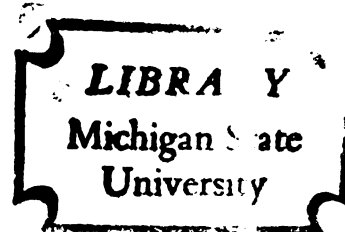


MAGNESIUM RELEASE AND UPTAKE
FROM SELECTED MICHIGAN SOILS

Thesis for the Degree of Ph. D.
MICHIGAN STATE UNIVERSITY
DONALD ROBERT CHRISTENSON
1968



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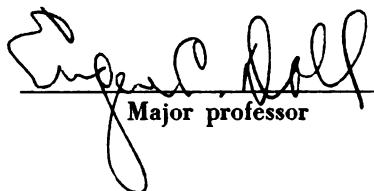
Magnesium Release and Uptake From
Selected Michigan Soils

presented by

Donald Robert Christenson

has been accepted towards fulfillment
of the requirements for

Ph.D. degree in Soil Science


Major professor

Date April 24, 1968

ABSTRACT

MAGNESIUM RELEASE AND UPTAKE FROM SELECTED MICHIGAN SOILS

By Donald Robert Christenson

Selected Michigan soils were studied to evaluate:
1) the effect of soil type and rate of magnesium application on magnesium uptake by successive crops of oats and on the extractable magnesium levels of soils; 2) the effect of soil calcium level and soil pH on magnesium release from the soil and uptake by oats; and 3) the relation of type of soil minerals in different soil fractions to the availability of magnesium for plants. The seven soils studied were: Munising fine sandy loam from a cropped and an uncropped location, Karlin loamy sand from one location, Montcalm loamy sand from three different locations and Sims clay loam from one location.

In the first experiment, three levels of magnesium (0, 10, and 20 ppm) were applied to these soils and to a 5% bentonite-sand mixture. Seven consecutive crops of oats were grown without any additional magnesium application.

Yield increases due to applied magnesium were obtained only after the third crop. After six crops had been removed, the level of readily available magnesium was extremely low on all soils.

The linear correlation coefficient between the ratio of potassium:magnesium in the soil and the uptake of magnesium by plants was -0.418 . When soil magnesium alone was used, rather than potassium:magnesium, the correlation coefficient was 0.243 .

In a second experiment, different calcium levels were applied to each of three pH levels (pH 4.5, 5.5, and 6.5) and eight consecutive crops of oats were grown.

Soil pH had more of an effect on yield, tissue magnesium content (%) and magnesium uptake (mg/culture) than did calcium level. Yields at pH 6.5 were 1.3 times greater than at pH 4.5. Magnesium content of the tissue was greater at pH 4.5 than at pH 6.5, which was attributed to increased growth at the higher pH level.

Release of magnesium from nonextractable forms was 1.8 times as great when calcium carbonate was applied as when calcium hydroxide was applied, while the total uptake for the eight crops was 15% less. These differences were not explained by the data obtained.

Sufficient quantity of different particle sized fractions from soils and clay minerals to supply 20 milligrams of magnesium were mixed quartz sand and cropped to two crops of oats.

The relative order of magnesium availability according to particle size was as follows:

$< 0.08 = 0.08-0.2 > 0.2-2.0 = 2.0-20 \geq 20-50\mu$ total soil

Chlorite supplied more magnesium than bentonite; bentonite approximately the same as soil clays.

Release of magnesium was linearly correlated with magnesium content of the fractions for the $0.2-2.0\mu$ clay, but not for the 0.08μ , $2.0-20\mu$ or $20-50\mu$ fraction. This indicated that magnesium was released from interlayer sites for the $0.2-2.0\mu$ clay and for the second crop for the $0.08-0.2\mu$ clay. The release in the other fractions was predominantly from the crystal edges.

Differential release of magnesium between the clay fractions could not be related to differences in kinds of minerals present.

X-ray diffraction patterns of some soil fractions indicate that interlayer material was removed by cropping.

MAGNESIUM RELEASE AND UPTAKE FROM
SELECTED MICHIGAN SOILS

By

Donald Robert Christenson

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

Department of Soil Science

1968

G51456

TO CAROL

This thesis is dedicated to my wife

ACKNOWLEDGEMENTS

The author wishes to express his appreciation to Dr. E. C. Doll for his patient guidance in the conduct of these studies.

A special note of appreciation is extended to Dr. K. V. Raman for his suggestions and assistance in the mineralogical studies.

The writer is grateful to Mr. O. G. Pierce for his assistance in the laboratory.

Special acknowledgement is given to Miss. J. K. Bennett for her effort conducting the many laboratory analyses.

The writer would also like to thank Mrs. Nellie Galuzzi for her assistance in the statistical analyses of the data.

Financial assistance by International Minerals and Chemical Corporation is gratefully acknowledged.

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MAGNESIUM RELEASE AND UPTAKE FROM SELECTED MICHIGAN SOILS

INTRODUCTION

Magnesium was first shown to be essential for plant growth in the latter part of the 19th century (Loew, 1892). Since that time it has been proven to be metabolically linked in the activation of several enzymes involved in glycolysis and respiration. Magnesium is also the coordinating atom of the chlorophyll molecule.

Geologically, magnesium ranks as the seventh most abundant element in the earth's crust. During the primordial stages of differentiation of the earth, i.e., cooling of the molten magma, the distribution of the various chemical elements was essentially controlled by their chemical affinity for oxygen and sulfur. Crystallization involved a selection of various atomic ions according to their size and coordination number. Thus, ions of similar size and coordination number will tend to appear in the same crystal lattice. According to Goldschmidt (1945), the possibility

of large scale isomorphous substitution in minerals from magmas will be limited to pairs of ions in which the radii do not differ by more than 10-15 per cent. Magnesium with an ionic radius of $0.78 \text{ \AA}$ and ferrous iron with a radius of $0.83 \text{ \AA}$ freely replace each other in ionic crystals. Thus, magnesium and iron are found occupying the same coordination habitat in many minerals.

In soils, magnesium is a constituent of dolomitic limestone and of primary silicate minerals including biotite, hornblende, augite and olivine. Magnesium occupies an octahedral coordinating position in secondary silicates which include talc, serpentine, chlorite, vermiculite, illite and montmorillonite. It is also present in trace amounts in kaolinitic minerals. In addition, magnesium occupies cation exchange sites on the surfaces of silicate minerals and organic matter.

Even though magnesium deficiencies have been reported on acid podzols in Europe and on the acid soils of the Gulf and Atlantic coastal states, only a few instances of magnesium deficiency had been reported on Michigan soils and crops until 1963. Tobin and Lawton (1962) found no yield response to magnesium fertilizers on 14 different

field crops on 37 different soil types. However, their results did show that the uptake of magnesium was generally increased in most crops by the application of $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ (Epsom salts) or $\text{K}_2\text{SO}_4 \cdot 2\text{MgSO}_4$ (sulfate of potash-magnesia). They concluded that the application of magnesium containing fertilizers was not necessary at that time. The possibility that magnesium deficiencies might occur in the future was stressed because of more intensive cropping accompanied by higher yields and larger applications of high-analysis fertilizers.

In 1964 in Michigan, Doll and Hossner reported a definite response to applied magnesium on Karlin and Kalkaska soils, but no response on Emmet and Montcalm soils. The pH and exchangeable magnesium potassium and calcium levels were comparable on the Kalkaska and Montcalm soils. These workers felt that factors other than soil acidity and exchangeable cation levels must have affected the availability of magnesium and thus the oat yields on these soils.

This study was undertaken to evaluate the following factors on selected Michigan soils:

1. Effect of soil type and rate of magnesium application on magnesium uptake by successive crops of oats and on the extractable magnesium levels of soils in a greenhouse study.

2. Effect of soil calcium level and soil pH on magnesium release from soil and uptake by oats.
3. Relation of type of soil minerals in different soil fractions to the availability of magnesium for plants.

LITERATURE REVIEW

Magnesium Deficiency Symptoms in Plants

A description of Mg deficiency has been given by Cook and Millar (1953) as follows:

Symptoms of magnesium deficiency first appear on the older leaves. Yellowing appears in patches between the veins and around the leaf edges. Leaf edges usually roll slightly. As the magnesium-deficient leaf becomes older, the yellow areas scattered over the leaf blade become necrotic until finally the tissue may disintegrate to leave holes in the leaf.

Carolus (1933) described the condition in potatoes as characterized by (1) a yellowing of the leaves of the plant, the lower leaves and especially the apical leaflets yellowing from the margin toward the midrib, (2) stunted growth of the plant during the early stages of growth and (3) new terminal growth of the plant consists of small half-closed leaves purplish-gray in color. On oats it has been described as appearing like a "string of pearls" within the leaves (Schachtschabel, 1957). In a discussion of early work on Mg (Ferrari and Sluijsmans, 1955), it was mentioned that this disorder was called "Hooghalen disease" or "acid

disease." In cereals it was characterized as a "curdling" of the chlorophyll giving the leaves a mottled ("tigered") appearance. As the condition progressed, the amount of chlorophyll decreased and the leaves became yellow colored. In many cases the symptoms would occur on a young growing plant, but would disappear before the plant reached maturity.

Potassium-Magnesium Relationships in Soils and Plants

The fact that high rates of potassium applied to soils can induce Mg deficiency in crops is well documented (Adams and Henderson, 1962; Boyton and Burrill, 1944; Carolus, 1937; Constable, 1955; Cooper and Wallace, 1937; Drosdoff and Kenworthy, 1944; Drouineau and Nageotte, 1941; Embelton and Boyton, 1950; Hovland and Caldwell, 1960; Lucas and Scarseth, 1947; Scharrer and Mengel, 1958; Sluijsmanns et al., 1959 and many others). In many cases the deficiency of Mg was confirmed by the low content of Mg in the tissue with an accompanying high K content. In the literature reviewed, no consistent ratio between these ions was established in the plant which was definitely related to deficiency or sufficiency. However, Hossner et al. (1968)

reported that when soil K: Mg ratio exceeded five, K- induced Mg deficiency occurred on potatoes grown on an acid sandy podzol in northern Michigan. Other reported values for this ratio have ranged from 6:1 to 3:1. The dominant factor in Mg uptake appears to be the ratio between soil K and Mg levels or even the soil K level rather than the Mg level in the soil. Wehunt and Purvis (1954) reported a correlation coefficient (r) of -0.69 between leaf Mg and available K in the soil. Tucker and Smith (1952) stated that K exerted control over Mg rather than Mg over K.

The occurrence of K-induced Mg deficiency can be explained in two ways. First, according to the law of mass action, additions of K to the soil releases exchangeable Mg to the soil solution which may be subsequently leached from the root zone. However, this does not completely explain K-induced Mg deficiency because it occurs in the greenhouse experiments where leaching is not a factor. Secondly, an antagonism between the two ions may exist within the plant (translocation mechanism) or at the root surface (uptake-mechanism). Scharrer and Mengel (1958) reported that a physiological antagonism exists which is independent of the colloidal effects of the soil and of the anion of the K salt

applied. Their results suggest that this antagonism is restricted to the green tissues, especially the leaves. Cain (1955), working with the apple trees in sand cultures, found that the effect of K in reducing the leaf concentration of Mg was much greater than was that of Mg in reducing leaf concentration of K. He suggested that the interaction or antagonism between these two nutrient elements was associated entirely within the plant.

Other workers reported that when large applications of potassium are applied, the Mg concentration in the leaves is decreased (Foy and Barber, 1959; Hashimoto, 1955; Hovland and Caldwell, 1960; Larsen et al., 1959; Lucas and Scarseth, 1947; Southwick, 1943; and others).

This evidence indicates that this K-Mg relationship is probably localized, for the most part, in the uptake or translocation of these ions. However, no evidence was found in the literature explaining a mechanism for this antagonism.

Calcium-Magnesium Relationships in Plants

Several investigators have reported that high Ca:Mg ratios suppress Mg uptake by plants (Blair et al., 1939; Halstead, et al., 1958; Jacoby, 1961; Salmon, 1964; and

others). As in the case of potassium, this appears to be an interaction within the plant rather than completely soil related. Moore et al. (1961), reported that Mg absorption by 6-day old excised barley roots was sensitive to low temperature and dinitrophenol. Excess Mg absorption was also associated with organic acid production in the root, further confirming the metabolic nature of the process. A large part of the Mg absorption was effectively blocked by Ca. This blockage was very pronounced even at low Ca concentrations where there was a net loss of Ca from the tissue. Jacoby (1961), using a split-root technique, demonstrated that impaired Mg uptake at the Mg:Ca ratio of 0.05 in the medium was not due to low Mg content, but rather to an excess of Ca. Komai and Noda (1959) reported that Ca decreased the rate of Mg uptake by barley roots.

On the other hand, when acid soils are limed, it has been reported that Mg uptake is increased over unlimed treatments (Doll and Hossner, 1964; Korableva, 1954; Carolus, 1933). This may be attributed to two factors. First, even though calcitic sources of lime were used, these materials may contain "contaminating" Mg. Secondly, the associated increase in pH decreases the factors of H ion injury to the

plant root and blockage of uptake mechanisms. Rains et al. (1964) stated that H ions appear to block the uptake of nutrients or damaged the carrier system. The presence of Ca ions minimizes injury. Moore et al. (1961) reported that Mg uptake from MgBr_2 increased with rising pH and Ca level, reaching a maximum at pH 6.0-6.5.

Although there is no direct evidence for such a statement, it appears that a minimum ratio of Ca:Mg is required for Mg uptake, there is also a maximum ratio above which Mg uptake is suppressed. Bear and Prince (1945) postulated that each cation has at least two functions in the plant, one specific and the other(s) of the type that can be performed by the other three cations (K, Ca, Mg). Once the supply of each cation is adequate to meet the specific need for it, there can be a wide range in ratios and quantities that are absorbed by the plant to meet its total needs.

Magnesium Fertilizer Recommendations Based on Soil Tests

In the Michigan State University Soil Testing Laboratory, Mg is extracted from soils with neutral N ammonium

acetate (Doll and Christenson, 1966). Soil pH is determined on a 1:1 soil to water ratio using a glass electrode. Magnesium recommendations are made on this basis. Dolomitic limestone is recommended for acid sandy soils ($\text{pH} < 6.5$) which have less than 75 pounds of Mg per acre. On sandy soils above pH 6.5, which contain less than 75 pounds Mg, soluble Mg fertilizers are recommended at a rate of 50 to 100 pounds of Mg per acre. Magnesium sulfate, sulfate of potash-magnesia or magnesium oxide are all considered satisfactory carriers of Mg. Foliar sprays are also suggested at a rate of 10 to 20 pounds of magnesium sulfate in 100 gallons applied to an acre. When soil tests indicate that the K/Mg ratio is greater than 4:1, crops should be watched for Mg deficiency.

Schachtschabel (1957) reported that a good correlation was obtained between CaCl_2 extracted Mg and availability to the plant. The critical level reported was 100 pounds per acre.

Lancaster (1958) reported an excellent chance of response when less than 3% of the exchange complex was Mg saturated.

Adams and Henderson (1962) reported that soils with $< 4\%$ of the exchange capacity Mg saturated were deficient.

Fixation of Magnesium in Soils

MacIntire and Shaw (1926) were among the first to report that magnesium was fixed in soils. Four years after the application of 3750 pounds of CaCO_3 equivalent per acre of MgO or dolomitic limestone, the amount of fixation was about 14 times the average loss due to leaching. After four years of outdoor exposure without cropping or cultivation MacIntire et al. (1934) found that fixation was greater from applications of 32 tons than 8 tons per acre. The adsorbed Mg was found to be resistant to 8 successive leachings with NH_4Cl . An increase in soluble aluminum on the Mg treatments suggested that Mg had disrupted the Al complex, possibly in the octahedral layer. Cheminade and Drouineau (1936) suggested that Mg was fixed by octahedral coordination at exposed edges of clay particles. Echevin (1935), in leaching studies, also suggested that Mg was adsorbed by soils. Out of 20 New Jersey soils Prince et al. (1947) found that Mg fixation occurred on one-half of the soils studied. Hossner et al. (1968) found that a significant portion of Mg applied in the spring was not extracted by ammonium acetate the following fall. No data were presented to show whether or not this loss was due to fixation or leaching.

Release of Nonexchangeable Magnesium

Release of any element to a form available for plants is essentially brought about by processes collectively known as weathering. Jackson et al. (1948) described weathering as a function of capacity and intensity factors. Intensity factors are: temperature, leaching rate, acidity, the degree and fluctuation of oxidation; capacity factors: specific surface of particles and specific nature of the mineral. Weathering of primary minerals in nature may release substantial amounts of plant nutrients. Vageler (1933) states that tropical soils are worthless unless their content of primary minerals is substantial. In Indonesian soils, Van Der Marel (1947) found that primary minerals were the source of nearly all of the calcium, magnesium and potassium for plant growth.

Lea and Smith (1938) found a very low availability of Mg from serpentine and olivine in pot experiments in the greenhouse. Longstaff and Graham (1951) measured the release of Mg from hornblende, olivine, talc, magnesite and dolomite by cropping sand cultures with these minerals as the source of Mg. Plants supplied with magnesite and dolomite were able to utilize 45 and 66.5 per cent, respectively,

of the total magnesium present. Olivine supplied sufficient magnesium to produce nearly the same amount of growth. Talc and hornblende supplied insufficient magnesium to produce nearly the same amount of growth. Talc and hornblend supplied insufficient amounts of Mg for plant growth.

Colloidal inorganic soil materials could possibly break down sufficiently to result in a portion of the lattice Mg becoming available for plant consumption (Albrecht, 1938) .

Rudgers (1966) found calcined magnesite and calcined brucite a better source of Mg when coated on mono-ammonium phosphate or dicalcium phosphate than uncalcined brucite or serpentine applied in the same manner. Hossner et al. (1968) reported that from 15 to 20 pounds of Mg was released between the fall and the following spring on a Karlin loamy sand. Noda et al (1956) found that by increasing the K:Mg ratio, Mg released from bentonite and kaolinite was decreased.

Release of Lattice Magnesium by
Chemical Weathering

Magnesium is generally found in primary and secondary minerals in an octahedral coordination and has been thought to be released too slowly to meet the requirements of rapidly growing plants. Personal observation, that by co-workers and reports in the literature (Ferrari and Sluijsmans (1955) support this observation. Fast growing plants will develop Mg deficiency symptoms, but later will "outgrow" these symptoms with no apparent decrease in yield.

Laboratory methods of measuring the release of Mg from minerals generally consist of acid dissolution methods. Stahlberg (1961) found that augite and hornblende released more Mg than Ca when boiled in normal HCl; phlogopite and particularly biotite were less stable. Semb and Oien (1961) found that the solubility of olivine was directly proportional to the acidity. Octahedral cations of biotite and glauconite were completely removed by heating (74-100° C) in 2 N HCl for eight hours (Gastuche and Fripiat, 1962). It was demonstrated that octahedral cations were much more mobile and susceptible to acid dissolution than were those in the tetrahedral layer. Several mechanisms have been

proposed to describe the dissolution or removal of ions from minerals. Barshad (1960) reported that the relative proportions of Mg and Al displaced was dependent on the total MgO and Al_2O_3 contents of the crystal structure of the acidified minerals, the nature of the acidifying solution and the technique used to acidify the clay. He postulated, on the basis of geometry of the crystal, that the H ions enter the interior of the lattice as a bare proton. Droste (1960) suggests that the weathering of the brucite layer of chlorites includes a hydration envelope at the weathered edges of the lattice. This is caused by the conversion of exposed hydroxyl groups to water by hydrogen ions. Each hydroxyl would leave half of a divalent charge and one-third of a trivalent charge with a resulting positive charge accumulation. Ultimately this would lead to a certain number of octahedral cations free to go into solution and leave the structure. Only those cations necessary to balance the charge of the mica layers would persist in the lattice. Oxidation of iron in the lattice with the subsequent release of magnesium from chlorite and illite was proposed by Murray and Leininger (1956).

Release of Lattice Ions as a Rate Process

Release of lattice ions has been characterized as a first order kinetic reaction. Kerr et al. (1956) found that release from H-hectorite followed two consecutive first order reactions. First, the strong acid underwent a rapid, spontaneous reaction to weak acid. Secondly, a slower spontaneous reaction of the weak acid yielded a neutral clay. For each milliequivalent of strong-acid hydrogen undergoing reaction, one millequivalent of Mg ion was released from the crystal lattice. Besides, for each millequivalent of weak acid hydrogen ion undergoing reaction, one millimole of silica was released from the lattice. They proposed that the rate determining step in the first reaction consisted of a proton attacking the monohydroxylated Mg at the crystal edge resulting in the formation of water. This would release the Mg ion from the lattice and a second proton would become attached to the highly nucleophilic Si-O system. The resulting dihydroxylated silicon would be a monobasic weak acid. From this acid resulted the second-first order reaction. This was envisioned to be a hydrolysis or depolymerization releasing a low molecular weight silicate or silicic acid. After the release of the Mg and silica the freshly

exposed crystal edge would be identical with the crystal before attack and the process could be repeated.

Removal of lattice ions which do not grossly alter the structure have also been reported. Mortland (1958), Ellis and Mortland (1959), and Mortland and Ellis (1959) showed that removal of K from vermiculite and biotite by 0.1 N CaCl could be described by a first-order reaction; also that the rate limiting step was film diffusion. Diffusion of ions through a solution film is a first-order reaction and can be written as:

$$\ln \frac{dC}{dt} = \ln B - \frac{qD}{VL} t$$

where c is the amount of ion remaining in the mineral at time t , B is a constant, q is the cross-sectional area of the diffusion film, V is the volume of the diffusion chamber, L the thickness of the diffusion film, and D the diffusion coefficient. Meller and Bright (1958) reported that diffusion of an ion from a mineral particle could be represented by a similar equation, except that a reaction constant, A , was substituted for the quantity, $\frac{qD}{VL}$.

Hossner (1956) found that the logarithmic rate of release of Mg from vermiculite, mica, and prochlorite plotted against time decreased linearly after an initial

nonlinear decline of about 3000 minutes. Release of Mg was affected by pH and particle size. As either decreased the rate of Mg released increased.

Mortland and Lawton (1961), working with biotite, noted that K release from different particle sizes depended upon stage of alteration. Potassium concentration of the solution phase was related to total K content of the biotite after equilibrating for 90 days. The rate of release of lattice potassium from 2:1 minerals was described by the following equation:

$$r = B(C_1 - C)$$

where r is rate of release of lattice K, B is the diffusion velocity constant containing the diffusion coefficient and geometry parameters, C_1 is the activity of K in the lattice and C is the activity of K in the solution phase. As long as C_1 is greater than C , release occurs. When r is 0, then $C_1 = C$ allowing the determination of the activity of the lattice K by measuring the activity of the K in the solution phase at equilibrium.

Doll et al. (1965) cropped various fractions of six soils. The K content of the silt and clay was linearly correlated with the logarithm of the K uptake from each fraction,

except for the silt fraction of one soil. No correlation was noted between the uptake of K and the K content of the entire soil. In an equilibrium experiment, the concentration of K in solution from the different clays was linearly correlated with the K content of the clay. They suggested that the plants acted as a sink to remove released K from solution in the cropping experiments, while released K remained in solution and would tend to depress further release of K in the equilibrium experiment.

MATERIALS AND METHODS

A. Sources of Soils and Minerals

Soils were selected from different locations within a soil series and from different soil series with known differences in Mg level, history of response to applied Mg and different mineralogical composition. The initial Mg level and pH of the series are listed in Table 1. Samples from the A_p horizon of these soils were collected from field locations during August and September, air dried and screened through a one-quarter inch screen. Two-hundred pounds of each soil was thoroughly mixed and saved for these studies.

Bentonite and chlorite minerals were obtained from Ward's Natural Science Establishment. The minerals were broken into small pieces with a hammer and chisel. These pieces were then ground in a ball mill. Contents were removed every 8-16 hours, screened through a 12 mesh sieve and the coarse material replaced for continued grinding. Finally, the ground material was mixed and saved for further use.

Table 1.--Soil series, collection site, initial pH, initial Mg level and particle size distribution for soils used in these studies.

Soil Series	Location	pH	Mg	Separate		
				Sand	Silt	Clay
			ppm	-----	%-----	-----
Munising fine* sandy loam (1)**	Houghton county	4.7	43	72.2	23.7	4.1
Munising fine sandy loam (2)	Houghton county	5.1	30	74.0	21.0	5.0
Karlin loamy sand	Otsego county	4.6	11	81.5	14.5	4.0
Montcalm loamy sand (1)	Montcalm county	4.8	29	73.5	21.7	4.8
Montcalm loamy sand (2)	Montcalm county	5.9	91	68.7	25.6	5.7
Montcalm loamy sand (3)	Montcalm county	7.1	93	75.0	18.4	5.6
Sims clay loam	Saginaw county	7.7	181	34.4	33.5	32.1

*Not recently cropped, surface 6 inches sampled.

**Numbers in parenthesis refer to different locations within a series.

B. Fractionation of Soils and Minerals

In order to separate the various sized fractions from the soils, sufficient soil to yield the desired quantity of clay was buffered with sodium acetate-acetic acid buffer, pH 4.8, and then treated with H_2O_2 to remove the organic matter, followed by leaching with more buffer and then with water to remove the salts. The treated soil was suspended in water and the pH adjusted to the phenolphthalein end-point with NaOH. Dispersion was completed by shaking the suspension for 48 hours on a reciprocating shaker, with periodic readjustments of the pH. The sand fraction ($>50\mu$) was separated by wet sieving and the silt ($2-50\mu$) fraction separated from the clay by sedimentation. The clay was separated into fine, medium, and coarse fractions (<0.08 , $0.08-0.2$ and $0.2-2\mu$ respectively) with a Sharples centrifuge. Free iron was removed from the clay prior to this separation by treatment with sodium citrate and sodium dithionite as outlined by Jackson (1956).

Samples of the clay minerals as prepared in the ball mill, were placed in water and ground in a Waring blender. The minerals were then sodium saturated with repeated washings of NaCl and then washed free of chloride; followed by

suspension in water and separation into the three clay sized fractions as above.

The silt was separated into a fine fraction (2-20 μ), and a coarse fraction (20-50 μ) by sedimentation. All fractions were saturated with Ca^{++} and dialyzed free of excess salts against distilled water. Several drops of toluene were added to retard microbial growth and the samples were stored in that condition.

C. Cropping Procedures and Treatments

1. General Greenhouse Procedure

Oats (variety Garry) was used as an indicator crop in all of the studies. The seeds were planted at a depth of 1/2 inch and thinned to the required number of plants after 10-14 days of growth. The plants were harvested when the inflorescence was beginning to emerge from the sheath, except on the cropping of soil fractions which is described in that section. In all cases, the harvested tissues were dried at 65° C, weighed, ground to pass a 20 mesh sieve and saved for chemical analysis.

Cultures were watered daily as required and brought to field capacity once per week except on the cropping of soil fractions where it was required daily.

2. Intensive Cropping Study

In order to determine the pattern of response to applied Mg and the supplying characteristics of these soils, seven successive crops were grown in the greenhouse. Initially, 3600 grams of soil and the same amount of a quartz sand-vermiculite mixture (5% clay material) were weighed into gallon cans lined with plastic sacks. Rates of 0, 10, and 20 parts per million (ppm) were established using $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ (Epsom salts). The granulated salt was mixed with the soil prior to placement into cans. Each treatment on each soil was replicated four times. Each pot was brought to field capacity with distilled water and seeded with 30 seeds; later thinned to 23 plants. Initially, 50 ppm of N as NH_4NO_3 , P as $\text{Ca}(\text{H}_2\text{PO}_4)_2 \cdot \text{H}_2\text{O}$ and K as KCl were added in solution with the initial water. Supplemental N at a rate of 25ppm was added as NH_4NO_3 to the first two crops; thereafter supplemental N was added as $\text{Ca}(\text{NO}_3)_2$. On successive crops, these amounts of N were used, but P and K were added at rates considered adequate based on soil tests.

Prior to seeding the third crop, 3.6 ml of Hoaglund's (1950) micronutrient solution was added to each pot.

Between seedings, the soils were removed from each pot while the soil was still moist, screened through a

one-quarter inch sieve, mixed and replaced with the water and nutrients added as described above. A sample of soil was removed for chemical analysis after the soil was mixed.

3. pH-Calcium Level Study

Calcium and pH levels were established on pots containing 3600 gm of Karlin loamy sand soil. Treatments are given in Table 2.

Table 2.--Treatments, initial pH and initial Ca levels for the pH-Ca level study.

Treatment Code	Treatment	pH	Ca
pH_1Ca_1	118 ppm Al as $\text{Al}_2(\text{SO}_4)_3$	4.3	184
pH_1Ca_2	118 ppm Al as $\text{Al}_2(\text{SO}_4)_3$ 1100 ppm Ca as CaSO_4	4.2	957
pH_2Ca_1	512 ppm Ca as CaCO_3	5.7	644
pH_2Ca_2	512 ppm Ca as CaCO_3 514 ppm Ca as CaSO_4	5.4	975
$\text{pH}_3\text{Ca}_{2a}$	1012 ppm Ca as CaCO_3	6.7	1030
$\text{pH}_3\text{Ca}_{2b}$	1012 ppm Ca as $\text{Ca}(\text{OH})_2$	6.5	883
Check	Check (No amendments)	4.6	239

The salts listed in Table 2 were mixed with the soil which was then placed in gallon cans lined with a plastic sack. Each treatment was replicated four times. Sufficient water was added to each pot to bring the soil to field capacity. The plastic was tied around a piece of glass tubing inserted into the soil and the soil was incubated for 8 weeks. Moisture content of the soil was readjusted to field capacity periodically during the incubation period. The soil was removed from the pots and prepared for cropping as described in the previous section. Initially, 50 ppm of each--N, P, and K--was added as the same sources as described for the previous experiment.

Eight successive crops were grown with the same general procedure as described under the intensive cropping section except that supplemental N was added as NH_4NO_3 . Soil was kept moist between crops, except crops 1 and 2, 6 and 7.

4. Cropping of Soil and Clay Mineral Fractions

In order to crop the various sized fractions, sufficient amounts of each fraction and of each soil to supply 20 mg of Mg were placed in a waxed carton and mixed with 100 gm

of acid washed quartz sand. Five-hundred grams of sand was placed over this and sufficient water added to bring the sand to 10% moisture. Sixteen oat seeds were placed over the surface of the sand and were covered with an additional 100 gms of sand. A modified Hoagland's solution (1950) (less Mg, and 4 ppm Fe as Chel 138[®]) was added at a rate of 50 ml each week during the growth. Plants were harvested when the vegetative growth had reached what was considered its maximum.

After the first crop was removed, the fractions were recovered by wet sieving on a 270 mesh sieve. The exchangeable Mg was removed by leaching with CaCl_2 and the excess salts were removed by leaching with water. Each separate from each pot was suspended in 50 ml of water and a 5 ml aliquot was removed for chemical analysis. The remainder of the sample was replaced into the carton as described above, except that an additional 100 gm of sand plus the additional water requirement were added. The second crop was grown in the same manner and was harvested when the Mg deficiency symptoms were considered to be at the maximum.

[®] Sodium ferric ethylenediamine di-(o-hydroxyphenylacetate), Geigy Chemical Corporation.

After the second crop was removed the separates were recovered in the same manner as above. The fractions were Ca saturated and dialyzed against distilled water. The fractions were saved for x-ray and chemical analysis.

D. Laboratory Procedures

1. Soil Analysis

Soil samples were air dried and sieved through a 20 mesh sieve. The cations were extracted with 1 N ammonium acetate using a 1:8 soil to solution ratio and one hour shaking time. Clear extracts were obtained by filtering. Potassium was determined on a Coleman Model 21 flame photometer; Ca and Mg on a Perkin Elmer Model 290 or 303 absorption spectrophotometer using 1500 ppm La to suppress interfering ions. Water soluble Mg was determined in the same manner.

Soil pH was determined in a 1:1 soil to water suspension with a glass electrode and a calomel reference cell.

2. Tissue Analysis

Tissue samples were dry ashed according to the procedure described by Jackson (1958). One gram of tissue was

ashed at 400-425° C for 15 hours, followed by cooling and the addition of 25 ml of 1 N HNO₃. The acid was evaporated to dryness on a hot plate over a period of 2-3 hours. Reignition at 400° C for 10 minutes, dissolving in 25 ml of N HCl and filtering completed the digestion. Cations were determined on this solution after dilution to 100 ml.

3. Total Magnesium Analysis of Fractions

Samples of soil fractions and of soils were decomposed with HF as described by Jackson (1958). After drying at 110° C, the sample was weighed, moistened with a few drops of water, then 0.5 ml of HClO₄ and 5 ml of Af were added. The decomposition was completed by evaporating the acids to dryness on a sand bath at a temperature of 200-215°C. The residue was then taken up in HCl and Mg was determined on Model 303 Perkin Elmer Atomic Absorption Spectrophotometer.

4. X-Ray Characterization of Soil and Clay Mineral Fractions

Oriented clay specimens were prepared for x-ray diffraction by depositing 25-30 mg of material on ceramic plates. Specimens were then Mg saturated, glycerol solvated.

Diffraction patterns were made with a Phillips-Norelco X-ray unit using a copper source and nickle filter. Prior to heat treatments of 300° and 550° C, the specimens were K saturated with 1 N KCl and washed free of chlorides. Samples were characterized prior to cropping and after the second crop.

Silt sized fractions were Mg saturated, glycerol solvated and patterns were made on random powder samples before cropping only.

5. Statistical Analyses

The analyses of variance for the intensive cropping study were made using a factorial analysis with 8 factors (soil) and 3 levels (Mg levels). For the pH-Ca level experiment factorial analyses with 3 factors (pH) and 2 levels (Ca) were used. On the cropping of soil fractions study, various combinations of factorial analyses were used due to the unequal replication.

Tukey's honestly significant difference (HSD) as described by Steel and Torrie (1960) was used to test differences between means for the first two experiments. The LSD (Steel and Torrie) was used for the fraction cropping study.

The HSD is similar to the LSD, but is more severe and probably gives a more accurate estimate of the significant differences when there are more than a few treatments or treatment combinations in an experiment.

RESULTS AND DISCUSSION

A. Intensive Cropping Study

Three Mg levels were applied to seven soils of different Mg-supplying characteristics and to a bentonite-sand mixture. Seven consecutive crops were grown without any further additions of Mg. Yields of oat tops, tissue cation content and extractable cation levels of the soil and were measured for crops 2 to 7. The tissue from crop 1 was burned in the drying oven.

1. Growth Response to Applied Magnesium and Magnesium Uptake

Yields were different between soils for all crops (Table 3), as could be expected since soils were selected for differences in Mg-supplying characteristics.

Yield differences due to Mg application were obtained only on crops 4 to 7, inclusive. The different soils responded differently to applied Mg from crop to crop so that no consistent trends with response and yield differences were obtained.

Table 3.--Yields of oat tops as affected by soil type and rate of applied Mg under intensive cropping.

Soil	Initial Soil Mg Level	Rate of Applied Mg	-----Crop Number-----					
			2	3	4	5	6	7
	ppm	ppm	-----g/pot-----					
Munising fine sandy loam (1)	43	0	6.20	11.71	6.44	3.76	5.08	2.40
		10	6.23	11.81	11.08	3.98	5.54	2.68
		20	6.58	12.07	12.75	4.54	6.13	2.68
Munising fine sandy loam (2)	30	0	4.95	10.02	8.53	3.13	5.41	2.29
		10	5.40	11.19	10.90	4.95	6.17	2.60
		20	5.20	11.21	11.06	4.51	6.93	3.01
Karlin loamy sand	11	0	6.61	10.46	7.38	2.00	4.57	2.33
		10	6.93	10.53	9.33	2.22	5.41	2.70
		20	6.65	11.11	9.87	2.65	5.92	2.82
Montcalm loamy sand (1)	29	0	7.75	11.65	12.68	4.23	6.75	3.46
		10	7.58	11.39	12.14	4.00	6.84	3.14
		20	7.26	11.02	12.18	4.18	7.06	3.23
Montcalm loamy sand (2)	91	0	6.71	11.15	5.34	3.15	5.49	2.19
		10	6.00	10.84	11.32	3.91	6.39	2.24
		20	6.39	11.24	11.63	4.01	6.98	3.29
Montcalm loamy sand (3)	93	0	7.10	11.07	4.59	3.18	6.00	2.62
		10	7.57	11.20	11.14	3.13	5.60	2.50
		20	7.42	11.09	11.64	3.70	6.18	3.15
Sims Clay Loam	181	0	5.60	11.23	6.16	3.16	5.84	2.54
		10	6.56	11.51	12.36	2.93	6.18	2.49
		20	6.81	11.86	12.31	3.47	5.92	3.05
Bentonite sand mixture	185	0	7.23	9.98	10.38	2.62	4.60	2.36
		10	6.95	9.92	11.18	2.19	4.19	2.54
		20	7.44	9.81	10.53	2.39	3.82	2.18
HSD .05 *			N.S.	N.S.	2.18	N.S.	1.25	0.70
HSD .01 *			N.S.	N.S.	2.49	N.S.	1.42	0.79

*Tukey's honestly significant difference.

The Mg content of the oat tissue generally decreased as cropping progressed, except for the Sims soil and the bentonite-sand mixture (Table 4). Increases in the Mg content of the plant tissue due to applied Mg tended to become relatively greater as cropping progressed, which indicated that the initially available Mg was becoming depleted.

The two Munising soils responded differently to applied Mg. On crop 4, yields were increased when Mg was applied to the uncropped soil (Munising 1), and yields tended to be higher, but not significantly higher, on the following crops. On the cropped Munising (Munising 2), yields were increased by the 10 ppm increment of Mg on crops 4 and 6, and were further increased by the second increment of applied Mg (20 ppm) on crop 7. Consequently, yields were increased more by applied Mg on the cropped than on the uncropped Munising soils. This would indicate a decrease in available soil Mg plus a depletion of applied Mg under intensive cropping. More of the applied Mg was removed by crops 2 to 4 from the uncropped Munising, leaving less of the applied Mg for uptake on subsequent crops. These trends were reflected in the Mg content of the tissue (Table 4) and uptake (Table 5). However, the depletion of available Mg

Table 4.--Mg content of oat tops as affected by soil type and rate of applied Mg under intensive cropping.

Soil	Initial Soil Mg Level	Rate of Applied Mg	-----Crop Number-----					
			2	3	4	5	6	7
	ppm	ppm	-----%-----					
Munising fine sandy loam (1)	43	0	0.414	0.447	0.220	0.155	0.192	0.176
		10	0.464	0.453	0.243	0.150	0.231	0.218
		20	0.467	0.454	0.236	0.181	0.266	0.245
Munising fine sandy loam (2)	30	0	0.465	0.371	0.235	0.179	0.204	0.240
		10	0.512	0.434	0.224	0.183	0.281	0.286
		20	0.482	0.478	0.266	0.208	0.300	0.334
Karlin loamy sand	11	0	0.161	0.206	0.135	0.100	0.122	0.157
		10	0.264	0.278	0.149	0.124	0.146	0.169
		20	0.321	0.291	0.156	0.149	0.174	0.204
Montcalm loamy sand (1)	29	0	0.307	0.251	0.170	0.145	0.189	0.216
		10	0.408	0.334	0.224	0.160	0.231	0.279
		20	0.486	0.348	0.239	0.192	0.247	0.290
Montcalm loamy sand (2)	91	0	0.631	0.511	0.324	0.350	0.316	0.352
		10	0.620	0.559	0.310	0.369	0.419	0.395
		20	0.625	0.551	0.312	0.400	0.521	0.560
Montcalm loamy sand (3)	93	0	0.456	0.390	0.295	0.321	0.282	0.370
		10	0.487	0.444	0.294	0.324	0.332	0.369
		20	0.500	0.223	0.318	0.363	0.441	0.468
Sims clay loam	181	0	0.406	0.338	0.248	0.308	0.412	0.456
		10	0.442	0.352	0.253	0.306	0.464	0.491
		20	0.416	0.376	0.270	0.296	0.508	0.575
Bentonite sand mixture	185	0	0.200	0.224	0.170	0.265	0.268	0.284
		10	0.200	0.208	0.178	0.278	0.271	0.341
		20	0.233	0.367	0.186	0.302	0.296	0.355
HSD .05*			0.080	0.104	0.056	N.S.	0.075	0.074
HSD .01*			0.091	0.119	0.064	N.S.	0.085	0.084

*Tukey's honestly significant difference.

Table 5.--Uptake of Mg by oat tops as affected by soil type and rate of applied Mg under intensive cropping.

Soil	Initial Soil Mg Level	Rate of Applied Mg	-----Crop Number-----					
			2	3	4	5	6	7
	ppm	ppm	-----mg/pot-----					
Munising fine sandy loam (1)	43	0	25.5	52.4	14.2	5.82	9.79	4.24
		10	29.0	53.4	27.0	5.96	12.8	5.86
		20	30.7	55.2	30.1	8.19	16.3	6.57
Munising fine sandy loam (2)	30	0	22.8	37.2	20.0	5.61	11.1	5.58
		10	27.8	48.5	24.4	9.14	17.3	7.45
		20	25.1	53.6	29.4	9.52	20.8	10.1
Karlin loamy sand	11	0	10.6	21.5	9.90	1.98	5.59	3.67
		10	18.3	29.5	13.9	2.74	7.84	4.57
		20	21.3	32.4	15.3	3.91	10.3	5.76
Montcalm loamy sand (1)	29	0	28.7	29.3	21.5	6.10	12.8	7.51
		10	31.0	38.0	27.1	6.42	15.8	8.81
		20	35.3	38.4	29.2	8.18	17.5	9.42
Montcalm loamy sand (2)	91	0	42.4	56.9	17.2	11.0	17.4	7.74
		10	37.1	60.5	35.1	14.2	26.9	8.83
		20	40.1	62.1	36.4	15.9	36.5	18.5
Montcalm loamy sand (3)	93	0	32.4	43.2	13.5	10.2	16.9	9.71
		10	36.9	49.8	33.0	10.1	18.8	9.23
		20	37.1	24.8	37.1	13.4	27.3	14.8
Sims clay loam	181	0	23.0	37.8	15.1	9.76	24.1	11.7
		10	29.1	40.6	31.3	8.99	28.8	12.3
		20	28.3	44.7	33.3	9.82	30.3	17.6
Bentonite sand mixture	185	0	14.6	22.3	17.6	6.89	12.3	6.79
		10	14.2	20.6	19.9	5.93	11.3	8.61
		20	17.5	36.0	19.6	7.15	11.4	7.73
HSD .05*			9.2	14.3	7.4	3.9	7.1	0.35
HSD .01*			N.S.	16.3	8.4	N.S.	8.1	0.40

*Tukey's honestly significant difference for soils X Mg rate interaction.

is not reflected in extractable Mg levels of the soil (Table 6). The levels of significance (Table 7) for Mg content and uptake further reflect the depletion of available Mg on these soils.

A pattern similar to the uncropped Munising soil was obtained on the Karlin soil. Yields were increased by applied Mg on crop 4, probably due to the high level of K (100 ppm) applied at seeding time. Other crops received 25-50 ppm K. Magnesium deficiency symptoms were present at the 0 ppm level of applied Mg on all crops, but were eliminated at the 10 and 20 ppm levels. Magnesium content of the tissue was not increased by applied Mg until crop 7. These two facts suggest that the threshold level in the plant for deficiency symptoms and for a decrease in yield are not the same. Furthermore, these data indicate that the difference in Mg content between producing symptoms and eliminating them is very small. These data suggest that the critical level for deficiency symptoms is approximately 0.160% Mg.

The uptake response to applied Mg on crop 7 reflects the depletion of available Mg in this soil.

The three Montcalm soils also responded differently to applied Mg. Yields on the first soil (Montcalm 1) were

Table 6.--Extractable Mg levels as affected by soil type and rate of applied Mg under intensive cropping.

Soil	Initial Soil Mg Level	Rate of applied Mg	-----Crop Number*-----					
			2	3	4	5	6	7
	ppm	ppm	-----ppm-----					
Munising fine sandy loam (1)	43	0	40	44	41	26	31	30
		10	51	50	58	30	34	35
		20	55	53	65	32	35	34
Munising fine sandy loam (2)	30	0	32	42	37	24	34	36
		10	38	41	51	24	34	33
		20	41	59	55	32	44	35
Karlin loamy sand sand	11	0	19	21	12	12	17	23
		10	26	25	18	14	14	25
		20	32	31	23	15	21	25
Montcalm loamy sand (1)	29	0	31	19	17	21	14	19
		10	42	25	22	20	18	23
		20	36	37	28	25	24	27
Montcalm loamy sand (2)	91	0	92	86	72	72	74	62
		10	95	100	78	68	78	60
		20	109	104	94	77	83	58
Montalm loamy sand (3)	93	0	91	96	82	81	88	81
		10	94	102	80	79	87	75
		20	102	109	90	82	94	78
Sims clay loam	181	0	186	183	171	174	197	217
		10	194	189	188	176	200	207
		20	203	194	200	184	201	211
Bentonite sand mixture	185	0	70	83	81	81	92	71
		10	63	80	91	86	99	78
		20	81	84	108	92	102	92

*Value from soil sample prior to seeding.

Table 7.--Probabilities for significance of differences between means using Tukey's HSD for yields, Mg content, and Mg uptake for the intensive cropping experiment.

Soil	Crop Number	Yield			Mg Content			Mg Uptake		
		Means Compared (Mg applied)								
		Ovs10	Ovs20	10vs20	Ovs10	Ovs20	10vs20	Ovs10	Ovs20	10vs20
-----Probability level(2)-----										
Munising fine sandy loam(1)	2	NS	NS	NS	NS	NS	NS	NS	NS	NS
	3	NS	NS	NS	NS	NS	NS	NS	NS	NS
	4	0.01	0.01	NS	0.05	0.01	NS	NS	NS	NS
	5	NS	NS	NS	NS	NS	NS	NS	0.05	NS
	6	NS	NS	NS	0.05	0.01	NS	NS	0.01	NS
	7	NS	NS	NS	0.01	0.01	0.01	0.01	0.01	0.01
Munising fine sandy loam(2)	2	NS	NS	NS	0.01	0.01	NS	NS	NS	NS
	3	NS	NS	NS	NS	NS	NS	NS	NS	NS
	4	0.05	0.01	NS	NS	NS	NS	NS	0.01	NS
	5	NS	NS	NS	NS	NS	NS	NS	0.05	NS
	6	NS	0.01	NS	0.05	0.01	NS	NS	0.01	NS
	7	NS	0.05	NS	NS	0.01	NS	0.01	0.01	0.01
Karlin loamy sand	2	NS	NS	NS	NS	NS	NS	NS	0.05	NS
	3	NS	NS	NS	NS	NS	NS	NS	NS	NS
	4	NS	0.01	NS	NS	NS	NS	NS	NS	NS
	5	NS	NS	NS	NS	NS	NS	NS	NS	NS
	6	NS	0.05	NS	NS	NS	NS	NS	NS	NS
	7	NS	NS	NS	NS	NS	NS	0.01	0.01	0.01
Montcalm loamy sand(1)	2	NS	NS	NS	NS	0.01	NS	NS	NS	NS
	3	NS	NS	NS	NS	0.05	NS	NS	NS	NS
	4	NS	NS	NS	0.05	0.01	NS	NS	0.05	NS
	5	NS	NS	NS	NS	NS	NS	NS	NS	NS
	6	NS	NS	NS	NS	NS	NS	NS	NS	NS
	7	NS	NS	NS	NS	NS	NS	0.01	0.01	0.01
Montcalm loamy sand(2)	2	NS	NS	NS	NS	NS	NS	0.01	0.01	0.01
	3	NS	NS	NS	NS	NS	NS	0.01	0.01	0.01
	4	0.01	0.01	NS	NS	NS	NS	0.01	0.01	0.01
	5	NS	NS	NS	NS	NS	NS	NS	0.05	0.01
	6	NS	0.01	NS	0.01	0.01	0.01	0.01	0.01	0.01
	7	NS	0.01	0.01	NS	0.01	0.01	0.01	0.01	0.01
Montcalm loamy sand(3)	2	NS	NS	NS	NS	NS	NS	NS	NS	NS
	3	NS	NS	NS	0.01			NS		
	4	0.01	0.01	NS	NS	NS	NS	0.01	0.01	NS
	5	NS	NS	NS	NS	NS	NS	NS	NS	NS
	6	NS	NS	NS	NS	0.01	0.01	NS	0.01	0.01
	7	NS	NS	NS	NS	0.01	0.01	NS	0.01	0.01
Sims clay	2	NS	NS	NS	NS	NS	NS	NS	NS	NS
	3	NS	NS	NS	NS	NS	NS	NS	NS	NS
	4	0.01	0.01	NS	NS	NS	NS	0.01	0.01	NS
	5	NS	NS	NS	NS	NS	NS	NS	NS	NS
	6	NS	NS	NS	NS	NS	NS	NS	NS	NS
	7	NS	NS	NS	NS	0.01	0.01	0.01	0.01	0.01
Bentonite sand mixture	2	NS	NS	NS	NS	NS	NS	NS	NS	NS
	3	NS	NS	NS	NS	0.01	0.01	NS	NS	NS
	4	NS	NS	NS	NS	NS	NS	NS	NS	NS
	5	NS	NS	NS	NS	NS	NS	NS	NS	NS
	6	NS	NS	NS	NS	NS	NS	NS	NS	NS
	7	NS	NS	NS	NS	0.05	NS	0.01	0.01	NS

not increased by applied Mg on any crop, although Mg uptake was increased by applied Mg in crop 7. Yields on the second soil (Montcalm 2) were increased over the check by the first increment (10 ppm) of applied Mg on crop 4 only, but were to the second increment (20 ppm) on crops 4, 6, and 7 (Table 3). A yield response was obtained between the first and second increments of applied Mg on crop 7. Magnesium content of the tissue and uptake also reflect this depletion of available Mg.

On the third Montcalm (Montcalm 3) soil, yield increases due to applied Mg were obtained only on crop 4. However, increases in Mg content and uptake from applied Mg reflect the depletion of available Mg from this soil.

Differences between Montcalm 2 and 3 were due to the more rapid depletion of available and extractable Mg (Table 6) on the second soil than on the third soil. This is supported by the average amount of Mg released from these soils (Table 8).

On the other hand, these data do not suggest any explanation for this lack of response to applied Mg on the first soil; even though this soil had a lower extractable Mg level and an equal or greater measure of Mg release as compared to Montcalm 2 and 3.

Table 8.--Total Mg uptake and change in extractable Mg (mg/3600g soil) for crop 2 through crop 7 of the intensive cropping experiment.

Soil	Rate of applied Mg*	Total Uptake**	Δ Ex-tractable Mg***	Mg# released
	ppm	mg/pot	mg/pot	
Munising	0	106	-36	70
fine sandy loam (1)	10	134	-58	76
	20	147	-76	71
Munising	0	102	14	116
fine sandy loam (2)	10	135	-18	117
	20	149	-22	127
Karlin	0	53	11	64
loamy sand	10	77	-4	73
	20	89	-25	64
Montcalm	0	106	-43	63
loamy sand (1)	10	127	-68	59
	20	138	-32	106
Montcalm	0	153	-108	45
loamy sand (2)	10	183	-126	57
	20	210	-184	26
Montcalm	0	126	-36	90
loamy sand (3)	10	158	-68	90
	20	154	-83	71
Sims clay loam	0	121	112	231
	10	151	47	198
	20	164	29	193
Bentonite-sand mixture	0	80	4	84
	10	81	54	135
	20	101	40	141

*0, 10, 20 ppm equal 0, 36 and 72 mg, Mg respectively.

**Total uptake crops 2-8, Table 5.

*** (Extractable mg crop 2 - Extractable Mg crop 7) x 3.6 (Table 6).

#Sum of total uptake and Δ extractable Mg.

A yield response due to applied Mg was obtained only on the fourth crop on the Sims soil. This was due to the large K application at seeding. These data indicate that even though a soil may have a high Mg level a deficiency can be induced by a large K application.

Yields on the bentonite-sand mixture were not increased by applied Mg. This "soil" released more Mg than did the other soils except the Sims. This indicates that the Mg in bentonite is readily available to plants. However, the growth on this "soil" was never as vigorous as on the other soils, probably because of poor physical conditions in the sand-mineral mixture.

Even though yields on the Sims soil and the bentonite-sand mixture were not increased by applied Mg, the uptake response to applied Mg on crop 7 indicates that available Mg levels were becoming depleted.

2. Extractable Soil Magnesium and Release of Unextractable Mag- nesium During Cropping

The level of extractable Mg in all soils tended to decrease as cropping proceeded at all three soil Mg levels, except for the Sims soil and the bentonite-sand mixture, on which extractable Mg increased from crop 2 to crop 7 (Table 6).

The level of extractable Mg increased from 2 to 24 ppm on nearly all soils between crops 5 and 6, probably because the soils were allowed to dry completely between these crops. The Sims soil released the most Mg during this period, while Montcalm 1 actually fixed Mg against extraction with ammonium acetate. The decrease in extractable Mg from crop 4 to 5 was probably caused by K application (100 ppm) prior to seeding crop 4.

The algebraic sum of the change in extractable Mg between crop 2 and crop 7 and total uptake reflects the Mg released by these soils (Table 8). Averaging across Mg levels for each soil gives a measure of the relative supplying capability of these soils. The order was as follows: Sims clay loam >> Munising fine sandy loam 2 > bentonite-sand mixture $\geq$ Montcalm loamy sand 3 $\geq$ Montcalm loamy sand 1 $\sim$ Munising fine sandy loam 1 $\geq$ Karlin loamy sand $\geq$ Montcalm loamy sand 2.

The data in Tables 6 and 7 suggest that Mg applied to the soils was fixed against extraction by ammonium acetate. However, the "fixed" forms were "released" for uptake by subsequent crops grown on these soils. This release was not reflected in the extractable Mg levels during the

cropping sequence, except when the soil was allowed to dry between crops 5 and 6.

The mechanism of Mg fixation is not clear from the literature. However, it has been suggested that it occurs through coordination at the broken edges of the octahedral layer (Cheminade and Drouineau, 1936). A second mechanism would be the trapping of Mg ions perforations in the surface of oxygen layers due to collapse of the sheets when K is applied in large quantities. If Mg were fixed by either of these mechanisms, it could be available for plants through further "weathering" of the soil.

3. Linear Correlations of Plant Tissue Magnesium Content and Uptake Correlated with Extractable Magnesium, Potassium, and Calcium Levels.

As cropping proceeded, the correlation between extractable Mg and Mg content and uptake became higher (Table 9). This indicates that the ammonium acetate extraction was more accurately predicting Mg availability of these soils as cropping progressed. However, using Mg uptake as the best indicator of Mg availability, only 32% of the variability in uptake was accounted for by the relationship between soil Mg

Table 9.--Linear correlation coefficients (r) for Mg content and uptake of magnesium for each crop as a function of various independent variables.

Independent Variable	Mg Content (%) Oat Tops						
	2	3	4	5	6	7	
Extractable Mg	0.233*	0.127	0.390**	0.667**	0.763**	0.728**	
Extractable K	0.140	-0.027	0.318**	0.355**	-0.131	0.193	
Extractable K/Mg	-0.387**	-0.398**	-6.600**	-0.791**	-0.732**	-0.770**	
Extractable Ca/Mg	0.010	-0.322**	-0.382**	-0.774**	-0.455**	-0.367**	

Independent Variable	Mg Uptake (mg/pot) by Oat Tops						
	2	3	4	5	6	7	
Extractable Mg	0.243*	0.137	0.309**	0.406**	0.396**	0.568**	
Extractable K	0.268	-0.014	0.210*	0.241*	-0.059	0.019	
Extractable K/Mg	-0.301**	-0.370**	-0.409**	-0.632**	-0.564**	-0.602**	
Extractable Ca/Mg	-0.080	-0.257*	-0.224*	-0.510**	-0.280**	-0.187	

*0.05 significance level.

**0.01 significance level.

and uptake on crop 7. A lower correlation was obtained on other crops. Even so, this correlation was better than that reported by Wehunt and Purvis (1954) who found no relationship between soil Mg and Mg content of apple leaves. The better correlation in this study was attributed reduction in variation by greenhouse control and the more accurate prediction of Mg availability by the ammonium acetate extraction than by the electrodialysis used in their study.

The correlation between Mg uptake and the soil K:Mg ratio was higher than with the extractable soil Mg alone. Even still this correlation accounted for less than 40% of the variation of the uptake data. However, the correlation between Mg content and soil K:Mg was higher than the correlation with uptake.

Extractable Ca/Mg did not correlate with Mg uptake as well as did K/Mg. On crops 2 and 7 there was no correlation between soil Ca/Mg and uptake and r values of -0.224 to -0.510 were obtained on the remaining crops. Extractable K/Mg correlated with uptake on all crops and accounted for more variability of the uptake of Mg. This indicates that the Ca/Mg antagonism on Mg uptake is less severe than the K-Mg antagonism. Secondly, Ca does not sterically hinder Mg release from clay minerals to the extent that K does.

There is no relationship between soil K and Mg uptake which is contrary to the findings of Wehunt and Purvis (1954). This was attributed greenhouse control and different K fertilization rates between soils. The smaller correlation between Mg content and extractable Mg on the cropped Munising than the uncropped was attributed to Mg being fixed in forms which were not extracted with ammonium acetate, but were available to plants (Table 10). This supports the response pattern discussed earlier.

Correlations between these variables in the Karlin soil were as high as for the Munising 1. Extractable Mg and Mg content of the tissue correlated better on this soil than on Munising. "Fixed" forms were evidently more readily extractable on this soil than on the other soils.

On Montcalm 1 there was lower correlation between uptake of Mg and soil K/Mg and Ca/Mg than on Montcalm 2 and 3. This was borne out by the lack of response on this soil. Magnesium content of the tissue was not correlated with extractable Mg on Montcalm 3.

Soil K/Mg level exerted the greatest influence on Mg uptake for both the bentonite-sand mixture and the Sims soil. However, only 10% of the variability in uptake was accounted

Table 10.--Linear correlation coefficients (r) for Mg content and uptake of Mg for each soil as a function of various independent variables.

Soil and Independent Variable	Mg Content of Oat Tops	Mg Uptake by Oat Tops
Munising fine sandy loam (1)		
Extractable Mg	0.513	0.643
Extractable K/Mg	-0.786	-0.649
Extractable Ca/Mg	-0.618	-0.649
Extractable K	-0.801	-0.523
Munising fine sandy loam (2)		
Extractable Mg	0.317	0.652
Extractable K/Mg	-0.810	-0.615
Extractable Ca/Mg	-0.545	-0.713
Extractable K	-0.869	-0.464
Karlin loamy sand		
Extractable Mg	0.816	0.620
Extractable K/Mg	-0.760	-0.614
Extractable Ca/Mg	-0.704	-0.510
Extractable K	-0.764	-0.647
Montcalm loamy sand (1)		
Extractable Mg	0.750	0.567
Extractable K/Mg	-0.750	-0.471
Extractable Ca/Mg	-0.641	-0.364
Extractable K	-0.651	-0.345
Montcalm loamy sand (2)		
Extractable Mg	0.512	0.774
Extractable K/Mg	-0.759	-0.783
Extractable Ca/Mg	-0.696	-0.597
Extractable K	-0.700	-0.504
Montcalm loamy sand (3)		
Extractable Mg	0.142 [#]	0.607
Extractable K/Mg	-0.522	-0.645
Extractable Ca/Mg	-0.163 [#]	-0.385
Extractable K	-0.535	-0.555
Sims Clay loam		
Extractable Mg	0.677	0.089 [#]
Extractable K/Mg	-0.636	-0.353 [#]
Extractable Ca/Mg	-0.360	0.171 [#]
Extractable K	-0.543	-0.342
Bentonite-sand mixture		
Extractable Mg	0.085 [#]	-0.020 [#]
Extractable K/Mg	0.137 [#]	-0.484
Extractable Ca/Mg	0.271 [*]	-0.351
Extractable K	0.141 [#]	-0.399

[#]Non-significant

^{*}Significant at 0.05 level, all others highly significant.

for by this relationship on the Sims soil and 23% for the bentonite-sand mixture.

The above data indicate that this extractant does not accurately predict the availability of Mg for plant uptake. Considering all soils, the extractable K/Mg or Ca/Mg ratio better predicts the uptake of Mg by plants than does extractable Mg alone.

Extractable K correlated better with Mg uptake for individual soils than it did for all soils (Table 9). This was attributed to different K rates applied to each soil to establish a certain level of K. Thus, the relationship between K and Mg was less variable within a soil than for all soils.

The multiple correlation coefficient for plant Mg content as a function of plant Ca and K content was 0.493 for all soils and all crops. The associated partial correlation coefficients were -0.457 and 0.394 for K and Ca, respectively. All are highly significant. The partial correlation coefficients indicate that Ca and Mg content of the plant tissue vary directly with each other, while Mg content varies inversely with K content. Since for this correlation uptake and tissue content are the same, this supports the

content an antagonism between K and uptake of Mg. Conversely, the positive correlation between Mg and Ca indicates a certain dependency of Mg uptakes on the amount of Ca uptake.

The linear correlation coefficients for extractable Mg, K:Mg and Ca:Mg and uptake of Mg by plants for all soils and crops were 0.243, -0.418, and -0.313, respectively. This further indicates that cation levels extracted by ammonium acetate do not accurately predict Mg availability by plants.

B. pH-Calcium Level Study

Treatments were composed of two calcium levels at each of three pH levels on Karlin loamy sand. Eight successive crops of oats were grown; yields and cation contents of the oat tops from each crop were measured. Extractable cation levels and pH were measured on soil samples from each treatment before and after each of the eight crops.

1. Yields

Yields were higher for the higher pH levels (pH_2 and pH_3) than for the more acid level (pH_1) for all crops (Table 11), but there was not a consistent relationship between the yields of the two higher pH levels. These relationships are

Table 11.--Yields of oat tops as affected by pH and Ca levels under intensive cropping. Analyzed statistically as a 3x2 factorial.*

Treatments**	Crop Number							
	1	2	3	4	5	6	7	8
	gms/pot							
pH ₁ Ca ₁	11.09	5.38	4.68	4.15	5.99	5.93	4.42	2.39
pH ₁ Ca ₂	12.22	5.75	4.27	4.43	6.30	6.94	3.76	2.76
pH ₂ Ca ₁	13.70	5.59	5.55	6.97	7.99	6.28	5.93	2.40
pH ₂ Ca ₂	14.28	5.96	5.74	6.84	8.62	7.80	6.21	3.17
pH ₃ Ca _{2a}	13.79	7.01	5.26	6.21	8.33	6.99	6.00	2.87
pH ₃ Ca _{2b}	14.28	6.56	5.19	6.90	8.71	7.67	6.53	2.78
Check	13.34	4.68	5.19	4.74	6.27	4.49	4.85	2.14
Effect	Effect Means***							
pH ₁	11.65	5.56	4.48	4.29	6.15	6.43	4.09	2.58
pH ₂	13.99	5.77	5.65	6.91	8.31	7.04	6.07	2.78
pH ₃	14.03	6.79	5.23	6.56	8.52	7.33	6.27	2.83
Ca ₂	13.59	6.09	5.07	6.06	7.88	7.47	5.50	2.90
Ca ₁	12.86	5.99	5.16	5.79	7.44	6.40	5.45	2.55
pH HSD _{.05} #	0.61	0.29	0.20	0.25	0.27	0.19	0.29	N.S.
pH HSD _{.01} #	0.79	0.38	0.26	0.32	0.35	0.25	0.38	N.S.
Ca HSD _{.05} #	N.S.	N.S.	N.S.	N.S.	N.S.	0.11	N.S.	0.10
Ca HSD _{.01} #	N.S.	N.S.	N.S.	N.S.	N.S.	0.14	N.S.	0.14

*Omitting check treatment and pooling Ca_{2a} in Ca₁ level.

**pH₁=4.3, pH₂=5.5, pH₃=6.5, Ca₁=Low, Ca₂=high, Ca_{2a}=CaCO₃, Ca_{2b}=Ca(OH)₂, see Table 2.

***pHxCa level interaction was nonsignificant.

#Honestly significant difference.

reflected in the Mg uptake data (Table 13), but not in the Mg content data (Table 12).

On crops 6 and 8, yields were higher for the high Ca level (Ca_2) than for the low Ca level (Ca_1). A decrease in soil pH for pH_3 was attributed to the cause of this effect (Table 14). A decrease in differences due to different pH levels allowed the Ca effect to become more dominate.

Increased yields at the higher pH levels were due to more favorable soil-plant relationships at pH 6.5 than below pH 6. Nutrients are more available, fewer toxicities occur and less H-ion injury to plant tissue occurs in this pH range than at lower pH levels. When soil acidity increased after crop 5, the higher Ca level probably minimized the injurious effect of the H-ion (Rains et al., 1964).

2. Soil pH

Soil pH values established by means of soil amendments (pH_2 and pH_3) were consistent for crops 1-5, inclusive (Table 14). Then the pH of these treatments decreased, tending to approach the initial pH of the soil. However, the effect of the amendments could be detected in the final pH

Table 12. Mg content of oat tops as affected by pH and Ca levels under intensive cropping. Analyzed statistically as a 3x2 factorial.*

Treat- ments**	Crop Number							
	1	2	3	4	5	6	7	8
	%							
pH ₁ Ca ₁	0.076	0.167	0.176	0.238	0.148	0.085	0.107	0.113
pH ₁ Ca ₂	0.070	0.134	0.144	0.234	0.147	0.095	0.114	0.115
pH ₂ Ca ₁	0.095	0.204	0.214	0.182	0.100	0.073	0.102	0.100
pH ₂ Ca ₂	0.101	0.220	0.244	0.196	0.094	0.069	0.104	0.094
pH ₃ Ca _{2a}	0.072	0.131	0.156	0.146	0.090	0.079	0.123	0.113
pH ₃ Ca _{2b}	0.103	0.190	0.232	0.175	0.097	0.072	0.130	0.108
Check	0.091	0.204	0.210	0.230	0.124	0.094	0.109	0.122
HSD _{.05} [#]	0.008	0.012	0.026	0.012	N.S.	0.055	N.S.	N.S.
HSD _{.01} [#]	0.010	0.015	0.033	0.015	N.S.	0.069	N.S.	N.S.

*Omitting check treatment and pooling Ca_{2a} in Ca₁ level.

**pH₁=4.3, pH₂=5.5, pH₃=6.5, Ca₁=low, Ca₂=high, Ca_{2a}=CaCO₃,

Ca_{2b}=Ca(OH)₂; see Table 2.

#Honestly significant differences for pH x Ca level interaction.

Table 13.--Mg uptake by oat tops as affected by pH and Ca levels under intensive cropping. Analyzed statistically as a 3x2 factorial.*

Treat- ments**	-----Crop Number-----							
	1	2	3	4	5	6	7	8
	-----mg/pot-----							
pH ₁ Ca ₁	8.57	8.81	8.27	9.86	8.89	5.04	4.76	2.71
pH ₁ Ca ₂	8.59	7.71	6.13	10.4	9.29	6.58	4.30	3.18
pH ₂ Ca ₁	13.0	11.4	11.9	12.7	8.04	4.60	6.02	2.40
pH ₂ Ca ₂	14.4	13.1	14.0	13.4	8.08	5.41	6.43	3.00
pH ₃ Ca _{2a}	9.90	9.20	8.21	9.10	7.52	5.51	7.37	3.27
pH ₃ Ca _{2b}	14.7	12.4	12.0	12.1	8.47	5.54	8.52	3.02
Check	12.1	9.46	11.0	10.9	7.79	4.21	5.24	2.59
HSD .05#	1.79	0.96	1.71	0.60	N.S.	0.38	N.S.	N.S.
HSD .01#	2.23	1.20	2.13	0.79	N.S.	0.47	N.S.	N.S.

* Omitting check treatment and pooling Ca_{2a} in Ca₁ level.

** pH₁ =4.3, pH₂ =5.5, pH₃ =6.5, Ca₁ =low, Ca₂ =high, Ca_{2a} =CaCO₃, Ca_{2b} =Ca(OH)₂; see Table 2.

Honestly significant differences for pH x Ca level interaction.

Table 14.--Soil pH as affected by pH and Ca level under intensive cropping.

Treat- ments**	-----Crop Number*-----								Final
	1	2	3	4	5	6	7	8	
pH ₁ Ca ₁	4.3	4.3	4.5	4.6	4.5	4.4	-	4.2	4.3
pH ₁ Ca ₂	4.1	4.2	4.2	4.2	4.3	4.2	-	4.2	4.6
pH ₂ Ca ₁	5.4	5.5	5.8	5.6	5.5	5.2	-	4.8	4.8
pH ₂ Ca ₂	5.3	5.4	5.4	5.3	5.2	4.9	-	4.8	4.7
pH ₃ Ca _{2a}	6.6	6.6	6.8	6.6	6.3	6.0	-	5.8	5.3
pH ₃ Ca _{2b}	6.2	6.2	6.5	6.3	6.1	5.8	-	5.6	5.2
Check	4.5	4.8	4.9	4.8	4.5	4.5	-	4.5	4.3

* Value on samples taken prior to seeding, e.g., crop 1 is initial value prior to first seeding.

** pH₁ = 4.3, pH₂ = 5.5, pH₃ = 6.5, Ca₁ = low, Ca₂ = high,

Ca_{2a} = CaCO₃, Ca_{2b} = Ca(OH)₂; see Table 2.

determination. Extractable Ca (Table 15) did not decrease during this period, but extractable K and Mg (Tables 16 and 17) decreased on pH levels 2 and 3.

Table 15.--Soil Ca levels as affected by pH and Ca level under intensive cropping.

Treat- ments**	-----Crop Number-----							
	1	2	3	4	5	6	7	8
	-----ppm-----							
pH ₁ Ca ₁	184	276	350	265	221	267	-	359
pH ₁ Ca ₂	957	1157	1362	1141	1154	947	-	1067
pH ₂ Ca ₁	644	644	569	700	589	479	-	644
pH ₂ Ca ₂	975	993	883	901	901	773	-	948
pH ₃ Ca _{2a}	1030	957	1214	1067	1067	837	-	956
pH ₃ Ca _{2b}	833	1288	1040	791	791	746	-	821
Check	239	368	221	276	213	249	-	249

* Value on samples taken prior to seeding.

** pH₁ = 4.3, pH₂ = 5.5, pH₃ = 6.5, Ca₁ = low, Ca₂ = high,

Ca_{2a} = CaCO₃, Ca_{2b} = Ca(OH)₂, see Table 2.

Table 16.--Soil Mg levels as affected by pH and Ca level
under intensive cropping.

Treat- ments**	-----Crop Number*-----								
	1	2	3	4	5	6	7	8	Final
	-----ppm-----								
pH ₁ Ca ₁	20	20	20	16	19	17	-	24	24
pH ₁ Ca ₂	20	20	20	16	21	18	-	23	27
pH ₂ Ca ₁	14	16	12	9	7	9	-	12	12
pH ₂ Ca ₂	16	14	12	8	10	8	-	9	8
pH ₃ Ca _{2a}	10	12	6	9	8	6	-	8	8
pH ₃ Ca _{2b}	17	16	18	8	11	8	-	9	6
Check	18	20	20	14	11	16	-	19	21

* Value on samples taken prior to seeding.

** pH₁ = 4.3, pH₂ = 5.5, pH₃ = 6.5, Ca₁ = low, Ca₂ = high,

Ca_{2a} = Ca CO₃, Ca_{2b} = Ca(OH)₂; see Table 2.

Table 17.--Soil K levels as affected by pH and Ca level under intensive cropping.

Treat- ments**	-----Crop Number*-----							
	1	2	3	4	5	6	7	8
	-----ppm-----							
pH ₁ Ca ₁	106	76	30	22	12	20	-	66
pH ₁ Ca ₂	105	75	30	24	11	20	-	68
pH ₂ Ca ₁	102	70	28	26	18	20	-	27
pH ₂ Ca ₂	102	68	22	21	18	20	-	26
pH ₃ Ca _{2a}	100	68	26	30	11	22	-	31
pH ₃ Ca _{2b}	102	77	23	28	19	22	-	30
Check	98	70	30	28	14	17	-	72

* Value on samples taken prior to seeding.

** pH₁ = 4.3, pH₂ = 5.5, pH₃ = 6.5, Ca₁ = low, Ca₂ = high,

Ca_{2a} = CaCO₃, Ca_{2b} = Ca(OH)₂; see Table 2.

3. Soil Magnesium Levels and Magnesium Uptake

At the lowest pH level and on the check treatment, extractable Mg increased during the cropping period. But, at the two higher pH levels (pH₂ and pH₃) extractable Mg decreased during the same period (Table 16). Uptake of Mg was similar on both Ca levels at the two higher pH levels, except

for $\text{pH}_3\text{Ca}_{1a}$ for all crops. However, Mg release to the extractable form during the cropping sequence generally increased with soil acidity (Table 18). Hossner (1965) reported that the rate of release of Mg from clay minerals increased with increasing acidity. In the present experiment, more Mg was released to the extractable form at pH 5.5 than

Table 18.--Total uptake of Mg and Δ -Extractable Mg for the pH-Ca experiment.

Treatments*	Total** Uptake mg/pot	Δ -Extractable # Mg (Mg/3600g soil) mg/pot	Mg*** Released mg/pot
$\text{pH}_1 \text{ Ca}_1$	57	14	71
$\text{pH}_1 \text{ Ca}_2$	56	25	81
$\text{pH}_2 \text{ Ca}_1$	70	-7	63
$\text{pH}_2 \text{ Ca}_2$	79	-14	65
$\text{pH}_3 \text{ Ca}_{2a}$	60	-7	53
$\text{pH}_3 \text{ Ca}_{2b}$	70	-40	30
Check	63	11	74

* $\text{pH}_1 = 4.3$, $\text{pH}_2 = 5.5$, $\text{pH}_3 = 6.5$, $\text{Ca}_1 = \text{low}$, $\text{Ca}_2 = \text{High}$,
 $\text{Ca}_{2a} = \text{CaCO}_3$, $\text{Ca}_{2b} = \text{Ca(OH)}_2$; see Table 2.

** Total uptake crops 1-7, Table 12.

(Final extractable Mg minus extractable Mg crop 1) x 3.6
 (Table 16).

***Sum of total uptake and Δ -extractable Mg.

at higher pH levels, even though Mg uptake was essentially the same on all treatments. The greater release is reflected by higher extractable Mg levels after cropping.

Release of Mg to an extractable form was greater for the $\text{pH}_3\text{Ca}_{2a}$ (CaCO_3) treatment than for $\text{pH}_3\text{Ca}_{2b}$ treatment (Table 18). But, total uptake was 15% less for crops 1-8, inclusive. The data presented here suggest no explanation for these differences and indicate the need for more definitive research to study these differences.

4. Linear Correlations of Plant Tissue Magnesium Content and Uptake Correlated with Extractable Soil Magnesium, Potassium, and Calcium Levels.

The poor correlations obtained between Mg uptake and content with extractable Mg, K/Mg and Ca/Mg (Table 19) are probably the result of the dominate effect of soil acidity.

Extractable Mg was correlated with Mg content of the tissue on crops 4, 5, and 6, but not with uptake. The plants were unable to fully utilize available Mg at the lower pH levels (pH_1), resulting in a negative correlation between Mg uptake by plants and extractable soil Mg. At the higher soil pH levels (which also had a lower extractable Mg

Table 19.--Linear correlation coefficients (r) for Mg content and uptake as a function of various independent variables for crops grown on the pH-Ca level experiment.

Independent Variable	Mg Content (%) of Oat Tops							
	1	2	3	4	5	6	8	
Extractable Mg	-0.025	-0.019	-0.014	0.835**	0.883**	0.728**	0.163	
Extractable K/Mg	-0.183	-0.142	-0.251	-0.907**	-0.814**	-0.517**	0.187	
Extractable Ca/Mg	-0.138	-0.193	-0.335	-0.787**	-0.763**	-0.421*	0.256	
Extractable Ca	-0.012	-0.218	-0.321	-0.482	-0.328	-0.179	0.321	

Independent Variable	Mg Uptake (mg/pot) by Oat Tops							
	1	2	3	4	5	6	8	
Extractable Mg	-0.201	-0.490**	-0.183	-0.425*	0.324	0.049	-0.096	
Extractable K/Mg	-0.002	0.401	-0.092	0.230	-0.307	0.066	0.122	
Extractable Ca/Mg	-0.075	0.382*	-0.205	0.218	-0.249	0.316	0.294	
Extractable Ca	0.170	0.285	-0.285	-0.017	0.047	0.771**	0.464*	

*0.05 level of significance.

**0.01 level of significance.

level plant growth was greater, which resulted in more total uptake, but a lower Mg content (%) in the plants.

Extractable K/Mg ratio was correlated with Mg content on crops 4, 5, and 6, but not on any of the other crops or with uptake. Again, the lack of correlation is related to greater growth at the higher pH.

Extractable Ca/Mg ratio was correlated negatively with Mg content, but was not correlated with uptake. These results do not agree with the data presented in the preceding section on the intensive cropping experiment. At the high pH levels, the increased plant growth resulted in a lower concentration of Mg in the plants, while at low pH levels the inverse was true. Also, a high soil Ca level (wide Ca:Mg ratio) was associated with the high pH level.

C. Cropping of Soil Fractions

A sufficient quantity of five fractions of different particle size from seven soils, three fractions from bentonite and two from chlorite to supply 20 mg of Mg was mixed with quartz sand and cropped to two crops of oats.

Yield and tissue Mg content were measured on each of two successive crops. The content of Mg was measured in each

fraction before and after each crop. The mineralogical composition of each fraction was determined by means of X-ray diffraction before the first crop and after the second crop.

The quartz sand used in the cultures contained 0.1% material less than 50 μ in size which had a total Mg content of 0.4%. Approximately 2 mg of Mg was added to each culture from this source.

1. Magnesium Content of Plant Tissue

Magnesium content of the oat tops was less in the second crop than in the first crop (Table 20). Oats grown on the finer fractions contained more Mg than those grown on the coarser fractions. The relative Mg content of the oats between fractions varied from soil to soil for crop 1. For crop 2, it was the same from soil to soil (lack of soil by fraction interaction), following more closely to fraction size; tissue from the finer fractions having a higher Mg content.

Table 20.--Mg content of fractions, Mg uptake by oat tops and Mg content of oat tops as affected by soil type and particle size.

Soil	Fraction Size	Mg Content in Soil Fractions			Mg Uptake by Oats		Mg Content of Oat Tops	
		Before Cropping	After Crop 1	After Crop 2	Crop 1	Crop 2	Crop 1	Crop 2
		-----%-----			-mg/culture-		-----%-----	
Munising fine sandy loam(1)	<0.08	1.15	1.08	0.769	1.65	1.45	0.129	0.0987
	0.08-0.2	1.44	1.30	0.928	1.86	1.19	0.134	0.0877
	0.2-2	0.699	0.637	0.498	1.77	1.20	0.138	0.0857
	2-20	0.144	0.130	0.075	1.90	1.19	0.103	0.0833
	20-50	0.0714	0.0645	0.0390	1.94	1.19	0.141	0.0856
	Total Soil	0.0786	0.0725	-	1.59	-	0.128	-
Munising fine sandy loam(2)	<0.08	1.03	0.935	0.433	1.85	1.36	0.136	0.0977
	0.08-0.2	1.58	1.42	0.899	1.92	1.25	0.141	0.0853
	0.2-2.0	1.11	1.01	0.879	1.80	1.13	0.130	0.0880
	2-20	0.267	0.242	0.208	1.87	1.05	0.131	0.0777
	20-50	0.136	0.124	0.120	1.80	1.18	0.135	0.0853
	Total Soil	0.121	0.112	-	1.54	-	0.118	-
Karlin loamy sand	<0.08	1.10	1.01	0.145	1.61	1.23	0.124	0.0950
	0.08-0.2	1.17	1.06	0.561	1.82	1.27	0.136	0.0843
	0.2-2.0	0.986	0.901	0.747	1.71	1.10	0.129	0.0807
	2-20	0.314	0.286	0.240	1.73	1.17	0.130	0.0830
	20-50	0.196	0.182	0.109	1.46	1.04	0.103	0.0773
	Total Soil	0.126	0.116	-	1.52	-	0.123	-
Montcalm loamy sand(1)	<0.08	0.844	0.772	0.422	1.70	1.30	0.130	0.0880
	0.08-0.2	1.10	0.990	0.669	1.98	1.20	0.143	0.0833
	0.2-2.0	0.993	0.907	0.742	1.78	1.23	0.126	0.0827
	2.0-20	0.336	0.307	0.254	1.75	1.13	0.125	0.0797
	20-50	0.205	0.186	0.149	1.81	1.08	0.134	0.0753
	Total Soil	0.184	0.169	-	1.55	-	0.124	-
Montcalm loamy sand(2)	<0.08	0.828	0.749	0.538	1.88	1.34	0.143	0.0850
	0.08-0.2	1.14	1.04	0.738	1.85	1.21	0.136	0.0847
	0.2-2.0	1.08	0.993	0.696	1.62	1.09	0.126	0.0747
	2.0-20	0.338	0.308	0.268	1.75	1.16	0.126	0.0817
	20-50	0.194	0.178	0.132	1.71	1.03	0.128	0.0730
	Total Soil	0.184	0.169	-	1.54	-	0.122	-
Montcalm loamy	<0.08	0.943	0.863	0.397	1.70	1.31	0.122	0.0850
	0.08-0.2	1.26	1.14	0.733	1.81	1.14	0.138	0.0797
	0.2-2.0	0.970	0.882	0.786	1.83	1.04	0.128	0.0817
	2.0-20	0.325	0.298	0.253	1.70	1.14	0.121	0.0763
	20-50	0.200	0.182	0.139	1.76	1.07	0.119	0.0770
	Total Soil	0.132	0.121	-	1.56	-	0.121	-
Sims clay loam	<0.08	1.24	1.13	0.713	1.80	1.20	0.131	0.0860
	0.08-0.2	1.44	1.31	0.569	1.78	1.10	0.129	0.0767
	0.2-2.0	1.24	1.13	0.920	1.78	1.17	0.129	0.0833
	2.0-20	0.776	0.711	0.549	1.64	1.24	0.120	0.0857
	20-50	0.762	0.699	0.609	1.69	1.10	0.137	0.0803
	Total Soil	0.590	0.543	-	1.59	-	0.136	-
Bentonite	<0.08	1.56	1.43	0.794	1.67	1.21	0.125	0.0843
	0.08-0.2	1.48	1.37	0.779	1.69	1.21	0.133	0.0847
	0.2-2.0	1.12	1.02	0.903	1.71	1.07	0.129	0.0753
Chlorite	0.08-0.2	3.18	2.87	1.13	1.91	1.38	0.133	0.0980
	0.2-2.0	3.49	3.17	1.63	1.96	1.37	0.146	0.0927

2. Magnesium Uptake and Availability from Different Fractions

The finer fractions supplied more Mg than did the coarser fractions. Based on the total uptake for both crops (Table 21), the following relative order of supply (release from the fraction) was obtained for all soils:

$<0.08 = 0.08-0.2 > 0.2-2.0 = 2.0-20 > 20-50 \mu > \text{total soil.}$

Table 21.--Means of Mg uptake by oat tops and Mg content of oat tops as affected by fraction size.

Fraction Size	Mg Uptake by Oat Tops			Mg Content of Oat Tops	
	Crop 1	Crop 2	Total	Crop 1	Crop 2
---μ---	-----mg/culture-----			-----%-----	
<0.08	1.74	1.31	3.05	0.130	0.0908
0.08-0.2	1.86	1.19	3.05	0.137	0.0831
0.2-2.0	1.76	1.14	2.90	0.129	0.0824
2.0-20	1.76	1.15	2.91	0.126	0.0810
20-50	1.74	1.10	2.84	0.128	0.0791
LSD 0.05	0.15	0.10	-	0.008	0.008
0.01	0.20	0.13	-	0.011	0.010

Doll et al. reported the clay fraction supplied more K to wheat crops than did the silt fraction. Large amounts of K were removed from the coarse clay (0.2-2.0 μ). The differential release was attributed to decrease in activity of interlayer K when the K content of the clay decreased. This was confirmed by a positive correlation between fraction K content and logarithm of K uptake.

In the present study, Mg content of the soil fractions correlated with uptake on the coarse clay fraction only (Table 22).

Table 22.--Linear correlation coefficients (r) between uptake of Mg and Mg content of fractions at start of each crop.

Fraction Size μ	Crop 1	Crop 2
<0.08	-0.271	-0.428
0.08-0.2	0.111	0.512**
0.2-2.0	0.496**	0.638**
2.0-20	-0.511*	0.319
20-50	-0.143	-0.058
Total Soil	0.130	-

*0.05 level of significance.

**0.01 level of significance.

Each fraction had a different number of observations.

The lack of correlation between fraction Mg content and Mg uptake for the silt fraction and the fine and medium fractions may be explained in two ways. First, Mg release is governed by factors other than those for K release and second, Mg is present in different forms in these fractions. For example, the dominant mineral species which would supply Mg from the coarse clays was the interstratified vermiculite-chlorite-illite systems or discrete minerals belonging to these species (Table 23). The medium clay fraction contained similar mineral species. However, the fraction Mg content correlated with uptake only on the second crop. This suggests that Mg on the crystal edges was easily released for plant uptake. When this was removed by the first crop Mg release was governed by the same factors as for the coarse clay.

On the fine clay fraction, the lack of correlation between fraction Mg content and Mg uptake can be explained on the same basis. Magnesium released had shorter diffusion paths to move through making it more readily available. Secondly, the larger surface area allowed more of the Mg to be at the crystal edge and concurrently more surface was exposed for weathering and release.

Table 23.--Minerals present in various particle size fractions of seven Michigan soils.

Soil	Particle Size	Predominant Minerals
	μ	
Munising fine loam(1)	0.08-0.2	Kaolinite, illite, ordered interstratified vermiculite-chlorite-montmorillonite system
	0.2-2.0	Kaolinite, illite, vermiculite
	2.0-20	Quartz, feldspars, goethite, boehmite
	20-50	Quartz, feldspars, goethite, boehmite
Munising fine sandy loam(2)	0.08-0.2	Kaolinite, interstratified chlorite-vermiculite-illite system
	0.2-2.0	Kaolinite, illite, interstratified chlorite-vermiculite system
	2.0-20	Quartz, feldspars, goethite, boehmite
	20-50	Quartz, feldspars, goethite, boehmite
Karlin loamy sand	0.08-0.2	Kaolinite, interstratified illite-vermiculite-chlorite system
	0.2-2.0	Kaolinite, illite, chlorite, interstratified vermiculite-chlorite system
	0.2-2.0	Kaolinite, illite, chlorite, interstratified vermiculite-chlorite system
	2.0-20	Quartz, feldspars, goethite, boehmite
	20-50	Quartz, feldspars, goethite, boehmite
Montcalm loamy sand(1)	0.08-0.2	Kaolinite, interstratified vermiculite-chlorite system
	0.2-2.0	Kaolinite, illite, interstratified vermiculite-chlorite system
	2.0-20	Quartz, feldspars, goethite, boehmite
	20-50	Quartz, feldspars, goethite, boehmite

Table 23. (Continued)

Soil	Particle Size	Predominant Minerals
	μ	
Montcalm loamy sand(2)	0.08-0.2	Kaolinite, illite, montmorillonite, interstratified vermiculite- chlorite system
	0.2-2.0	Kaolinite, illite, interstratified vermiculite-chlorite system
	2.0-20	Quartz, feldspars, goethite, boehmite
	20-50	Quartz, feldspars, goethite, boehmite
Montcalm loamy sand(3)	0.08-0.2	Kaolinite, illite, interstratified vermiculite-chlorite system
	0.2-2.0	Kaolinite, illite, interstratified vermiculite-chlorite system
	2.0-20	Quartz, feldspars, goethite, boehmite
	20-50	Quartz, feldspars, goethite, boehmite
Sims clay loam	0.08-0.2	Kaolinite, illite, interstratified illite-vermiculite-chlorite system
	0.2-2.0	Kaolinite, illite, vermiculite
	2.0-20	Quartz, feldspars, goethite, boehmite
	20-50	Quartz, feldspars, goethite, boehmite

On the silt fraction the main source of Mg would be the feldspars and possibly goethite. These minerals are more resistant to weathering than the clay minerals, which would account for the lack of relationship between Mg content and lattice activity.

Mortland and Ellis (1959) reported that the rate limiting step for K release from vermiculite (K in interlayer

positions) was diffusion through the hydration film enveloping the clay particle. Doll et al. (1965) obtained a correlation between clay K content and logarithm of K uptake by wheat tops, suggesting that release was related to the activity of lattice K. These results indicate that release of interlayer cations is related to activity of the lattice ion and is controlled by film diffusion.

Thus, it is suggested that when the main source of Mg in the soil clay is from the interlayer position, as in the coarse clay, release is related to lattice activity similarly to K release. However, when most of the Mg is released from the crystal surfaces as in the case of fine clay and the first crop on the medium clay, factors other than film diffusion and the activity of the lattice Mg control its release. These factors probably include, as the rate limiting step, diffusion through weathered residues.

3. Comparison of Magnesium Availability of the Coarse Clay Fraction from the Montcalm Soils

As was discussed in the section describing the intensive cropping experiment, the three Montcalm soils were different with respect to Mg supplying power and to Mg

response. These differences appear to be explained by differences in Mg release from the coarse clay fraction. More Mg was released from the coarse clay fractions of Montcalm 1 than from this same fraction on the other two soils (Table 20). The ratio between the coarse, medium, and fine clays for all of these soils was approximately 7:2.4:1, respectively. Therefore, Montcalm 1 with a more active coarse fraction, supplied more Mg than did the other two. These differences in Mg supplying power were not due to differences in mineralogical composition or Mg content of the coarse clay, nor to mineralogical changes that could be attributed to cropping (Table 23).

4. Magnesium Content of the Fractions Before and After Cropping

Magnesium content of the soil and clay fractions decreased during cropping, but relative loss of Mg during cropping did not appear to be related to either fraction size or initial Mg content. Mortland and Lawton (1961) reported that biotite lost K in the initial stages of leaching in relation to particle size; the finer fractions losing more of their K than the coarser. However, as leaching progressed to later

stages of weathering, the large particles lost as much as the fine. The lack of consistency in relative loss of Mg content with fraction size and Mg content can be explained as follows:

Mineral species at different stages of weathering are present in various sized fractions. Release will occur, dependent upon the relative stage weathering as well as particle size and lattice ion activity.

Differential Mg release between mineral species will occur if the activity in one species is greater than in another (Mortland, 1961). Such a system was probably present in these soil clays and contributed to the inconsistent relative loss between the fractions.

5. Mineralogical Composition of Soil Fractions and Weathering During Cropping

The minerals occurring in the silt were quartz, feldspars, goethite, and boehmite (Table 23). The specific feldspars present were not identified by the technique employed. Within these minerals, Mg would probably be present as isomorphous substitutions in octahedral positions of the feldspars and goethite.

Nearly all of the clay fractions contained small amounts of illite (as defined by Grim, 1953) and kaolinite. With one exception, all clay fractions contained interstratified material between $10\text{\AA}$ and $14\text{\AA}$. Depending upon the pattern of collapse upon K saturation and heating, this interstratification was placed in either a tertiary interstratification of chlorite, vermiculite and illite or a binary interstratification between any two of this group. The medium clay from Munising 1 contained an ordered interstratification of chlorite, vermiculite, and montmorillonite.

Weathering of fractions by cropping was expected to follow one of two patterns (or both). Removal of interlayer Mg from brucite layers of chlorites would weaken interlayer bonding allowing these structures to expand to $17\text{\AA}$ upon glycerol solvation; or removal of the persistent $14\text{\AA}$ peak, characteristic of chlorite material, after K saturation and heating to 550°C . Since fine fractions of clay do not yield any information by X-ray diffraction analysis, only the medium and coarse clays were characterized before and after cropping. Only three gave any indication of weathering by cropping.

Figure 1 shows X-ray diffraction patterns before and after cropping for the coarse clay of the Karlin soil. The

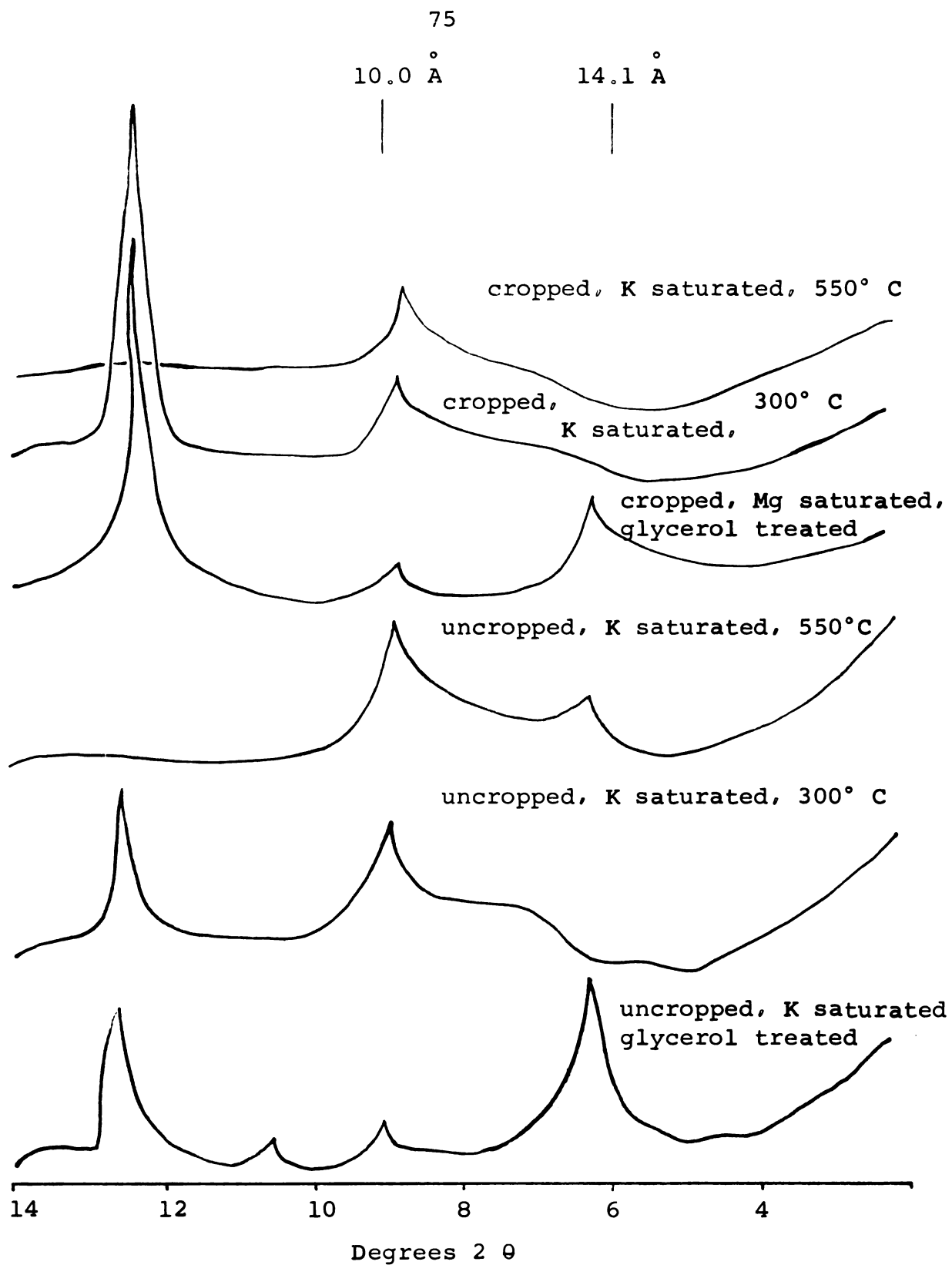


Figure 1.-- X-ray diffraction patterns for coarse clay (0.2-2.0 μ) of the Karlin loamy sand soil prior to and after cropping.

persistent $14\text{\AA}^{\circ}$ peak on heating to 550° was weakened by cropping as indicated by the broadening of the $10\text{\AA}^{\circ}$ peak with this treatment. Removal of the interlayer material allowed this collapse, resulting in a broadening of the $10\text{\AA}^{\circ}$ peak.

Sufficient interlayer material was removed from the medium clay of Montcalm 1 to cause a sharpening of the $14\text{\AA}^{\circ}$ peak after cropping (Figure 2, Mg-glycerol treatment). This indicates formation of a more discrete $14\text{\AA}^{\circ}$ material. Heating to 550° produced a sharpening of the $10\text{\AA}^{\circ}$ peak along with more symmetry of this peak, which indicates formation of a more discrete material of the vermiculite nature.

Changes for the medium clay of the Montcalm soil 3, followed the same pattern as described above. The degree of change was greater (Figure 3) as indicated by the formation of a more symmetrical $10\text{\AA}^{\circ}$ with heating to 550° . At 300° the cropped sample gave a very symmetrical $10\text{\AA}^{\circ}$ peak further indicating the removal of the interlayer material of this interstratified system.

Enhancement of the $7\text{\AA}^{\circ}$ peak after cropping was attributed to small amounts of kaolinitic material contaminating the sand used in the cultures.

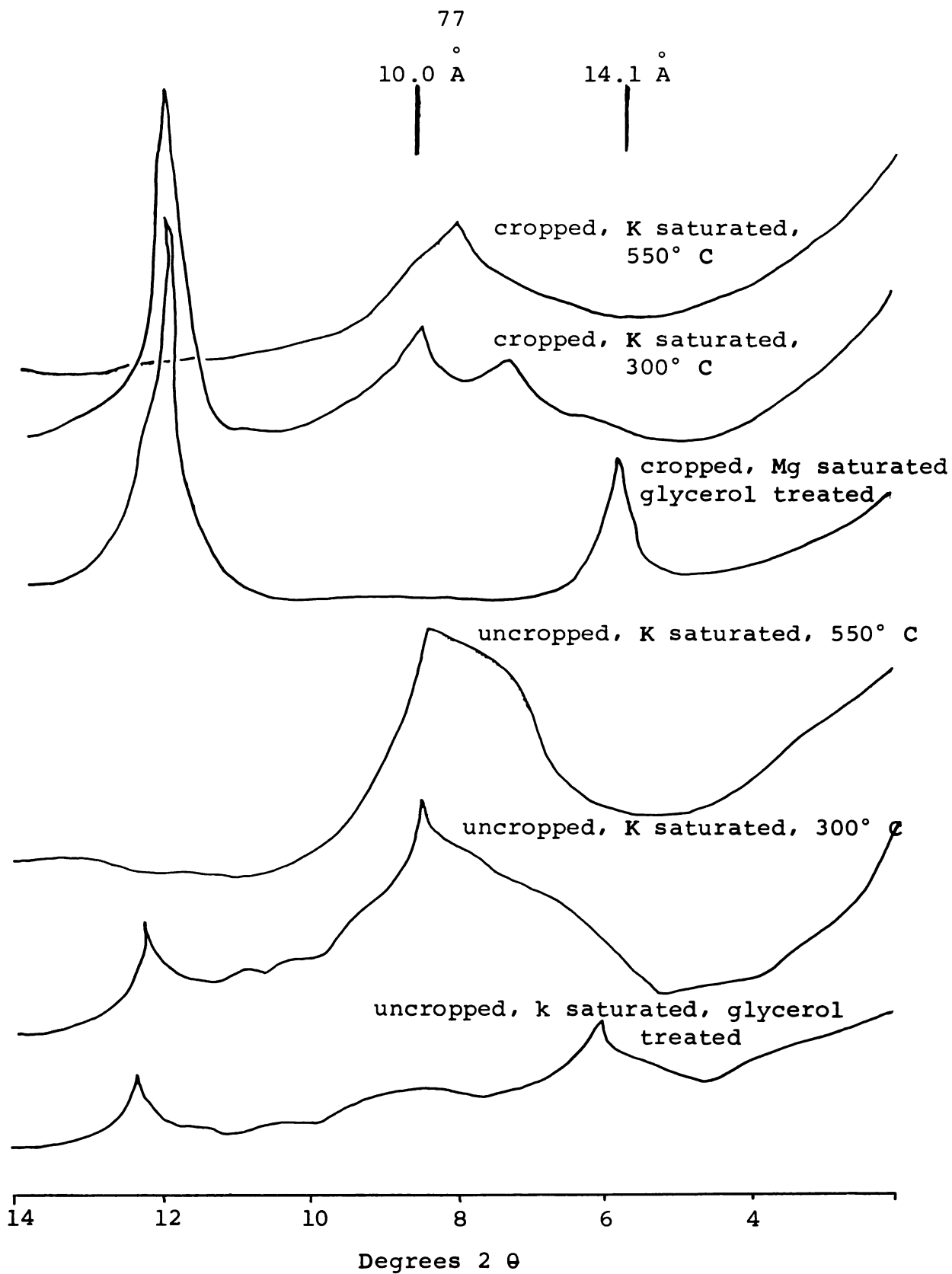


Figure 2.--X-ray diffraction patterns for medium clay (0.08-0.2 μ) for the Montcalm loamy sand (1) prior to and after cropping.

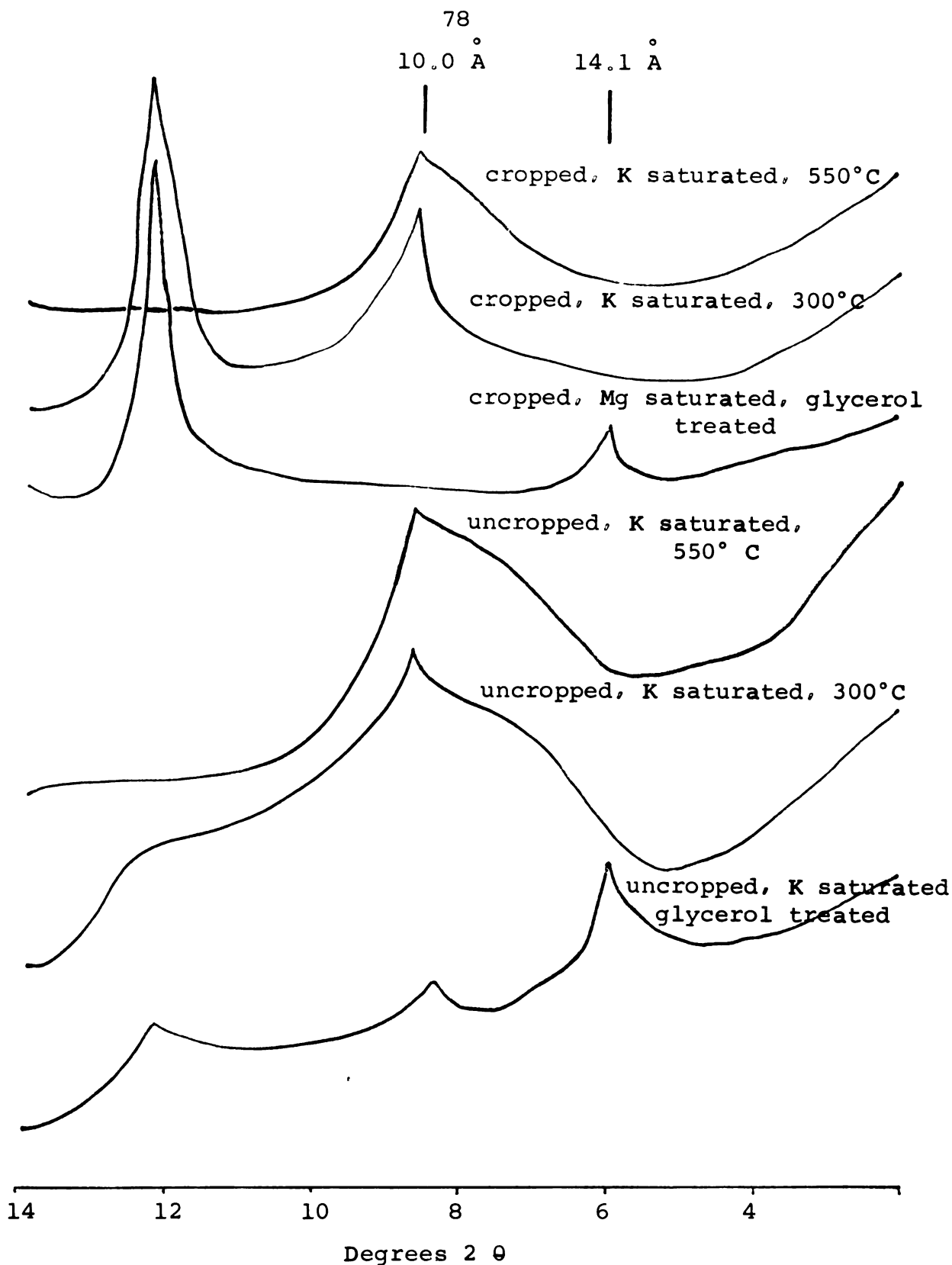


Figure 3.--X-ray diffraction patterns for medium clay (0.08-0.2 μ) of Montcalm loamy sand (3) prior to and after cropping.

SUMMARY

Three experiments were conducted to study some factors affecting release of soil Mg and uptake by oat plants. In the first experiment, three Mg levels (0, 10, and 20 ppm) were applied to seven Michigan soils and a bentonite-sand mixture. Seven oat crops were grown in the greenhouse without any additional Mg application. Extractable cations of the soil and Ca, K, and Mg content of oat tops were determined for each crop. In the second experiment, two Ca levels were applied to each of three pH levels and eight consecutive crops were grown. Extractable cations, soil pH and Ca, K and Mg of the tissue were determined for each crop. In a third experiment sufficient material to supply 20 mg Mg from each of five fractions of different particle size from seven soils, three from bentonite, and two from chlorite were cropped to two crops of oats in sand cultures. Tissue Mg content was measured for each crop. Fraction Mg content was measured before and after each crop.

Yield response to applied Mg was not obtained on any of the soils for the first three crops. Yield responses to applied Mg varied from soil to soil in the last 4 crops.

Relative release of Mg among the soils was as follows:

Sims clay loam >> Munising fine sandy loam 2 > bentonite-sand mixture $\geq$ Montcalm loamy sand 3 $\geq$ Montcalm loamy sand 1 $\simeq$ Munising fine sandy loam 1 $\geq$ Karlin loamy sand $\geq$ Montcalm loamy sand 2.

Montcalm loamy sand soils from three different locations responded differently to applied Mg. Yield and uptake responses to applied Mg were obtained on soils from two locations with an extractable Mg level of 90 ppm. Soil from the third location, which contained 40 ppm Mg, did not give a response to applied Mg. This was attributed to the 0.2-2.0 μ clay supplying more Mg for plant growth on this soil than on the other two. However, this Mg existed in a form not extracted by ammonium acetate.

Plant available Mg was depleted on all soils after seven crops; an uptake response to applied Mg was obtained on all soils on the seventh crop.

Extractable K/Mg correlated better with Mg availability (uptake, mg/culture) than did extractable Mg.

Forms of Mg are available to plants from some soils which are not extracted by the ammonium acetate extraction. It is suggested that these forms are located in interlayer

positions rather than at the crystal edge. The NH_4^+ ion, which fits into the perforations in the surface of the oxygen layers of the tetrahedral layer, causes these layers to collapse trapping interlayer Mg. Where the coarse clay fractions are most active, such as the Montcalm loamy sand which didn't respond to applied Mg, Mg is being supplied from interlayer positions and the NH_4 ion is interfering with the measurement of this plant available Mg.

Other workers (Schatschabel 1957; and Gonzales, 1963) have reported that extracting with CaCl_2 or 0.1 N NaCl or 0.1 N alphanaphthylamine-HCl gave better predictions of availability to plants than does ammonium acetate. Further evaluation of various extracting solutions is required.

The antagonism between K supply and Mg uptake is felt to be the predominate force in the reduction of Mg uptake rather than entrapment of interlayer Mg. However, in soils where the Mg supply is predominantly from interlayer positions, the physical entrapment becomes more important. Further research is required to evaluate the plant related K-Mg antagonism as well as the influence of K on Mg entrapment and subsequent Mg uptake.

Soil pH had more of an effect on yield, tissue Mg content, and Mg uptake than did Ca level. This was attributed to better soil-plant relationships at higher pH levels (above pH 6.0) than below.

The reasons for a larger amount of Mg released from unextractable forms and an associated smaller amount of Mg uptake when CaCO_3 was applied than when Ca(OH)_2 was applied were not explained by the data obtained. A more definitive study is required to clarify these differences.

Magnesium release increased with increasing soil acidity, which supported reports in the literature.

Relative order for Mg release according to particle size was as follows:

$< 0.08 = 0.08-0.2 > 0.2-2.0 = 2.0-20 \geq 20-50\mu > \text{total soil.}$

Chlorite and bentonite released more Mg than did the soil clays.

Magnesium uptake was linearly correlated with fraction Mg content for both crops on the coarse clay fraction, for the second crop on the medium clay fraction, but not for the fine clay or either silt fraction. These data indicate that interlayer Mg is released in relation to the activity of lattice Mg, but when Mg is released from the crystal

surface other factors govern release. It was suggested that diffusion through the weathered octahedral residue was probably the rate limiting step in the release of Mg.

Differential release of Mg between different clay sized fractions could not be related to different kinds of minerals present.

Silt sized fractions were too resistant to weathering for very much Mg release from interlayer sites, which explained the lack of correlation between Mg uptake and fraction Mg content. Differential release between the silt fractions could not be related to different kinds of minerals present.

X-ray diffraction patterns before and after cropping indicated that cropping had removed interlayer material from some soil fractions.

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