained in the treatment solutions for 1 h, after which they were rinsed for 1 min in 4 L of distilled deionized water held at room temperature, then transferred to a fresh aliquot of 4 L of distilled water and rinsed for 1 min. Seedling groups were then transferred to 25 mL of vigorously aerated distilled deionized water. Conductivity of the water was measured after 1, 3, 5, and 7 h of incubation.

After the completion of the 7 h leakage period, the seedling groups were lightly blotted and divided into root and shoot portions. Fresh weight and oven dry weights were measured and leakage of solutes per g fresh weight of root calculated.

Statistical analyses were conducted using linear regression. Only parameters with $p \leq 0.05$ were included in the regression equation. The

equation with the highest R^2 value was selected.

2. K leakage study

Barley kernels (cv Johnston) were soaked for 24 h in aerated distilled water, then transplanted to flats of vermiculite. The flats were kept moist and held in the dark at 20 C until seedling emergence. The seedlings were grown in a growth chamber with relative humidity of approximately 60% and a 16 h light and 8 h dark cycle with a light period temperature of 22 C and a dark period temperature of 15 C until they reached the 1 leaf stage. Bundles of 3 seedlings were then transferred in groups of 24 to 10 L of half strength Hoagland's solution, adjusted to pH 6.0. After 5 d, the solution was replaced with fresh, half strength solution, however the concentration of K was reduced to 0.5 mM K (low K solution). The remainder of the KNO_3 was replaced with NH_4NO_3 to maintain the level of nitrogen. The plants were grown in the low K solution for 4 days. The day prior to the leakage study, the nutrient solution was replaced with half strength low K solution which was labelled with 1.48×10^6 Bq of ^{86}Rb per mM of K.

After 24 h in the labelled solution, assessment of K leakage was initiated. Triplets of plants were removed from the nutrient culture solution and the roots rinsed for 1 min in distilled water and then for 30 seconds in each of two aliquots of 0.5 mM $CaCl_2$ solution. The beakers were then filled with 150 mL of vigorously aerated treatment solution. The formulation of the treatment solutions are given in Table 4.2.1. Ca and Mg were added as nitrate salts.

Table 4.2.1: Composition of leakage treatment solutions

TREATMENT	Ca	Mg	Ca:Mg
	mM		
1	14	2	7:1
2	12	4	3:1
3	8	8	1:1
4	4	12	1:3
5	2	14	1:7
6	0	0	0:0

Samples of 1 mL of the solutions were taken at 5, 20, 35, 50, 65, 95, 125, 155, 215, 245, 305, and 365 minutes. To maintain a constant solution volume, 1 mL of distilled water was returned to the solution for each 1 mL removed. Radioactivity in the solution was assessed by Cerenkov counting and measurements adjusted for dilution by addition of distilled water.

Following the leakage procedure, the plants were removed, lightly blotted, separated into the root and shoot portions and fresh weights of each portion obtained. Statistical analysis was conducted using linear regression.

It should be noted that in the first study conductance was used to measure leakage or efflux from roots. Calcium is normally added to all solutions for the maintenance of root membrane integrity (Lauchli and Epstein 1970). However, since this experiment was conducted to determine the effect of Ca and Mg on solute leakage, addition of Ca to the efflux solution was not desirable because the high background conductance of the solution would result in decreased sensitivity. The second experiment was designed to directly measure efflux of K (^{86}Rb) from roots into solutions varying in Ca and Mg concentration. Changes in ^{86}Rb content of solutions were used to measure leakage; efflux from roots directly into the treatment solutions was being measured, and with the exception of the distilled water treatment, each solution contained a minimum of 2 mM Ca.

4.2.3 Results

Leakage of solutes from intact barley seedling roots was influenced by Ca and Mg, when measured by (a) changes in conductivity of distilled water (electrolyte leakage technique) or (b) movement of ^{86}Rb out of the labelled roots (^{86}Rb leakage technique). Conductance as a function of time for the various concentrations of Mg and Ca in the pretreatment solutions are shown in Figures 4.2.1 to 4.2.3. Regression equations for leakage as assessed using the electrolyte leakage technique, were formulated separately for Mg parameters and Ca parameters. Only parameters with $p \leq 0.05$ were included in the equations. The resulting equations were:

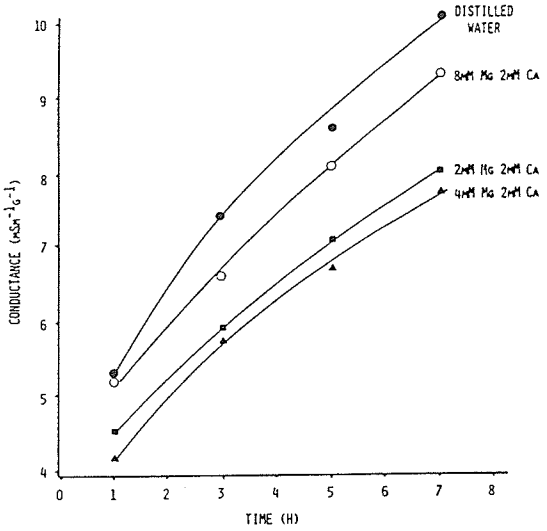

FIG. 4.2.1: LEAKAGE OF SOLUTES AS INDICATED BY CHANGE IN SOLUTION CONDUCTIVITY.

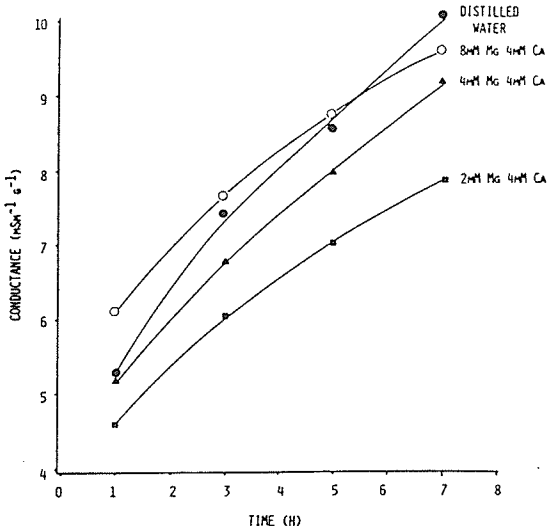

FIG. 4.2.2: LEAKAGE OF SOLUTES AS INDICATED BY CHANGE IN SOLUTION CONDUCTIVITY.

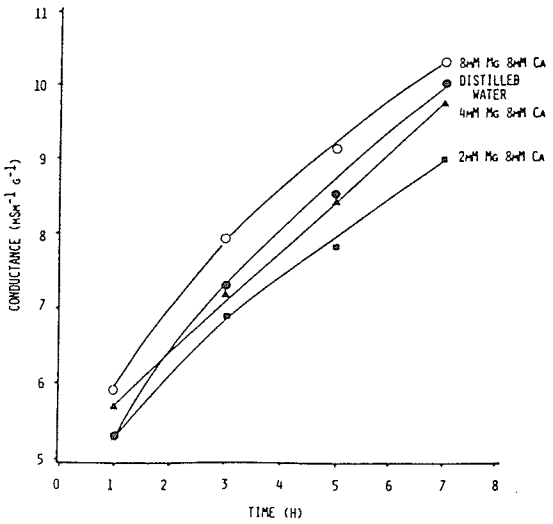

FIG. 4.2.3: LEAKAGE OF SOLUTES AS INDICATED BY CHANGE IN SOLUTION CONDUCTIVITY.

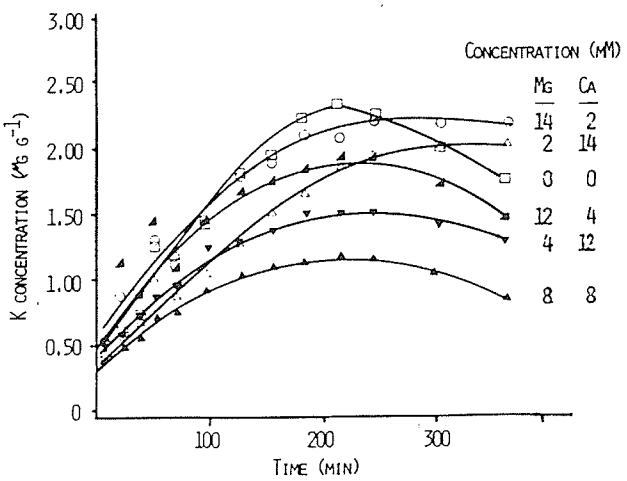

FIG. 4.2.4: K CONCENTRATION OF SOLUTIONS AS A FUNCTION OF EFFLUX TIME AS INFLUENCED BY CONCENTRATION OF CA AND MG.

$Y = 4.93 - 0.39\ Mg + 0.05\ Mg^2 + 0.64$ time

($p \leq 0.0001$ $R^2 = 0.58$) where Y = conductivity of the distilled water in mS m^{-1} per g root fresh weight per h, time in h, Mg in mM.

$Y = 4.81 - 0.29\ Ca + 0.04\ Ca^2 + 0.64$ time

($p \leq 0.0001$ $R^2 = 0.56$) where Y = Conductivity of the distilled water in mS m^{-1} per g root fresh weight per h, time in h, Mg in mM.

The value of conductivity extrapolated to time 0 for the individual treatments was in the order of 2.5 mS m^{-1}, which presumably reflects the basal conductivity of the distilled water plus the quickly released Ca and Mg which was not removed by the initial rinsing process.

The equations using Ca and Mg were very similar in form and the coefficients had approximately the same magnitude, indicating that Ca and Mg had similar effects on electrolyte leakage.

Concentration of K (^{86}Rb) accumulated in the solutions as a function of time of leakage for the various combinations of Mg and Ca are shown in Figure 4.2.4. Regression equations were formulated for leakage as indicated by K (Rb) concentration in the solutions. Separate equations were formulated for Mg and Ca parameters, and only parameters with p 0.05 were included in the regression equations. The resulting equations were:

$Y = 0.175 - 0.045\ Mg + 0.0029\ Mg^2 + 0.016$ time

($p \leq 0.0001$ $R^2 = 0.46$) where Y = K accumulation in solution in µg per g root weight, time in min, Mg in mM:

$Y = 0.186 - 0.041\ Ca + 0.0024\ Ca^2 + 0.016$ time

($p \leq 0.0001$ $R^2 = 0.47$) where Y = K accumulation in solution in μg per g root weight, time in min, Ca in mM.

As noted for the equations derived from the electrolyte leakage studies, the form and magnitude of the coefficients of the regression equations using Mg and Ca separately to describe ^{86}Rb leakage were similar, indicating that Ca and Mg were similar in their effects on Rb leakage. Leakage was slightly less when Ca was the dominant cation than when Mg predominated.

When leakage was assessed by changes in conductivity, leakage was initially higher after pretreatment with Ca and Mg than after pretreatment with distilled water, particularly at the highest cation concentration (Fig 4.2.1 to 4.2.3). After the initial measurements however, leakage was higher from the distilled water treatment. When leakage was averaged between the initial measurement and the final measurement (Table 4.2.2) both rate of leakage and total leakage was higher in the distilled water treatment than in any other solution. Similarily, when leakage was assessed by movement of ^{86}Rb to the solution, leakage was higher in the distilled water than in solutions containing Ca and Mg through most of the experiment (Fig 4.2.4). The decline in the latter part of the experiment may have been due in part to depletion of the Rb in the root. Recovery of the plants from shock due to transfer to the treatment solutions would also lead to renewed influx of Rb which would reduce the Rb in the external solution. Ca and Mg had similar effects on leakage, with mean overall leakage decreasing with initial increments of either Ca or Mg and increasing with high concentrations

of Ca or Mg. When leakage was assessed by changes in conductivity (Fig 4.2.1 to 4.1.3), leakage increased when either Ca or Mg was increased to 8 mM.

Table 4.2.2 Leakage rate and total leakage of solutes between initial (1 hour) and final(7 hours) measurements.

Ca	Mg	Rate	Total Leakage
----mM-----		$mS\ m^{-1}\ g^{-1}\ h^{-1}$	$mS\ m^{-1}\ g^{-1}$
0	0	7.98	4.79
2	2	5.77	3.46
2	4	5.83	3.50
2	8	6.93	4.16
4	2	5.48	3.29
4	4	6.68	4.00
4	8	5.83	3.50
8	2	6.31	3.79
8	4	6.86	4.12
8	8	7.35	4.41

Leakage also increased as the sum of Ca + Mg increased, possibly due to cations absorbed during the treatment period and not completely removed in the rinsing process.

When the ratio of Ca:Mg was changed while the sum of Ca + Mg remained constant, leakage of K increased when either Ca or Mg was increased above 8 mM (Fig 4.2.3). Ca and Mg had very similar effects on leakage, although leakage tended to be higher with the higher Mg concentrations than with the higher concentrations of Ca. This may reflect the greater mobility of Mg into the root as compared to Ca.

The length of time that the roots were immersed had a significant effect on rate of leakage, with leakage rate decreasing with time. In the ^{86}Rb leakage study, roots showed a net leakage of K until 245 minutes after treatment was initiated (Fig 4.2.4). Net leakage ceased after 245 minutes in the solutions containing a 7:1 ratio of Ca:Mg or Mg:Ca, while in the solutions containing a Ca:Mg or Mg:Ca closer to unity, net uptake of Rb began.

The pattern of efflux differed when leakage was measured by solution conductance and K leakage. Solution conductance continued to increase, at a decreasing rate, throughout the study period, while K concentration reached a peak and then began to decrease. This could reflect the difference in the type of diffusing ions being measured or the fact that the roots were surrounded by distilled water in the conductance studies and by Ca-Mg solutions in the K leakage study. Since K leakage into the distilled water treatment peaked and then declined, it appears likely that the difference between the two studies

lies in the difference between the types of ions being measured. Presumably, the efflux of K slowed and uptake began due to depletion of K reserves within the plant. Efflux of total ions as measured by changes in conductance may have continued for a longer period of time due to the existence of a larger reserve available for efflux.

4.2.4 Discussion

Solute leakage from intact barley plant roots was higher from roots immersed in distilled water than those immersed in solutions containing either Ca or Mg. In the conductivity study, leakage was initially higher from the roots pretreated with Ca and Mg, presumably due to efflux of Ca and Mg taken up during the treatment which was not removed from the free space by the desorption treatments. These results are similar to those of Handley et al. (1965) who found that leakage of Na from excised corn roots was initially higher when roots were placed in solutions containing 0.0025 M $CaCl_2$ or $SrCl_2$ as compared to pure water. However, in the study of Handley et al., leakage from the solutions containing cations decreased with time while rate of leakage from roots placed in pure water remained constant until rate of leakage was greater from roots placed in pure water.

In the current study, leakage was curvilinearly related to concentration with leakage rate decreasing to the greatest extent at concentrations of either Ca or Mg less than 8 mM. At concentrations of 8 mM or greater of either Mg or Ca, leakage began to increase. Pomeroy and Andrews (1985) found that Rb efflux from isolated winter wheat

cells did not differ significantly in the presence of 10 mM Ca as compared to 0 mM Ca. In the current study, leakage at 12 mM Ca was lower than at 0 mM Ca (distilled water), but was higher than at lower concentrations of Ca. Mg did not appear to interfere with Ca maintenance of membrane integrity. When both Ca and Mg were present in the solution, the response of leakage to Mg was similar to the response to Ca, although in the ^{86}Rb leakage study leakage tended to be somewhat higher when Mg was the more prevalent cation. Steveninck (1965) found that Mg was much less effective than Ca in reducing leakage of solutes from disks of beet root storage tissue. Kawasaki et al. (1973b) also observed that Ca repressed the exchange-desorption of monovalent cations, especially Rb, indicating that Ca reduced efflux of Rb from plant roots. Ca led to an overall increase in the nonexchangeable uptake of Rb by excised barley roots. Mg was not as effective as Ca in decreasing exchangeable and in increasing nonexchangeable Rb in the root. If the decrease in exchangeable and increase in nonexchangeable uptake of Rb is taken to indicate an increase in the efficiency of membrane operation then Mg was less effective than Ca in influencing membrane function. Bisson (1984), however found that Mg was generally as effective as Ca in restoring membrane function. Differences between the results obtained in this study and by Kawasaki et al (1973b) and Steveninck (1965) may be due in part to the low ion concentration used in the studies by these authors. Kawasaki et al. (1973b) used 0.5 mM Ca or Mg while Steveninck (1965) used 0.16 mM Ca or Mg. Further, the studies of Stevenink (1965), Kawasaki et al. (1973b) and Bisson (1984)

examined Ca or Mg in monoionic solutions. In the current study, all treatment solutions except for the distilled water treatment contained at least 2 mM Ca in the high concentration solutions. Therefore, leakage was not examined in the total absence of Ca. Mengel and Kirkby (1979) indicated that the concentration of Ca required for normal membrane permeability is in the order of 0.1 mM. Bisson (1984) also found that 0.5 mM Ca was as effective as 5 mM Ca in influencing membrane properties. The basal concentration of Ca present in the solutions may have been sufficient for requirements specific to Ca.

Steveninck (1965) suggested that the ability of other divalent cations to substitute for Ca indicated that apart from probable specialized physiological effects, all divalent cations have an unspecified effect on the colloid chemical behavior of the protoplast. He indicated that Ca might bridge the negative charges of the plasma surface and cell wall. Bisson (1984) suggested that Ca promotes the closing of channels in the plasma membrane used for K transport. The channels would also be closed if the membrane potential was sufficiently negative, so that the requirement for Ca is not absolute. The effect of Ca was mimicked quite well by Mg, thus the effect may be due to a general screening of charge rather than a specific interaction with the channel. This may explain the effectiveness of Mg in the current study in reducing leakage.

The increase in Rb leakage at high concentrations of either Ca or Mg, independent of total cation concentration may possibly reflect movement of the divalent cations into the root at high concentrations,

due to the high chemical gradient, resulting in a concurrent outward movement of K (Rb) to balance the charge gradient.

4.2.5 Conclusions

The rate of leakage of solutes from intact roots as measured by either changes in solution conductivity or Rb leakage, was greater when the external solution was pure distilled water than a solution containing Ca and Mg. Leakage decreased with increasing concentration of Ca and Mg to 8 mM but increased with increasing concentration of either Ca or Mg above 8 mM. Since concentrations of Ca in the soil solution of unamended systems normally range from 3 to 10 mM while concentrations of Mg normally range from 2 to 5 mM (Russell 1973) it is unlikely that excess concentration of Mg or Ca would interfere with membrane integrity in unamended soils. However, leakage may be a problem in fertilized soils, where Ca and Mg concentrations would be higher than those in unamended soils. Ca and Mg both were effective in reducing leakage from intact roots. However, leakage of K as indicated by ^{86}Rb leakage tended to be higher when the ratio of Ca:Mg deviated from unity and when Mg was the dominant cation.

5.0 The Effect of High Concentrations of Ca and Mg on the Yield and Nutrient Content of Johnston and Bonanza Barley

The previous studies, which examined the influence of Ca and Mg in solution on the uptake of K and the efflux of solutes by barley plants indicated that high concentrations of Mg and Ca could interfere to some extent with the short term accumulation of K. The effects were not large and it was not evident whether Mg and Ca would have an important effect on ion accumulation at the concentrations normally present in unamended soils. As well, uptake and efflux studies were conducted in solutions much simpler than those in which plants are normally grown. The uptake and efflux studies therefore provided only a view of the short term behavior of nutrient flux of barley seedlings in a simple environment.

Hydroponic culture has frequently been utilized to examine the effect of varying nutrient concentrations on plant growth. Although hydroponic culture does not reproduce the type of environment found in soil, it has the advantage of allowing for the evaluation of the chemical effects of varying nutrient concentrations in the absence of variations in soil structure, texture, pH or concentration of other nutrients.

In solution culture, Ohno and Grunes (1985) found yield of wheat was unaffected by concentrations of Mg of 0.1 to 4.5 mM and concentration of K of 0.1 to 6.0 mM. However, Fageria (1973) found that yield of groundnuts in a hydroponic system decreased when concentration of Mg increased above 0.75 mM when Ca and concentration

of K were maintained at 0.125 and 0.204 mM, respectively. Fageria (1983) reported that increasing the concentration of Mg in the medium decreased K and Ca absorption by rice.

In solution culture, Carter et al (1979a) found that the growth of barley at the seedling stage was reduced at Mg:Ca ratios of 1.3 to 2.5. Ca deficiency symptoms of barley occurred when grown in nutrient solutions and soils with Mg:Ca ratios of greater than 1.3.

Although solution culture can provide valuable information on the chemical effects of nutrient concentrations or plant growth, it does not necessarily follow that the same effects will be seen in soil culture. The soil is a complex system, with a multitude of reactions occurring which influence plant growth and nutrient relations. Therefore, the effects of Ca and Mg must be examined in soil as well as solution culture to determine possible effects on crop production.

Ca or Mg are generally applied to soils as calcitic or dolomitic limestone. A number of studies have examined the effect of "over-liming" on crop yields and nutrient relations. York et al. (1954) found that yield of corn and Sudangrass declined with high lime application. The reduced yields were not due to a deficiency of K or Mg. The authors suggested a deficiency of Mn or Fe may have occurred. High levels of Ca and Mg are normally associated with high soil pH levels. Availability of Mn and Zn tends to decline with increasing pH (Mengel and Kirkby 1979). Therefore, it is possible that high soil levels of Ca and Mg may interfere with the availability of Mn and/or Zn for plant growth. Racz and Haluschak (1974) found that the yield

of wheat on calcareous soils was lower than on noncalcareous soils. Concentration of Zn was lower in the plants grown on calcareous than on noncalcareous soils. Leibhardt (1979) found that corn and barley yields were depressed by lime applications of 8.96 Mg ha^{-1} as calcite or calcite plus dolomite. At high application rates, both Ca and Mg were negatively related to yield, but Ca was less deleterious in its effect on yield than Mg. Tissue analysis showed Mn and Zn levels in the deficiency range. The high soil Mg was associated with a decrease in plant Mn.

None of the above studies examined the individual and combined effects of high levels of Ca and Mg on crop yield and nutrient relations. The primary objective of the following studies were to determine the effect of high levels of Ca and Mg on the yield and tissue Mg, Ca, K, Zn and Mn relationships of barley, which is generally considered a calcicole plant, adapted to high Ca levels in the soil. In order to attain this goal, barley growth and nutrient relations were examined in three types of systems:

(a) Hydroponic nutrient culture

(b) Growth chamber soil culture

(c) Field culture

5.1 The Effect of High Concentrations of Ca and Mg in Hydroponic Solutions on the Yield and Mg, Ca, K, Zn and Mn Content of Johnston and Bonanza Barley

5.1.1 Introduction

The evaluation of cation interactions in a soil system is complicated by factors other than the simple chemical effects of the ions in question. Soil physical characteristics, pH, and concentration of other ions may vary or covary with the ions under study. Determination of the effects of Mg, Ca, and K on plant growth requires that other factors remain constant but at a level required for optimal growth of plants. Therefore, initial evaluation of the effect of Ca, Mg and K on barley growth was conducted in a series of nutrient solution studies. In this manner, effects of the cations in question on soil structure and their possible covariance with soil texture, pH and content of other ions were eliminated. Therefore, variations in plant growth and nutrient relations were due to the chemical effects of the concentration and ratios of the ions under study.

5.1.2 Methods and Materials

Barley (Hordeum vulgare) seeds were soaked in aerated, distilled water for 24 h and then transferred to flats of vermiculite. Flats were maintained in darkness at 22 C until the seedlings emerged. Seedlings were then transferred to a growth chamber maintained at 16 and 8 h light and dark periods, respectively, and light and dark

period temperatures of 22 and 16 C, respectively. The seedlings were grown to the two-leaf stage and then transplanted in groups of 24 into black painted plastic containers containing 10 L of aerated treatment solution. All solutions were modifications of a full strength Hoagland's California #1 solution (Hoagland and Arnon 1950). All modifications to solutions were made using nitrate salts and the level of nitrogen adjusted to a constant level using NH_4NO_3. The pH was adjusted to 6.5.

In each study, stepwise regression using maximum R^2 improvement (SAS Institute 1982) was used to find the best fit regression equation for yield and nutrient content, using $p \leq 0.05$ as the criterion for maintaining a parameter in the equation.

1. K-Mg study

A preliminary study was conducted to determine response of barley to Mg and K in the hydroponic solution. The barley cultivar used was Johnston. Treatment formulations consisted of full factorial combinations of K at 0.75, 1.50, 6.00 and 12.00 mM and Mg at 0.50, 1.00, 2.00, 4.00 and 8.00 mM. Ca was present in each solution at 5 mM. Solutions were changed every 3 d. Seedlings were removed and individually weighed weekly and harvests were taken after 4 wk of growth. Harvested plants were divided into root and shoot portions and each portion was analyzed individually for Mg, K and Ca.

2. Ca-Mg study

A second set of experiments were conducted to determine the influence of varying concentrations of Mg and Ca and Ca:Mg ratios on the

yield and nutrient content of barley. The cultivar of barley used was Bonanza. Treatments were replicated twice and the experiment was conducted twice. Solutions were formulated to give Mg:Ca ratios of 4:1, 2:1, 1:1, 1:2 and 1:4 (Table 5.1.1).

Table 5.1.1: Solution formulations in Ca-Mg studies

Treatment	Mg	Ca	Mg:Ca
	mM		
1	2.0	0.5	4:1
2	2.0	1.0	2:1
3	2.0	2.0	1:1
4	2.0	4.0	1:2
5	8.0	2.0	4:1
6	8.0	4.0	2:1
7	8.0	8.0	1.1
8	8.0	16.0	1:2
9	8.0	32.0	1:4

Each solution contained 1.0 mM Na. Nitrogen was added as NH_4NO_3 to adjust the N in solutions 1 to 7 to 49 mM, the concentration equal to that in the solution for treatment 8. N was adjusted to the concentration of treatment 8 rather than treatment 9 because the concentration of N for treatment 9 was considered excessively high.

Solutions were changed every 3 d during the experiment. Plants were harvested after 28 d in the treatment solutions. Fresh weights and oven dry weights were obtained for roots and shoots. Root and shoot samples were then analyzed individually for Ca, Mg, K, and Zn.

3. Ca-Mg cultivar study

Slightly different yield responses to Mg concentrations were observed in the initial study using Johnston barley and the second study using Bonanza barley. Therefore, the effect of concentrations of Mg and Ca and Ca:Mg ratios on the yield and nutrient content of Johnston and Bonanza barley were examined. A full factorial design was used with 12 solutions consisting of all combinations of Ca at 2, 4 and 16 mM and Mg at 2, 4, 8 and 16 mM. Each treatment was repeated twice and each pan contained 24 plants, 12 of Bonanza and 12 of Johnston barley. Treatment solutions were changed after 7 d and then every 3 d during the experimental period. Harvests were taken after 28 d. Fresh and oven dry weight of root and shoot were measured. Chemical analyses for Ca, Mg, K, Zn and Mn were conducted on roots and shoots.

5.1.3 Results

1. K-Mg Study

Shoot dry weight increased 2 to 3 fold when concentration of K in the solution was increased from 0.75 to 1.50 mM and increased only slightly at concentrations above 1.5 mM K (Table 5.1.2). Shoot dry weight was generally greatest at 1.0 to 2.0 mM Mg in the solution and tended to decrease when concentration of Mg increased to 4.0 mM or 8

Table 5.1.2 Dry Matter Yield, concentration of nutrients in tissue and total uptake of nutrients of K- Ca Hydroponic Study.

Treat.	Concentration in solution K	Concentration in solution Mg	Dry weight Shoot	Dry weight Root	Concentration in Tissue Ca in Shoot	Ca in Root	Mg in Shoot	Mg in Root	K in Shoot	K in Root	Total Uptake of Plants Ca	Mg	K
	-----mM------		-----g------		----------%----------						----------g pot^{-1}--------		
1	0.75	0.5	0.458	0.092	1.75	2.05	0.192	0.244	1.87	1.97	0.0106	0.00120	0.0118
2	1.50	0.5	1.553	0.293	0.90	1.08	0.138	0.122	3.22	1.61	0.0169	0.00247	0.0538
3	6.00	0.5	1.043	0.202	1.14	1.30	0.157	0.116	4.33	2.61	0.0146	0.00192	0.0520
4	12.00	0.5	1.528	0.272	1.09	1.02	0.146	0.192	4.98	4.07	0.0193	0.00267	0.0882
5	0.75	1.0	0.432	0.163	1.24	1.69	0.256	0.180	2.36	2.80	0.0090	0.00153	0.0180
6	1.50	1.0	0.870	0.173	1.32	1.53	0.246	0.224	3.26	1.52	0.0141	0.00249	0.0309
7	6.00	1.0	1.488	0.268	0.93	1.42	0.201	0.180	4.04	3.31	0.0166	0.00325	0.0695
8	12.00	1.0	1.493	0.313	1.02	0.99	0.186	0.169	4.55	4.92	0.0188	0.00334	0.0783
9	0.75	2.0	0.570	0.160	1.08	1.31	0.308	0.240	2.92	1.20	0.0085	0.00222	0.0176
10	1.50	2.0	1.212	0.227	1.07	1.32	0.366	0.295	2.56	1.95	0.0152	0.00512	0.0348
11	6.00	2.0	1.127	0.202	1.08	1.38	0.335	0.393	4.46	3.79	0.0141	0.00438	0.0498
12	12.00	2.0	1.197	0.265	1.00	0.84	0.301	0.222	4.20	5.18	0.0142	0.00423	0.0643
13	0.75	4.0	0.420	0.083	1.22	1.36	0.683	0.416	1.94	1.29	0.0058	0.00305	0.0091
14	1.50	4.0	0.858	0.162	1.14	1.20	0.632	0.423	3.04	1.59	0.0133	0.00706	0.0328
15	6.00	4.0	1.078	0.230	0.94	1.19	0.522	0.362	4.57	3.99	0.0131	0.00669	0.0583
16	12.00	4.0	0.713	0.143	1.03	1.40	0.457	0.343	5.21	4.65	0.0095	0.00359	0.0429
17	0.75	8.0	0.515	0.117	1.17	1.60	0.950	0.649	2.36	2.00	0.0085	0.00616	0.0142
18	1.50	8.0	1.103	0.164	0.73	0.97	0.844	0.603	3.14	2.44	0.0092	0.01105	0.0376
19	6.00	8.0	1.098	0.200	0.71	0.78	0.765	0.444	4.80	3.98	0.0095	0.00949	0.0601
20	12.00	8.0	0.937	0.205	0.51	1.59	0.600	0.552	5.29	5.00	0.0078	0.00657	0.0569

mM. The depression in shoot dry weight with increased Mg tended to be greatest at the 12 mM concentration of K. Root dry weight followed a similar pattern to that of shoot dry weight, with dry weight increasing with increasing K and decreasing with increasing Mg, although no significant K x Mg interaction occurred (Table 5.1.2 and regression equations below). Lowest yields of both root and shoot occurred at the lowest concentration of K, where a visual K deficiency was observed. The regression equation for shoot dry weight in grams per plant, as a function of concentration (mM) of K and Mg in solution was as follows:

$$Y = 1.4528 + 1.61268 \log K - 0.6812 K + 0.0287 K^2 - 0.0065 KxMg$$

($R^2 = 0.36$, $p \leq 0.0001$).

The regression equation for root dry weight in grams per plant, as a function of concentration (mM) of K and Mg in solution was as follows:

$$Y = 0.1754 + 0.0351 \log K - 0.0245 \log Mg$$ ($R^2 = 0.20$, $p \leq 0.0001$).

Concentration of all nutrients in the root and shoot tended to decrease with increasing dry matter production (Tables 5.1.2 and 5.1.3). This was primarily a result of biological dilution.

Concentration of Ca in the shoot decreased with increasing K and Mg in the solution while the concentration of Ca in the root decreased only with increasing concentration of Mg in the solution (Tables 5.1.2 and 5.1.3). Concentration of Mg in the root and shoot increased with increasing Mg in the solution. The increase in concentration of Mg in the shoot with increasing concentration of Mg in the solution was less pronounced at higher than at lower concentrations of K. Concentration of K in the root and shoot generally increased with increasing

Table 5.1.3 Regression equations showing relationships between nutrient concentration of the tissue or nutrient uptake by the plant and the concentration of Mg and K in the solution (Mg and K in mM and dry weight (d.w.) in g).

Nutrient	Regression equation	R^2
Ca in shoot(%)=	1.472 - 0.055 Mg - 0.082 log K - 0.805 root d.w.	0.33
Ca in root (%)=	1.801 - 0.104 log Mg - 0.436 shoot d.w.	0.25
Mg in shoot(%)=	0.074 + 0.172 Mg - 0.008 Mg^2 - 0.004 MgxK	0.84
Mg in root (%)=	0.213 + 0.050 Mg - 0.051 shoot d.w.	0.56
K in shoot (%)=	3.128 - 0.115 K + 1.496 log K - 0.529 shoot d.w.	0.75
K in root (%)=	0.886 + 0.419 K + 0.257 log Mg - 0.122 K^2 + 1.745 root d.w.	0.78
Ca:Mg in shoot=	5.16 + 0.471 Mg - 3.62 log Mg - 0.343 shoot d.w.	0.88
Ca:Mg in root =	10.66 - 3.50 log Mg - 10.9 root d. w.	0.38
Ca uptake(mg) =	3.912 - 0.555 Mg + 8.02 shoot d.w. +11.43 root d.w.	
Mg uptake(mg) =	-0.0181 + 0.0052 Mg + 0.0126 log Mg - 0.0001 K^2 + 4.30 shoot d.w.	0.74
K uptake(mg) =	-0.0592 + 10.47 log K + 29.38 shoot d.w. +0.4730 root d.w.	0.91
Ca:Mg uptake =	5.58 + 0.442 Mg - 3.58 log Mg - 0.479 shoot d.w.	0.89

concentration of K in the solution. The concentration of K in the root also increased with increasing concentration of Mg in the solution, presumably due to the reduced yield at high concentrations of Mg.

The ratio of Ca:Mg in the root and shoot decreased with increasing Mg concentration and was not influenced by concentration of K in the nutrient solution (Tables 5.1.2 and 5.1.3). Ca:Mg ratio in the tissue increased as dry matter yield decreased, due to the high concentration of Ca in the tissue when yield was restricted at low K concentrations in the solution.

Total uptake of all nutrients increased with increasing dry matter yield (Tables 5.1.2 and 5.1.3). Uptake of Ca decreased with increasing concentration of Mg in the solution. Uptake of Mg increased with increasing concentration of Mg and decreased with increasing concentration of K in the solution. Increasing the concentration of K in the solution increased the uptake of K. The ratio of uptake of Ca to uptake of Mg followed the same pattern as the concentration ratio, decreasing with increasing Mg in the solution and with dry matter production.

2. Ca-Mg study

Results for the two experiments conducted were similar, thus the data from the two experimental runs were combined and analyzed together. The oven dry weight of root, and shoot are shown in Fig. 5.1.1.

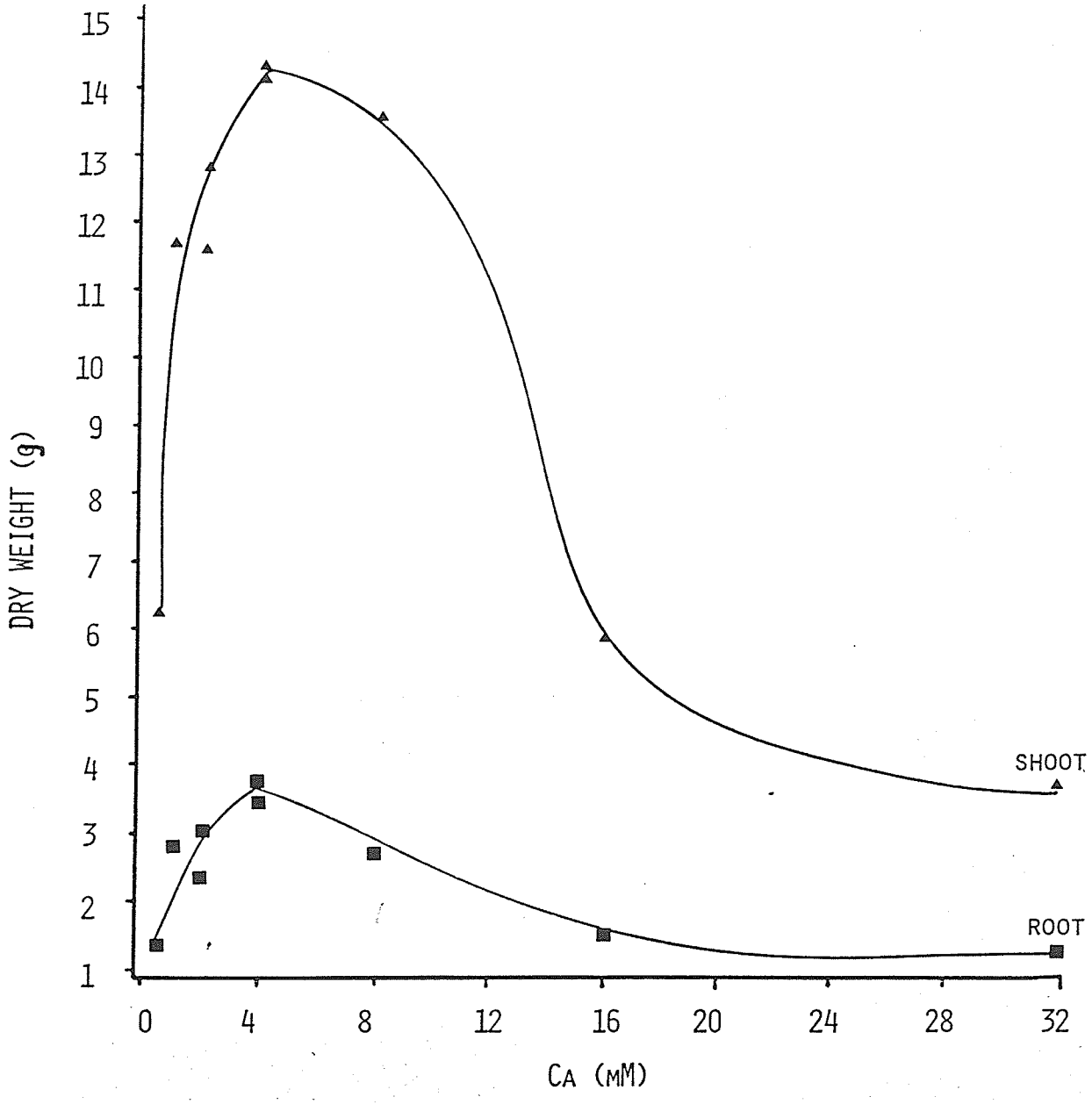

FIG. 5.1.1: ROOT AND SHOOT DRY WEIGHT AS A FUNCTION OF C_A CONCENTRATION OF THE SOLUTION.

Table 5.1.4.: Regression equations for yield (g) as affected by concentrations (mM) of Ca and Mg in solution

Yield Parameter	Regression Equation	R^2
Root dry weight	= 2.89 - 0.54 Ca + 0.0093 Ca^2 + 4.00 log Ca	0.41
Shoot dry weight	= 12.43 - 2.14 Ca + 0.034 Ca^2 + 7.09 log Ca	0.79
Total dry weight	= 15.32 - 2.68 Ca + 0.044 Ca^2 + 8.83 log Ca	0.68

Root, shoot and total dry weights were highest at Ca concentrations of 4 to 8 mM. Lowest yields were obtained with concentrations of 0.05 mM Ca and 32 mM Ca. Yield was not influenced by concentration of Mg in the solution (Table 5.1.4).

Table 5.1.5: Regression equations for tissue nutrient concentrations as affected by concentration (mM) of Ca and Mg in solution (dry weight in g).

Nutrient Parameter	Regression Equation	R^2
Ca in root(%)	= 0.194 + 0.00735 Ca^2 - 0.0000822 Ca^3	0.97
Ca in shoot(%)	= 0.198 +0.0987 Ca -0.00586 CaxMg	0.95
Mg in root(%)	= 0.171 - 0.000011 Ca^3 + 0.00312 CaxMg	0.82
Mg in shoot(%)	= 0.0843 - 0.0753 log Ca + 0.195 log Mg + 0.0495 Ca/Mg	0.80
K in root(%)	ns	
K in shoot(%)	ns	
Zn in root (ug g^{-1})	= 95.3 + 0.189 Ca^2	0.45
Zn in shoot (ug g^{-1})	= 189 - 5.90 shoot dry weight	0.12
Ca:Mg root	= 0.672 + 0.00446 Ca^2 + 0.838 Ca/Mg	0.93
Ca:Mg shoot	= 1.073 + 0.161 Ca + 1.826 Ca/Mg	0.63

The concentrations of the various nutrients in the tissue, with the exception of K, were influenced by concentration of Mg and/or Ca in the nutrient solution (Table 5.1.5). However, since yield also varied among treatments, some of the effect of Ca and/or Mg on tissue nutrient concentration was due to dilution or concentration by promotion or depression of dry matter yield, respectively.

Concentration of Ca in the shoot increased with increasing

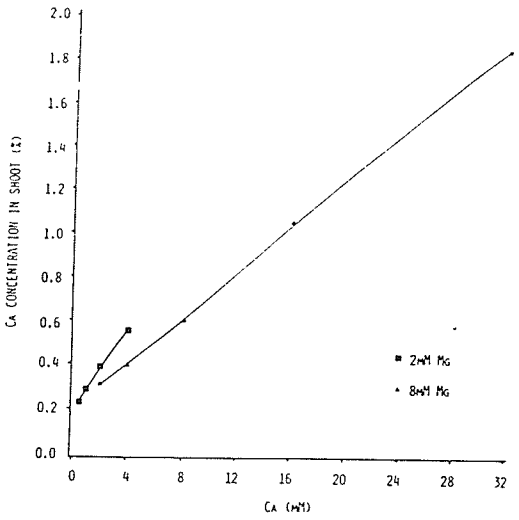

FIG. 5.1.2: Ca CONCENTRATION OF SHOOT AS A FUNCTION OF Ca CONCENTRATION OF THE SOLUTION AT 2 AND 8 mM Mg.

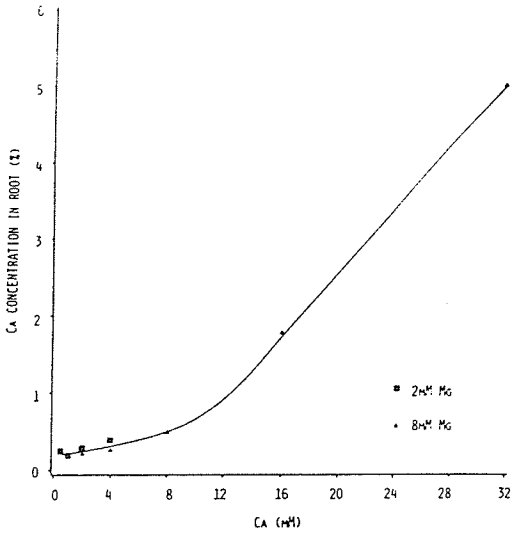

FIG. 5.1.3: Ca CONCENTRATION OF ROOT AS A FUNCTION OF Ca CONCENTRATION OF THE SOLUTION AT 2 AND 8 mM Mg.

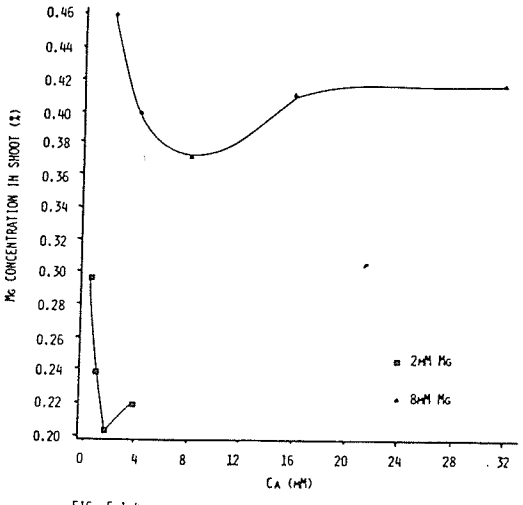

FIG. 5.1.4: Mg CONCENTRATION OF SHOOT AS A FUNCTION OF Ca CONCENTRATION OF THE SOLUTION AT 2 AND 8 mM Mg.

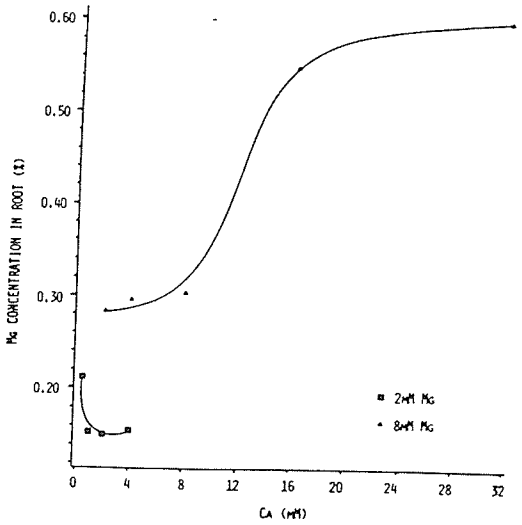

FIG. 5.1.5: Mg CONCENTRATION OF ROOT AS A FUNCTION OF Ca CONCENTRATION OF THE SOLUTION AT 2 AND 8 mM Mg.

concentration of Ca in the nutrient solution, particularly at the low concentration of Mg (Fig. 5.1.2, Fig. 5.1.3 and Table 5.1.5).

Concentration of Mg in the shoot and root decreased with increasing concentration of Ca at the low level of Mg in the nutrient solution (Fig. 5.1.4, Fig. 5.1.5 and Table 5.1.5) whereas concentration of Mg in the root and shoot increased when concentration of Mg in the nutrient solution was increased from 2 to 8 mM. Concentration of Mg in the root increased when Ca concentration in the nutrient solution increased to 16 or 32 mM. Reduction in dry matter yield at the high concentration of Ca may have led to the high concentration of Mg in the tissue, since the Mg taken up by the plant would have been distributed through a smaller quantity of dry matter.

Solution levels of Ca and Mg did not significantly affect concentration of K in the root and shoot (Table 5.1.5).

Concentration of Zn in the root (Table 5.1.5, Fig. 5.1.6) increased when concentration of Ca in the nutrient solution increased to 16 or 32 mM, while concentration of Zn in the shoot was significantly affected only by shoot dry weight (Table 5.1.5, Fig. 5.1.7).

The ratio of Ca:Mg in the root and shoot increased with increasing ratio of Ca:Mg and concentration of Ca in the solution (Table 5.1.5, Fig. 5.1.8 and Fig. 5.1.9).

Total uptake of the different nutrients (shoot dry weight x concentration in the shoot) + (root dry weight x concentration in the root)) was influenced by the dry matter yield (Table 5.1.6). Uptake of Ca (Table 5.1.6 and Fig. 5.1.10) increased as concentration of Ca in

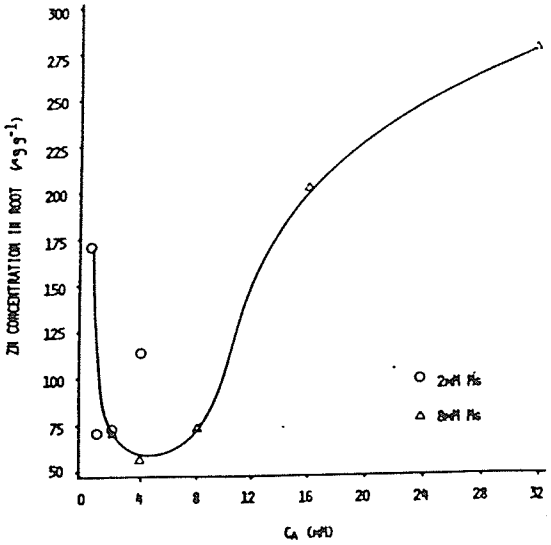

FIG. 5.1.6: ZN CONCENTRATION OF ROOT AS A FUNCTION OF C_A CONCENTRATION OF THE SOLUTION AT 2 AND 8 mM Mg.

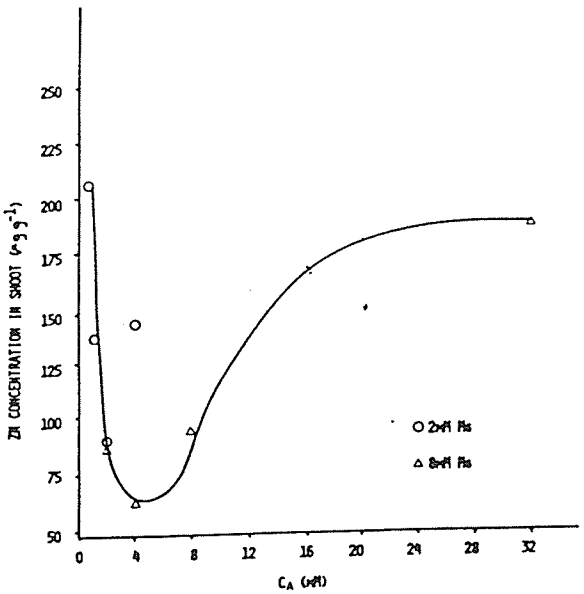

FIG. 5.1.7: ZN CONCENTRATION OF SHOOT AS A FUNCTION OF C_A CONCENTRATION OE THE SOLUTION AT 2 AND 8 mM Mg.

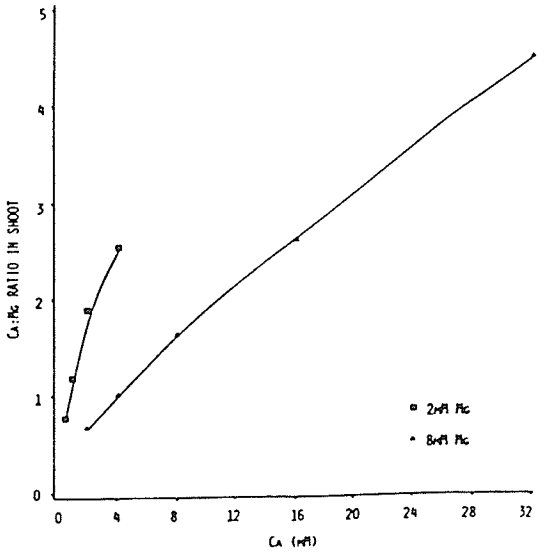

FIG. 5.1.8: C_A:Mg RATIO IN SHOOT AS A FUNCTION OF C_A CONCENTRATION OF THE SOLUTION AT 2 AND 8 mM Mg.

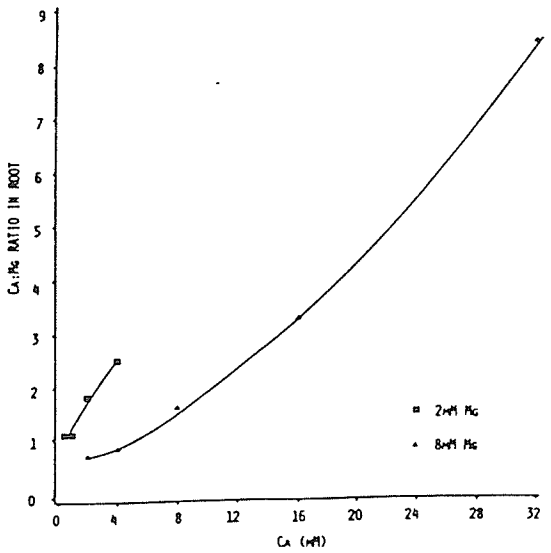

FIG. 5.1.9: C_A:Mg RATIO OF ROOT AS A FUNCTION OF C_A CONCENTRATION OF THE SOLUTION AT 2 AND 8 mM Mg.

the solution increased, as well as with increases in dry matter yield.

Table 5.1.6: Regression equations for total uptake of nutrients (g per pot) as affected by concentration (mM) of Ca and Mg in solution

Nutrient	Regression Equation	R2
Ca uptake	= -0.02784 + 0.00458 Ca + 0.00597 shoot d.w.	0.72
Mg uptake	= -0.01316 + 0.00520 Mg - 0.01210 log Ca + 0.00315 shoot d.w.	0.92
K uptake	= 0.03244 + 0.03330 shoot d.w.	0.71
Zn uptake	= ns	
Ca:Mg uptake	= 0.588 + 0.000028 Ca^3 + 1.033 Ca/Mg	0.96

Uptake of Mg primarily reflected yield (Table 5.1.6 and Fig. 5.1.11) but also increased as concentration of Mg in the solution increased and decreased as the concentration of Ca in the solution increased. Total uptake of K was influenced only by dry matter yield (Table 5.1.6, Fig. 5.1.12). Total uptake of Zn was not significantly influenced by treatment. Ratio of Ca:Mg uptake increased with increasing Ca and Ca:Mg ratio in the nutrient solution (Table 5.1.6 and Fig. 5.1.13).

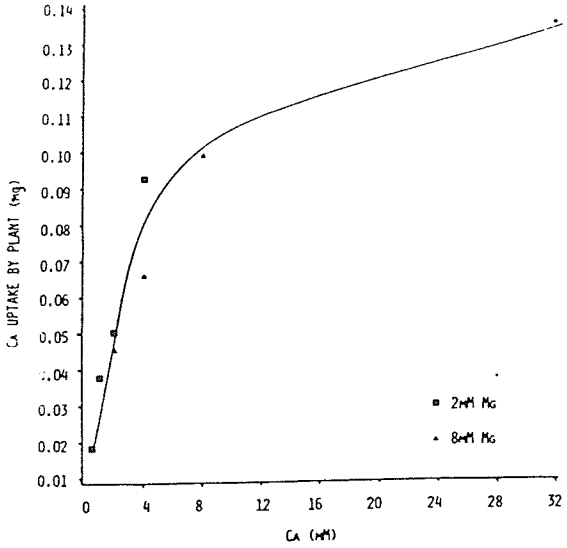

FIG. 5.1.10: Ca UPTAKE BY THE PLANT (mg) AS A FUNCTION OF Ca CONCENTRATION OF THE SOLUTION AT 2 AND 8 mM Mg.

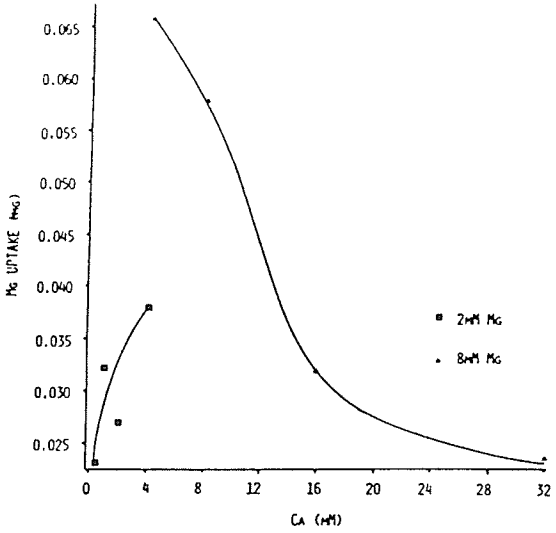

FIG. 5.1.11: Mg UPTAKE BY THE PLANT (mg) AS A FUNCTION OF Ca CONCENTRATION OF THE SOLUTION AT 2 AND 8 mM Mg.

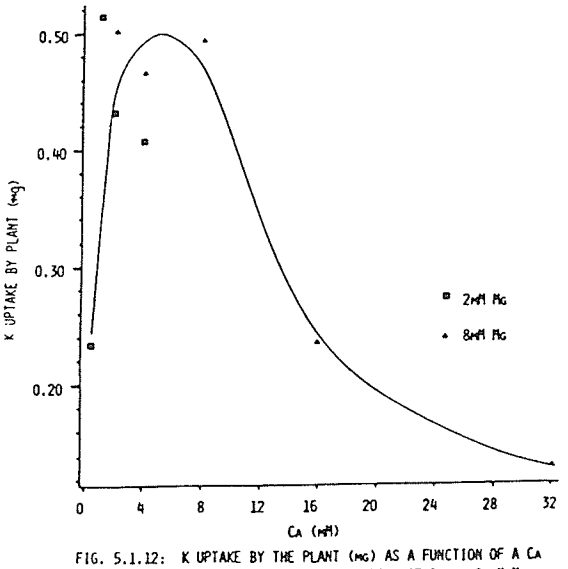

FIG. 5.1.12: K UPTAKE BY THE PLANT (mg) AS A FUNCTION OF A Ca CONCENTRATION OF THE SOLUTION AT 2 AND 8 mM Mg.

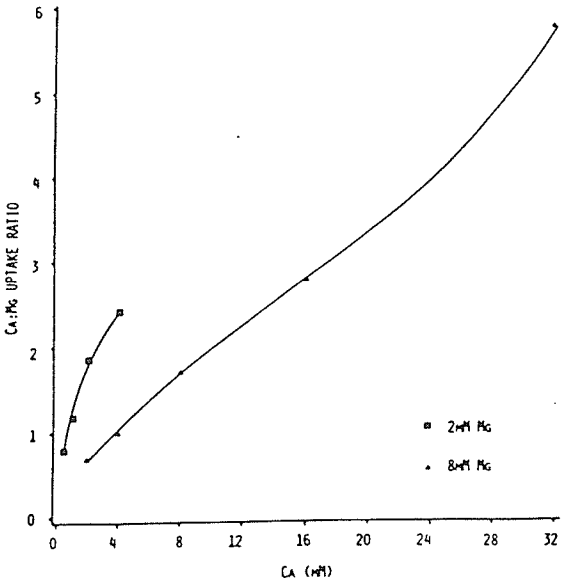

FIG. 5.1.13: Ca:Mg UPTAKE RATIO AS A FUNCTION OF Ca CONCENTRATION OF THE SOLUTION AT 2 AND 8 mM Mg.

3. Ca-Mg cultivar study

Shoot and root dry weight of both Johnston and Bonanza barley increased with initial increments of Ca in the nutrient solution and decreased at concentrations above 8 mM (Fig. 5.1.14 to 5.1.17 and Table 5.1.7). Root and shoot dry weights decreased with increasing concentration of Mg in the nutrient solution, particularly above 8 mM. Johnston barley had higher dry matter yield of root and shoot than Bonanza, but yield of Johnston decreased more in response to high levels of Ca and Mg than did yield of Bonanza.

Table 5.1.7: Regression equations for dry matter yield (g) of root and shoot as affected by cultivar and concentration (mM) of Ca and Mg in solution (cul refers to cultivar where Johnston was given a value of 1.0 and Bonanza a value of 0.0).

Dry Matter Yield (grams per pot)	Regression equation	R^2
Root dry weight =	$1.371 + 1.727\ cul - 0.0623\ Mg - 0.00757\ Ca^2 + 0.714\ \log Ca - 0.0581\ cul \times Ca$	0.87
Shoot dry weight=	$3.304 + 13.994\ cul + 1.535\ Ca - 0.202\ Mg - 0.086\ Ca^2 - 0.205\ cul \times Ca - 0.482\ cul \times Mg$	0.92

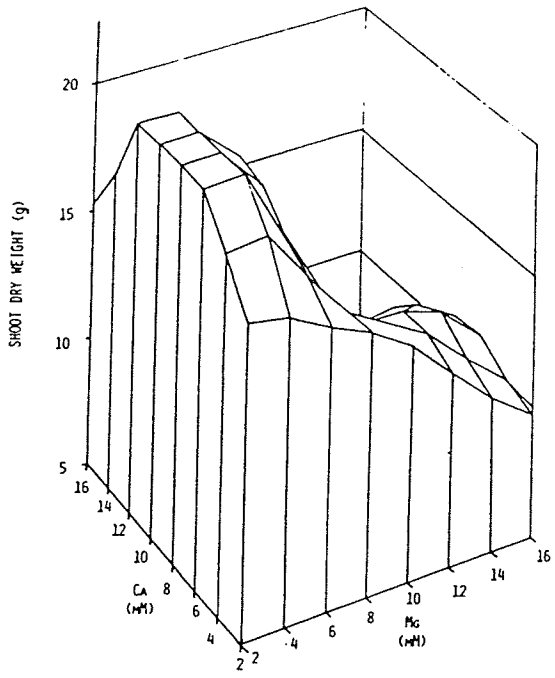

FIG. 5.1.14: SHOOT DRY WEIGHT OF JOHNSTON BARLEY AS A FUNCTION OF Ca AND Mg IN THE SOLUTION.

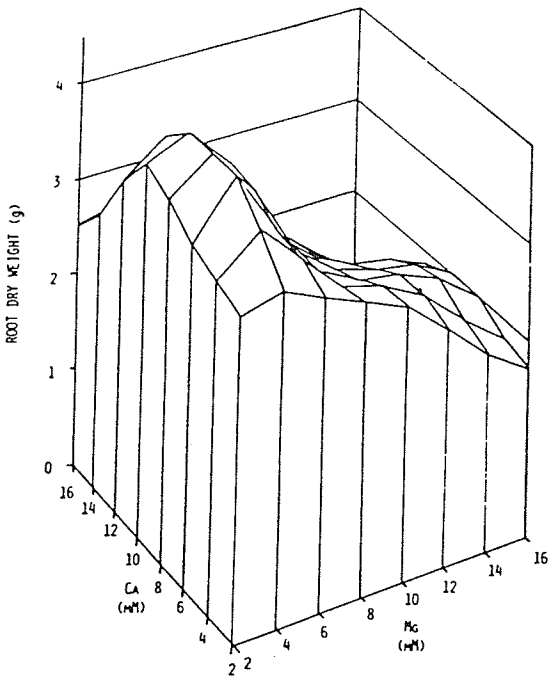

FIG. 5.1.15: ROOT DRY WEIGHT OF JOHNSTON BARLEY AS A FUNCTION OF Ca AND Mg IN THE SOLUTION.

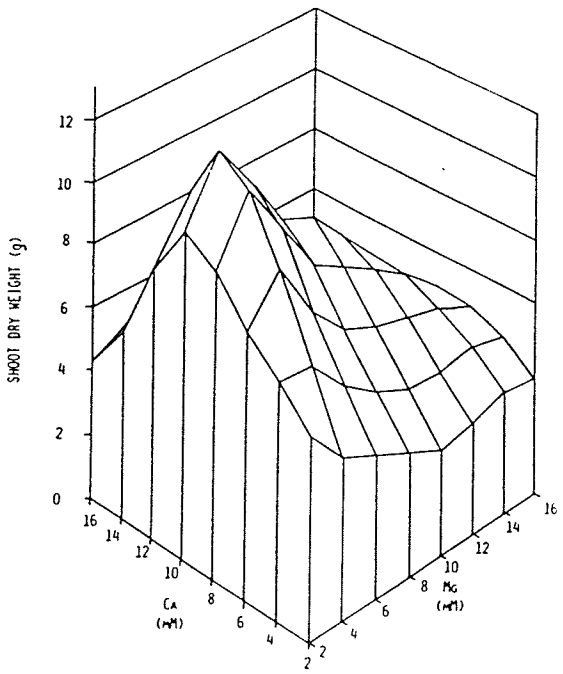

FIG. 5.1.16: SHOOT DRY WEIGHT OF BONANZA BARLEY AS A FUNCTION OF Ca AND Mg IN THE SOLUTION.

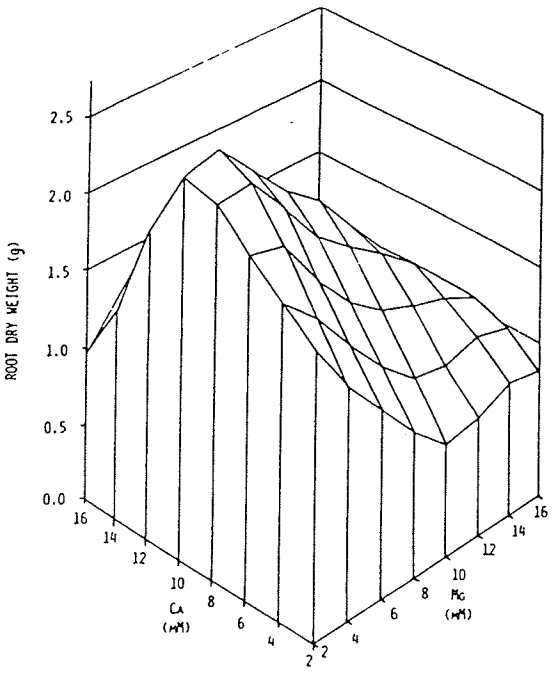

FIG. 5.1.17: ROOT DRY WEIGHT OF BONANZA BARLEY AS A FUNCTION OF Ca AND Mg IN THE SOLUTION.

Concentration of Ca in the root and shoot (Table 5.1.8, Fig. 5.1.18 and 5.1.19) increased with increasing Ca concentration in the nutrient solution, particularly at low concentrations of Mg. Since no cultivar x nutrient interaction existed, data for Johnston and Bonanza were graphed together.

Increasing the Mg concentration of the nutrient solution increased concentration of Mg in both root and shoot (Table 5.1.8, Fig. 5.1.20 and Fig. 5.1.21). The increase in concentration of Mg in the root with increasing concentration of Mg in the nutrient solution was less pronounced at the higher levels of Mg and Ca in the nutrient solution. Concentration of Mg in the root decreased with increasing concentration of Ca in the solution and with increasing Ca:Mg ratio in the solution. Concentration of Mg in the shoot decreased as shoot dry weight increased and increased as Ca:Mg ratio in the nutrient solution increased.

Increasing the concentration of Mg and Ca in solution increased concentration of K in the root (Table 5.1.8 and Fig. 5.1.22). Concentration of K in the root increased more slowly in response to increasing concentrations of Mg in the solution at high than at low solution levels of Ca. Concentration of K in the shoot of Johnston and Bonanza barley (Table 5.1.8, Fig. 5.1.23 and 5.1.24) increased with increasing Ca in the solution and with increasing concentration of Mg for Johnston only.

Concentration of Zn and Mn in the shoots of Johnston and Bonanza barley (Table 5.1.8, Figs. 5.1.24 to 5.1.27) increased with

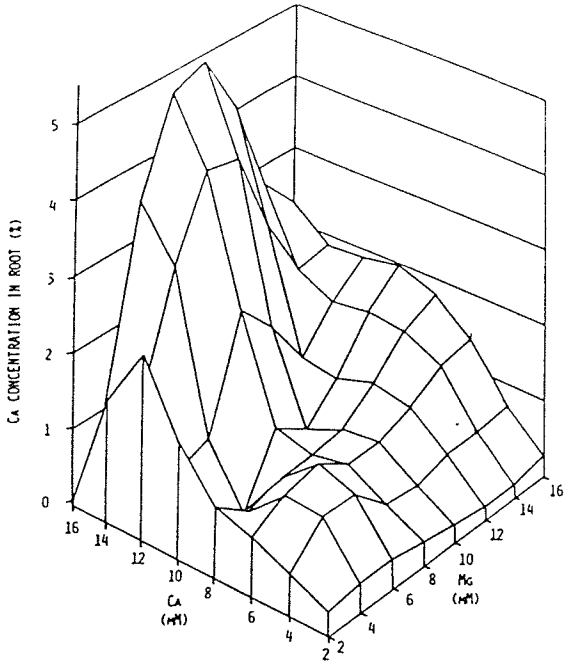

FIG. 5.1.18: Ca CONCENTRATION OF BARLEY ROOTS AS A FUNCTION OF Ca AND Mg IN THE SOLUTION.

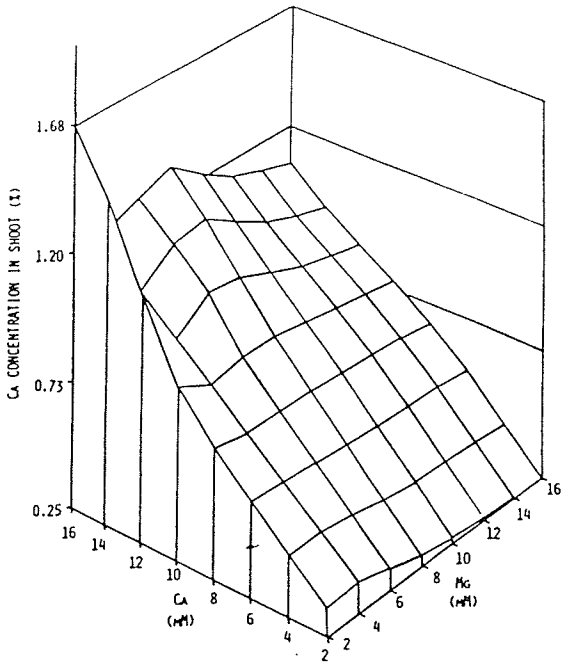

FIG. 5.1.19: Ca CONCENTRATION OF BARLEY SHOOTS AS A FUNCTION OF Ca AND Mg IN THE SOLUTION.

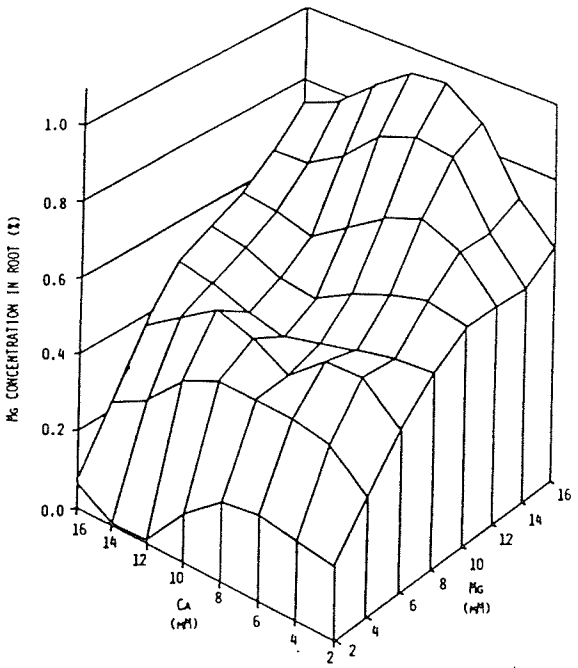

FIG. 5.1.20: Mg CONCENTRATION OF BARLEY ROOTS AS A FUNCTION OF Ca AND Mg IN THE SOLUTION.

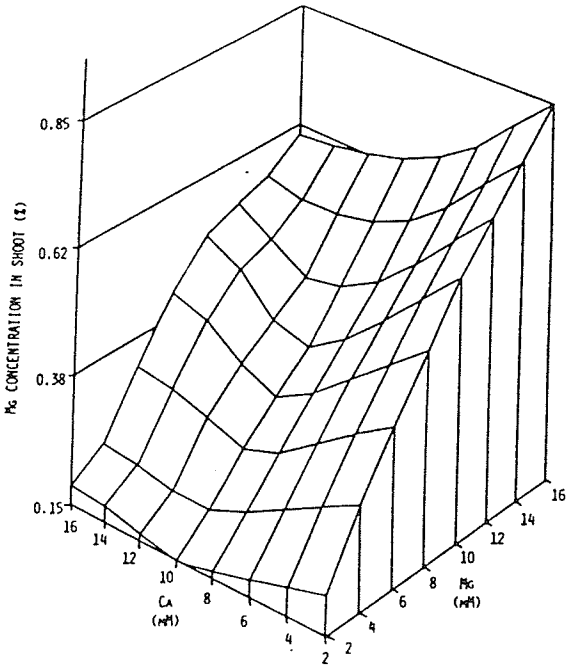

FIG. 5.1.21: Mg CONCENTRATION OF BARLEY SHOOTS AS A FUNCTION OF Ca AND Mg IN THE SOLUTION.

Table 5.1.8: Regression equations for concentration of nutrients in tissue as a function of concentration (mM) of Ca and Mg in the nutrient solution. (cul refers to cultivar where Johnston was given a value of 1.0 and Bonanza a value of 0.0).

Nutrient	Regression equation	R2
Ca in root(%)	= 0.0124 + 0.0973 Ca - 0.00601 CaxMg	0.51
Ca in shoot(%)	= 0.153 + 0.0855 Ca - 0.00182 CaxMg	0.86
Mg in root(%)	= 0.174 + 0.0640 Mg - 0.000326 Ca^2 - 0.0618 Ca:Mg - 0.00114 CaxMg	0.92
Mg in shoot(%)	= 0.224 - 0.00783 shoot d.w. + 0.0252 Mg + 0.383 Ca:Mg	0.92
K in root(%)	= 2.601 + 0.135 Mg + 0.747 log Ca - 0.006 CaxMg	0.43
K in shoot(%)	= 4.235 - 0.00179 Ca^2 + 0.335 log Ca + 0.031 cul x Mg	0.34
Zn in shoot (ug g^{-1})	= 67.11 + 0.0464 Ca^2 + 0.156 Mg^2 -2.830 shoot d.w. - 1.440 cul x Ca	0.78
Mn in shoot (ug g^{-1})	= 53.316 + 4.126 Mg + 0.230 CaxMg -1.764 shoot d.w. - 2.948 cul x Mg	0.72
Ca:Mg in root	= 1.782 + 0.0197 Ca^2 - 0.00803 Mg^2	0.70
Ca:Mg shoot	= 2.657 + 0.493 Ca + 0.407 Mg - 3.108 log Mg - 0.0274 Ca x Mg	0.96

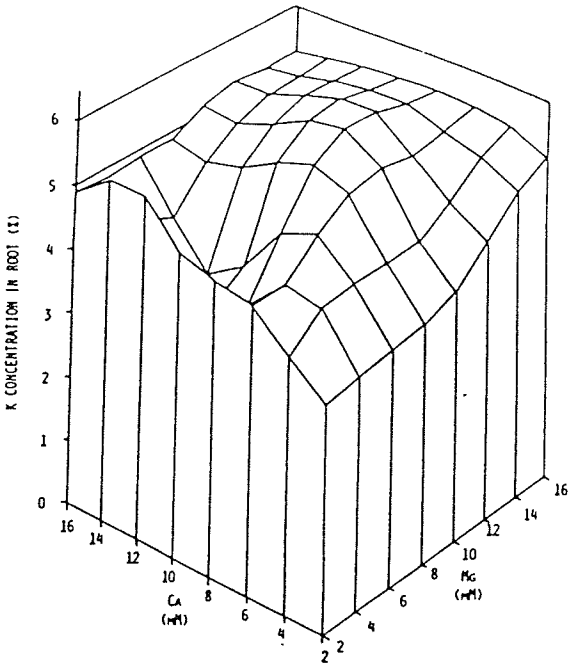

FIG. 5.1.22: K CONCENTRATION OF BARLEY ROOTS AS A FUNCTION OF Ca AND Mg IN THE SOLUTION.

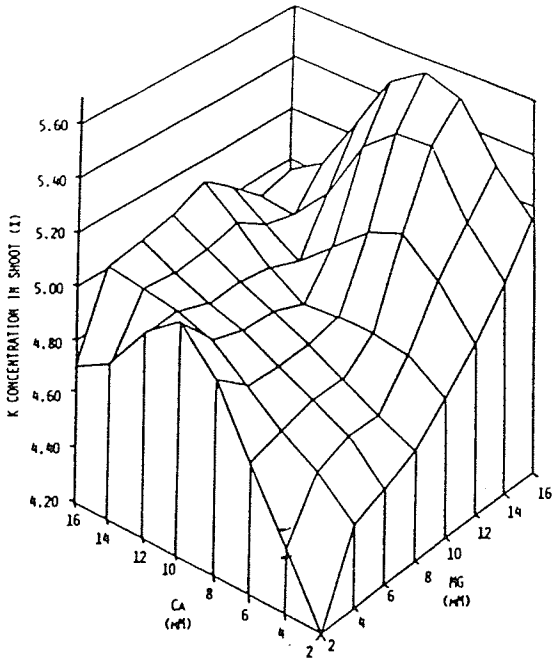

FIG. 5.1.23: K CONCENTRATION OF JOHNSTON BARLEY SHOOTS AS A FUNCTION OF Ca AND Mg IN THE SOLUTION.

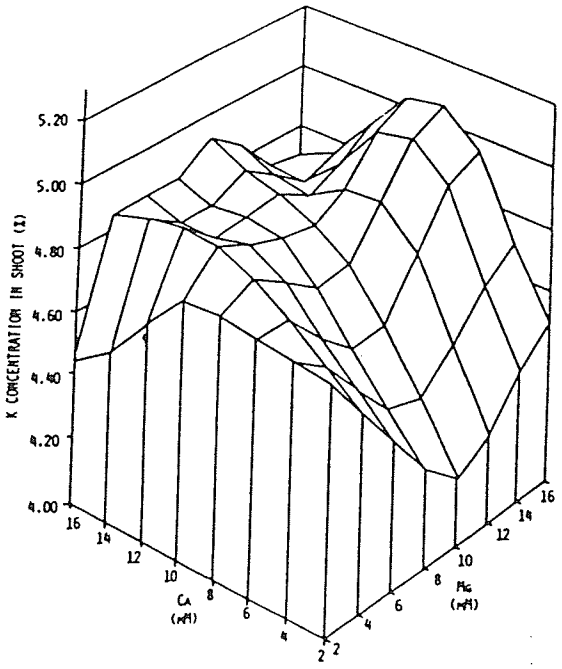

FIG. 5.1.24: K CONCENTRATION OF BONANZA BARLEY SHOOTS AS A FUNCTION OF Ca AND Mg IN THE SOLUTION.

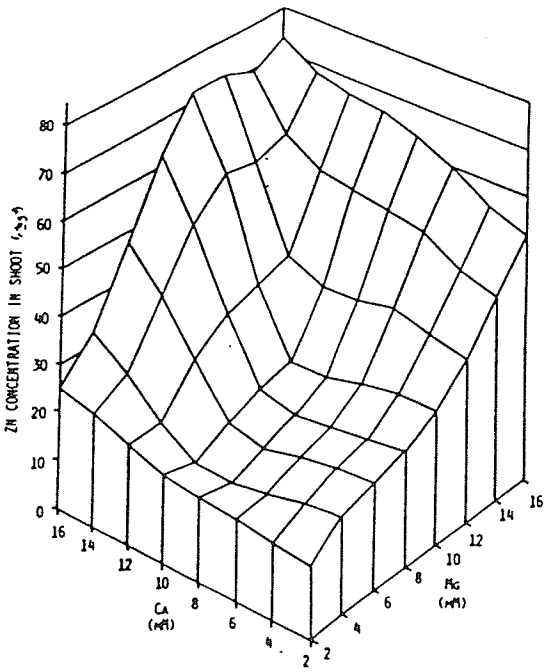

FIG. 5.1.25: ZN CONCENTRATION IN SHOOTS OF JOHNSTON BARLEY AS A FUNCTION OF Ca AND Mg IN THE SOLUTION.

increasing concentration of Mg in solution. Concentration of Zn in the shoot also increased with increasing Ca in the solution; the increase being less for Johnston than Bonanza. The increase in concentration of Mn in the shoot in response to increasing solution concentration of Mg was more pronounced at the higher than at the lower Ca levels (Table 5.1.8, Figs. 5.1.27 and 5.1.28) and more pronounced for Bonanza than for Johnston.

Ca:Mg ratio in the root (Table 5.1.8 and Fig. 5.1.29) and shoot (Fig 5.1.30) increased with increasing concentration of Ca and decreased with increasing concentration of Mg in the nutrient solution. Ca:Mg ratio in the shoot increased more slowly with increasing Ca at high than at low concentration of Mg in the nutrient solution.

Total uptake of Ca (Table 5.1.9, Figs. 5.1.31 and 5.1.32) increased with increasing concentration of Ca in the nutrient solution, but the increase in uptake in response to increasing concentration of Ca in the solution was less pronounced at higher than at lower concentrations of Mg.

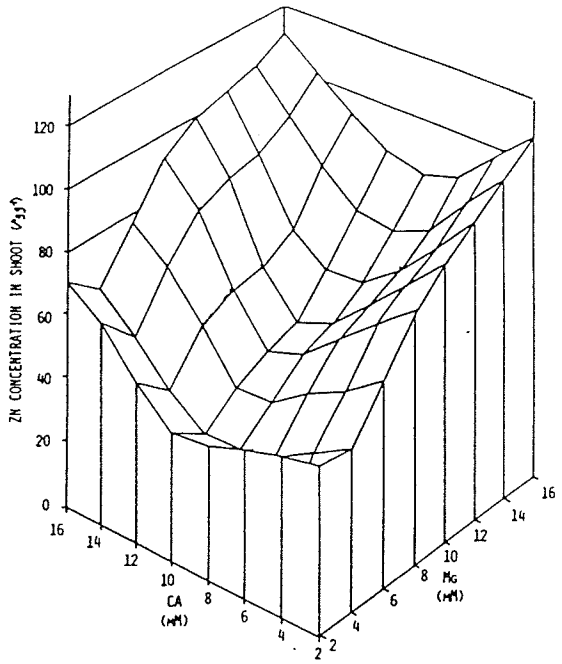

FIG. 5.1.26: ZN CONCENTRATION IN SHOOTS OF BONANZA BARLEY AS A FUNCTION OF Ca AND Mg IN THE SOLUTION.

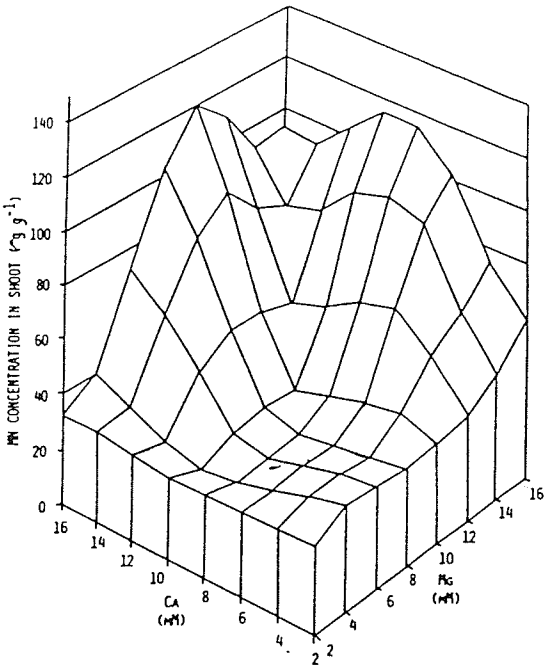

FIG. 5.1.27: MN CONCENTRATION IN SHOOTS OF JOHNSTON BARLEY AS A FUNCTION OF Ca AND Mg IN THE SOLUTION.

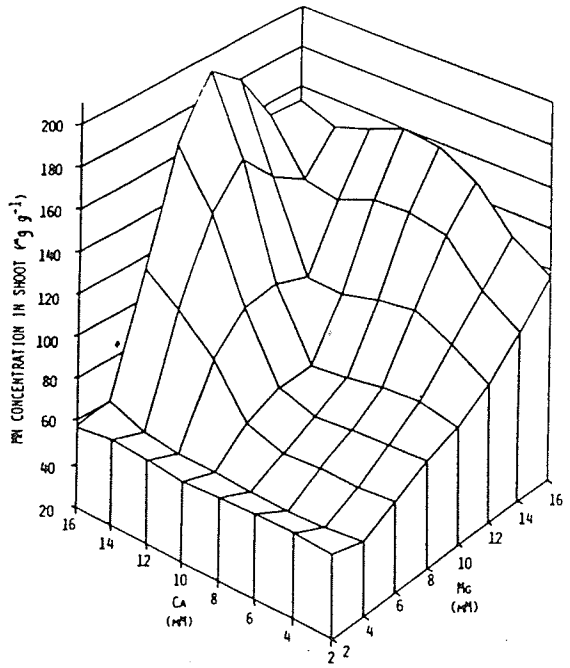

FIG. 5.1.28: MN CONCENTRATION IN SHOOTS OF BONANZA BARLEY AS A FUNCTION OF Ca AND Mg IN THE SOLUTION.

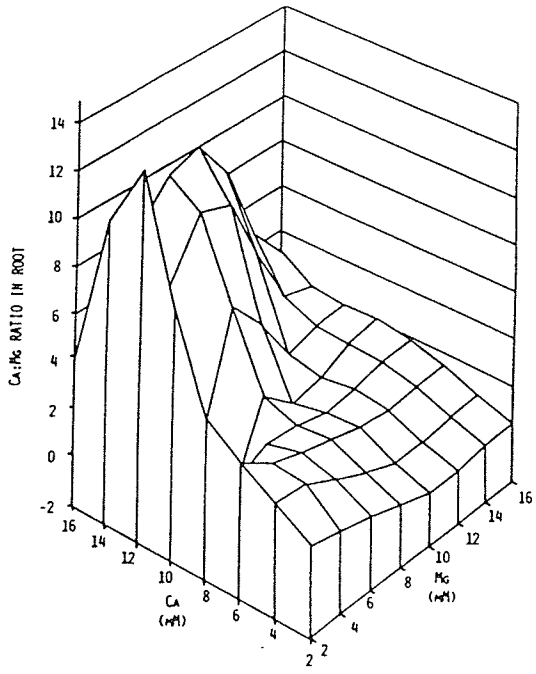

FIG. 5.1.29: Ca:Mg RATIO OF BARLEY ROOTS AS A FUNCTION OF Ca AND Mg IN THE SOLUTION.

Table 5.1.9: Regression equations for total uptake of nutrients as affected by cultivar of barley and concentration (mM) of Ca and Mg. (cul refers to cultivar where Johnston was given a value of 1.0 and Bonanza a value of 0.0).

Nutrient	Regression Equation	R^2
Ca uptake (g pot^{-1})	= -0.0288 + 0.004431 log Ca - 0.000201 Ca x Mg + 0.00431 shoot d. w. + 0.00583 cul x Mg -0.00203 cul x Ca	0.87
Mg uptake (g pot^{-1})	= -0.0146 + 0.180 log Mg - 0.0000640 Ca x Mg + 0.00256 shoot d. w. - 0.000871 cul x Mg +0.00190 cul x Ca	0.94
K uptake (g pot^{-1})	= -0.0453 - 0.000410 Ca^2 + 0.0657 log Ca + 0.0525 shoot d.w. + 0.00357 cul x Ca	0.98
Mn uptake (mg pot^{-1})	= -0.218 + 0.002 Mg^2 + 0.100 log Ca +0.433 root d.w. - 0.047 shoot d.w.	0.55
Zn uptake (mg pot^{-1})	= 0.335 + 0.038 log Ca + 0.014 cul x Mg	0.41
Ca:Mg uptake	= 0.225 + 0.299 Ca + 0.660 Ca:Mg - 0.009 Ca x Mg	0.97

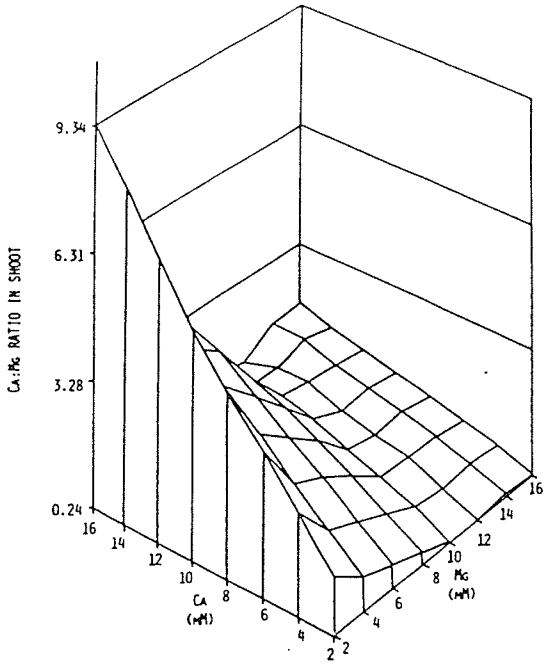

FIG. 5.1.30: Ca:Mg RATIO OF BARLEY SHOOTS AS A FUNCTION OF Ca AND Mg IN THE SOLUTION.

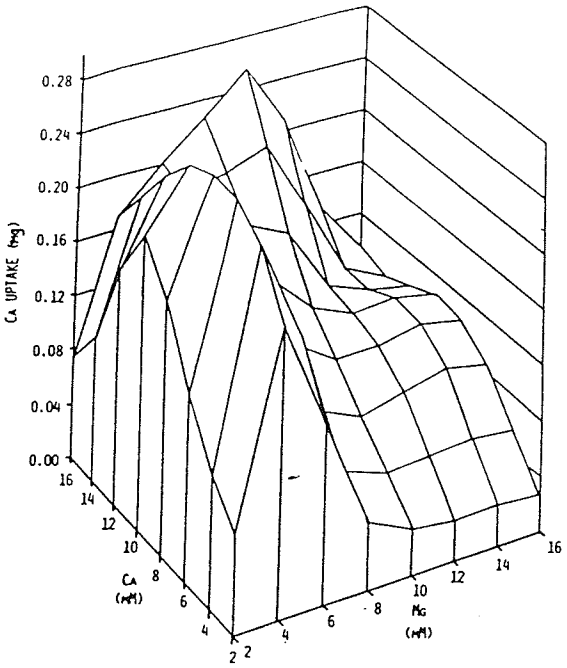

FIG. 5.1.31: Ca UPTAKE BY JOHNSTON BARLEY AS A FUNCTION OF Ca AND Mg IN THE SOLUTION.

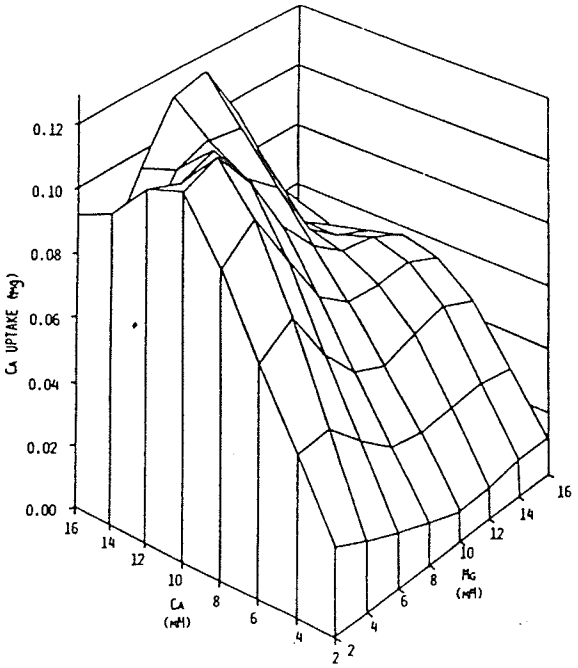

FIG. 5.1.32: Ca UPTAKE BY BONANZA BARLEY AS A FUNCTION OF Ca AND Mg IN THE SOLUTION.

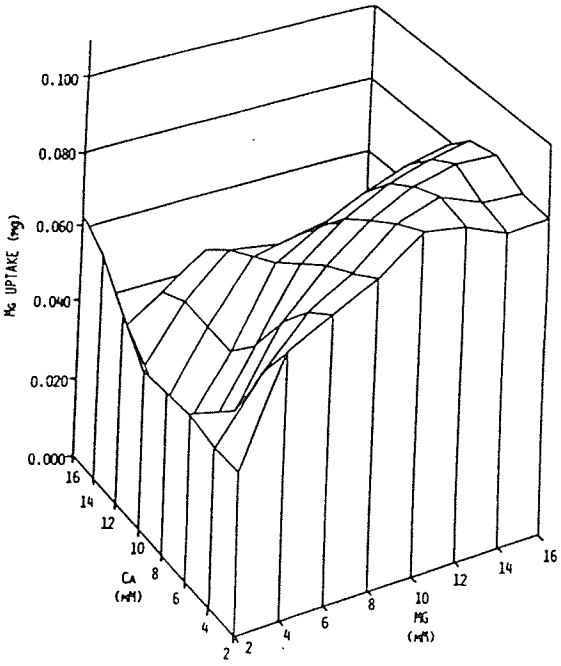

FIG. 5.1.33: Mg UPTAKE BY JOHNSTON BARLEY AS A FUNCTION OF Ca AND Mg IN THE SOLUTION.

Total uptake of Mg (Table 5.1.9, Figs. 5.1.33 and 5.1.34) increased with increasing concentration of Mg, but the increase was less pronounced at higher than lower levels of Ca.

Uptake of K (Table 5.1.9, Fig. 5.1.35 and 5.1.36) decreased with increasing concentration of Ca in the solution; the decrease was less in Johnston than in Bonanza.

Increasing concentration of Ca in the nutrient solution increased uptake of Zn (Table 5.1.9, Fig. 5.1.37 and 5.1.38). Uptake of Zn by Johnston barley increased with increasing concentration of Mg in solution. Uptake of Mn (Table 5.1.9 and Fig. 5.1.39) decreased with increasing concentration of Ca and increased with increasing concentration of Mg in the nutrient solution.

Ratio of uptake of Ca to Mg (Table 5.1.9 and Fig. 5.1.40) increased with increasing Ca and Ca:Mg ratio in the nutrient solution.

5.1.4 Discussion

1. Yield

Yield in the preliminary K-Mg study increased with increasing concentrations of K and decreased with increasing concentrations of Mg in the nutrient solution. In the study using two cultivars, yield increased with increasing concentration of Mg in the nutrient solution to 8 mM and decreased at higher Mg levels. Yield also tended to increase with increasing concentration of Ca in the nutrient solution to 8 mM and decrease when concentration increased above this level. The optimal solution concentration of both Ca and Mg in these studies

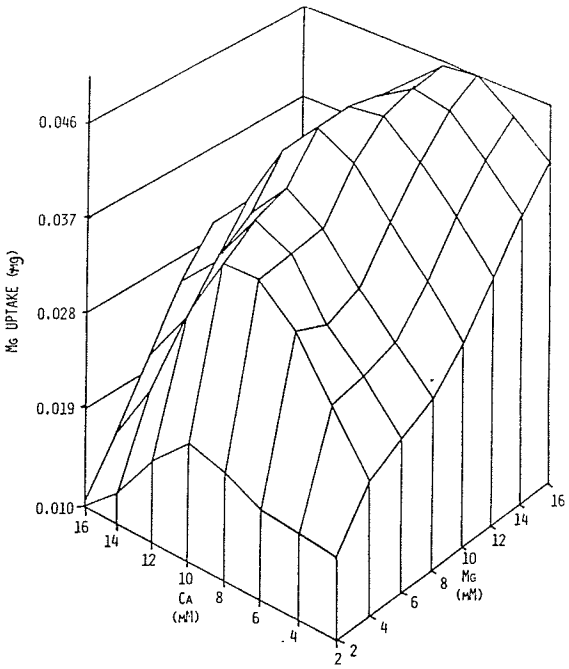

FIG. 5.1.34: Mg UPTAKE BY BONANZA BARLEY AS A FUNCTION OF Ca AND Mg IN THE SOLUTION.

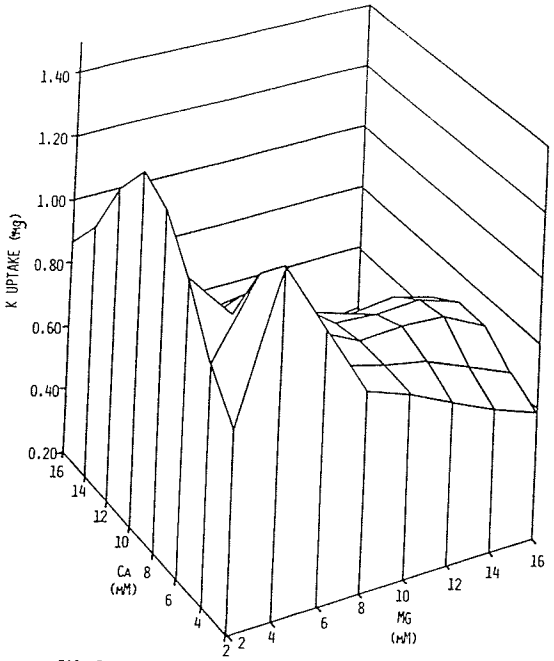

FIG. 5.1.35: K UPTAKE BY JOHNSTON BARLEY AS A FUNCTION OF Ca AND Mg IN THE SOLUTION.

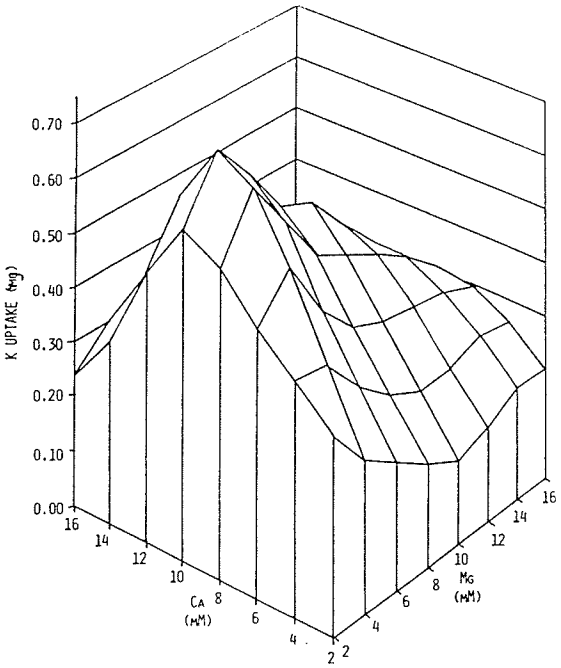

FIG. 5.1.36: K UPTAKE BY BONANZA BARLEY AS A FUNCTION OF Ca AND Mg IN THE SOLUTION.

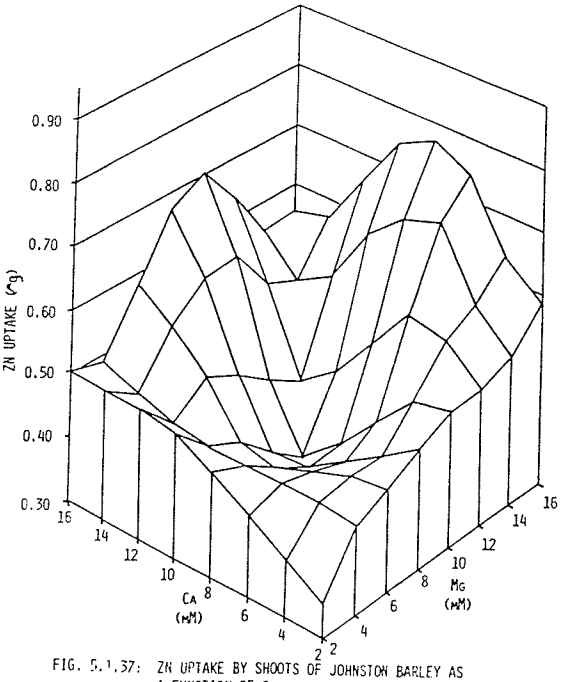

FIG. 5.1.37: ZN UPTAKE BY SHOOTS OF JOHNSTON BARLEY AS A FUNCTION OF Ca AND Mg IN THE SOLUTION.

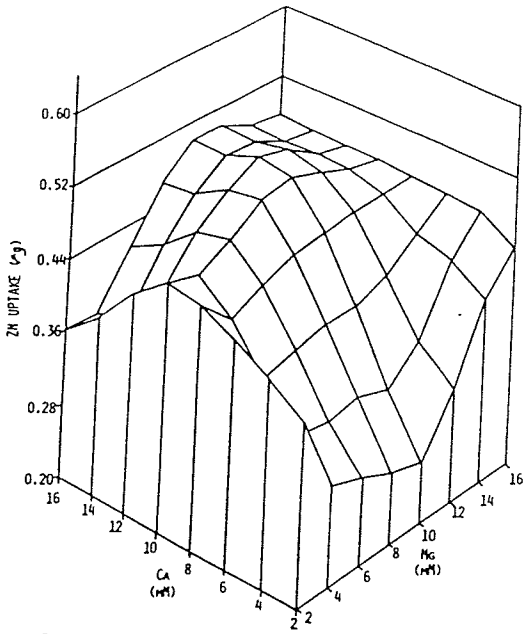

FIG. 5.1.38: ZN UPTAKE BY SHOOTS OF BONANZA BARLEY AS A FUNCTION OF Ca AND Mg IN THE SOLUTION.

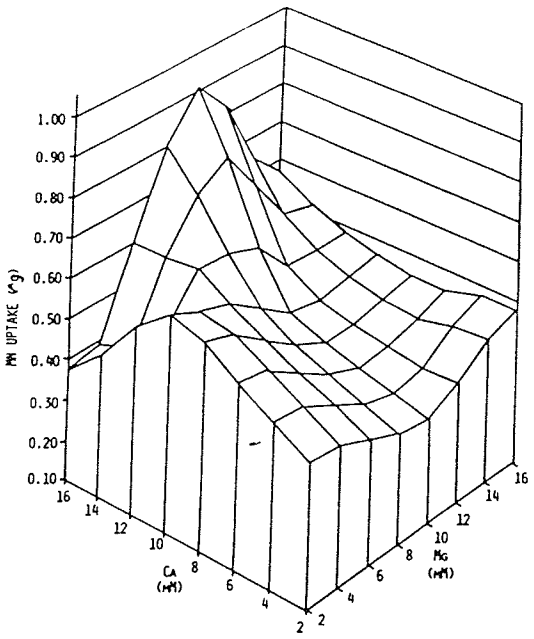

FIG. 5.1.39: MN UPTAKE BY SHOOTS OF BARLEY PLANTS AS A FUNCTION OF Ca AND Mg IN THE SOLUTION.

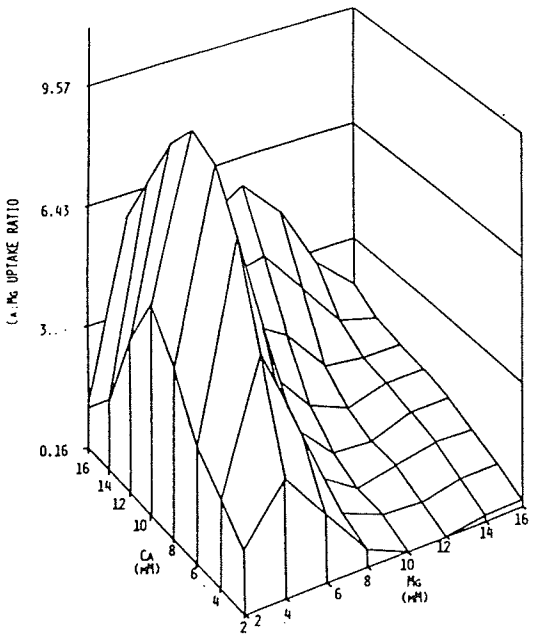

FIG. 5.1.40: Ca:Mg UPTAKE RATIO OF JOHNSTON BARLEY AS A FUNCTION OF Ca AND Mg IN THE SOLUTION.

was between 4 and 8 mM, regardless of the ratio of Ca to Mg. Similar results were obtained by Jeffries and Willis (1964), who grew four species of plants adapted to different pH ranges in sand culture varying in concentration of Ca. They found that plants that were adapted to soils of moderate pH grew well over a range of concentrations of Ca but were inhibited by very high or very low Ca levels. Growth of Origanum vulgare, a calcicole, was also inhibited by Ca concentrations above 12.5 mM.

Studies conducted previously indicated that yield reductions were not likely due to interference with membrane integrity or uptake of other nutrients such as K. The very large yield reductions therefore appear to be due to direct effects of Ca and/or Mg on plant growth.

Reduced plant growth would result if concentration of Ca in the cytoplasm increased. Excess concentrations of Ca in the cytoplasm may cause precipitation of phosphates, inhibit the action of enzymes such as alkaline lipase and inhibit biochemical wall loosening, which would restrict cell expansion (Marmé 1983). High Ca concentrations could also inhibit photosynthesis and interfere with K fluxes within the plant (Rorison and Robinson 1984). Alternately, if the plant is successful in maintaining concentration of Ca in the cytoplasm at low levels, a high electrochemical gradient would result between the cytoplasm and the vacuole and/or soil system. The maintenance of this gradient would require a large input of energy (Hanson 1984).

Varietal differences occurred between Bonanza and Johnston in response to high concentrations of Ca or Mg. With Bonanza, highest

yields were obtained with 4 to 8 mM of Ca in the Ca-Mg study and 8 mM Ca in the cultivar trial. In both cases, yield was reduced at low and high levels of Ca. With Johnston, highest yields were also obtained with 8 mM Ca, but the depression at higher or lower concentration of Ca was greater than in Bonanza, particularly at high Mg levels. The existence of varietal difference in tolerance to high concentrations of Ca and Mg indicates that it may be possible to select cultivars suitable for production on soils high in Ca or Mg.

2. Nutrient relations

(a) Calcium

In the initial K-Mg experiment, concentration of Ca in the shoot decreased with increasing levels of Mg and K whereas concentration of Ca in the root decreased only with increasing concentration of Mg in the nutrient solution. A decrease in concentration of Ca with increasing K was observed by Fageria (1983) in rice. The uptake of Ca decreased with increasing Mg. The decrease in uptake of Ca at high concentration of Mg in the solution was due both to decreased yield and to the effect of high concentration of Mg per se. In both the Ca-Mg and Ca-Mg cultivar trials, Mg tended to decrease concentration of Ca in the root and shoot tissue. Mg concentration in the nutrient solution had a slight effect on uptake of Ca in the cultivar trial. Mg was observed to decrease concentration of Ca in the tissue and uptake of Ca in rice by Fageria (1983), in alfalfa by Halstead et al. (1958), and in citrus plants by Martin and Page (1965). Ohno and Grunes (1985)

also found that concentration of Ca in shoots of wheat was decreased by increasing Mg but not K concentration in the solution.

Concentration of Ca in the roots and shoots and uptake of Ca increased with increasing concentration of Ca in all studies. The greatest increase in uptake occurred with the first increments of Ca. The greater response to the initial increments of Ca reflects the simultaneous increase in yield and concentration of Ca.

The decrease in concentration of Ca in plant tissue with increasing concentration of K and Mg in the nutrient solution was not likely due to competition for an active uptake site for Ca, since uptake of Ca is generally believed to be primarily a passive process (Mengel and Kirkby 1979). A plant must maintain charge neutrality in the tissue, within fairly strict limits. Thus, an increase in the concentration of one cation in the tissue must be effectively balanced by a decrease in the concentration of another cation or by an increase in the concentration of anions. The sum of the charges of (Ca + Mg + K + Na) generally remains within reasonably narrow limits when the form of N utilized by the plant is not altered. Thus, when the nutrient solution was dominated by high concentrations of Mg and/or K, which were readily absorbed by the plant, uptake of Ca apparently decreased, since a greater proportion of the anion equivalents of the plant were being neutralized by Mg and K. The concentration of the cations in the cytoplasm is regulated fairly closely. The major portion of the cell is occupied by the vacuole so changes in cation content of the tissue will primarily reflect changes in the composition of the contents of

the vacuole.

(b) Magnesium

In the initial K-Mg experiment, concentration of Mg in the root and shoot and uptake of Mg increased with increasing concentration of Mg in solution. Concentration of Mg in the shoot and total uptake of Mg tended to decrease with increasing solution K levels. Fageria (1983) also reported a decrease in uptake and concentration of Mg in rice at very high levels of K. Ohno and Grunes (1985) reported a decrease in shoot concentration of Mg in wheat forage but no effect on root concentration or total uptake of Mg with increasing concentration of K in the solution. The decrease in concentration and uptake of Mg with increasing concentration of K in the nutrient solution may be due to either a direct competition of K for an active uptake site for Mg, or to a competition for neutralization of anion equivalents within the tissue. Uptake of Mg by the plant is believed to be primarily a passive process (Mengel and Kirby 1979), thus competition for neutralization of anion equivalents within the tissue is the probable avenue for depression of uptake of Mg by K. Concentration of Mg in the tissue and total uptake of Mg by the plant increased with increasing solution concentration of Mg in all hydroponic studies. Uptake of Mg by the plant generally decreased with increasing concentration of Ca in the nutrient solution. Fageria (1983) found that uptake and concentration of Mg in rice decreased at high rates of Ca in the solution. Halstead et al (1958) found a similar result in alfalfa

grown in soil with additions of lime. The decrease in concentration of Mg with increasing Ca was likely due to competition for anion equivalents. As the concentration of Ca in the nutrient solution increased, Ca was able to neutralize a greater proportion of negative charge, thus concentration of Mg decreased.

The reduction in uptake of Mg by the addition of Ca suggests that excess uptake of Mg by the plant could be alleviated by application of high concentrations of Ca. However, dry matter yield decreased when when concentrations of Ca were very high. This phenomenon, i.e.: the decrease in yield at high concentrations of either Ca or Mg, virtually precludes the addition of large amounts of Ca to alleviate Mg toxicity.

(c) Potassium

In the initial K-Mg study, concentration of K and total uptake increased with increasing solution K. Concentration of K in the shoot was unaffected by solution Mg, while concentration of K in the root increased with increasing solution Mg. The increase was apparently due to the depression in dry matter yield by Mg. These results are in contrast to those of Aulakh and Pasricha (1978) who found an antagonistic effect of Mg on concentration of K and uptake of K by rapeseed. Liebhardt (1979), however, found no effect of Mg on concentration of K in corn. Halstead et al.(1958) found that concentration of K in alfalfa generally declined when Ca or Mg carbonates were added to soil. Fageria (1983) found that in solution culture, high levels of Ca or Mg decreased the concentration and rate of uptake of K in rice.

Concentration of K was not significantly influenced by either Ca or Mg in the Ca-Mg study. In the Ca-Mg cultivar trial, concentration of K in the root increased as concentration of Ca and Mg in the solution increased, the rate of increase in concentration of K of the tissue decreasing at higher concentrations of Ca and Mg in the solution. The overall uptake of K followed the yield curves very closely, however, indicating that the bulk of the effect of Ca and Mg on the concentration and uptake of K was due to their effects on overall dry matter yield. Effects of Ca and Mg per se on uptake of K appeared to be minor. Thus, the yield reductions noted at high concentrations of Ca and Mg were not due to lack of uptake of K.

At present, certain soil testing laboratories suggest that additions of K fertilizer on soils high in Ca or Mg may increase yield of cereal grains, even when soil levels of K are high. The lack of direct inhibition of uptake of K by Ca and Mg observed in these studies indicate that addition of K fertilizer on soils high in Mg and Ca may be in ineffective in increasing crop yield, unless K content of the soil is low.

(d) Zinc

Concentration of Zn in the initial Ca-Mg study was primarily a function of dry matter yield and biological dilution. In contrast, concentration of Zn in plants obtained from the Ca-Mg cultivar study was increased by increasing Mg and Ca levels in the solution. Increasing Mg levels in the nutrient solution increased the

concentration of Zn in the tissue of Johnston less than in Bonanza. Uptake of Zn increased with increasing concentration of Ca in the solution in the Ca-Mg cultivar trial. Uptake also increased with increasing concentration of Mg in the solution in Johnston but not in Bonanza, although in both cultivars, the highest uptake occurred with 16 mM Mg in the treatment solution. Liebhardt (1979) found that high rates of Mg added as dolomite decreased concentration of Zn in the tissue. Kumar et al. (1981) found that concentration of Zn in wheat decreased with increasing concentration of Mg in sand culture studies. Ologunde and Sorenson (1982) showed an increase in Zn concentration in sorghum with increasing concentration of Mg in hydroponic nutrient solutions. They were unable to explain why this occurred. Reeves et al. (1985) found concentration of Zn in Prunus leaf tissue increased at high concentration of Ca in hydroponic culture. Wallace (1984) found that concentration of Zn in corn was often higher in limed than unlimed soils, and suggested that liming decreased uptake of Mn, which allowed the uptake of higher levels of Zn. Martini and Mutters (1985) found no effect of dolomitic limestone on Zn uptake or concentration.

(e) Manganese

Concentration of Mn in the tissue in the Ca-Mg cultivar study increased with increasing concentration of Mg in the solution, particularly at high concentration of Ca in the solution. The concentration of Mn in the tissue was essentially constant at 2 and 4 mM Mg for all concentrations of Ca in the solution. Concentration of

Mn in the tissue increased less in Johnston than Bonanza at high Mg concentrations. Concentrations of Mn in the tissue were extremely high at 16 mM Mg and at 8 mM Mg plus 16 mM Ca. Uptake of Mn was also extremely high at 16 mM Mg and 8 mM Mg plus 16 mM Ca. Uptake increased with increasing Mg and decreased with increasing Ca.

Kumar et al. (1981) working with wheat in sand culture, found that increasing Mg concentration in the medium to 30 ug g^{-1} increased concentration of Mn in the tissue and total uptake of Mn. Increasing Mg concentration above 30 ug g^{-1} decreased both concentration and uptake of Mn. Liebhardt (1979) found that high levels of Mg added as dolomite decreased uptake of Mn. York et al. (1954) found that concentration of Mn in the tissue decreased with increased applications of Ca as lime. Martin and Page (1965) found a tendency for concentration of Mn in the leaf of oranges to increase as the percent Mg on the cation exchange of soils increased. Reeves et al. (1985) found no effect of increasing Ca concentration in the solution on concentration of Mn in Prunus grown in hydroponic solutions.

Uptake of Mn and Zn were highly correlated ($r = 0.80$). At low concentrations of Mg and Ca in solution, uptake of these elements was determined primarily by yield and concentration in the tissue was essentially unaffected by dry matter yield. However, at the very high concentrations of Mg or where the combined concentration of Mg and Ca were high, the plants apparently lost their ability to limit the uptake of Zn and Mn and the concentration in the tissue and uptake of the two nutrients increased greatly. The studies conducted previously

examining solute leakage indicated that membrane integrity decreased to some extent at high or unbalanced concentrations of Ca and Mg in solution. Possibly, the extremely high concentrations of Ca and Mg used in these solution culture studies reduced the selectivity of the membrane in limiting the uptake of Zn and Mn. A breakdown in membrane function may have led to the increase in tissue concentration observed.

It is also possible that the increased uptake of the micronutrient cations in the hydroponic studies could be related to the NH_4^+ - NO_3^- balance in the solutions. All Mg and Ca additions were made as nitrate salts. The solutions were brought to the N concentration of the highest Mg and Ca solutions with additions of NH_4NO_3. Therefore, the solutions with the highest concentrations of Ca and Mg would have the highest ratio of NO_3^-: NH_4^+. Increasing proportions of NO_3^- in plant nutrition tends to increase the uptake of cations by the plant (Mengel and Kirkby, 1979). Rorison and Robinson (1984) stated that in solution cultures, NH_4^+ tends to decrease Mn uptake while NO_3^- enhances it. Therefore, there may have been an overall trend towards higher uptake of cations at the higher concentration of Ca and Mg, due to the higher NO_3 levels present in those treatments. Uptake of Zn and Mn was positively correlated with the ratio of NO_3^-:NH_4^+ in the hydroponic solution. The final effect on concentration and uptake of the particular cation would depend on the combined effects of the nitrogen source and competitive effects of Ca and Mg on uptake and dry matter yield. Although it is possible that the NO_3:NH_4 could be playing some part in the increase in the concentration of Mn and Zn in the tissue at

high concentration of Mg and Ca, it is unlikely that it would lead to the large increases observed. As well, one would expect uptake of K to increase. A change in membrane selectivity appears to be the more probably cause.

Studies conducted by other researchers and discussed previously were conducted using soils as a medium with additions of lime and generally showed a decrease in the uptake and concentration of Mn, and Zn with increasing concentrations of Mg or Ca. Soil pH, as affected by amount of lime added would have a large effect on plant availability of Mn and Zn. Increasing the amount of lime or dolomite added to the soil would increase soil pH. The availability of the micronutrients tends to decrease with increasing soil pH, thus the results of these experiments would not be strictly comparable to a hydroponic system where pH was initially adjusted to a level of 6.5. The increase in the uptake of Mn and Zn with increasing levels of Mg and Ca observed in a hydroponic system was unexpected, although such effects have been observed previously by Ologunde and Sorenson (1982) with Zn in corn and by Kumar et al. (1981) with Mn and Cu in radish.

(f) Ca:Mg ratio

In the initial K-Mg study, Ca:Mg ratio in the tissue decreased as Mg concentration in the nutrient solution increased. In the Ca-Mg study, the tissue Ca:Mg ratio generally followed the solution Ca:Mg ratio. In the Ca-Mg cultivar trial, Ca:Mg ratio in the tissue tended to increase with increasing concentration of Ca and decrease with increasing concentration of Mg in the nutrient solution. In all cases where Ca and Mg were variables, Ca:Mg ratio in the solution was the

best single predictor of Ca:Mg ratio in the tissue indicating a simple competition between Ca and Mg for uptake and concentration in the tissue. It appears possible, therefore, that excessive levels of Mg could induce a Ca deficiency in soils which would otherwise have adequate Ca for plant growth.

5.1.5 Conclusions

Yield of barley was shown to be inhibited by high concentrations of Ca and/or Mg in solution. High concentrations of Mg were more detrimental to yield than high concentrations of Ca. The deleterious effects of high Mg concentrations cannot be overcome by adding high concentrations of Ca since high Ca also suppresses growth. It was interesting to note that high concentrations of Ca or Mg did not inhibit or only slightly inhibited uptake of K by the plant. Thus effects of high concentrations of Ca and Mg on yield were primarily a direct effect and not due to ion antagonism.

Uptake of Zn and Mn increased 2 to 4 fold at high levels of Mg or Ca. The increase could be related in part to the NO_3:NH_4 ratio in the solutions which increased as the concentration of Mg + Ca increased. However, it is possible that the high concentrations of Mg and Ca led to an increase in membrane permeability, leading to an increased influx of Zn and Mn.

In summary, the major finding of this study was that very large decreases in dry matter yield occurred through direct chemical effects of high concentrations of Ca and Mg in barley, a calcicole plant.

5.2 The Influence of Extractable and Solution levels of Ca, Mg and K and DTPA Extractable Mn and Zn on the Growth and Nutrient Content of Barley Grown on Nonsaline Chernozemic Soils.

5.2.1 Introduction

Information collected from the previous hydroponic studies showed that high concentrations of Ca and/or Mg in the nutrient solution decreased the yield of barley and altered the Ca, Mg, K, Zn and Mn content of the tissue. While the hydroponic studies gave an indication of the potential effects of high concentrations of Ca and Mg concentrations on yield, effects in a soil system may differ. In a soil, nutrient availability is influenced by soil physical characteristics such as structure, texture and cation exchange capacity. Presence of other ions may influence nutrient availability. Also, soil pH can have important effects on plant growth and nutrient uptake. Differences in tortuosity and rate of flow of cations to the plant root also differ among soils. Observation that an effect exists in nutrient culture does not necessarily indicate that a similar effect will occur in a soil system.

Routine soil analysis for extractable cation content in the Canadian Prairies generally involves NH_4 displacement of the cations at pH 7.0, by use of ammonium acetate (McKeague 1981). The NH_4 displacement method provides a measure of the exchangeable cations, as well as cations solubilized from solid phases such as gypsum and/or carbonate salts. The method however does not provide a direct measure of the

cations in the soil solution. Since the soil solution is the medium bathing the plant roots and is the phase from which the roots extract the nutrients required for growth, it is conceivable that a soil solution extract would provide a more accurate assessment of amount of a particular cation available for plant growth than a measure of exchangeable cations.

Howard and Adams (1965) used root growth as a parameter to study Ca deficiency in soils and in cultural solutions and found that Ca deficiency was related to the Ca:total cations ratio in the solution. Bennett and Adams (1970) found that soil solution cations expressed as ionic activities provided a better measure of plant availability of cations than ionic concentration.

A major problem in using soil solutions for examining nutrient availability lies in the extraction of a representative sample of the soil solution. Adams (1974) listed five classes of techniques used for extraction of soil solutions and the limitations associated with them.

Adams et al. (1980) examined column displacement and centrifuge techniques for extracting soil solutions from soils wetted to field capacity. They found that the methods tested yielded comparable values for concentration of the major cations. The centrifuge technique was found to be easy to use, with the added advantage of being a nondestructive technique which left the sample available for subsequent analyses.

Addition of fertilizer materials to the soil will alter the composition of the soil solution. For example, information on the

effect of additions of N fertilizer on the concentration of cations in the soil solution is necessary to determine the ionic environment that will occur during plant growth.

Information on the correlations between extractable cations, solution concentration, solution activity and the availability of the cations for plant uptake for nonsaline soils containing high amounts of Ca and Mg was not found in the literature. As well, information on the effects of high concentrations of Ca and Mg in soils on plant growth and nutrient uptake is limited.

The major objectives of this study were therefore to:

(1) Determine the concentration and activity of Ca, Mg and K in soil solution of test soils and how solution concentration is influenced by amendments such as N fertilizers.

(2) Determine the effect of concentrations and ratios of Ca, Mg and K in nonsaline soils on the yield and Ca, Mg, K and Zn and Mn content of barley.

(3) Determine the relationships between NH_4 acetate-extractable Ca, Mg and K, solution concentrations or activities of these ions and availability of these nutrients to barley plants grown in nonsaline soils.

5.2.2 Materials and Methods

(1) Soil selection and analysis

Ten nonsaline chernozemic soils, varying in concentration of NH_4 acetate extractable Mg in the Ap horizon from low to very high, were

selected for study. The NH_4 acetate-extractable and soil solution concentration and activities of Ca, Mg and K as well as soil solution concentration of SO_4-S, pH, conductance and DTPA extractable Zn, Cu, Mn and Fe were determined in unfertilized soil samples (Tables 5.2.1 and 5.2.2). Procedures for nutrient analysis and calculation of ionic activities were described in section 3.2.

Two representative soils, a silty clay of the Assiniboine complex and a Red River clay (#7), were used to examine the effect of added N fertilizer on the concentration of cations in the soil solution. A 300 g sample of air dry soil was treated with reagent grade NH_4NO_3, dissolved in sufficient distilled water to increase the soil water content to field capacity. N was applied at concentrations of 0, 50, 100, 150 and 200 $\mu g\ g^{-1}$ of N and 3 replicates of each rate in each soil were sampled. Soils were incubated for 1 wk in glass beakers sealed with parafilm. After incubation, soils were thoroughly mixed, 45 g subsamples were centrifuged and the solutions were analyzed for Ca, Mg and K, as described in section 3.2.

(2) Barley growth studies

Two studies using barley as a test crop were conducted, with 8 soils being used in the first study and 7 soils being used in the second study. Three replications of each soil type were used. Plants were grown in a growth chamber maintained at 16 and 8 hr light and dark periods, respectively and light and dark period temperatures of 22 and 16 C, respectively.

Prior to potting, the soils were amended with 200 $\mu g\ g^{-1}$ N applied

Table 5.2.1 NH_4 acetate-extractable Ca, Mg and K concentration and activities of Ca, Mg, and K in soil solutions of test soils

	Soil	Texture	Extractable			Soil-Solution concentration			Soil-Solution activity		
			Ca	Mg	K	Ca	Mg	K	Ca	Mg	K
			---------g ---ug^{-1}---------			----------mM----------			----------mM----------		
1.	Newdale	clay loam	3050	460	1260	3.82	1.60	5.32	2.15	0.94	4.56
2.	Fyala	clay	4800	2600	510	3.32	5.20	0.41	1.77	2.92	0.35
3.	Morris	clay	5490	2510	430	5.73	6.17	0.34	2.66	3.05	0.28
4.	Assiniboine complex	silty clay	3850	1570	610	3.99	2.96	0.69	2.26	1.75	0.59
5.	Red River	clay	6060	2110	230	4.27	6.57	0.14	2.14	3.49	0.17
6.	Red River	clay	3370	2240	450	1.07	2.00	0.21	0.68	1.30	0.18
7.	Red River	clay	5140	1850	490	3.44	3.10	0.34	1.99	1.86	0.29
8.	Balmoral	clay	4700	1870	230	4.59	8.39	0.33	2.25	4.36	0.27
9.	Newdale	clay loam	3050	460	1260	3.81	1.60	5.32	2.15	0.94	4.56
10.	Assiniboine complex	silty clay	3850	1570	610	3.99	2.97	0.69	2.26	1.75	0.59
11.	Balmoral	clay	4700	1870	230	4.59	8.39	0.33	2.25	4.36	0.27
12.	Morris	clay	5490	2510	430	5.73	6.16	0.34	2.66	3.05	0.28
13.	Fyala	clay	4800	2600	510	3.32	5.20	0.41	1.77	2.92	0.35
14.	Pipestone	silty clay	4380	560	370	4.29	2.15	0.48	2.51	1.30	0.42
15	Justice	clay	4630	750	480	2.56	1.05	0.34	1.66	0.69	0.30

Table 5.2.2 Soil solution S, DTPA extractable Zn, Mn, Cu and Fe, pH, conductance, carbonate and organic content of test soils

Soil	Texture	S mM	DTPA Extractable Zn	Mn	Cu	Fe	pH	Conductivity S m^{-1}	CO_3 %	Organic content %
			ug g^{-1}							
1. Newdale	clay loam	0.52	6.5	24.0	0.55	65.0	7.19	0.0255	1.16	8.10
2. Fyala	clay	0.64	3.1	19.0	1.80	23.0	7.98	0.0340	1.66	9.52
3. Morris	clay	2.21	2.0	3.6	2.10	16.0	7.86	0.0670	2.69	10.50
4. Assiniboine complex	silty clay	0.28	2.5	17.0	2.00	12.0	7.76	0.0200	0.25	4.94
5. Red River	clay	1.08	2.7	9.9	2.40	34.0	8.05	0.0370	1.92	11.60
6. Red River	clay	0.52	3.3	14.0	1.80	54.0	7.07	0.0205	0.00	7.50
7. Red River	clay	0.25	2.4	7.1	1.30	20.0	7.46	0.0255	0.93	8.28
8. Balmoral	clay	0.62	1.3	2.9	0.89	7.4	8.12	0.0520	2.01	7.03
9. Newdale	clay loam	0.52	6.5	24.0	0.55	65.0	7.19	0.0255	1.16	8.10
10. Assiniboine complex	silty clay	0.28	2.5	17.0	2.00	12.0	7.76	0.0200	0.25	4.94
11. Red River	clay	0.62	1.3	2.9	0.89	7.4	8.12	0.0520	1.93	7.03
12. Morris	clay	2.22	2.0	3.6	2.10	16.0	7.86	0.0670	2.69	10.50
13. Fyala	clay	0.64	3.1	19.0	1.80	23.0	7.98	0.0340	1.66	9.52
14. Pipestone	silty clay	0.11	1.8	22.0	0.83	21.0	8.12	0.0165	2.76	3.69
15. Justice	clay	0.25	1.6	17.0	1.20	16.0	7.83	0.0149	0.24	5.06

as NH_4NO_3, 50 ug g^{-1} P as $NH_4H_2PO_4$ and 50 ug g^{-1} S added as $(NH_4)_2SO_4$. The fertilizers were thoroughly mixed with the soil. Two kg of soil were placed in 2-L waxed cardboard containers (30 cm high by 10 cm square). Kernels of barley of uniform size, seeds which passed through a 3.5 mm screen but not through a 3.1 mm screen, were selected. Six kernels of barley were planted in each pot at a uniform depth of 2.5 cm. The soils were wetted to field capacity moisture content, using distilled water. Pots were weighed every day and adjusted to field capacity when the weight deviated by more than 10 percent from the field capacity weight. An additional 200 ug g^{-1} of N was added after two weeks of growth, as NH_4NO_3 broadcast on the surface immediately prior to watering.

Plants were harvested by cutting the plant stem 1.5 cm above the soil. In the first study, the harvest was taken when the plants attained 50% head. In the second study, the harvest was taken after the plants were fully headed. Fresh and dry weights were measured and the K, Ca, Mg, Zn and Mn concentrations of the tissues determined as described in section 3.1.

Correlation coefficients were calculated to examine the relationships among yield, nutrient concentration and nutrient uptake and the levels of the various soil nutrients on the exchange and in the soil solution. Regression equations were calculated for the relationships between additions of N and concentration of Ca, Mg and K in solution and the ratio of Ca:Mg.

Data obtained for the two experiments were combined for analysis,

however due to the difference in the time of final harvest in the two studies, merging the harvest data at times led to a loss of significance of the correlation coefficients. Therefore, the data for the two studies were analyzed separately as well as when combined. Instances in which the correlations for the individual experiments deviated greatly from those of the combined data were noted and discussed.

5.2.3 Results

1. Soil relations

The activity of Ca, Mg and K increased with increasing concentration of the corresponding cation in the solution of the unfertilized soils (Table 5.2.3, Figs. 5.2.1 to 5.2.3). The relationship between activity and concentration was closer for K than for the divalent ions, since monovalent ions undergo less ion pairing than divalent ions. Activity and concentration of Mg and K increased with increasing NH_4 acetate-extractable Mg and K, respectively (Table 5.2.3, Figs. 5.2.1 and 5.2.3). In contrast, activity of Ca increased only slightly over the range of NH_4 acetate-extractable Ca, while concentration of Ca increased to a greater extent with increasing NH_4 acetate-extractable Ca. Two separate groups of data points (indicating high and low solution concentration of Ca at a particular level of extractable Ca) were obtained when concentration of Ca in the solution was plotted as a function of NH_4 acetate-extractable Ca (Fig. 5.2.2). Several possible causes for the dichotomy were investigated, such as $CaCO_3$ content, pH, conductivity and SO_4 content of the soils. None of the

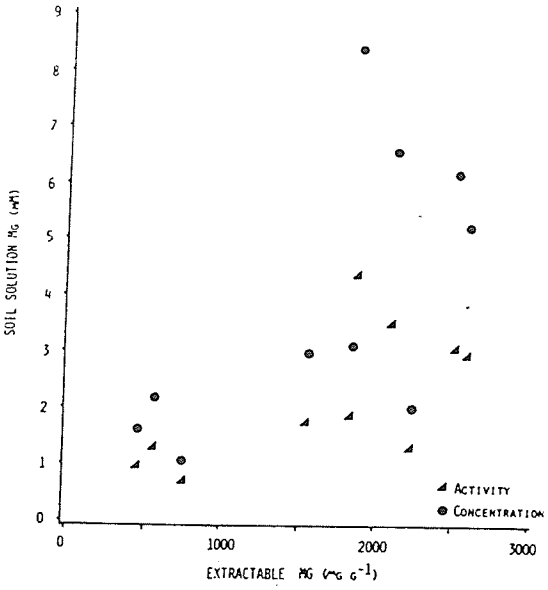

FIG. 5.2.1: CONCENTRATION AND ACTIVITY OF Mg IN SOIL SOLUTION AS A FUNCTION OF EXTRACTABLE Mg.

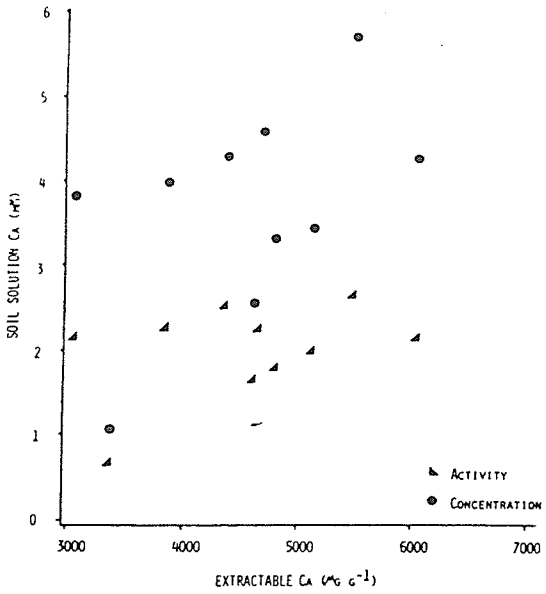

FIG. 5.2.2.: CONCENTRATION AND ACTIVITY OF Ca IN SOIL SOLUTION AS A FUNCTION OF EXTRACTABLE Ca.

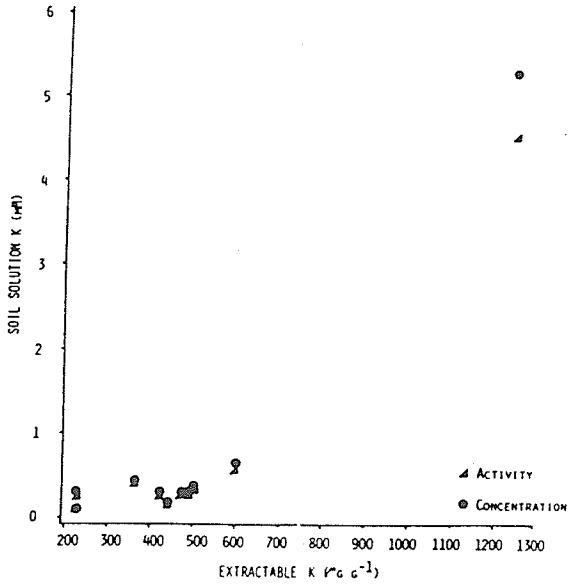

FIG. 5.2.3: CONCENTRATION AND ACTIVITY OF K IN SOIL SOLUTION AS A FUNCTION OF EXTRACTABLE K.

Table 5.3.2 Correlation coefficients (r) for relationships among NH_4 acetate-extractable Ca, Mg and K (ex), soil solution concentration [ ] and activity ( ) of Ca, Mg and K, DTPA extractable Mn and Zn and ratio of activity of Ca:Mg in test soils

	[Ca]	(Ca)	Ca ex	[Mg]	(Mg)	Mg ex	[K]	(K)	K ex	Mn	(Zn	Ca)/(Mg)
[Ca]	---	---	---	---	---	---	---	---	---	---	---	---
(Ca)	0.96***[1]	---	---	---	---	---	---	---	---	---	---	---
Ca ex	0.45**	0.32**	---	---	---	---	---	---	---	---	---	---
[Mg]	0.58***	0.38*	0.63***	---	---	---	---	---	---	---	---	---
(Mg)	0.53**	0.33*	0.63***	0.99***	---	---	---	---	---	---	---	---
Mg ex	NS	NS	0.61***	0.63***	0.65***	---	---	---	---	---	---	---
[K]	NS	NS	-0.68***	-0.44**	-0.46**	-0.65***	---	---	---	---	---	---
(K)	NS	NS	-0.68***	-0.44***	-0.47**	-0.66***	0.99***	---	---	---	---	---
K ex	NS	NS	-0.73***	-0.61***	-0.63***	-0.59***	0.94***	0.94***	---	---	---	---
Mn	--0.44**	0.46**	-0.68***	-0.74***	-0.76***	-0.60***	0.57***	0.57***	0.68***	---	---	---
Zn	NS	NS	-0.66***	-0.49**	-0.51**	-0.44**	0.92***	0.91***	0.93***	0.66***	---	---
(Ca)/(Mg)	NS	NS	-0.50**	-0.74***	-0.77***	-0.88***	0.61***	0.62***	0.65***	0.68***	0.93***	---

1 * $P \leq 0.05$ ** $P \leq 0.01$ *** $P \leq 0.0001$

variables examined explained the phenomenon.

DTPA extractable Mn and Zn decreased with increasing concentration and activity of Mg in the soil solution and with NH_4 acetate-extractable Ca and Mg in the unfertilized soils (Table 5.2.3). DTPA extractable Mn and Zn increased with increasing concentration and activity of K in soil solution and with increasing NH_4 acetate-extractable K. DTPA extractable Mn and Zn were positively correlated with one another.

Addition of N as NH_4NO_3 to the Red River and Assiniboine complex soils increased the concentration of Ca, Mg and K in the soil solution (Table 5.2.4, Figs. 5.2.4 to 5.2.6).

Table 5.2.4 Regression equations for Ca, Mg and K concentrations (mM) in the solution and the Ca:Mg concentration ratio as a function of N applied in Red River and Assiniboine complex soils.

Red River

Ca	= 3.46 + 0.045 N	(r^2 = 0.97)
Mg	= 3.64 + 0.038 N	(r^2 = 0.98)
K	= 0.38 + 0.0022 N	(r^2 = 0.97)
Ca:Mg	= 0.88 + 0.019 N	(r^2 = 0.58)

Assiniboine

Ca	= 1.50 + 0.056 N	(r^2 = 0.99)
Mg	= 1.68 + 0.050 N	(r^2 = 0.99)
K	= 0.56 + 0.0044 N	(r^2 = 0.98)
Ca:Mg	= 0.91 + 0.014 N	(r^2 = 0.86)

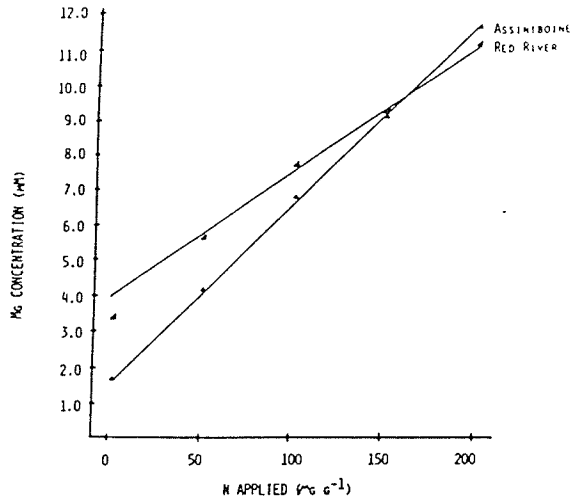

FIG. 5.2.4: Mg CONCENTRATION IN THE SOIL SOLUTION AS A FUNCTION OF N APPLIED IN RED RIVER AND ASSINIBOINE SOILS.

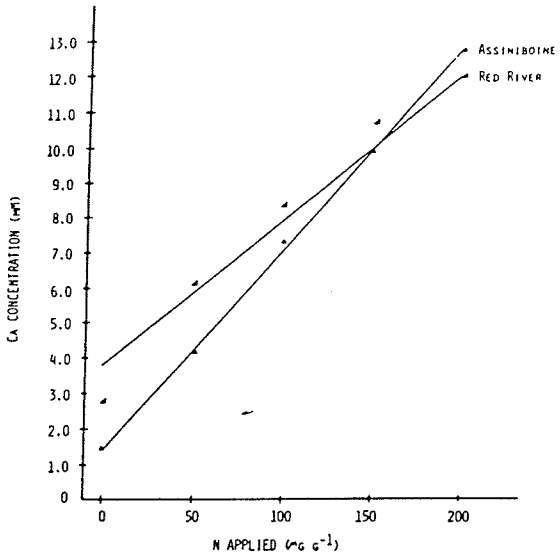

FIG. 5.2.5: Ca CONCENTRATION IN THE SOIL SOLUTION AS A FUNCTION OF N APPLIED IN RED RIVER AND ASSINIBOINE SOILS.

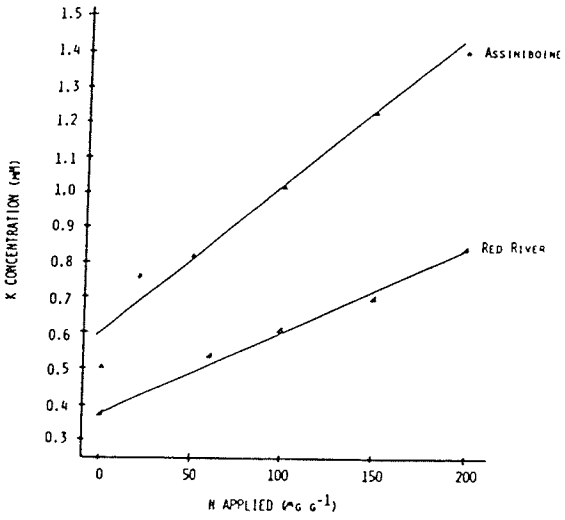

FIG. 5.2.6: K CONCENTRATION IN THE SOIL SOLUTION AS A FUNCTION OF N APPLIED IN RED RIVER AND ASSINIBOINE SOILS.

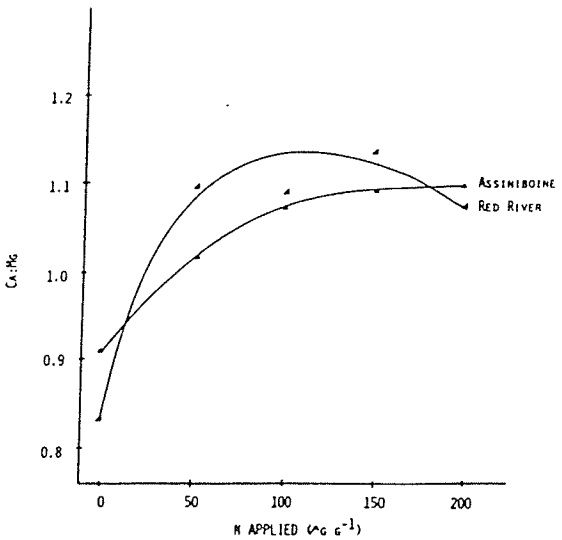

FIG. 5.2.7: Ca:Mg CONCENTRATION RATIO IN THE SOIL SOLUTION AS A FUNCTION OF N APPLIED IN ASSINIBOINE AND RED RIVER SOILS.

The increase in concentration of Ca, Mg and K with amount of N added was essentially linear. Ca concentration increased to a slightly greater extent than Mg which increased to a greater extent than K in each soil. For each cation, the rate of increase with increasing additions of N was higher in the Assiniboine than the Red River soil. The sum of the concentration of cations (expressed in equivalents L^{-1}) in the Assiniboine soil increased 1.00 equivalent for each 1.00 equivalent increase in NO_3^- plus NH_4^+ added (r^2 = 0.9996), while in the Red River soil, the increase was 0.78 equivalent for each 1.00 equivalent increase in NO_3^- plus NH_4^+ (r^2 = 0.989). This indicated either that NH_4^+ displaced cations from the soil exchange complex or that NH_4^+ was rapidly converted to NO_3^- and contributed to the anion content of the solution. In the Red River soil, some N was probably fixed, since the correspondence was less than 1 equivalent of cation per equivalent of N added. The ratio of concentration of Ca:Mg increased with increasing N to 100 $\mu g\ g^{-1}$ of N and increased only slightly with further increases in N (Fig. 5.2.7).

2. Dry matter yield

Yield of barley decreased as NH_4 acetate-extractable Ca, and concentration and activity of Mg in the soil solution increased (Table 5.2.5 and 5.2.6). Yield increased as all three measures of soil K increased, as DTPA extractable Mn and Zn increased and as the ratio of activity of Ca to activity of Mg (Ca:Mg ratio) increased.

The correlation coefficients for NH_4 acetate-extractable and soil

Table 5.2.5 Dry matter yield and chemical composition of barley grown on test soils

Soil	Texture	Dry Matter Yield (g)	Tissue concentration Ca	Mg	K	Mn	Zn	Ca/Mg Ratio
			---------- % ----------			---- ug g^{-1} ----		
Newdale	clay loam	10.30	0.72	0.21	5.07	36.0	26.3	3.37
Fyala	clay	7.15	0.67	0.48	4.80	34.3	19.0	1.40
Morris	clay	7.46	0.62	0.44	4.87	23.3	15.5	1.42
Assiniboine complex	silty clay	7.01	0.61	0.32	5.13	41.0	19.7	1.89
Red River	clay	7.07	0.78	0.60	3.53	33.7	18.3	1.30
Red River	clay	6.90	0.61	0.47	4.93	24.3	21.8	1.31
Red River	clay	6.00	0.79	0.38	5.53	29.7	18.7	2.06
Balmoral	clay	6.57	0.67	0.59	3.37	22.3	17.5	1.14
Newdale	clay loam	8.00	0.64	0.18	3.40	28.3	24.0	3.56
Assiniboine complex	silty clay	8.88	0.48	0.24	3.16	26.3	19.8	1.99
Balmoral	clay	5.56	0.52	0.45	3.10	14.3	9.2	1.16
Morris	clay	7.54	0.43	0.31	2.89	13.0	15.2	1.38
Fyala	clay	8.78	0.45	0.34	2.88	22.7	17.6	1.31
Pipestone	silty clay	7.22	0.81	0.20	3.03	50.0	14.1	4.01
Justice	clay	7.34	0.66	0.19	3.18	45.3	18.0	3.43

Table 5.2.6 Correlation coefficients (r) for relationship between yield and chemical composition of barley and soil nutrient measures (combined data)

	[Ca][1]	(Ca)	Ca ex	[Mg]	(Mg)	Mg ex	[K]	(K)	K ex	DTPA extractable Mn	DTPA extractable Zn	(Ca):(Mg)
Dry Matter yield	NS	NS	-0.37*[2]	-0.36**	-0.37**	NS	0.51**	0.51**	0.58***	0.52**	0.55***	0.35*
Ca tissue concentration	NS	NS	NS	NS	NS	-0.39**	NS	NS	NS	NS	NS	NS
Mg tissue concentration	NS	NS	0.53**	0.72***	0.75***	0.69***	-0.51**	-0.51**	-0.63***	0.64**	-0.39*	-0.81***
K tissue concentration	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Mn tissue concentration	NS	NS	-0.42*	-0.65**	-0.65**	-0.63**	NS	NS	0.45*	0.80***	0.75**	NS
Zn tissue concentration	-0.48*	-0.45*	-0.75***	-0.68**	-0.70**	-0.72***	0.75***	0.75***	0.79***	0.73**	0.80***	NS
Ca uptake	NS	NS	NS	-0.46**	-0.47**	-0.55***	0.52**	0.53**	0.49**	0.54**	0.53**	0.53**
Mg uptake	NS	NS	0.47**	0.62***	0.64***	-0.70**	-0.38**	-0.39**	-0.47**	0.45**	NS	-0.75***
K uptake	NS	NS	-0.41**	-0.42**	-0.43**	NS	0.48**	0.48**	0.59***	0.37*	0.59**	NS
Mn uptake	NS	NS	-0.43*	-0.72**	-0.71**	-0.70**	0.65**	0.66**	0.68**	0.78***	0.70**	NS
Zn uptake	NS	NS	-0.62**	-0.56**	-0.55**	-0.60**	0.80***	0.79***	0.85***	0.68**	0.89***	NS
Ca/Mg concentration	NS	NS	-0.50**	-0.74***	-0.76***	-0.92***	0.58***	0.58***	0.59***	0.44*	NS	0.93***

1 [ ] denotes concentration in soil solution
( ) denotes activity in soil solution

2 * $P < 0.05$ ** $P < 0.01$ *** $P < 0.0001$

solution concentration and activity of each nutrient with dry matter yield were compared to determine which method of measurement was most closely related to dry matter yield. Dry matter yield was most closely related to the NH_4 acetate-extractable content for Ca and K and the activity or concentration of Mg in soil solution.

The concentrations of Ca and Mg found in the soil solution of unfertilized soils in this study were in all cases lower than the concentrations found to reduce yield in the hydroponic Ca-Mg studies. But, the addition of N fertilizer tended to increase concentration of all cations in the soil solution significantly. Addition of a total of 400 ug g^{-1} of N to the soil, as occurred in this experiment, would be sufficient to increase the concentration of Ca and Mg in the soil solution to levels which produced yield depressions in the hydroponic culture.

3. Nutrient relations

(a) Calcium

Concentration of Ca in plant shoots was not significantly related to any measurement of Ca in the soil (Table 5.2.6). The concentration of Ca was apparently high enough in all soils that uptake was not restricted by a Ca limitation. As well, activity of Ca in the soil solution was relatively uniform in all soils. Other factors, such as the supply of other cations influenced concentration of Ca in the plant. Concentration of Ca in the tissue was apparently influenced to the greatest extent by exchangeable Mg, which decreased Ca concentration in the tissue to a limited extent. There was a tendency

for plant concentration of Ca to be positively correlated with Ca:Mg ratio in the soil solution ($p=0.0568$). Concentration of Ca in the tissue was lower than that in tissue of barley grown in hydroponic solutions where excess Mg and Ca depressed barley yield. Uptake of Ca decreased with increasing levels of Mg on the exchange and in the soil solution, and increased with increasing Ca:Mg ratio in the soil solution (Table 5.2.6).

(b) Magnesium

Concentration of Mg in the tissue increased with increasing concentration and activity of Mg in the soil solution and with increasing NH_4 acetate-extractable Mg (Table 5.2.6). Mg in the tissue was slightly more closely related to activity of Mg in the soil solution than to concentration of Mg or NH_4 acetate-extractable Mg. Concentration of Mg in the tissue increased with increasing levels of NH_4 acetate-extractable Ca but decreased with increasing soil K. The increase in tissue concentration of Mg with increasing NH_4 acetate-extractable Ca and the decrease with soil K, Mn and Zn reflected the similar relationships among these cations in the soil solution (Table 5.2.2). This indicated that the concentration of Mg in the tissue was not influenced greatly by Ca, or K content in the soil per se. Concentration of Mg in the tissue decreased with increasing Ca:Mg ratio, which reflects the decrease in the ratio with increasing Mg in the solution. This indicates that concentration of Mg in the tissue reflected the concentration of Mg and Ca:Mg ratio in the soil

solution. Concentration of Mg in the tissue was lower than that in tissue of barley grown in hydroponic solutions where excess Mg and Ca depressed barley yield.

Uptake of Mg increased with all measures of soil Mg and was most closely related to NH_4 acetate-extractable Mg (Table 5.2.6). Uptake of Mg also increased with increasing NH_4 acetate-extractable Ca but decreased with increasing levels of all measures of soil K. The negative relationship was partially due to the negative relationship between the Mg and K content of the soils. It appeared that there was also a direct competitive effect of K on uptake of Mg possibly due to substitution of K for Mg in the vacuole of the plant cells. Uptake of Mg decreased with increasing Ca:Mg ratio. Overall, the best relationship of uptake of Mg was the decrease with increasing Ca:Mg ratio and the increase with increasing NH_4 acetate extractable Mg. This indicates that uptake of Mg was a function of the concentration of Mg in the soil and was influenced only slightly by competition or enhancement of uptake by Ca or K.

(c) Potassium

Concentration of K in the tissue was not related to any measure of K, Mg, Ca, Zn or Mn in the soil when the two experiments were combined (Table 5.2.6). However, when the data was analyzed separately for the two experiments, concentration of K in the tissue increased with increasing NH_4 acetate-extractable K in experiment 1 ($p = 0.08$) and increased with increasing levels of all measures of soil K in

experiment 2 ($p = 0.06$). Combining the data negated the relationships within the separate experiments. Concentration of K in the tissue was not influenced by soil contents of the other cations when the data was combined or for experiment 1. However, in experiment 2, concentration of K in the tissue decreased with increasing levels of NH_4 acetate-extractable Ca and Mg ($r = -0.49$ and $r = -0.44$, respectively). The reason for the difference between the two experiments is unclear.

Uptake of K increased with increasing levels of all measures of K and with increasing DTPA extractable Mn and Zn (Table 5.2.6). Uptake of K decreased with increasing levels of NH_4 acetate extractable Ca and with increasing activity and concentration of Mg in the solution (Table 5.2.6). The negative correlation reflected the negative relation between K and Ca and Mg in the soil (Table 5.2.3). This indicates that uptake of K was primarily determined by the content of K in the soil and was not influenced greatly by competitive effects of Ca and Mg. Depressive effects of Mg on yield and on concentration of K in the tissue would accentuate the depression in uptake of K with content of Mg in the soil.

(d) Manganese

Concentration of Mn in the tissue increased with increasing NH_4 acetate-extractable K and with increasing DTPA extractable Mn and Zn (Table 5.2.6). Concentration of Mn in the tissue decreased with increasing NH_4 acetate-extractable Mg and with increasing concentration and activity of Mg in the solution. Ratio of Mn to Mg in the tissue

Table 5.2.7 Correlation coefficients (r) for ratios of Mn and Zn to Mg in the soil and tissue, and with dry matter yield

	Tissue dry weight	Mn:Mg in tissue	Zn:Mg in tissue
Experiment 1			
Tissue dry weight	----	0.65**	0.75***
Mn:Mg in soil	0.84***[1]	0.87***	0.95***
Zn:Mg in soil	0.84***	0.82***	0.93***
Experiment 2			
Tissue dry weight	----	NS	NS
Mn:Mg in soil	NS	0.74***	0.80***
Zn:Mg in soil	NS	NS	0.80***

1 * $P < 0.05$ ** $P < 0.01$ *** $P < 0.0001$

increased with increasing ratio of Mn to Mg in the soil within an experiment, although the relationship was not as evident when the studies were pooled (Table 5.2.7).

As noted for concentration of Mn in tissues, uptake of Mn increased with increasing levels of soil K and with increasing DTPA extractable Mn and Zn. Uptake of Mn decreased with increasing NH_4 acetate-extractable Ca and Mg and with increasing soil solution activity and concentration of Mg (Table 5.2.6).

(e) Zinc

Concentration of Zn in the tissue increased as NH_4 acetate-extractable K, concentration and activity of K in the soil solution and DTPA extractable Mn and Zn increased (Table 5.2.6). Concentration of Zn in the tissue decreased as NH_4 acetate-extractable Mg and Ca and as concentration and activity of Mg and Ca in the soil solution increased. Ratio of Zn:Mg in the tissue increased as the ratio of Zn:Mg in the soil increased (Table 5.2.7).

Uptake of Zn increased with increasing levels of all measures of soil K and with increasing DTPA extractable Mn and Zn (Table 5.2.6). Uptake of Zn decreased with increasing NH_4 acetate-extractable Ca and Mg and with activity and concentration of Mg in the soil solution.

(f) Ca:Mg ratio

The ratio of Ca:Mg in the tissue decreased with increasing NH_4 acetate-extractable Ca and with increases in all measurements of soil

Mg (Table 5.2.6). Ratio of Ca:Mg in the tissue increased with increasing Ca:Mg ratio in the soil solution. The Ca:Mg ratio in the tissue closely reflected the Ca:Mg ratio in the soil solution.

5.2.4 Discussion

Concentrations of Ca and Mg in the soil solutions of unfertilized soils were lower than concentrations of Ca and Mg which reduced the dry matter yield in the hydroponic studies. But, addition of N fertilizer increased the concentration of the cations in solution. With the addition of 200 ug g^{-1} of N, concentrations of Ca and Mg were each in the range of 12 mM which were found to reduce dry matter yield in hydroponic culture. Concentration of Ca and Mg in the soil near a fertilizer granule would be even higher than in a bulk solution. Concentrations of 10 mM Ca and 8.5 mM Mg have been reported with additions of KH_2PO_4 fertilizer (Racz and Soper 1967). These extremely high concentrations may have implications with respect to root growth and root membrane integrity in fertilizer bands.

Addition of NH_4NO_3 increased the concentration of Ca and Mg in soil solution by two processes: (1) addition of NH_4NO_3 increased the ionic strength of the solution which favored the dissolution of salts such as $CaCO_3$ and $CaSO_4$ (salt effect) and (2) addition of NH_4NO_3 increased the anion concentration of the soil solution and shifted the equilibrium among solid, exchangeable and solution phases toward increased concentration in solution.

Ca increased in solution to a greater extent than Mg or K when

NH_4NO_3 was added. This may have been due to dissolution of Ca salts such as $CaSO_4$. The increase in the Ca:Mg ratio would tend to have beneficial effects on plant growth. At equivalent concentrations, Mg was found to increase leakage to a greater extent than Ca (section 4.2) and high concentrations of Mg decreased yield slightly more than soil concentrations of Ca (section 5.1).

Dry matter yield decreased with increasing Ca and Mg and increased with increasing K, Zn and Mn in the soil. The complex correlations between the soil factors make determination of a cause and effect relationship for yield depression difficult. The decrease in dry matter yield observed with increases in Mg and Ca in the soil could be due to a direct toxicity of Mg and Ca, as was observed in the hydroponic studies, or could be due to deficiency of Mn or Zn associated with high Mg and Ca levels in the soil.

Absorption of Mn and Zn has been observed to decline in the presence of high concentrations of Mg and Ca. Availability of Mn and Zn also decline as pH increases (Mengel and Kirkby 1979). Soluble Mn decreases with increasing pH. Increasing pH also favors the formation of Mn-soil organic matter complexes which decrease Mn availability. High pH soils with high organic matter reserves are prone to Mn deficiency. High pH values are normally associated with high levels of Mg and Ca in the soil. Therefore, in systems high in Mg and Ca, availability of Mn and Zn is likely to be low.

Ca and Mg have high affinities for chelates such as EDTA and citrate. Citrate binding is believed important in the transport of Mn

and possibly Zn within the plant. High concentrations of Mg and Ca in the xylem fluid may interfere with the formation of citrate complexes of Mn and Zn, interfering with their transport within the plant (Mortvedt et al. 1977). Levels of less than 25 μg g^{-1} of Zn and 20 ug g^{-1} of Mn in plant tissue are considered deficient (Russell 1973). In the current study, tissue levels of Zn and Mn at or below these levels occurred (Table 5.2.5). As well, dry matter yield was positively correlated with concentration of Zn in the tissue, indicating that Zn deficiency may have been placing a limitation on dry matter yield.

Concentration of Mg and K in the tissue and the uptake of these nutrients by the plant generally reflected the concentration or activity of the respective ion in the soil solution or its content on the exchange. There was little evidence of interference in uptake of any of these ions by the other ions in the system, although there may have been a tendency for K to increase at the expense of Mg in the vacuole at high levels of K. In contrast, concentration of Ca in the tissue and uptake of Ca by the plant was strongly reduced by increasing levels of NH_4 acetate-extractable Mg in the soil and was not related to any measure of Ca in the soil. This indicates that the uptake of Ca by the plant was influenced to a greater extent by interference of Mg in the soil than by the content of Ca in the soil. Concentration of K in the tissue and total uptake of K were generally more closely related to extractable K than to concentration or activity of K in the solution. The converse was true for Mg. Therefore, when conducting detailed studies of plant nutrition with K and Mg, it may be advisable to

examine both exchangeable and solution levels of these ions.

5.2.5 Conclusions

High concentrations of Ca and Mg in soils had deleterious effects on growth of barley plants, with yield decreasing with increasing concentrations of Ca and Mg in the soil. Concentrations of Mg and Ca in unfertilized soils were below those which depressed yield in hydroponic studies. However, addition of NH_4NO_3 increased Ca and Mg concentrations to potenitally harmful levels. Mn and Zn content in soils and plant tissue were low in soils high in Mg and Ca, and yield increased with increasing concentrations of Mn and Zn in the soil and tissue. Reduction in dry matter yield on soils high in Mg and Ca was due either to Mg and/or Ca toxicity or to low availability of Mn and/or Zn associated with high Mg and Ca.

Tissue concentration and uptake of Mg, K, Mn and Zn were closely related to the levels of these nutrients in the soil, indicating that there was little effect of interference on the uptake of these ions. In contrast, concentration and uptake of Ca was more influenced by interference from Mg than by the level of Ca in the soil. Concentration and uptake of K in the tissue were more closely related to NH_4 acetate extractable K than to solution measures of K. The close relation of K content of the plant to NH_4 acetate-extractable K suggests that both intensity and capacity factors were important in plant uptake of nutrients. Concentration or activity in the soil solution were not always closely related to amounts on the exchange or

amounts displaced by NH_4 acetate. Concentration and activity of K were closely related to NH_4 acetate displaceable K content of the soil, whereas with Ca and Mg this relationship was not particularly close.

The study also indicated that concentration of Mg in the tissue was more closely related to solution than extractable measures of Mg. Ratios of Mn:Mg and Zn:Mg in the soil may be more valuable than DTPA extractable Mn and Zn alone in predicting Mn and Zn availability in soils high in Mg.

5.3 The Effect of Additions of $CaSO_4$ and KCl on the Yield and Ca, Mg, K, Mn and Zn content of Johnston Barley grown on Nonsaline Chernozemic soils.

5.3.1 Introduction

The previous hydroponic and soil culture studies showed that the Mg, Ca, K, Mn and Zn content of the growth medium affected the yield and nutrient content of barley. Reductions in dry matter yield were observed on soils high in Mg and Ca. The reductions in dry matter yield were thought to be due either to direct toxic effects of Ca or Mg or to low availability of Mn and/or Zn associated with high levels of Mg or Ca. Although short-term uptake studies indicated that high levels of Mg and Ca could interfere to a limited extent with K uptake and accumulation, long-term growth studies in hydroponic and soil systems showed no major interference of Mg on K accumulation by barley plants. The concentration of the various nutrients in the plant tissue closely reflected concentration of the nutrients in the growth medium.

Therefore, one should be able to alter the yield and nutrient content of barley plants by altering the concentration of cations in the soil system. Certain soil testing laboratories recommend the addition of KCl to soils containing high levels of Mg. However, experimental results supporting this recommendation are lacking. A growth chamber soil study was therefore conducted to examine the effect of banded and broadcast treatments of $CaSO_4$ and KCl on the production of barley on a number of soils varying in content of Mg, Ca and K. These treatments were used in an attempt to lower the Mg content of barley and/or to increase K content and thus increase yield.

5.3.2 Methods and Materials

Seven soils were selected covering a wide range of Mg content and Ca:Mg ratios (Table 5.3.1).

Five treatments were applied to each soil. Treatments were:

1. $CaSO_4$ banded at 60 kg ha^{-1} of Ca
2. $CaSO_4$ broadcast at 6000 kg ha^{-1} of Ca
3. KCl banded at 60 kg ha^{-1} of K_2O
4. KCl broadcast at 400 kg ha^{-1} of K_2O
5. Check.

All soils were treated with 200 μg g^{-1} of N applied as NH_4NO_3 and 50 μg g^{-1} of P as ammonium phosphate thoroughly blended with the soil. S, as $(NH_4)_2SO_4$, was banded into the soil in treatments 3, 4, and 5 to compensate for the S added with the $CaSO_4$ band in treatment 1. No attempt was made to compensate for the S added as $CaSO_4$ in treatment 2,

Table 5.3.1 NH_4 acetate-extractable Ca, Mg, K, and Na, concentration of Ca, Mg, K and Na in soil solution, DTPA extractable Mn and Zn, pH and conductivity of test soils

		Extractable				Soil-Solution concentration					Conductivity	DTPA extractable	
		Ca	Mg	K	Na	Ca	Mg	K	Na	pH	S m^{-1}	Mn	Zn
Soil	Texture	----------μg g^{-1}----------				----------mM----------						----μg g^{-1}------	
Newdale	clay loam	3050	460	1260	15	3.82	1.60	5.32	0.22	7.19	0.0255	24.0	6.5
Assiniboine complex	silty clay	3850	1570	610	63	3.99	2.96	0.69	1.57	7.76	0.0200	17.0	2.5
Balmoral	clay	4700	1870	230	76	4.59	8.38	0.33	2.39	8.12	0.0520	2.9	1.3
Morris	clay	5490	2510	430	69	5.73	6.16	0.34	1.08	7.86	0.0670	3.6	2.0
Fyala	clay	4800	2600	510	82	3.32	5.20	0.41	1.60	7.98	0.0340	19.0	3.1
Pipestone	silty clay	4380	560	370	31	4.29	2.15	0.48	1.24	8.12	0.0165	22.0	1.8
Justice	clay	4630	750	480	15	2.56	1.05	0.34	0.25	7.83	0.0149	17.0	1.6

due to potential toxicity from other available carriers applied at this high level. To compensate for the banded N added in the $(NH_4)_2SO_4$, an equivalent amount of N was banded into the soil in treatments 1 and 2 as NH_4NO_3. 1800 g of soil was placed into each pot and wetted to field capacity with distilled water. The fertilizer bands were placed in a line across the centre of the pot. The bands were covered with 200 g of soil. Three seeds of barley (cv. Johnston), selected for uniformity of seed size, were placed 1.5 cm on each side of the fertilizer band, for a total of 6 seeds per pot. The seeds were then gently covered with an additional 200 g of soil, and the soils were wetted to field capacity with distilled water.

Pots were covered with dark plastic and maintained at 20 C until seedling emergence. The pots were then placed in a growth chamber maintained at 22 C d/16 C night temperature with a 16 h d and 8 h night period. Relative humidity was approximately 60%. Pots were adjusted to field capacity with distilled water every 3 to 4 d, to maintain weight within 10% of the original. Plants were thinned to 4 per pot after they reached the 2-leaf stage.

A harvest was conducted after 30 d of growth, at full heading. Fresh and dry weights were measured and a complete nutrient analysis of the tissue was conducted.

Statistical analyses were conducted using the SAS Anova procedure and mean separation tested using Tukey's procedure. Correlation coefficients were calculated across all treatments where applicable using the SAS Corr procedure. Regression equations were calculated

where applicable using stepwise regression, by the maximum R^2 improvement technique (SAS Institute Inc 1982b).

5.2.3 Results and Discussion

1. Dry matter yield

Yield was not significantly affected by application of KCl or $CaSO_4$ except on the Assiniboine complex soil. In the Assiniboine complex soil, which contained a high level of K and moderate levels of Ca and Mg, application of broadcast KCl increased yield (Table 5.3.2).

Yield of dry matter, averaged over treatment was highest in the Assiniboine complex soil and lowest in the Balmoral soil (Table 5.3.3). Yield, averaged over treatment increased with increasing NH_4 acetate-extractable K and concentration of Zn in the plant tissue and decreased with increasing concentration of Mg in the soil solution, concentration of Ca in the plant tissue and concentration of Mg in the plant tissue (Tables 5.3.4 and 5.3.5). The increase in yield with increasing concentration of Zn in the tissue indicated that a Zn deficiency was probably restricting yield on some of the soils.

The general lack of response of dry matter yield to additions of K, in spite of the positive relationship between soil K and dry matter yield indicated that the restriction on yield was not a K deficiency per se, but a restriction due to a soil factor correlated with content of K in the soil, such as Mg or Ca toxicity or a micronutrient deficiency. Concentrations of Mg and Ca in the unfertilized soil

Table 5.3.2 Dry matter yield as influenced by addition of $CaSO_4$ or KCl, banded or broadcast, in 7 test soils

Treatment	Newdale	Assiniboine complex	Balmoral	Morris	Fyala	Pipestone	Justice
$CaSO_4$ banded	7.72[1]	9.29 ab[1]	6.38	7.33	6.91	6.10	8.41
$CaSO_4$ broadcast	7.19	9.92 ab	4.67	7.01	6.89	4.38	6.74
KCl banded	7.64	10.23 ab	6.29	7.75	6.71	5.92	7.61
KCL broadcast	5.83	10.82 a	5.25	7.38	7.77	6.67	7.94
Check	8.00	8.38 b	5.57	7.54	8.78	7.22	7.34
Mean square error	NS	0.68	NS	NS	NS	NS	NS

[1] Numbers within a column followed by the same letter do not differ at the 5% level of significance.

Table 5.3.3 Dry matter yield, concentration of Ca, Mg, K, Mn and Zn in tissue and total uptake of Ca, Mg, K, Mn and Zn averaged over treatments

Soil	Dry matter yield (g)	Ca concentration (%)	Ca uptake (g)	Mg concentration (%)	Mg uptake (g)	K concentration (%)	K uptake (g)	Mn concentration ($\mu g\ g^{-1}$)	Mn uptake (mg)	Zn concentration ($\mu g\ g^{-1}$)	Zn uptake (mg)
Newdale clay loam	7.28 bc[1]	0.66 b	0.048 a	0.18 d	0.013 b	3.21 a	0.23 b	31.7 c	0.228 c	24.3 a	0.177 a
Assiniboine complex silty clay	9.75 a	0.49 c	0.047 a	0.25 c	0.024 a	3.20 ab	0.31 a	29.2 cd	0.285 b	20.7 b	0.202 a
Balmoral clay	5.63 d	0.50 c	0.027 b	0.41 a	0.023 a	2.89 b	0.16 d	14.1 e	0.077 d	9.3 f	0.051 d
Morris clay	7.40 bc	0.48 c	0.035 b	0.34 b	0.025 a	3.08 ab	0.23 b	16.7 e	0.121 d	16.8 d	0.123 b
Fyala clay	7.41 bc	0.46 c	0.034 b	0.34 b	0.025 a	2.94 ab	0.22 bc	25.7 d	0.188 c	19.6 bc	0.142 b
Pipestone silty clay	6.06 dc	0.80 a	0.048 a	0.20 d	0.012 b	2.95 ab	0.18 cd	51.8 a	0.310 ab	14.3 e	0.086 c
Justice clay	7.61 b	0.66 b	0.050 a	0.19 d	0.015 b	3.12 ab	0.24 b	46.0 b	0.350 a	17.9 cd	0.136 b
Mean square error	1.78	0.0025	5.3×10^{-5}	6.9×10^{-4}	1.4×10^{-5}	0.0828	0.00177	10.7	1.9×10^{-3}	4.24	6.2×10^{-4}

Numbers within a column followed by the same letter do not differ at the 0.05 significance level.

Table 5.3.4 Correlation coefficients (r) for relationships of plant yield, concentration of Ca, Mg, K, Mn and Zn in tissue and uptake of Ca, Mg, K, Mn and Zn with NH_4 acetate-extractable Ca, Mg and K, concentration of Ca, Mg and K in the soil solution and DTPA extractable Mn and Zn.

	Extractable Ca	Solution Concentration of Ca	Extractable Mg	Solution Concentration of Mg	Extractable K	Solution Concentration of K	DTPA extractable Mn	DTPA extractable Zn
Dry matter yield	NS	NS	NS	-0.24*	0.22*	NS	NS	NS
Ca tissue Conc.	-0.34**[1]	-0.25**	-0.82***	-0.63***	NS	0.25**	-0.64**	NS
Mg Tissue Conc.	0.59***	0.39***	0.81***	0.91***	-0.55***	-0.46***	-0.75**	NS
K Tissue Conc.	-0.22*	NS	NS	-0.26**	0.29**	0.22*	0.51*	0.59*
Mn tissue Conc.	NS	NS	-0.74***	-0.79***	NS	NS	0.71***	NS
Zn tissue Conc.	-0.67	NS	-0.19*	-0.56***	0.84***	0.65**	0.60***	0.72***
Ca uptake	-0.43***	-0.35**	-0.61***	-0.72***	0.35**	0.25**	0.84***	NS
Mg uptake	0.42***	0.27**	0.79***	0.60***	-0.32**	-0.40***	-0.52*	NS
K uptake	-0.25**	NS	NS	-0.32***	0.31**	NS	NS	0.59*
Mn uptake	NS	NS	-0.63***	-0.82***	NS	NS	0.68***	NS
Zn uptake	-0.64**	NS	NS	-0.48**	0.78**	0.58*	0.47**	0.52**

[1] *P < 0.05 ** P < 0.01 *** P < 0.0001

Table 5.3.5 Correlation coefficients (r) for relationships among dry matter yield, concentration of Mg, Ca, K, Mn and Zn in the tissue and total uptake of Mg, Ca, K, Mn and Zn.

		Tissue concentration					Total Uptake By Plants				
	Dry Matter Yield	Ca	Mg	K	Mn	Zn	Ca	Mg	K	Mn	Zn
Dry matter yield	---	-0.35**[1]	-0.27**	NS	NS	0.31**	0.63***	0.55***	0.94***	0.46***	0.80***
Ca tissue conc.	-0.35***	----	-0.61***	0.20*	0.90***	NS	0.49***	-0.79***	-0.24*	0.81**	NS
Mg tissue conc.	-0.27**	-0.61***	---	NS	-0.74**	-0.72***	-0.72***	0.63***	-0.29**	-0.79**	-0.59*
K tissue conc.	NS	0.20*	NS	---	NS	0.64*	NS	NS	0.36**	NS	NS
Mn tissue conc.	NS	0.90**	-0.74**	NS	---	NS	0.70***	-0.36**	NS	0.96***	NS
Zn tissue conc.	0.31**	NS	0.72**	0.64*	NS	---	NS	0.53**	0.69***	NS	0.91***
Ca uptake	0.63***	0.49***	-0.72***	NS	0.80**	0.55*	---	NS	0.66***	0.87***	NS
Mg uptake	0.55***	-0.79***	0.63***	NS	-0.74**	NS	NS	---	0.46***	-0.65*	NS
K uptake	0.94***	-0.24*	-0.29**	0.36*	NS	0.68**	0.66***	0.46***	---	NS	0.89***
Mn uptake	0.46***	0.81***	-0.79***	NS	0.96***	NS	0.87***	-0.65*	NS	---	NS
Zn uptake	0.80***	NS	-0.59*	NS	NS	0.91***	NS	NS	0.89***	NS	---

[1] * $P < 0.05$ ** $P < 0.01$ *** $P < 0.0001$

considerably lower than the concentrations in hydroponic solutions associated with depression in plant growth. However, additions of fertilizer would increase the concentrations of Mg and Ca to levels which could reduce dry matter yield. Therefore, reductions in dry matter yield could have been caused by a direct effect of high levels of Mg or Ca, or by a deficiency of Zn associated with low levels of Mn and Zn. Additions of Ca or K did not ameliorate either of these problems.

2. Nutrient Relations

Concentration or uptake of Ca, Mg and K were virtually unaffected by the application of KCl or $CaSO_4$. Concentration of Mn in the tissue increased above that of control plants when 6000 kg ha^{-1} of Ca or 400 kg ha^{-1} of K was added (Table 5.3.6). Zn concentration in plants grown with 6000 kg ha^{-1} of Ca was higher than in plants grown on the control soil. Zn and Mn uptake, however, were unaffected by treatment in any soil. The increase in concentration in the tissue was associated with a decrease in dry matter yield, indicating that the effect of tissue concentration was a reflection of minor yield depressions caused by treatment.

Soil affected yield and chemical composition of barley. Relationships found were similar to that observed in the previous experiment. Mg and K content of tissues reflected the concentration of these cations in the soil whereas concentration of Ca in the tissue was not closely related to Ca concentration in the soil but was decreased by increasing Mg content of the soil.

Table 5.3.6 Dry matter yield, Mn and Zn concentration in the tissue and total uptake of Mn and Zn treatments averaged over soils.

Treatment	Dry Matter Yield g pot^{-1}	Concentration in Tissue		Total Uptake By Plants	
		Mn	Zn	Mn	Zn
		ug g^{-1}		mg	
$CaSO_4$ Banded	7.45	30.48 BC[1]	17.46 AB	0.226	0.133
$CaSO_4$ Broadcast	6.69	33.33 A	18.73 A	0.220	0.131
KCl Banded	7.45	29.86 BC	17.07 AB	0.219	0.129
KCl Broadcast	7.32	31.48 AB	17.68 AB	0.230	0.131
Check	7.62	28.57 C	16.84 B	0.218	0.131
Mean square error	NS	10.70	4.24	NS	NS

[1] Numbers within a column followed by the same letter do not differ at the 5% significance level.

Concentration of Mn and Zn in the tissue decreased as Mg content of the soil increased but increased with increases in DTPA extractable content of Mn and Zn, respectively.

5.3.4 Conclusions

With the exception of the Assiniboine complex soil, which showed an increase in dry matter yield with application of broadcast KCl, application of $CaSO_4$ or KCl either as banded or as broadcast treatments, had no beneficial effect on barley growth or nutrient uptake. The general lack of response of yield to the addition of KCl and $CaSO_4$ in soils high in Mg indicates that application of these nutrients to such soils would not be economic.

Minor differences in concentration of Mn and Zn in the tissue occurred due to treatment, but were apparently due to nonsignificant changes in dry matter yield. Uptake of Mn and Zn were not influenced by any treatment. The inverse relationship between dry matter yield and concentration of Mn and Zn in the tissue and lack of any effect of treatment on the uptake of Mn and Zn indicate that the availability of these nutrients may have been a limiting factor in plant yield.

5.4 The Effect of Banded and Broadcast Applications of KCl and CaSO4 Alone and in Combination on the Yield and Ca, Mg and K Content of Barley Grown Under Field Conditions

5.4.1 Introduction

The hydroponic and pot studies conducted previously demonstrated that reduced dry matter yields of barley were associated with high concentrations of Ca and Mg in the growth medium. Although the solution concentrations of Ca and Mg in unamended soils were lower than those found to reduce yield in hydroponic culture, addition of N fertilizer increased Ca and Mg concentration to potentially deleterious levels. Additions of KCl increased dry matter yield in a soil of the Assiniboine complex, but generally, additions of KCl or $CaSO_4$ did not influence dry matter yield in pot studies.

Field conditions tend to differ significantly from conditions in pot trials. Root volume in pot studies is restricted, watering regime is fixed and the soil temperature and air temperature are both set at fixed values. Therefore, although results obtained in pot studies may provide information about the soil-plant system, they may not accurately reflect the response that will occur in the field. Therefore, a field study was established on the Assiniboine soil, in order to further investigate the effects of soil amendments on barley growth in high Mg systems.

5.4.2 Materials and Methods

A field site was established in 1984 to evaluate the effect of various Ca and K treatments alone and in combination on the yield of barley (cv. Bonanza). The soil type at the Alexander site (SE 34-10-22) was a calcareous black chernozemic silty clay of the Assiniboine complex. Treatments were as listed in Table 5.4.1 .

Table 5.4.1: Treatments for field study

Treatment	1984	1985
	kg ha^{-1} of Ca or K	kg ha^{-1} of Ca or K
1	Check	Check
2	60 $CaSO_4$ banded	60 $CaSO_4$ banded
3	60 KCl banded	60 KCl banded
4	60 $CaSO_4$ banded + 60 KCl banded	60 $CaSO_4$ banded + 60 KCl banded
5	6000 $CaSO_4$ broadcast	0
6	6000 $CaSO_4$ broadcast + 400 KCl broadcast	0
7	6000 $CaSO_4$ broadcast + 60 KCl banded	60 KCl banded
8	6000 $CaCl_2$ broadcast + 60 KCl banded	0
9	400 KCl broadcast	0

Broadcast treatments were uniformly spread by hand and rototilled into the soil to a depth of 10 cm prior to seeding operations. All plots were treated with 91 kg ha^{-1} of N as NH_4NO_3 as a broadcast treatment. Phosphorus at 40 kg ha^{-1} of P as $NH_4H_2PO_4$ was sidebanded 5 cm to the side and 5 cm below the seed. $CaSO_4$ and KCl bands were placed 5 cm deep parallel to and to the side of the seedrows. When both $CaSO_4$ and KCl were applied in a treatment, they were blended and banded together. $(NH_4)_2SO_4$ was banded in treatments that did not include a $CaSO_4$ band, to compensate for the S applied with the Ca in the band. No attempt was made to compensate for S applied in the broadcast $CaSO_4$ treatment.

Barley (cv. Bonanza in 1984 and Johnston in 1985) was seeded at a depth of 3 cm at 120 kg ha^{-1} with a triple-disc plot seeder. Row spacing was 30 cm in 1984 and 20 cm in 1985. Seeding occurred on May 26 in 1984 and on May 3 in 1985. In 1985, poor emergence necessitated reseeding. Glyphosate was applied to kill the barley that had emerged and reseeding was completed on May 22.

In 1984, Hoe-grass II (diclofop methyl plus bromoxynil) was used for control of grassy and broadleaf weeds. In 1985, Avenge plus Buctril M (difenzoquat, bromoxynil plus MCPA ester) was used for weed control.

Soil samples were taken in treatments 1, 5, 6, 7 and 8 at depths of 0 to 15 and 15 to 30 cm on June 22, July 11, August 1 and August 15, 1984. In 1985, soil samples were taken at the 0-15, 15-30 and 30-60 depths on May 1, prior to fertilizer application and on July 3 and September 12. Plant samples for yield and chemical composition and

soil samples were taken on July 11 and August 15, 1984 and July 3 and September 12, 1985.

Plant samples were analyzed for Mg, Ca, K, Mn and Zn while soil samples were analyzed for pH, conductivity, NH_4 acetate-extractable Mg, Ca and K and for soil solution concentrations of Mg, Ca, and K.

Statistical analysis was conducted using analysis of variance and separation of treatment means tested using Tukey's test.

5.4.3 Results

(a) Grain yield

Final grain yield was significantly influenced by treatment in both years (Table 5.4.2). Grain yield in 1984 with 400 kg ha^{-1} of K as KCl broadcast and with 60 kg of Ca as $CaSO_4$ ha^{-1} applied as a banded application was significantly greater than that obtained on the control (Table 5.4.2). Grain yields in 1985 with 6000 kg ha^{-1} of Ca as $CaSO_4$ broadcast plus 60 kg ha^{-1} of K as KCl banded and with application of 400 kg ha^{-1} of K as KCl broadcast were significantly greater than on the control plot. The lowest yield was obtained with application of 6000 kg ha^{-1} of Ca as $CaCl_2$. Plant growth was virtually completely suppressed and no grain yield was obtained when $CaCl_2$ was applied at 6000 kg Ca ha^{-1}. The yield depression was presumably due primarily to increased soil salinity caused by the readily soluble $CaCl_2$.

Grain yield increased with additions of 400 kg ha^{-1} of K applied alone but not when applied with 6000 kg ha^{-1} of Ca. The lack of response to KCl may have been due to the large increase in the

Table 5.4.2 Grain yield at final harvest, 1984 and 1985

TREATMENT	GRAIN YIELD (Mg ha^{-1})		
	1984	1985	Mean
1. Check	3.34 cd	2.94 bc	3.17 d
2. 60 kg Ca ha^{-1} $CaSO_4$ banded	4.64 ab	2.86 bc	3.75 abc
3. 60 kg K ha^{-1} KCl banded	3.64 cd	2.49 c	3.07 d
4. 60 kg Ca ha^{-1} $CaSO_4$ banded + 60 kg K ha^{-1} KCl banded	3.37 cd	2.48 c	2.92 d
5. 6000 kg Ca ha^{-1} $CaSO_4$ broadcast	3.28 d	3.10 bc	3.19 d
6. 6000 kg Ca ha^{-1} $CaSO_4$ broadcast + 400 kg K ha^{-1} KCl broadcast	4.02 abcd	2.87 bc	3.44 bcd
7. 6000 kg Ca ha^{-1} $CaSO_4$ broadcast + 60 kg K ha^{-1} KCl banded	4.08 abc	3.82 a	3.95 ab
8. 6000 kg Ca ha^{-1} $CaCl_2$ broadcast + 60 kg K ha^{-1} KCl banded	0.00 e	0.01 d	0.01 e
9. 400 kg K ha^{-1} KCl broadcast	4.78 a	3.42 a	4.10 a
Mean square error	1.1×10^{-1}	7.8×10^{-2}	1.0×10^{-1}

[1] Numbers within a column followed by the same letter do not differ at the 5% level of significance.

concentration of Ca and Mg in the soil solution when $CaSO_4$ was added. Increasing the concentration of Ca and Mg in the soil solution would increase the competition of the divalent cations with K for uptake into the root, which could decrease the benefical effect of K on dry matter production.

(b) Tissue nutrient content

(i) Calcium

Concentration of Ca in the tissue at the interim harvest was not influenced by treatment in 1984 (Table 5.4.3). In 1984, plant growth was completely suppressed by the addition of $CaCl_2$ and insufficient plant material was available for analysis. In 1985, concentration of Ca in the tissue of plants at the interim harvest was increased by the addition of $CaCl_2$. Concentration of Ca in the vegetative tissue at final harvest in 1984 was higher in plants treated with high levels of $CaSO_4$ applied alone than in plants grown on the control plot (Table 5.4.4). The concentration of Ca in the tissue was lower in plants treated with banded $CaSO_4$ than in plants grown on the control plot. Concentration of Ca in the vegetative tissue at the final harvest in 1985 was lower in plants grown with the addition of broadcast KCl than in plants grown on the control plot.

(ii) Magnesium

Concentration of Mg in the tissue at interim harvest was not influenced by treatment in either year (table 5.4.3). However,

Table 5.4.3 Concentration of Ca, Mg and K in barley tissue at Interim Harvest (July 11, 1984 and July 3, 1985)

Treatment	Ca %		Mg %		K %	
	1984	1985	1984	1985	1984	1985
1. Check	0.25	0.52a[1]	0.24	0.28	2.67c	4.75ab
2. 60 kg Ca ha^{-1} $CaSO_4$ banded	0.34	0.59a	0.20	0.28	2.76	5.14ab
3. 60 kg K ha^{-1} KCl banded	0.35	0.54a	0.22	0.30	3.19	5.16ab
4. 60 kg Ca ha^{-1} $CaSO_4$ banded + 60 kg K ha^{-1} KCl banded	0.34	0.52a	0.20	0.28	3.56	4.97ab
5. 6000 kg Ca ha^{-1} $CaSO_4$ broadcast	0.35	0.57a	0.20	0.30	2.68	5.08ab
6. 6000 kg Ca ha^{-1} $CaSO_4$ broadcast + 400 kg K ha^{-1} KCl broadcast	0.36	0.52a	0.21	0.28	3.34	5.46a
7. 6000 kg Ca ha^{-1} $CaSO_4$ broadcast + 60 kg K ha^{-1} KCl banded	0.32	0.60a	0.18	0.30	2.71	5.38a
8. 6000 kg Ca ha^{-1} $CaCl_2$ broadcast + 60 kg K ha^{-1} KCl banded	----	1.07b	----	0.29	----	4.54b
9. 400 kg K ha^{-1} KCl broadcast	0.35	0.51a	0.20	0.28	3.20	5.30a
Mean square error	ns	0.00474	ns	ns	ns	0.096

[1] Numbers within a column followed by the same letter do not differ at the 5% level of significance.

Table 5.4.4 Concentration of Ca, Mg and K in barley tissue at final harvest

Treatment	Ca %		Mg %		K %	
	1984	1985	1984	1985	1984	1985
1. Check	0.43b	0.42a	0.24ab	0.23ab	2.87	1.40bc
2. 60 kg Ca ha^{-1} $CaSO_4$ banded	0.34c	0.42a	0.20b	0.20abcd	2.86	1.20c
3. 60 kg K ha^{-1} KCl banded	0.45ab	0.46a	0.25ab	0.24ab	3.12	1.55bc
4. 60 kg K ha^{-1} KCl banded + 60 kg Ca ha^{-1} $CaSO_4$ banded	0.39bc	0.48a	0.23b	0.25a	2.89	1.64bc
5. 6000 kg Ca ha^{-1} $CaSO_4$ broadcast	0.52a	0.46a	0.29a	0.20abcd	3.07	1.23c
6. 6000 kg Ca ha^{-1} $CaSO_4$ broadcast + 400 kg K ha^{-1} KCl broadcast	0.40bc	0.39ab	0.23b	0.21abcd	3.14	1.79b
7. 6000 kg Ca ha^{-1} $CaSO_4$ broadcast + 60 kg K ha^{-1} KCl banded	0.41bc	0.37ab	0.22b	0.17bcd	3.03	1.54bc
8. 6000 kg Ca ha^{-1} $CaCl_2$ broadcast + 60 kg K ha^{-1} KCl banded	------	0.52a	------	0.16cd	----	2.60a
9. 400 kg K ha^{-1} KCl broadcast	0.40bc	0.29b	0.23b	0.15d	3.35	1.66bc
Mean square error	0.00209	0.00393	6.1×10^{-4}	7.9×10^{-4}	ns	0.036

concentration of Mg in the tissue at the final harvest in 1984 was higher in plants grown with the addition of high levels of $CaSO_4$ than in any other plants with the exception of untreated plants and the plants treated with banded KCl (table 5.4.4).

Addition of broadcast KCl, and broadcast $CaCl_2$ reduced concentration of Mg in the tissue at the final harvest below that of plants grown on the control plots in 1985.

(iii) Potassium

Concentration of K of the tissue at the interim harvest was not influenced by any treatment in 1984 (table 5.4.3), but was lower in plants grown with the addition of high $CaCl_2$ than in plants grown with the addition of 6000 kg ha^{-1} of Ca as $CaSO_4$ + 400 kg ha^{-1} of K broadcast, 6000 kg ha^{-1} of Ca as $CaSO_4$ broadcast + 60 kg ha^{-1} of K banded or 400 kg ha^{-1} of K broadcast in 1985. Concentration of K in the tissue at the final harvest in 1984 was not influenced by treatment (table 5.4.4). Concentration of K in plants grown on plots treated with $CaCl_2$ was higher than in any other plants at final harvest in 1985, due to the restricted dry matter production of this treatment.

(iv) Mn and Zn

Concentration of Mn and Zn in tissue were not significantly influenced by treatment (data not included).

5.4.4 Discussion

Addition of 400 kg ha^{-1} of K as KCl consistently increased final grain yield in spite of the high concentration of NH_4 acetate-extractable K found in the soil. Although this soil was relatively high in Mg, it was lower in Mg than several of the soils used in the growth chamber studies and tested higher in K than most soils used in the growth chamber studies. The consistent year to year response to KCl in the field study and response to KCl in the previous growth chamber study supports the fact that this was a real response and not simply an experimental artifact. Since Cl was also added, it is possible that the yield response was due to the addition of Cl. Effects of Cl on plant growth and yield, however, were not investigated.

Application of $CaSO_4$ at 6000 kg Ca ha^{-1} plus KCl at 60 kg K ha^{-1} banded near the seed increased yield above that obtained on the control plot in 1985. $CaSO_4$ banded at 60 kg Ca ha^{-1} near the seed increased the ratio of Ca and Mg in the plant and increased yield in 1984. These results suggest that application of $CaSO_4$ may have some beneficial effects on soils high in Mg. This is in contrast to the observations noted in the previous pot experiment in which seven soils were amended with $CaSO_4$. The pot studies showed no effect of application of $CaSO_4$ on either yield or Ca and Mg content of barley.

5.4.5 Conclusions

Application of KCl at 400 kg ha^{-1} of K led to an increase in grain yield of barley in a field study on a soil testing high in extractable

K. The response to applied K on a soil testing high in NH_4 acetate-extractable K may indicate that factors other than the level of NH_4 acetate-extractable K may influence availability of K to the plant. Effects of applied Ca as $CaSO_4$ on yield were inconsistent among treatments and years.

5.5 The Effect of Additions of CaSO and KCl on Extractable Ca, Mg, and K and the Concentration of These Ions in Solution

5.5.1 Introduction

Fertilizer studies in the growth chamber indicated that additions of KCl and $CaSO_4$ had little effect on barley yield, with the exception of a beneficial effect of KCl additions on one soil type. A field study established on that particular soil type supported the beneficial effect of KCl additions on yield on that soil. In order to understand the effects of additions of KCl and $CaSO_4$ on the growth of barley, an understanding of the effect of these compounds on the concentration of nutrients in the soil solution is required. Therefore, soil analyses were conducted at the Alexander site. The primary objective of this study was to determine the effect of additions of $CaSO_4$ and KCl on NH_4 acetate-extractable Ca, Mg and K and their concentration in the soil solution under field conditions during the growing season. A secondary objective was to relate soil solutions concentration of Ca, Mg and K to those required for optimal growth.

5.5.2 Materials and Methods

General methods and materials for this study were outlined in section 5.4.2. Soil samples were obtained from only the following soil treatments.

(1) Check

(5) 6000 kg ha-1 of Ca as $CaSO_4$ broadcast

(6) 6000 kg ha^{-1} of Ca as $CaSO_4$ broadcast + 400 kg ha^{-1} of K as KCl broadcast

(7) 6000 kg ha^{-1} of Ca as $CaSO_4$ broadcast + 60 kg ha^{-1} of K as KCl banded

(8) 6000 kg ha^{-1} of Ca as $CaCl_2$ broadcast + 60 kg ha^{-1} of K as KCl banded

(9) 400 kg ha^{-1} of K as KCl broadcast

Soil samples were collected on (1)June 22, (2)July 11, (3)August 1 and (4)August 15 in 1984 and on (5)May 1, (6)July 3 and (7)September 12 in 1985. Two locations in each plot were sampled and samples from each plot were bulked by depth. Soil samples were collected from the 0 to 15 and 15 to 30-cm depths on each sampling date and also from the 30 to 60-cm depth on May 1, 1985 and September 12, 1985.

The NH_4 acetate-extractable Ca, Mg and K and the concentration of these nutrients in the soil solution were determined as described in section 3.2.

5.5.3 Results

(1) Calcium

NH_4 acetate-extractable Ca in the 0 to 15 cm depth increased when Ca was added, particularly when added as $CaCl_2$ (Fig. 5.5.1). When Ca was applied as $CaCl_2$, extractable Ca initially increased rapidly, reached a maximum on August 15, 1984, and then decreased during the winter period. In contrast, when Ca was added as $CaSO_4$, NH_4 acetate-extractable Ca initially increased more slowly and to a lesser

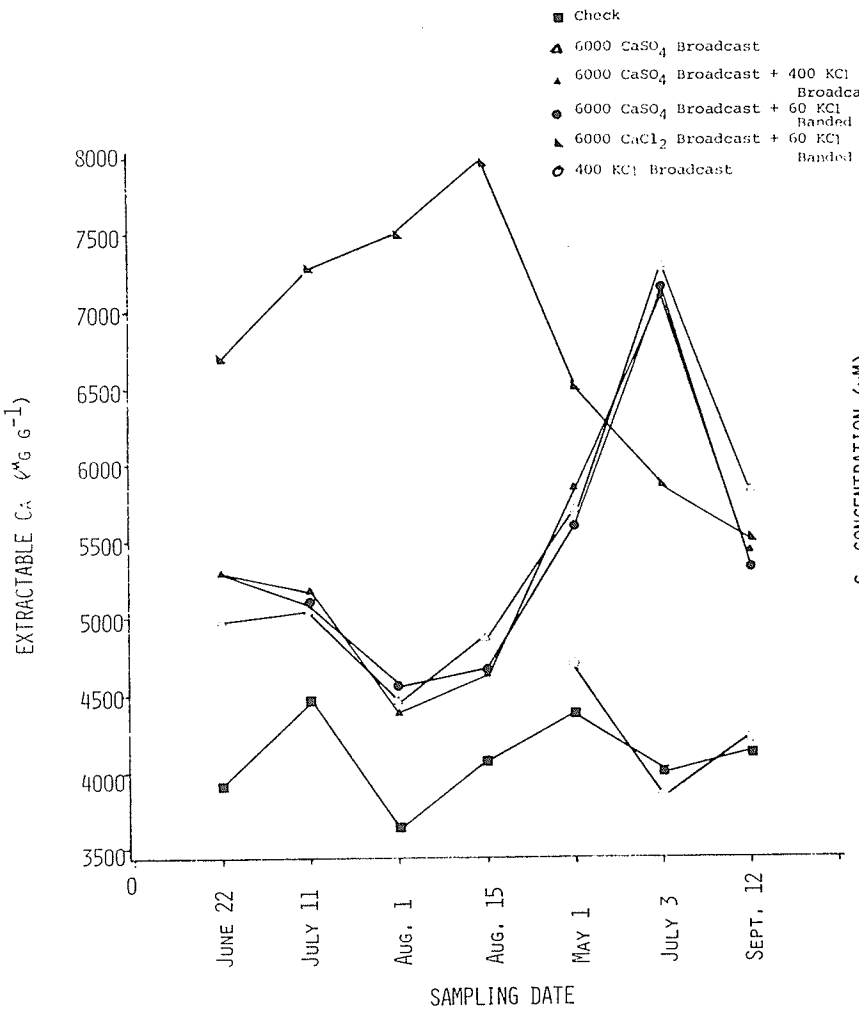

FIG. 5.5.1: EXTRACTABLE Ca IN THE 0 TO 15 CM DEPTH AS A FUNCTION OF SAMPLING DATE FOR SELECTED TREATMENTS.

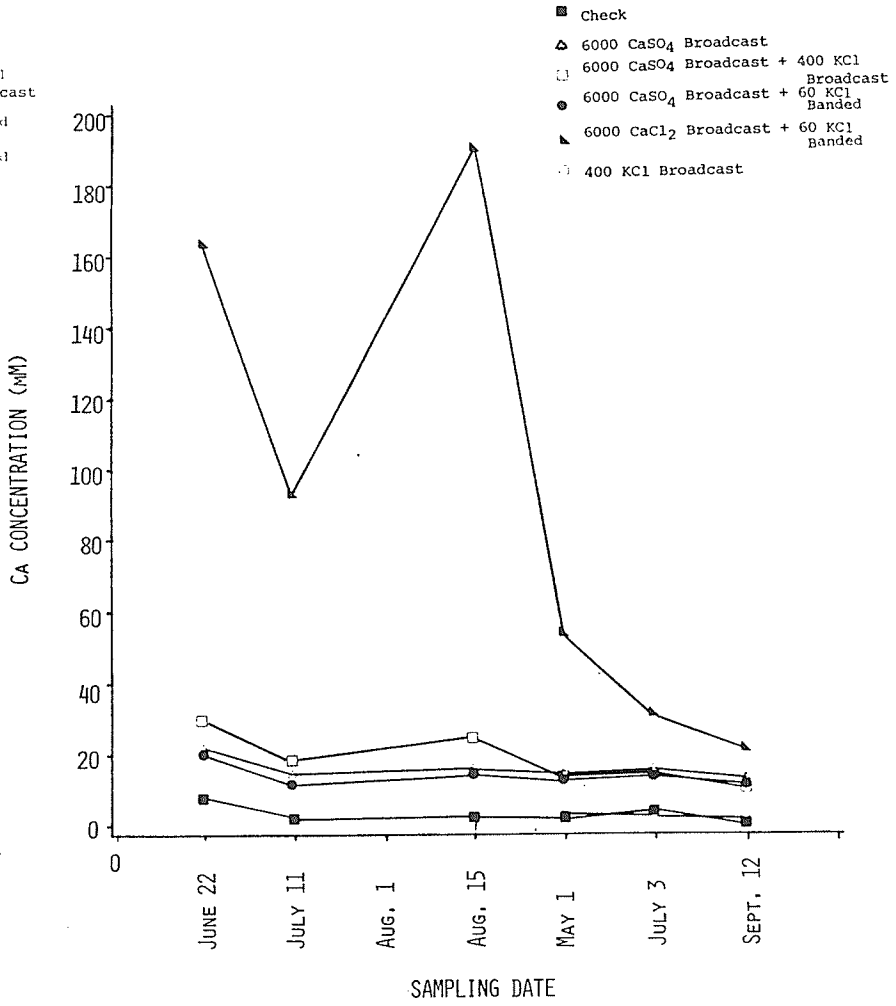

FIG. 5.5.2: SOLUTION CONCENTRATION OF Ca IN THE 0 TO 15 CM DEPTH AS A FUNCTION OF SAMPLING DATE FOR SELECTED TREATMENTS.

extent, and reached a maximum on July 3, 1985. Addition of KCl with the $CaSO_4$, either as a broadcast treatment or as a band, had no effect on extractable Ca in the 0 to 15-cm depth. Extractable Ca in soils treated with high concentrations of Ca was significantly greater than for untreated soils for the duration (2 years) of the study.

Concentration of Ca in the soil solution in the 0 to 15-cm depth at the initial sampling was higher in all treatments (including the control) than the 8 mM concentration above which yield decreased in the hydroponic studies (Fig. 5.5.2). The high concentration in the untreated soil was probably due to the addition of fertilizer N at the time of seeding. Concentration of Ca in the $CaCl_2$ treatment was more than five times higher than in any other treatment at the first sampling date. The concentration of Ca in the solution was substantially higher than the 8 mM concentration above which yield decreased in the hydroponic studies. Solution concentration of Ca remained higher in the $CaCl_2$ treatment than in the other treatments for the duration of the study period, although by September 12, 1985 the difference between the $CaCl_2$ treated soil and all other treatments was much smaller. Concentration of Ca in the soil solution of soils treated with broadcast $CaSO_4$ was higher than in untreated soils and this difference persisted throughout the study period. During the first year, the concentration of Ca in the soil solution was slightly higher when $CaSO_4$ plus KCl broadcast was added than when $CaSO_4$ was applied alone or with a band application of KCl. The difference can likely be attributed to the effect of the readily soluble KCl on ionic

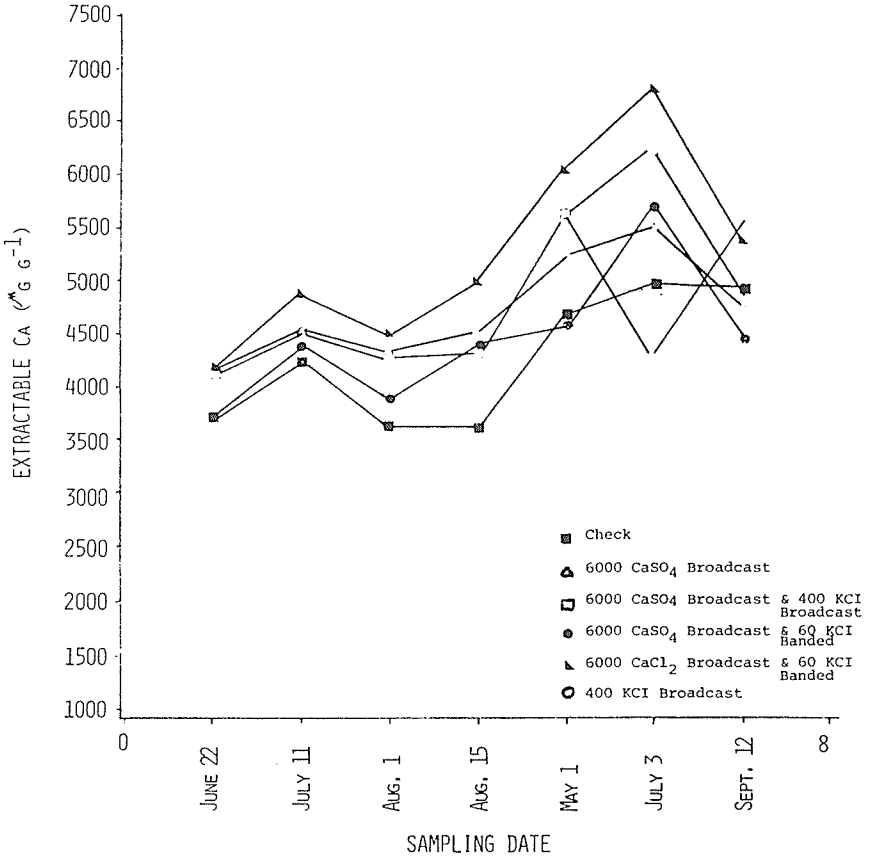

FIG. 5.5.3: EXTRACTABLE Ca IN THE 15 TO 30 CM DEPTH AS A FUNCTION OF SAMPLING DATE FOR SELECTED TREATMENT.

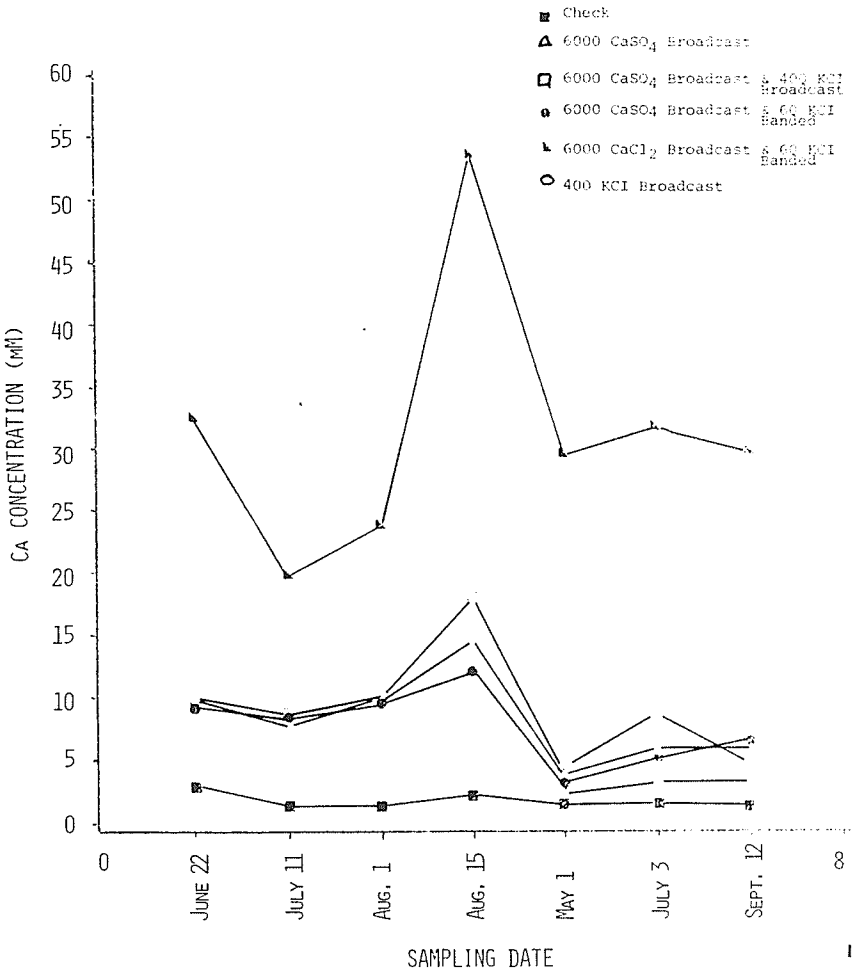

FIG. 5.5.4: SOLUTION CONCENTRATION OF Ca IN THE 15 TO 30 CM DEPTH AS A FUNCTION OF SAMPLING DATE FOR SELECTED TREATMENTS.

strength of the solution. Increasing the ionic strength of the solution would tend to increase the molar solubility of the $CaSO_4$, increasing the concentration of Ca in the solution.

NH_4 acetate-extractable Ca content of the 15 to 30-cm depth was higher in soils treated with broadcast $CaSO_4$ or $CaCl_2$ than in the check at the initial sampling date (Fig. 5.5.3). NH_4 acetate-extractable Ca content of soils treated with Ca increased between the fall of 1984 and spring of 1985, apparently due to leaching from the surface soil by fall rains and/or spring snowmelt. Extractable Ca increased further between May 1 and July 3 and then decreased by September 12. NH_4 acetate-extractable Ca in the 15 to 30-cm depth was higher in soils treated with $CaCl_2$ than with $CaSO_4$ apparently due to the greater leaching of the more soluble $CaCl_2$ as compared to the $CaSO_4$. Differences in extractable Ca content between treated and nontreated soils were not as large for the 15 to 30-cm depth as those observed for the 0 to 15-cm depth samples.

$CaCl_2$ increased concentration of Ca in the solution in the 15 to 30 cm depth throughout the study period as compared to any other treatment (fig 5.5.4). Concentration of Ca in the solution of soils treated with $CaSO_4$ was also higher than in nontreated soils throughout the study period. Concentration of Ca in the soil solution decreased substantially from the final sampling date of 1984 to the initial sampling date in 1985 in all treatments where Ca had been applied, indicating that readily soluble Ca leached beyond this depth between fall and spring sampling, This is the period when precipitation

Table 5.5.1 Concentration of Ca, Mg, and K in soil solution at the 30 to 60 cm depth, May 1 and September 12, 1985.

May 15

Treatment	Ca concentration	Mg concentration	K concentration
	mM		
1. Check	0.69 B[1]	1.88 B	0.036 B
5. 6000 $CaSO_4$ broadcast	1.47 B	2.49 B	0.042 B
6. 6000 $CaSO_4$ broadcast + 400 KCl broadcast	1.34 B	2.00 B	0.034 B
7. 6000 $CaSO_4$ broadcast + 60 KCl banded	1.35 B	2.31 B	0.047 B
8. 6000 $CaCl_2$ broadcast + 60 KCl banded	9.14 A	14.16 A	0.146 A
9. 400 KCl broadcast	1.00 B	1.40 B	0.054 B
Mean square error	3.73	2.47	0.00047

September 12

1. Check	1.25 B	1.58 B	0.133 A
5. 6000 $CaSO_4$ broadcast	3.17 AB	5.91 B	0.109 A
6. 6000 $CaSO_4$ broadcast + 400 KCl broadcast	5.00 AB	5.80 B	0.362 B
7. 6000 $CaSO_4$ broadcast + 60 KCl banded	6.09 AB	6.33 B	0.224 AB
8. 6000 $CaCl_2$ broadcast + 60 KCl banded	16.71 A	24.88 A	0.303 AB
9. 400 KCl broadcast	5.33 AB	6.15 B	0.160 A
Mean square error	44.83	37.31	0.0052

[1] Numbers within a column followed by the same letter do not differ at the 5% significance level.

exceeds evapotranspiration.

NH_4 acetate-extractable Ca in the 30 to 60-cm depth was measured only in the second year. Extractable Ca at this depth was not affected by applications of $CaSO_4$ or $CaCl_2$. Concentration of Ca in the solution increased when $CaCl_2$ was added (Table 5.5.1). Addition of $CaSO_4$ also increased concentration of Ca in the solution, and the increase was statistically significant if the $CaCl_2$ treatment was excluded from the analysis. Solution concentration increased between May 1 and September 12, indicating a consistent movement of Ca into this depth from upper soil horizons.

(2) Magnesium

NH_4 acetate-extractable Mg in the 0 to 15-cm depth was not influenced by $CaSO_4$ additions, but tended to be slightly lower in the soils treated with $CaCl_2$ than in the non-treated soil throughout the study (Fig. 5.5.5). The high concentration of Ca provided by the $CaCl_2$ treatment replaced Mg on the exchange, allowing the Mg to leach from the surface layer.

Concentration of Mg in the soil solution in the soil treated with $CaCl_2$ was substantially higher than in soils from other treatments throughout the sampling period, although the differential decreased with time (Fig. 5.5.6). Concentration of Mg in the solution was higher in soils treated with broadcast $CaSO_4$ than in treatments where no Ca was applied. The initial concentration of Mg in the soil solution of the $CaCl_2$ treated soil was 75 mM as compared to approximately 25 mM in

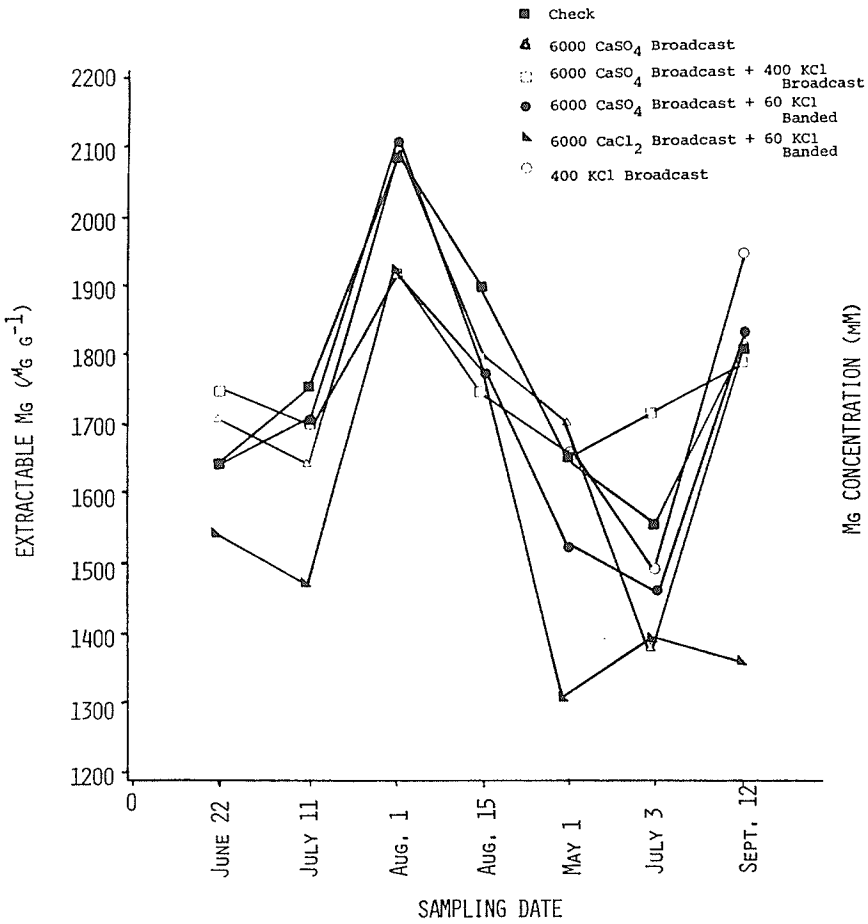

FIG. 5.5.5: EXTRACTABLE Mg IN THE 0 TO 15 CM DEPTH AS A FUNCTION OF SAMPLING DATE FOR SELECTED TREATMENTS.

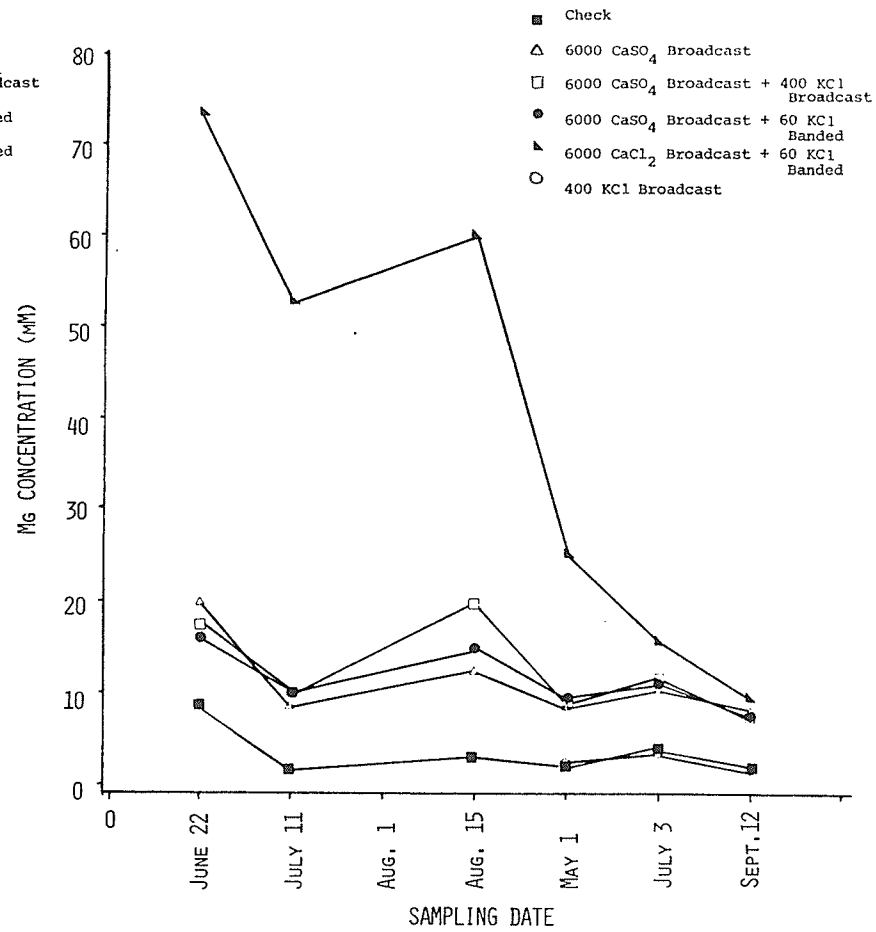

FIG. 5.5.6: SOLUTION CONCENTRATION OF Mg IN THE 0 TO 15 CM DEPTH AS A FUNCTION OF SAMPLING DATE FOR SELECTED TREATMENTS.

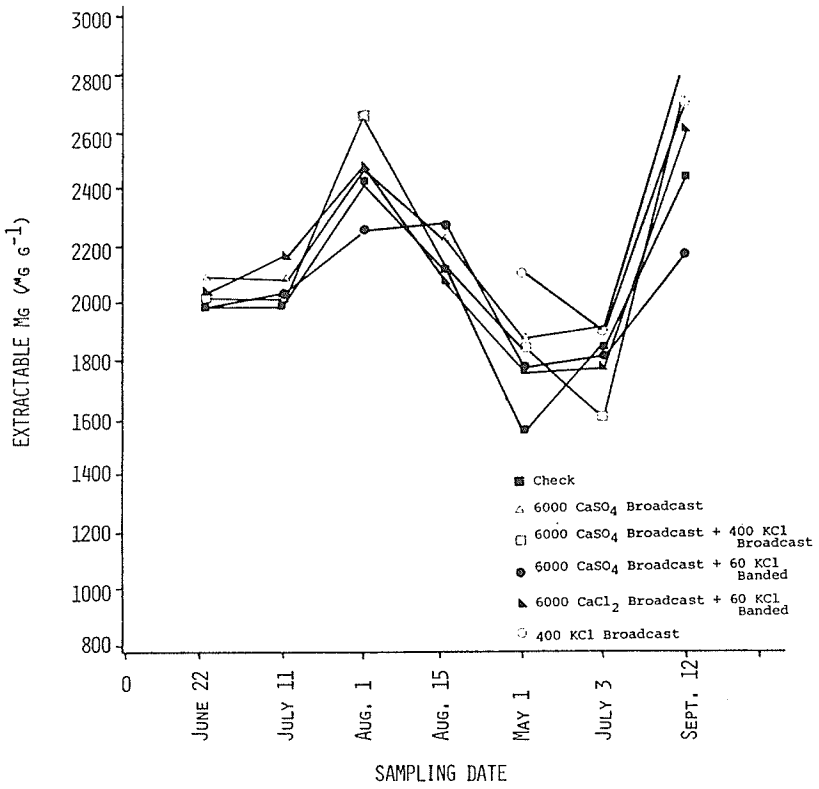

FIG. 5.5.7: EXTRACTABLE Mg IN THE 15 TO 30 CM DEPTH AS A FUNCTION OF SAMPLING DATE FOR SELECTED TREATMENTS.

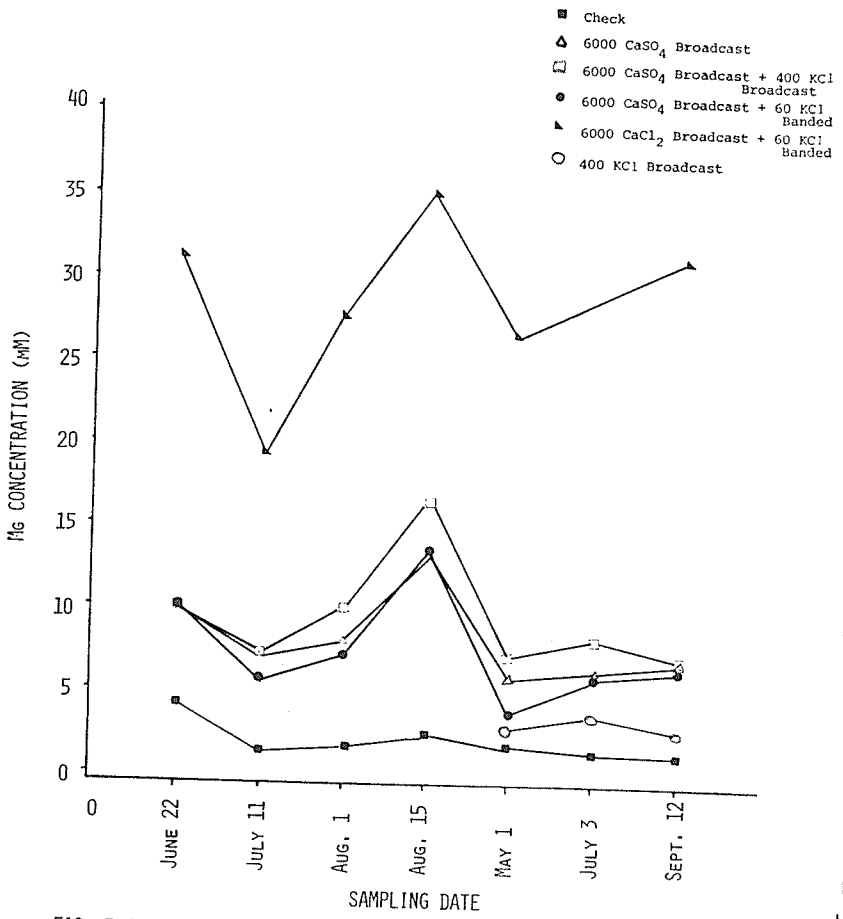

FIG. 5.5.8: SOLUTION CONCENTRATION OF Mg IN THE 15 TO 30 CM DEPTH AS A FUNCTION OF SAMPLING DATE FOR SELECTED TREATMENTS.

soils treated with $CaSO_4$ and 6 mM in the unamended soil. Amending the soils with Ca led to Ca replacing Mg on the exchange, and increases in the concentration of both Ca and Mg in soil solution. Decreases in activity of ions in the soil solution due to the increased concentration of Ca, SO_4 and Cl would also increase concentration of Mg in the solution. Since drymatter yield of barley decreased when concentration of Mg in the hydroponic solution exceeded 8 mM and additions of Ca as $CaSO_4$ or $CaCl_2$ produced concentrations of Mg in the soil solution that were much higher than optimal levels, applications of Ca as $CaCl_2$ and $CaSO_4$ to soils high in Mg could have negative effects on yield of crops.

NH_4 acetate-extractable Mg in the 15 to 30 cm depth was not significantly influenced by treatment (Fig 5.5.7), although some fluctuation occurred throughout the sampling period. Concentration of Mg in the soil solution was extremely high in soils treated with $CaCl_2$ and moderately high in soils treated with $CaSO_4$ (Fig 5.5.8). In the 15 to 30-cm depth, as in the 0 to 15-cm depth, concentration of Mg in the solution tended to increase concurrently with increases in concentration of Ca in the solution.

NH_4 acetate-extractable Mg in the 30 to 60-cm depth was not influenced by treatment (data not presented). However, concentration of Mg in the soil solution when $CaCl_2$ was added was higher than in any other soil (Table 5.5.1). Concentration of Mg in the soil solution

also tended to be higher with $CaSO_4$ than without added Ca, although the differences were not significant. The concentration of Mg in the soil solution of the 30 to 60 cm depth of soil also increased substantially between spring and fall indicating that downward movement of Mg continued throughout the study period.

(3) Potassium

NH_4 acetate-extractable K in the 0 to 15-cm depth was about 2 fold greater than that of the untreated soil when 400 kg ha^{-1} of K as KCl was added (Fig 5.5.9). The magnitude of the difference between the two treatments was greater than the amount of K applied. This may have been a result of problems with incorporation of KCl and subsequent sampling and/or an overestimate for the bulk density of the soil when conducting the calculations. The differential was sustained throughout the first season but decreased over the winter period. Extractable K was still substantially higher at the final sampling date, (September 12, 1985) where broadcast K had been applied than in other treatments. Extractable K was not influenced by additions of Ca, either as $CaSO_4$ or $CaCl_2$.

Concentration of K in the soil solution was more than 2 to 3 fold higher in soils treated with $CaCl_2$ or with broadcast KCl plus broadcast $CaSO_4$ than in the untreated soil throughout the first season (Fig 5.5.10). Concentration of K in the solution decreased substantially between fall and spring in soils treated with $CaCl_2$ or broadcast KCl plus broadcast $CaSO_4$, but was still approximately twice as great as

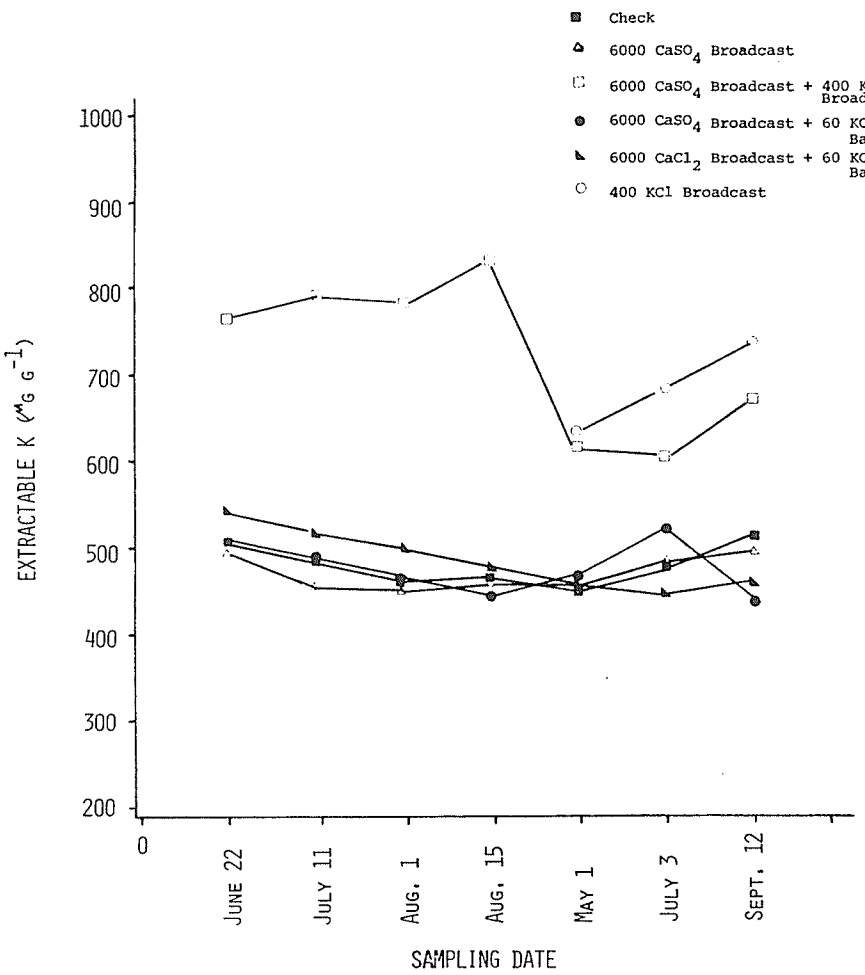

FIG. 5.5.9: EXTRACTABLE K IN THE 0 TO 15 CM DEPTH AS A FUNCTION OF SAMPLING DATE FOR SELECTED TREATMENTS.

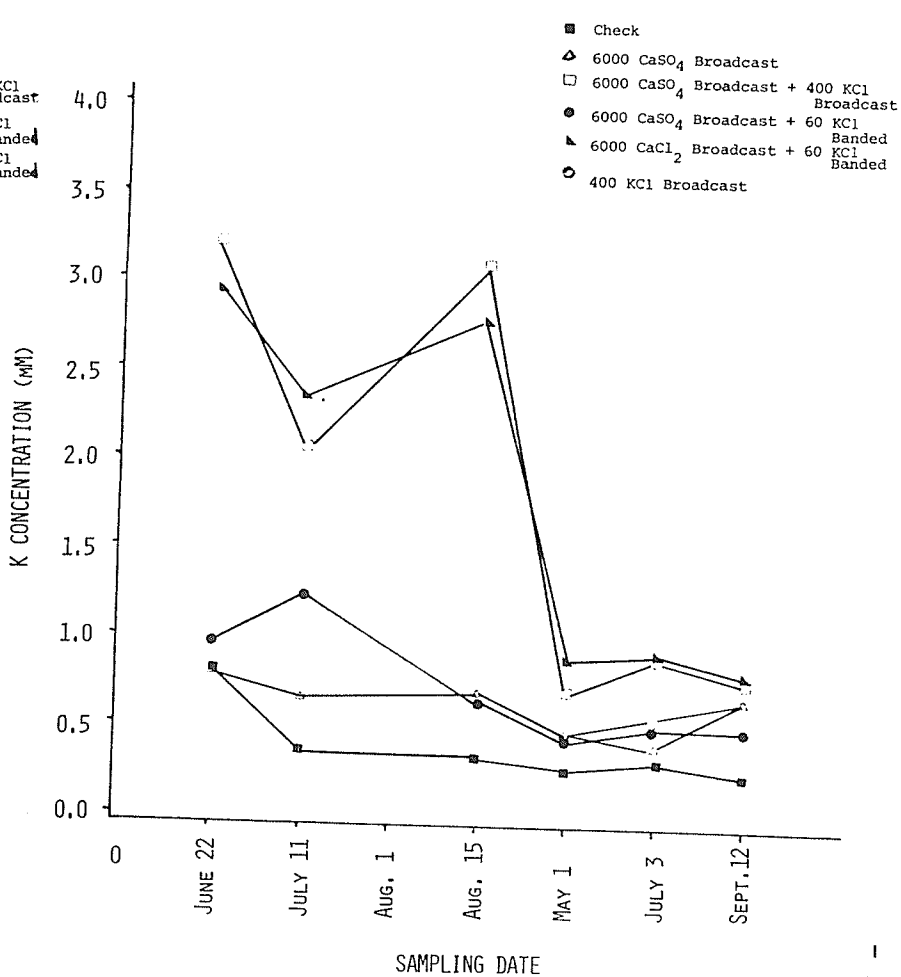

FIG. 5.5.10: SOLUTION CONCENTRATION OF K IN THE 0 TO 15 CM DEPTH AS A FUNCTION OF SAMPLING DATE FOR SELECTED TREATMENTS.

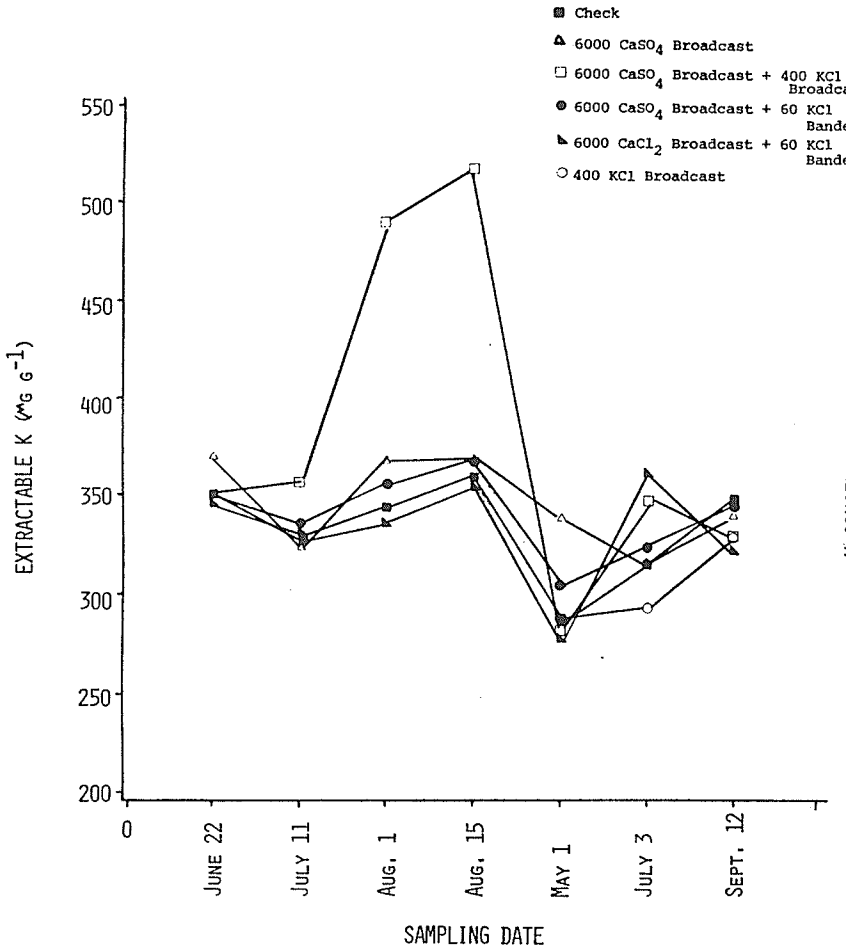

FIG. 5.5.11: EXTRACTABLE K IN THE 15 TO 30 CM DEPTH AS A FUNCTION OF SAMPLING DATE FOR SELECTED TREATMENTS.

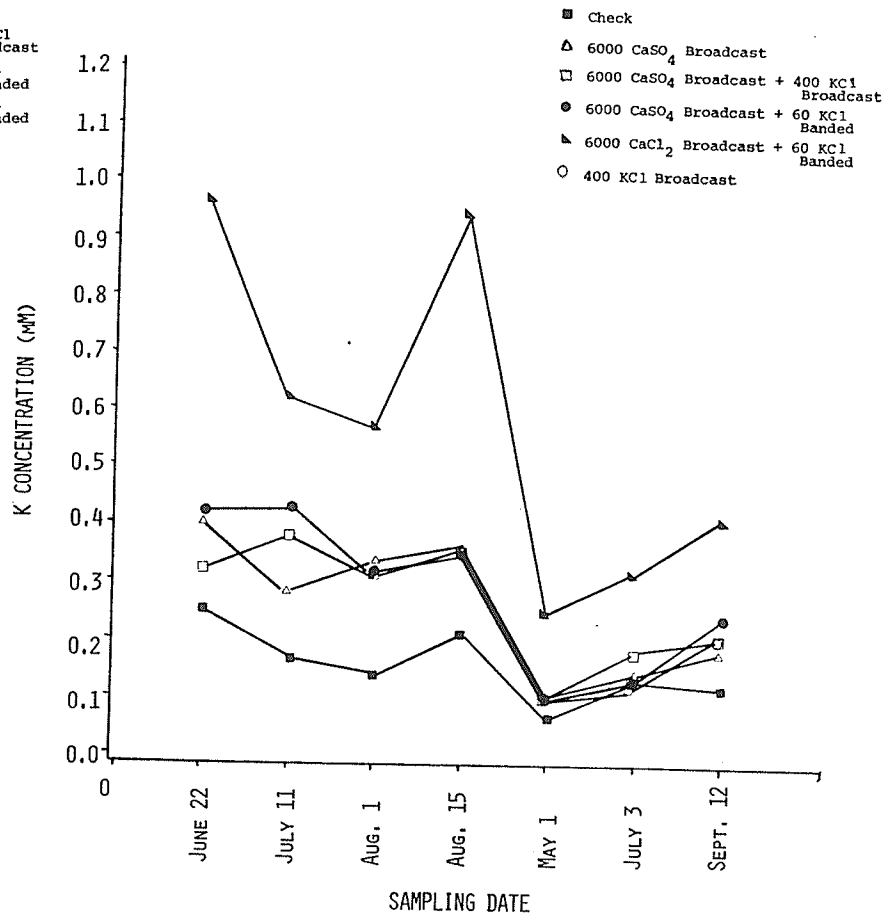

FIG. 5.5.12: SOLUTION CONCENTRATION OF K IN THE 15 TO 30 CM DEPTH AS A FUNCTION OF SAMPLING DATE FOR SELECTED TREATMENTS.

that in the control at the final sampling date. Concentration of K in the soil solution was slightly higher in soils treated with $CaSO_4$ than in the check after the first sampling date and the slight differential persisted throughout the study period. Concentration of K in the soil solution was slightly higher from May 1 to September 12, 1985 when broadcast KCl was applied with $CaSO_4$ than when KCl was applied alone. The increase in concentration of K in the soil solution associated with the addition of Ca reflects the replacement of K by Ca on the exchange and a shift in the equilibrium concentration of K due to a decrease in the activity coefficient of K with increased solution ionic strength. NH_4 acetate-extractable K in the 15 to 30-cm depth of soils treated with broadcast K plus $CaSO_4$ increased substantially between July 11 and August 1, 1984 and reached a maximum at August 15, 1984. This large increase in NH_4 acetate-extractable K was concomitant with the increase in NH_4 acetate-extractable K in the 0 to 15 cm depth. Therefore, it appears unlikely that it was due to leaching of K from the surface soil. Between the fall sampling and the spring sampling, NH_4 acetate-extractable K decreased sharply in the treatments where K had been broadcast and did not differ from the check throughout the second season. Since the disappearance of K from the 15 to 30-cm depth could not be explained strictly by leaching to lower depths, fixation of K in the clay lattices may have occurred. Extractable K in the 15 to 30-cm depth was not influenced by additions of Ca as $CaSO_4$ or $CaCl_2$.

Addition of $CaCl_2$ substantially increased the concentration of K in the soil solution in the 15 to 30-cm depth at the first sampling

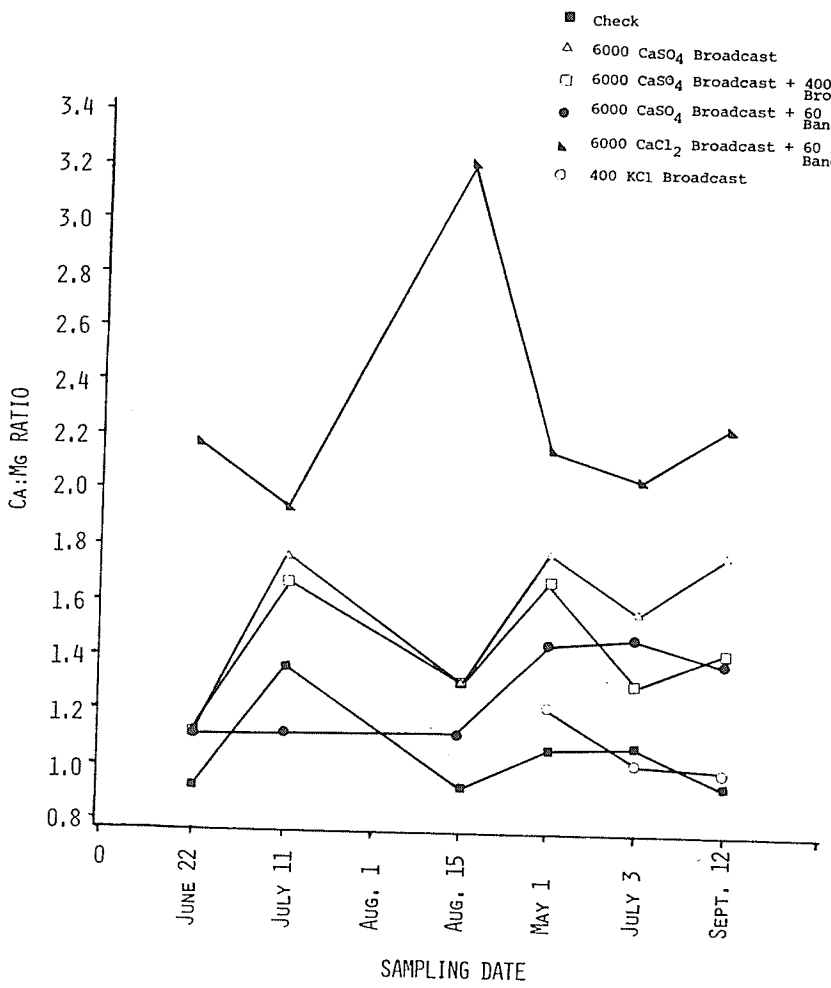

FIG. 5.5.14: RATIO OF Ca:Mg IN THE SOLUTION IN THE 0 TO 15 CM DEPTH AS A FUNCTION OF SAMPLING DATE FOR SELECTED TREATMENTS.

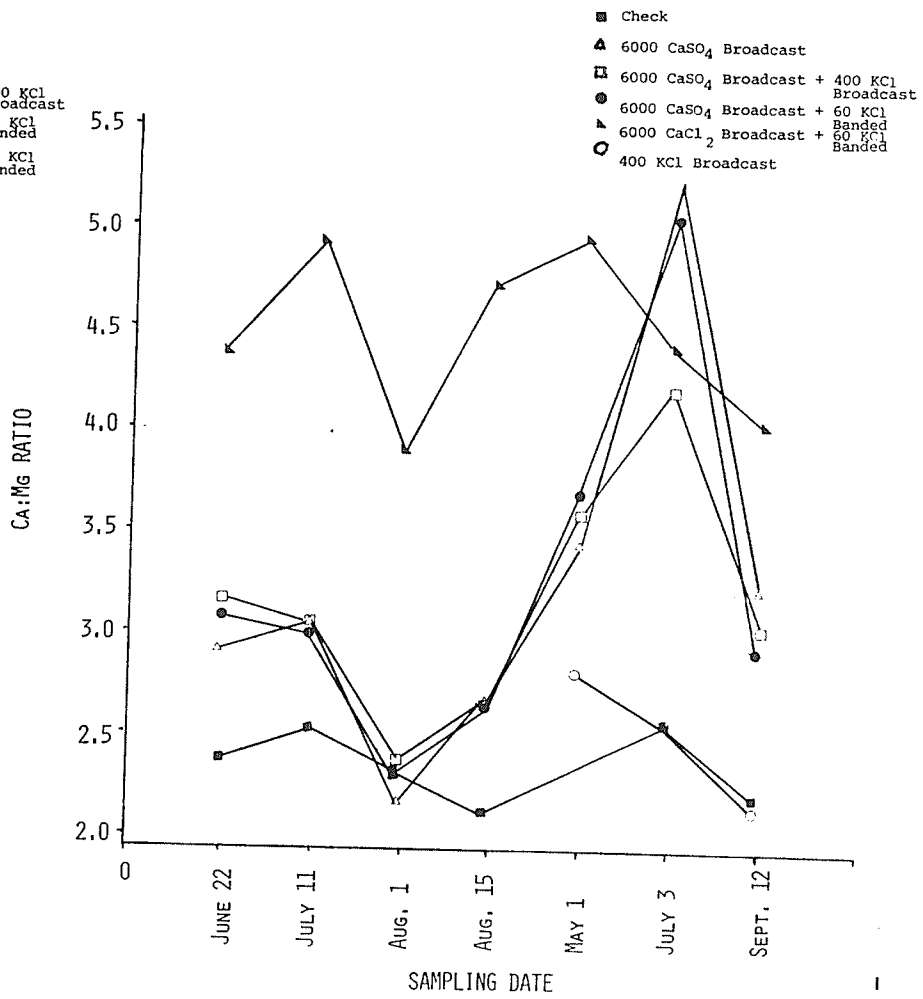

FIG. 5.5.13: RATIO OF EXTRACTABLE Ca:Mg IN THE 0 TO 15 CM DEPTH AS A FUNCTION OF SAMPLING DATE FOR SELECTED TREATMENTS.

date (Fig. 5.5.12). The increase in concentration persisted throughout the first season and to a lesser extent into the second season. Concentration of K in the soil solution was increased by addition of broadcast K plus $CaSO_4$ and by the addition of broadcast $CaSO_4$ to an essentially equal extent from June 22 to August 1, 1984. On August 15, 1985, the concentration of K in the solution of soil treated with $CaCl_2$ was substantially higher than that of other soils. The increase occurred concurrently with an increase in concentration of K in the solution in the surface depths of soils treated with $CaCl_2$ or broadcast K plus $CaSO_4$. Therefore, the increase was not simply due to downward leaching of K. The increase may have been due to sampling error.

NH_4 acetate-extractable K in the 30 to 60-cm depth was not influenced by additions of Ca or K (data not presented). However, concentration of K in the soil solution for soils sampled on May 1, 1985 was higher when $CaCl_2$ was added than for other treatments (Table 5.5.1). Increases in K concentration of the soil solution were also noted on September 12, 1985 for soils treated with $CaCl_2$ and KCl plus$CaSO_4$ broadcast.

(4) Ca:Mg ratio

The ratio of extractable Ca:Mg in the 0 to 15-cm depth of soil was increased when either $CaCl_2$ or $CaSO_4$ were added (Fig 5.5.13). The ratio changed with time and followed trends noted for changes in NH_4 acetate-extractable Ca.

The ratio of concentration of Ca:Mg in the soil solution also

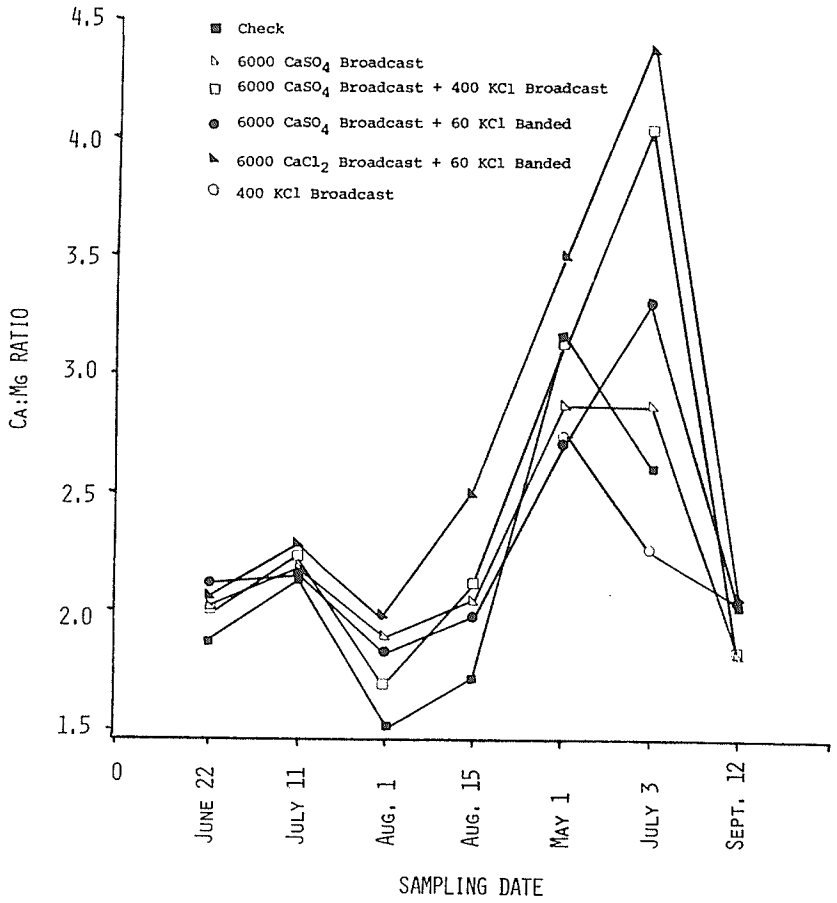

FIG. 5.5.15: RATIO OF EXTRACTABLE Ca:Mg IN THE 15 TO 30 CM DEPTH AS A FUNCTION OF SAMPLING DATE FOR SELECTED TREATMENTS.

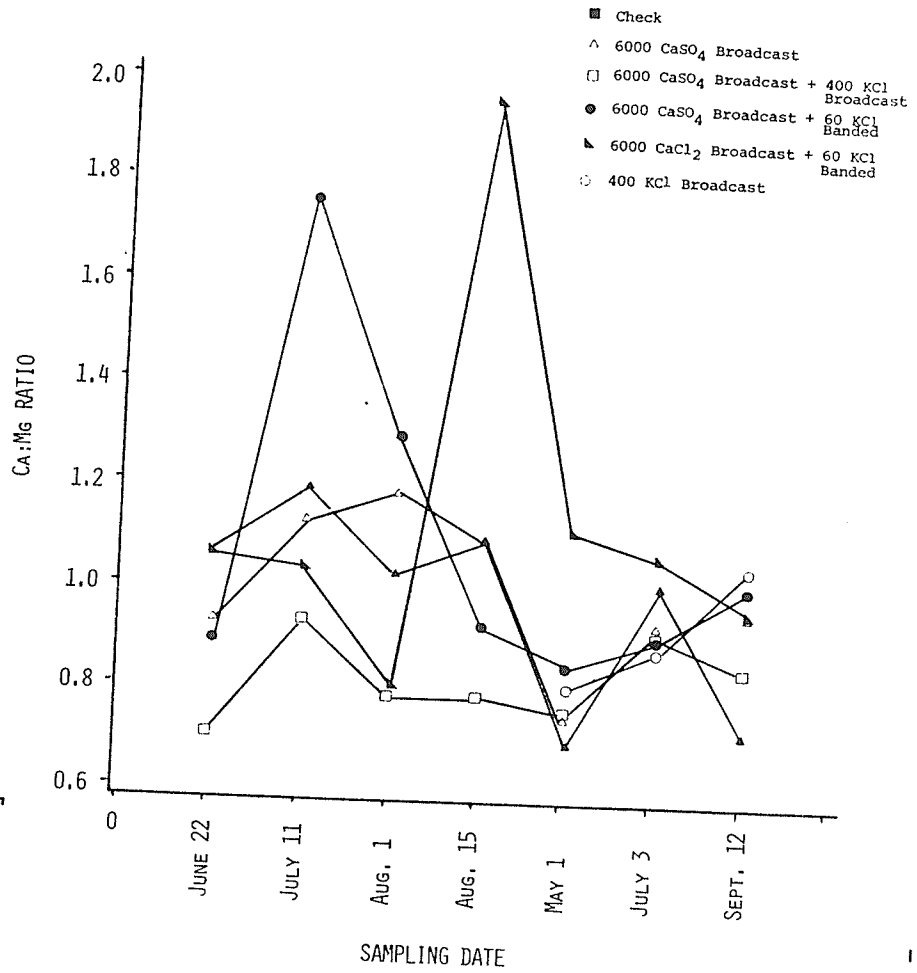

FIG. 5.5.16: RATIO OF Ca:Mg IN THE SOLUTION IN THE 15 TO 30 CM DEPTH AS A FUNCTION OF SAMPLING DATE FOR SELECTED TREATMENTS.

increased when $CaCl_2$ or $CaSO_4$ were added; the increase in ratio being much larger with $CaCl_2$ than with $CaSO_4$ (Fig. 5.5.14). The increase in Ca:Mg in the solution was smaller than expected due to the concomitant increase in concentration of both Ca and Mg in the soil solution when $CaCl_2$ or $CaSO_4$ was added.

The ratio of extractable Ca:Mg in the 15 to 30-cm depth was influenced very little by treatment until July 3, 1985 when the ratio increased in the soils amended with $CaCl_2$ or with $CaSO_4$ plus broadcast KCl (Fig. 5.5.15). This again largely reflects the increase in NH_4 acetate-extractable Ca.

Ratio of Ca:Mg in the solution was increased to some extent by August 15, 1984 by the addition of $CaCl_2$, but was affected only slightly at any other date (Fig. 5.5.16).

The ratio of Ca:Mg on the exchange and in the soil solution in the 30 to 60-cm depth was not influenced by any treatment (data not shown).

5.5.4 Discussion

Essentially all the Ca in $CaCl_2$ added was extractable from the 0 to 15 cm depth on the first sampling date. There was an increase in NH_4 acetate-extractable Ca over time during the first summer in the $CaCl_2$ treated soil and an increase in extractable Ca in the lower soil depths. The total increase in NH_4 acetate-extractable Ca over that of the untreated soil was greater than the amount of Ca added. This could possibly have been due to errors in sampling and/or an increase in Ca concentration in the solution as a result of dissolution of $CaCO_3$ or

other Ca salts due to the high ionic strength of the solution. NH_4 acetate-extractable Ca in the surface layer of the $CaCl_2$ treated soil decreased over the winter and decreased further during the 1985 season. The decrease in the surface layer was coupled to an increase in the lower soil layers, indicating downward movement of Ca.

NH_4 acetate-extractable Ca was initially much lower in the surface layer of the $CaSO_4$ treated soil than in the $CaCl_2$ treated soil, although higher than in the untreated soil. $CaSO_4$ is not as soluble as $CaCl_2$ in the soil or in the NH_4 acetate extractant. Therefore, less Ca was extracted by the NH_4 acetate from the $CaSO_4$ than the $CaCl_2$ treated soil. NH_4 acetate-extractable Ca in the $CaSO_4$ treated soil and the untreated soil decreased between July and August of 1984. As extractable Ca decreased, extractable Mg increased an equivalent amount. Throughout the study period, decreases in extractable Ca tended to be coupled with increases in extractable Mg in the $CaSO_4$ treated and untreated soils. It appeared that Ca was substituting for Mg in some form which was not readily extractable. This substitution tended to occur during the July to August period, when the soils tended to be dry. Drying of soils leads to precipitation of the ions in solution. Since the solubility of Ca salts is less than that of Mg salts, decreases in soil water may have led to preferential precipitation of soil solution Ca as Ca carbonate or other slightly soluble salts.

The simultaneous, but opposing changes in extractable Ca and Mg that occurred with time in these soils led to changes in the ratio of

extractable Ca:Mg which followed the changes in Ca content, but were more pronounced. Extractable Ca increased in the surface layers of the $CaSO_4$ treated soils over the winter period and increased further between May and July. This was apparently due to slow dissolution of the $CaSO_4$ over time. By July 3, 1985, the difference between the extractable Ca in the surface of the $CaSO_4$ treated soils and the untreated soils was equal to the total Ca applied. However, there was also an increase in Ca in the lower depths of the $CaSO_4$ treated soils. Thus it appears that (as found for the $CaCl_2$ treatment) the increase in extractable Ca was greater than the amount of Ca added. This was probably due to dissolution of slightly soluble forms of Ca due to the increased ionic strength of the solution and/or errors in sampling.

Concentration of Ca and Mg in the soil solution of soils treated with $CaCl_2$ or $CaSO_4$ were very high, particularly in the 0 to 15-cm depth of soil. Concentration of Ca was as high as about 180 mM while concentration of Mg was as high as about 75 mM. The high concentration of Ca in the soil solution was a result of adding large amounts of Ca as $CaSO_4$ or $CaCl_2$. Ca would tend to remain in solution due to the large concentration of anions in the soil solution and the effect of increased ionic strength of the soil solution. The increase in ionic strength would shift the equilibrium between exchangeable Ca (solid phase) and Ca in soil solution towards increasing concentration of Ca in the soil solution as a result of the decreasing activity coefficient of Ca with increasing ionic strength.

The high concentration of Mg in the soil solution resulted from

the displacement of Mg from the exchange complex by the added Ca and the increase in ionic strength of the solution.

As would be expected, addition of the soluble salt $CaCl_2$ led to a large increase in the concentration of Ca, Mg and K in the soil solution, in the 0 to 15 and to a lesser extent in the 15 to 30 depths. Concentrations of Ca and Mg were far higher than those which had inhibited plant growth in hydroponic culture. The concentration of these ions in solution remained high throughout the first growing season. Concentration of all cations in the solution decreased between fall and spring sampling. An increase in concentration of Ca, Mg and K was evident in the 30 to 60 cm depth in the spring sampling and the concentration in this depth increased from the spring to the final fall sampling, indicating downward leaching of the soluble cations, resulting in accumulation in the deeper soil layers.

Ca, Mg and K concentration in the soil solution also increased with application of $CaSO_4$. Ca and Mg concentrations were higher than those which had decreased yield in the hydroponic studies, but were initially only approximately 1/4 of the concentration in the $CaCl_2$ treated soil. Movement of cations followed the same pattern as that observed in the $CaCl_2$ treated soil, but the degree of leaching was less due to the lower concentration of the cations in solution and possibly to the lower mobility of SO_4^- as compared to Cl^-.

The ratio of Ca:Mg in the solution increased with additions of $CaCl_2$ or $CaSO_4$, the increase being greater with $CaCl_2$ than with $CaSO_4$. The increase was not as great as would be expected from the amount of Ca applied, since concentration of Mg in solution increased as

concentration of Ca in solution increased. With the exception of the $CaCl_2$ treatment, which showed a large increase in Ca:Mg ratio in both the 0 to 15 and 15 to 30 depth on August 15, 1984, Ca:Mg ratio in the solution was relatively constant throughout the two growing seasons within a treatment.

5.5.5 Conclusions

Application of 6000 kg ha^{-1} of Ca as either $CaCl_2$ or $CaSO_4$ substantially increased NH_4 acetate-extractable Ca and Ca in the soil solution in all soil depths. Large additions of Ca as either $CaCl_2$ or $CaSO_4$ increased the soil solution concentration of Ca and Mg to levels greater than those observed to reduce dry matter yield of barley in hydroponic culture. The increased levels of Ca and Mg persisted throughout the study period. Ca applied as $CaCl_2$ increased Ca and Mg concentration in the soil solution more rapidly than Ca applied as $CaSO_4$, due to the greater solubility of $CaCl_2$ as compared to $CaSO_4$. Increases were observed to the 30 to 60 cm depth by the second year indicating downward movement of Ca and Mg in the soil profile. Addition of $CaCl_2$ promoted more downward movement of Ca and Mg than did addition of $CaSO_4$.

Application of $CaCl_2$ or $CaSO_4$ to a soil high in Mg resulted in a Ca:Mg ratio more favorable for plant growth. However, concentrations of Ca and Mg in soil solutions increased to levels deleterious or toxic to plant growth. Leaching of the excess Ca and Mg would have to occur before beneficial effects of these treatments on plant growth would be

noted. Since leaching of ions in these soils is very slow, the deleterious effects of the initially high concentration of Ca or Mg in soil may negate any economic advantage to this practice.

6.0 Summary and Conclusions

Many soils in arid regions contain high levels of Mg and Ca, which may be detrimental to plant growth. This study was designed to investigate the relation between levels of Ca and Mg in the growth medium and barley yield and nutrient relations. Specific objectives of the project were (a) to determine the effect of varying concentrations of Ca and Mg on the uptake and efflux of K by barley roots, (b) to determine the chemical effects of high levels of Ca and Mg on growth and nutrient content of barley grown in hydroponic culture, (c) to determine the yield and nutrient content of barley grown on soils varying in Ca and Mg content, (d) to determine the relationship between NH_4 acetate-extractable Ca, Mg and K and soil solution concentration and activity of these ions, (e) to determine uptake of Ca, Mg and K as related to content of these ions in the soil, (f) relate soil solution concentration of Ca and Mg to critical concentrations as determined in hydroponic culture and (g) to determine the effects of additions of Ca or K on yield and nutrient content of barley in a variety of soils.

Uptake of K by excised barley roots decreased slightly with increasing concentration of Mg content at low concentrations of Ca, but not at high concentrations of Ca. Efflux of K from intact barley roots decreased when levels of Ca and Mg of up to 8 mM were present in

solution, but increased when concentration of either Ca or Mg increased beyond 8 mM. Efflux was slightly greater with Mg than with Ca.

Yield of barley decreased when concentration of either Ca or Mg increased above 8 mM in hydroponic culture. Concentration of Ca and Mg in the tissue increased with increases in concentration of the respective ion in solution. In contrast to the result of the excised root studies, there was no evidence that either Ca or Mg interfered with the uptake of K by the plant during long term growth in hydroponic culture. Uptake of Zn and Mn by barley plants increased substantially at high concentrations of Mg and Ca. This could possibly have been a result of impaired membrane function.

Concentrations of Ca and Mg in the soil solution of unamended test soils were lower than those which decreased yield in the hydroponic study. Addition of NH_4NO_3 increased concentration of Ca and Mg to potentially toxic levels. NH_4 acetate-extractable K was closely related to concentration and activity of K in the soil solution. In contrast, NH_4 acetate-extractable Ca and Mg were not always closely related to concentration and activity of the respective ion in the soil solution.

Barley yield decreased with increasing levels of Ca or Mg in the soil. Concentrations of Mg and K in the tissue were primarily determined by the levels of these nutrients in the soil. There was no evidence that high levels of Mg interfered with uptake of K by plants grown in a soil system, however, high levels of Mg did restrict the uptake of Ca. Concentrations of Zn and Mn in the soil and in plant

tissue decreased with increasing levels of Mg and Ca in the soil. Concentrations of Zn and Mn in the tissue were at or below critical levels in low yielding plants. Low yield of barley in soils high in Mg and/or Ca could therefore be due either to direct toxicity of Ca or Mg or to deficiencies of Zn and Mn associated with high levels of Ca and Mg in the soil. It is unlikely that yield depression occurred due to interference of Ca or Mg with uptake of K.

Applications of $CaSO_4$ or KCl to soils had no beneficial effect on plant growth with the exception of the Assiniboine complex soil where application of broadcast KCl increased grain yield. Application of $CaSO_4$ or $CaCl_2$ to the Assiniboine complex soil resulted in a Ca:Mg ratio more favorable for plant growth. But, concentration of Ca and Mg in soil solutions increased to levels deleterious to plant growth. Leaching of the excess Ca and Mg would have to occur before beneficial effects of these treatments on plant growth would be noted. Since leaching of these ions in these soils is very slow, the deleterious effects of the initially high concentrations of Ca or Mg in the soil would negate any economic advantage to this practice.

In summary, high concentrations of Ca and Mg in soils led to decreases in yield of barley. Decreases were not due to interference with uptake of K, but rather to either direct toxicity of Ca and/or Mg, or to deficiencies of Mn and/or Zn associated with soils high in Ca and Mg. Amendment of soils high in Mg with $CaSO_4$ or KCl did not generally lead to increased yield in the short term. Application of Mn or Zn may increase crop yield on soils high in Mg and/or Ca. Use of Mn and Zn fertilization on soils high in Mg and/or Ca warrants further study.

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APPENDIX

Table A1: Yield Parameters For Mg-Ca Hydroponics study (Section 5.1)

Treat.	Concentration in solution		Fresh weight of tissue			Dry weight in tissue		
	Ca	Mg	Root	Shoot	Total	Root	Shoot	Total
	----------mM----------		----------g----------			----------g----------		
1	0.5	2	21.39	41.56	62.94	1.34	6.24	7.58
2	1.0	2	47.20	89.18	136.38	2.79	11.72	14.50
3	2.0	2	35.46	79.06	114.52	2.33	11.60	13.94
4	4.0	2	61.01	105.97	166.98	3.76	14.13	17.89
5	2.0	8	53.76	91.48	145.23	3.07	12.83	15.89
6	4.0	8	61.84	107.38	169.22	3.43	14.36	17.79
7	8.0	8	42.53	94.40	136.93	2.73	13.60	16.34
8	16.0	8	21.49	39.14	60.63	1.48	5.86	7.34
9	32.0	8	14.45	21.95	36.40	1.26	3.70	4.96

Table A2: Nutrient Concentrations of nutrients in Tissue for Ca-Mg Hydroponic Study (Section 5.1)

	Concentration in solution		Nutrient Concentration in Tissue							
Treat.	Ca	Mg	Ca in Root	Ca in Shoot	Mg in Root	Mg in Shoot	Na in Root	Na in Shoot	Zn in Root	Zn in Shoot
	-----mM------		----------%----------						----------ppm----------	
1	0.5	2	0.245	0.225	0.212	0.292	0.072	0.105	170.75	208.25
2	1.0	2	0.178	0.282	0.152	0.238	0.090	0.102	70.75	131.50
3	2.0	2	0.259	0.388	0.150	0.205	0.100	0.085	72.50	90.50
4	4.0	2	0.390	0.552	0.155	0.218	0.085	0.072	113.00	144.68
5	2.0	8	0.215	0.310	0.282	0.458	0.102	0.082	70.25	81.25
6	4.0	8	0.262	0.402	0.295	0.398	0.118	0.070	56.75	62.00
7	8.0	8	0.500	0.602	0.302	0.370	0.120	0.068	73.25	85.25
8	16.0	8	1.780	1.055	0.548	0.408	0.078	0.088	203.00	168.25
9	32.0	8	5.020	1.852	0.600	0.415	0.100	0.080	276.75	184.75

Table A3: Dry Matter Yields of Root and Shoot For Ca-Mg Hydroponic Variety Study (Section 5.1)

Variety	Treat	Concentration in solution		Harvest 1		Harvest 2	
		Ca	Mg	Root Dry Weight	Shoot Dry Weight	Root Dry Weight	Shoot Dry Weight
		mM		g		g	
Bonanza	1	2	2	0.294	0.954	1.790	6.085
Bonanza	2	8	2	0.214	0.714	2.375	9.305
Bonanza	3	16	2	0.184	0.750	0.950	4.320
Bonanza	4	2	4	0.295	1.034	1.455	4.845
Bonanza	5	8	4	0.337	0.892	2.400	11.285
Bonanza	6	16	4	0.191	0.732	1.250	4.900
Bonanza	7	2	8	0.230	0.920	0.920	3.730
Bonanza	8	8	8	0.308	1.094	1.825	7.870
Bonanza	9	16	8	0.298	0.820	1.255	4.145
Bonanza	10	2	16	0.129	0.506	0.815	3.630
Bonanza	11	8	16	0.279	0.883	1.080	4.940
Bonanza	12	16	16	0.190	0.608	0.750	3.700
Johnston	1	2	2	0.349	1.548	3.180	16.664
Johnston	2	8	2	0.338	1.346	3.670	21.900
Johnston	3	16	2	0.197	1.088	2.525	15.325
Johnston	4	2	4	0.441	1.746	3.295	16.355
Johnston	5	8	4	0.420	1.717	4.265	22.300
Johnston	6	16	4	0.246	1.146	2.620	14.253
Johnston	7	2	8	0.346	1.396	2.925	14.820
Johnston	8	8	8	0.319	1.600	2.770	14.455
Johnston	9	16	8	0.243	0.896	2.230	8.905
Johnston	10	2	16	0.260	1.064	1.725	9.695
Johnston	11	8	16	0.266	1.021	2.005	10.835
Johnston	12	16	16	0.246	0.814	1.165	6.230

Table A4: Nutrient Concentration of nutrients in the Root and Shoot for Ca-Mg Hydroponic Variety Study (Section 5.1)

Variety	Treat.	Concentration in solution		Concentration of Nutrient in Tissue										
		Ca	Mg	Ca Root	Ca Shoot	Mg Root	Mg Shoot	K Root	K Shoot	Zn Root	Zn Shoot	Cu Shoot	Mn Shoot	Fe Shoot
		mM		%						ppm		ppm		
Bonanza	1	2	2	0.315	0.350	0.180	0.240	3.30	4.75	51.0	50.5	15.5	58.0	51.0
Bonanza	2	8	2	1.055	0.750	0.215	0.165	4.35	4.80	33.0	40.5	14.0	58.0	59.5
Bonanza	3	16	2	1.455	1.880	0.185	0.205	4.20	4.45	71.0	70.5	15.0	57.5	59.0
Bonanza	4	2	4	0.360	0.340	0.345	0.360	3.55	4.60	41.5	49.0	12.0	53.5	39.0
Bonanza	5	8	4	0.985	0.710	0.365	0.240	4.65	4.85	24.0	33.0	13.0	50.5	51.0
Bonanza	6	16	4	1.170	1.245	0.235	0.245	4.75	4.85	46.0	62.0	15.0	60.0	67.5
Bonanza	7	2	8	0.375	0.300	0.555	0.640	3.20	4.30	67.0	77.5	16.5	69.0	61.0
Bonanza	8	8	8	0.665	0.700	0.400	0.375	5.40	4.70	39.5	4.70	15.5	65.0	53.5
Bonanza	9	16	8	4.290	1.410	0.490	0.480	5.15	4.85	69.5	92.0	19.5	165.0	55.5
Bonanza	10	2	16	0.285	0.990	0.575	0.990	4.85	4.50	85.0	108.0	18.0	117.0	67.0
Bonanza	11	8	16	1.980	0.660	0.950	0.730	5.55	5.05	69.5	82.0	20.0	158.0	80.0
Bonanza	12	16	16	0.960	0.075	0.695	0.620	5.70	4.70	94.0	110.5	20.5	153.0	64.5
Johnston	1	2	2	0.305	0.360	0.195	0.205	3.55	4.20	34.5	14.5	7.5	31.5	54.5
Johnston	2	8	2	0.760	0.705	0.190	0.155	4.65	4.90	24.5	17.0	7.5	29.5	72.5
Johnston	3	16	2	1.485	1.475	0.195	0.155	4.60	4.70	47.5	25.0	10.0	32.5	58.5
Johnston	4	2	4	0.355	0.385	0.330	0.320	3.90	4.50	33.5	20.0	9.0	37.5	53.5
Johnston	5	8	4	1.115	0.700	0.430	0.215	4.20	4.80	21.5	15.5	7.0	26.0	67.0
Johnston	6	16	4	0.920	1.180	0.207	0.195	4.93	5.00	34.3	32.5	11.5	40.0	72.5
Johnston	7	2	8	0.245	0.280	0.450	0.440	4.15	4.60	43.0	24.0	10.5	35.0	50.5
Johnston	8	8	8	0.800	0.705	0.490	0.355	5.45	4.80	26.5	20.5	9.0	28.0	62.5
Johnston	9	16	8	5.145	1.220	0.500	0.380	4.60	5.05	50.5	62.0	13.0	103.0	56.0
Johnston	10	2	16	0.285	0.240	0.665	0.720	5.40	5.15	57.0	52.0	16.0	58.5	70.0
Johnston	11	8	16	1.595	0.645	0.935	0.610	5.40	5.55	56.0	63.5	15.0	115.0	85.0
Johnston	12	16	16	2.530	1.035	0.780	0.580	4.80	4.95	85.5	73.0	15.0	92.5	78.5

Table A5: Total uptake of nutrients by plants for Ca - Mg hydroponic variety study (Section 5.1)

Variety	Treat.	Concentration in solution Ca	Mg	Total uptake by Tissue Ca	Mg	K	Cu Uptake	Zn Uptake	Mn Uptake	Fe Uptake
		-----mM------		----------g----------			----------Mg----------			
Bonanza	1	2	2	0.027	0.0177	0.349	0.096	0.395	0.370	0.313
Bonanza	2	8	2	0.095	0.0202	0.550	0.130	0.461	0.568	0.566
Bonanza	3	16	2	0.092	0.0104	0.239	0.065	0.364	0.248	0.252
Bonanza	4	2	4	0.022	0.0225	0.270	0.057	0.307	0.266	0.187
Bonanza	5	8	4	0.104	0.0357	0.660	0.146	0.427	0.575	0.578
Bonanza	6	16	4	0.076	0.0151	0.296	0.072	0.359	0.272	0.317
Bonanza	7	2	8	0.013	0.0259	0.185	0.057	0.277	0.212	0.266
Bonanza	8	8	8	0.067	0.0368	0.468	0.122	0.458	0.511	0.421
Bonanza	9	16	8	0.112	0.0259	0.266	0.081	0.469	0.685	0.230
Bonanza	10	2	16	0.012	0.0406	0.204	0.065	0.439	0.409	0.247
Bonanza	11	8	16	0.054	0.0456	0.308	0.096	0.469	0.781	0.391
Bonanza	12	16	16	0.054	0.0278	0.217	0.073	0.474	0.562	0.231
Johnston	1	2	2	0.070	0.0403	0.810	0.125	0.352	0.523	0.904
Johnston	2	8	2	0.182	0.0409	1.243	0.164	0.459	0.638	1.570
Johnston	3	16	2	0.262	0.0285	0.839	0.153	0.503	0.499	0.906
Johnston	4	2	4	0.075	0.0632	0.866	0.145	0.434	0.609	0.881
Johnston	5	8	4	0.204	0.0663	1.250	0.156	0.437	0.580	1.495
Johnston	6	16	4	0.170	0.0293	0.748	0.145	0.487	0.504	0.914
Johnston	7	2	8	0.049	0.0782	0.805	0.157	0.484	0.523	0.750
Johnston	8	8	8	0.123	0.0644	0.847	0.130	0.370	0.400	0.910
Johnston	9	16	8	0.227	0.0450	0.554	0.116	0.670	0.910	0.516
Johnston	10	2	16	0.028	0.0811	0.591	0.153	0.587	0.555	0.676
Johnston	11	8	16	0.103	0.0846	0.708	0.158	0.772	1.196	0.914
Johnston	12	16	6	0.094	0.0452	0.364	0.093	0.554	0.575	0.489