EFFECT OF MAGNESIUM APPLICATIONS ON THE YIELD AND CHEMICAL COMPOSITION OF SOYBEANS, MILLET, AND WHEAT GROWN ON THIRTEEN MICHIGAN SOILS IN THE GREENHOUSE

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K. N. Satyapal

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By

K. N. Satyapal

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ABSTRACT

In order to evaluate the ability of Michigan soils to supplying magnesium to crops, a greenhouse experiment was conducted. Thirteen soils were used. Three crops, namely, soybeans, millet, and wheat, were grown to extract the magnesium from the soil. Magnesium was added as the commercial magnesium-potassium carrier known as Sul-Po-Mag, under three levels, namely, 60, 120, and 240 pounds MgO per acre. There was a control where no magnesium was added. Each treatment was replicated three times.

Dry weight determinations of the three crops were obtained, and the plants were analyzed for potassium, calcium, and magnesium. The last two elements were determined on the Beckman DU flame spectrophotometer, while potassium was analyzed on Perkin-Elmer flame spectrophotometer.

The soils were analyzed for pH, organic matter, sand, silt, and clay, exchange capacity, total exchangeable bases, and exchangeable calcium, magnesium, and potassium at the start of the experiment. Exchangeable magnesium, calcium, and potassium were determined on the soils after cropping by soybeans, millet, and wheat. All soils contained more than 10 per cent exchangeable magnesium of the total exchange capacity of the soils.

Significant response from added magnesium was obtained for soybeans in only one soil, namely, Miami sandy loam, while soybean yields were significantly decreased on Brookston clay loam.

For three soils, namely, Kalkaska sand, Brookston clay loam, and Houghton muck, significant increases in yield of millet were found, while a significant decrease in yield of millet on Oshtemo loamy sand, Plainfield loamy sand, and Kent clay loam was noted.

In only one soil, namely, Kent clay loam, was there a significant response in wheat yields from added magnesium, while for Warsaw loam, a significant decrease in yield of wheat was found.

Results of chemical analyses of the three crops reveal that in most soils with the exception of Emmet sandy loam, Warsaw loam, and Houghton muck, magnesium uptake was not increased beyond the 60 pounds MgO per acre level. In some cases, increase in soil magnesium enhanced the uptake of potassium by the crop, particularly in the case of millet and wheat, and this increased potassium uptake was associated with decreased yields.

On the soils used in this study, no magnesium deficiency could be found. All the soils used in this study had adequate amounts of magnesium in the exchange complex, and it is apparent that much response to magnesium additions would not be forthcoming.

Magnesium fixation occurred only in three soils, namely, Thomas sandy loam, Kalkaska sand, and Houghton muck, the highest values being found for the first and the last soils. The remaining ten soils released magnesium in varying amounts, but the greatest release was found in the heavier soils.

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INTRODUCTION

The agronomic importance of magnesium has been frequently demonstrated as a result of extensive experimental investigations. These have brought to light the very important role that this element plays in plant nutrition.

Agricultural soils differ widely in their magnesium content. Some soils contain only a trace of this element, while others are relatively rich. Much of this variation is due to the nature of the parent material and the soil-weathering processes. For instance, the process of podzolization results in a soil that is depleted of its plant nutrients in the surface layers. Intensive cropping and a gradual transition in fertilizer composition and practices are factors which have brought about the need for magnesium in certain areas, particularly those where the soils are coarse textured. Crops may remove as much as 15 pounds of magnesium per acre of soil. Commercial fertilizers increase the removal of magnesium. These fertilizers furnish anions like sulfate, chloride, nitrate, which form easily soluble magnesium compounds that are readily leached from the soil. The salts of magnesium in the order of their decreasing solubility are nitrate, chloride, sulfate and carbonate.

Once most all soils were believed to contain adequate amounts of magnesium for plant growth and its application was considered necessary for only a few crops grown on certain soils. Results of extensive experiments prove that this is not the case. Hence, it is evident that due consideration be given to magnesium in terms of requirements of individual crops grown on specific soils.

THE OBJECT OF THE INVESTIGATION

This investigation was undertaken to obtain information regarding the abilities of some Michigan soils for supplying magnesium to crops under greenhouse conditions, and also to determine the effect of varying amounts of added magnesium on the yield and chemical composition of crops. The main objectives of this study were as follows:

1. To determine the extent of magnesium deficiency as indicated by several crops grown on different soils in the greenhouse.

2. To determine the effect of magnesium fertilization on the yield of several crops.

3. To determine the uptake of magnesium and other elements by several crops as influenced by magnesium fertilization.

4. To correlate the magnesium content of the crops with growth response to added magnesium.

5. To study the effect of other cations upon the uptake of magnesium by crops.

6. To classify the soils studied in relation to their need for added magnesium under greenhouse conditions.

REVIEW OF LITERATURE

Occurrence and Distribution of Magnesium

Geochemical. Magnesium ranks seventh in abundance in the scale of elemental occurrence in the earth's crust. There is a total of 2.5 per cent magnesium in the outer 10 miles of the earth's lithosphere of which the oceans contain 0.14 per cent (12).*

Minerals. Magnesium-bearing minerals are quite abundant and widely distributed in nature. Among the primary minerals which are sources of magnesium, the most important ones are biotite (2-20 per cent), hornblende (2-26 per cent), augite (6-20 per cent), olivine (27-51 per cent), muscovite (0-3 per cent), tourmaline (0-12 per cent), and other pyroxenes and amphiboles. Chief among the secondary minerals containing appreciable quantities of magnesium worthy of mention are, montmorillonite (0-25 per cent), chlorite (35-38 per cent), vermiculite (22-24 per cent), sepiolite (5-23 per cent), and illite (1-4 per cent).

Magnesium deposits may also occur in the form of dolomite, a double carbonate of magnesium and calcium; magnesite, $MgCO_3$; talc or soapstone, $H_2Mg_3(SiO_3)_4$; asbestos, $Mg_3Ca(SiO_3)_4$; kieserite, a hydrate of $MgSO_4$ and $MgCl_2$ found in sea water and salt beds. In regions of limited rainfall, dolomite, magnesite, and epsomite may constitute appreciable sources of magnesium (1).

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*Figures in parenthesis refer to literature cited.

Total magnesium content of soils. Soils vary widely in their content of total magnesium as indicated by chemical analysis of soils coming from different regions. Uncultivated soils of the humid temperate regions are likely to contain about as much total magnesium as calcium. The very highly weathered lateritic soils of the tropics contain the least amounts of magnesium, the values for per cent MgO being as low as 0.2. In contrast, values as high as 4 to 5 per cent have been reported in some of the brown, chestnut, and black soils of the semi-arid parts of the world. In analyses of twenty soil types from New Jersey, Bear and co-workers (2) found that the total magnesium content ranged from less than 0.02 per cent to as much as 1 per cent. The values for magnesium in pounds per acre that these workers report for Lakewood sand and Fox gravelly loam are 400 and 23,400, respectively. Organic soils contain magnesium expressed as MgO from 0.05 - 3.0 per cent on an air dry basis. (1)

Exchangeable magnesium content of soils. The quantity of magnesium present in the exchangeable form is very small compared to the total content. Roughly, ten to fifty times as much magnesium is present in the total mineral as in the exchangeable form. In analyses of exchangeable magnesium in twenty New Jersey soils, Prince (34) found the exchangeable magnesium to range from 0.10 to 4.69 m.e. per 100 grams of soil. Analyses of several Michigan surface soils by Lawton (25) show that the exchangeable magnesium ranged from 0.23 to 2.21 m.e. per 100 grams of soil, while exchangeable calcium ranged from 0.26 to 14.92 m.e. per 100 grams soil.

Availability of soil magnesium to plants. The supply of magnesium that is available to plants is controlled by several factors. Availability is dependent upon the presence and the nature of the magnesium-bearing minerals, operation of magnesium fixation phenomena, the soil weathering processes, and the balance between exchangeable cations. (2)

Prince et al. (34) attempted to evaluate the magnesium-supplying powers of twenty New Jersey soils by growing alfalfa on them and by measuring the response obtained from applications of additional magnesium supplied at the rates of 40 and 80 pounds soluble MgO per acre. Yields were increased 38 per cent in one soil, more than 20 per cent in three soils, and more than 10 per cent in seven soils. These results suggest the inadequacy of magnesium in the soil for optimum yields on many New Jersey soils. Studies of cation values in these soils in relation to crop needs led these investigators to reach a decision that the exchange complex of the "ideal soil" should contain about 20 per cent hydrogen, 65 per cent calcium, 10 per cent magnesium, and 5 per cent potassium on an equivalent basis. In only 6 of the 20 soils studied was magnesium present in the exchange complex to the extent of 10 per cent. Crop response from magnesium applications was obtained whenever the amount of the element in the exchange complex fell below 6 per cent. The same authors also found that there was no correlation between the total magnesium in these soils and their crop-producing powers.

Nature of magnesium in the soil exchange complex. Much evidence has been presented to demonstrate that magnesium may occur in soils in a "fixed" or unavailable state. According to Mattson (29), about two-thirds to three-fourths of the monovalent and divalent bases occur in the natural colloids in this unavailable (non-exchangeable) state. This phenomenon is attributed by Mattson to their position within the crystal lattice structure or molecular aggregate of the colloid. Magnesium displays some peculiar properties in its colloidal behavior. On being subjected to electrodialysis, magnesium does not react as do alkaline metals as one would anticipate, but strangely behaves like iron or aluminum. Only upon removal of the major portion of the cations, potassium, sodium, and calcium from soils does the magnesium become mobile. The displacement of the cations from a soil with a neutral salt solution shows magnesium to behave in quite a different way. Under the latter treatment, magnesium is displaced in the normal lyotropic order and in no way resembles iron or aluminum.

Weigner and Jenny (41) stated that magnesium was the most difficult of the divalent cations to displace from the soil complex. The order of displaceability is Mg, Ca, Ba. This series is identical with their displacing power, as well as the insolubility of the hydroxides of these elements. The analogy between the solubility of the hydroxides and the release of the cations is associated with the fact that the inner layer of ions of a colloidal particle consists in part of OH ions in this position in the Helmholtz double layer exerting a binding effect on the Mg ions.

Jenny (21) stated that magnesium-fixation occurs principally through the OH ions of the clay colloids (sesquioxides), which bind the Mg ions firmly. This theory is contrary to the concept of Mattson (29), who presented evidence that the sesquioxides cannot be the seat of the reaction, since the bonding occurs between magnesium and the colloidal complex through a silicate group. It follows then that cation adsorption and cation exchange occur through the free valences of the silicate ions, which is the seat of magnesium fixation.

MacIntire and his co-workers (27) concluded that magnesium enters directly into the alumino-silicate complex when applied as a fertilizer. Exchangeable magnesium, however, continues to be released from the complex. The available magnesium is a product of isoelectric hydrolysis according to these workers. Free silicic acid is liberated, which produces a mobilizing effect on magnesium.

There is other evidence to show that magnesium is often fixed by a mechanism, which does not allow a normal cationic exchange. It has been observed that considerable quantities of magnesium may be fixed in this manner, which has been substantiated by the observations of several investigators working on magnesium fixation. Kardos and Joffe (24, 22), and Mattson (29), in working with synthetic complexes, found that magnesium was fixed in a relatively insoluble form.

Concluding this topic of magnesium fixation, it may be said that although some insight has been gained regarding magnesium fixation, its exact mechanism is still controversial.

Role of magnesium in plant nutrition. Magnesium is indispensable for the growth and reproduction of all plants regardless of the position that they occupy in the evolutionary scale (16). The specific functions of magnesium within the plant and the mechanism operating to achieve these functions are not yet entirely elucidated. Magnesium is known to occur in or be related to the following plant constituents and vital processes:

The leaves and reproductory organs of plants contain relatively more of this element than other parts. Magnesium in plants exists in at least 3 forms - combined in the chlorophyll molecule, in a soluble state in the cell-sap, and in combined form in the protoplasm. Sunflower, tobacco, spinach and sugarbeet leaves are notably rich in magnesium, the content of which ranges between 1 and 3 per cent on a dry weight basis (4). Legumes contain anywhere from 0.5 to 1.02 per cent magnesium. The latter contain two to three times more magnesium than the grasses (14). The functions of magnesium in plants may be summarized as follows:

1. An essential component of the chlorophyll molecule.

2. A constant constituent of cell plasma.

3. Functions as a carrier of phosphorus, being closely associated with phosphorus assimilation.

4. Associated with carbohydrate synthesis (35).

5. Acts as transporting agent for starch (42).

6. A major mineral component of reproductive organs.

7. Associated with protein and fat synthesis (35).

8. Functions in cationic balance.

9. Functions as a stimulant in bacterial nitrogen fixation (18).

10. A factor in the maturity and aging of plants.

Magnesium-calcium-potassium relationships in plants and soil. Exchangeable magnesium in soil regulates the uptake of other nutrients. The absorption of magnesium by plants is governed by other cations and, in turn, this nutrient regulates, in part, the uptake of other cations. Plant nutrition in relation to magnesium and other elements is not only complicated by variations in absorption phenomena within the plant, but also by base exchange relationships and availability differences in the soil. The proper understanding of these inter-relationships is of fundamental importance in the field of the mineral nutrition of plants.

Hunter (20) prepared a resume of nutrient absorption at various Ca+Mg ratios and the effect of these ratios on the uptake of other nutrients. This worker found that the magnesium content of alfalfa plants grown on soils with a constant level of magnesium increased when the Mg+K ratios in the soil were increased. Moreover, while the Mg+K ratios in the plants roughly paralleled the Ca+K ratios, the former varied widely and never attained the same magnitude as the latter, commonly being only from 35 to 50 per cent as large as the Ca+K ratios. It was also observed that magnesium uptake by the plant increased with increasing Ca+K soil ratios, whereas the potassium uptake decreased. Hunter's data also showed that with successive alfalfa harvests, plant absorption of magnesium increased from 0.28 per cent in cutting 1 and to 0.42 per cent in cutting 7. This increase in plant magnesium coincided with decreased supplies of available potassium in the soil.

Fonder (17) showed that the quantity of magnesium in alfalfa leaves remained relatively low as long as the potassium level in the plant was relatively high. High applications of potash caused leaves of sugar beets to become chlorotic. Magnesium sulfate applied at the rate of 100 pounds per acre corrected this chlorosis and also increased the yields of beets.

Walsh and Clarke (38) using tomatoes in their work, showed that the K+Mg ratio within the plant determined the extent of magnesium uptake. When this ratio was sufficiently high, chlorosis developed even when the culture medium had a relatively large content of available magnesium.

Walsh and O'Donohoe (39), in extensive experiments conducted in potash manuring of potatoes, tobacco, sugar beets, wheat, barley, and mangold, found that in most cases high potash fertilization induced magnesium deficiency even when this element was abundant in the soil. The plants were also shown to contain low amounts of magnesium. The authors conclude that the K:Mg ratio of both the soil and plant merits attention in accounting for the development of magnesium deficiency.

Boynton and associates (6) made an investigation of the potassium, magnesium, calcium, and phosphorus contents of McIntosh apple leaves from orchards of New York State. In comparing the results of tests in 1941 and 1942, they found that in both years in areas where potassium was highest, magnesium was lowest, and where potassium was lowest, magnesium was highest. In 1941, when the mean leaf potassium percentage in 148 sampled plots was 1.36 and the average magnesium content was 0.27 per cent, potassium deficiency scorch was more prevalent and magnesium deficiency symptoms less prevalent than in 1942, when the contents of leaf potassium and magnesium were 1.53 and 0.22 per cents, respectively.

Bradfield and Peech (9) observed that in soils with a limited supply of potassium, addition of calcium or magnesium suppressed the absorption of potassium by the plant.

In a 26-year lysimeter experiment, McIntire (28) found that a calcic liming material decreased the solubility of both potassium and magnesium of the soil. When a magnesia liming material was used, a decrease in the solubility of both potassium and calcium resulted. Dolomite and limestone exerted similar effects on soil potash. These repressions in solubility were reflected in the composition of the plant ash.

Obenshain (31) found a decrease in magnesium and calcium in the expressed sap and tissue of corn plants when the potassium content of the sand culture medium was increased.

Wallace and his co-workers (37) grew potatoes in 1942 on plots on which a fertilizer experiment on black currants had been in progress from 1927-41. Potassium deficiency symptoms were prevalent on the leaves where potassium had not been applied, while the need for magnesium was evident when potassium had been applied. Magnesium deficiency symptoms were not too noticeable where farmyard manure had been used.

Carolus (11) observed that in the case of potassium deficiency, vegetables had an extremely low concentration of potassium and a high concentration of magnesium and calcium in the stems and petioles. A deficiency of magnesium in the presence of other nutrients resulted in a low concentration of magnesium, and generally, in a high concentration of potassium in the stems and petioles of the plants under observation.

Southwick (36) working on orchard soils, presented evidence to show that potash fertilization, even with heavy mulching alone, raised the level of available potassium in some apple orchard soils so as to cause an actual shortage of magnesium. Magnesium deficiency was evident in the form of leaf scorch. This worker questioned the advisability of using potassium for apple orchards until the magnesium supply was built up.

Boynton and Compton (7) observed the effect of potash fertilization in sharply raising leaf potassium and simultaneously lowering leaf magnesium. They showed that in orchards showing magnesium deficiency symptoms, leaf potassium tended to be abnormally high even though soil replaceable potassium was low and no potash supplements had been used. It appeared that high leaf potassium was a sign of magnesium deficiency. Leaf analyses for potassium and magnesium were helpful in diagnosing magnesium deficiency.

Cooper (13) showed that many plants selectively absorb the relatively strong ions and the magnesium content in most plants was significantly lower than those of calcium or potassium.

Webb et al. (40), working with soybeans, found that magnesium deficient plants absorbed slightly larger amounts of calcium and potassium on a per cent basis.

Lucas and Scarseth (26) concluded that there is a reciprocal relationship between the potassium, calcium, and magnesium contents of plants. This relationship helps to account for the need of maize for additional potassium when growing on a high lime soil that had a high content of exchangeable potassium (140-200 pounds per acre plow layer.) In a soil high in magnesium, a magnesium-starved plant may grow if the intake of calcium, and/or potassium are high. The sum of these cations when calculated on an ionic equivalent basis tends to be a constant.

Prince et al. (3), investigating the uptake of nutrients by alfalfa plants from different soils, found that when the soil was too liberally fertilized with potassium, this element was taken up at the expense of magnesium with subsequent induction of magnesium deficiency in the plant. There was a definite correlation between the abnormal increase in uptake of potassium and low yields from some of the soils that were low in magnesium. The sum of the potassium, calcium, and magnesium expressed as equivalents, was found to be constant. Response to magnesium additions was controlled partly by its ratio to other cations in the exchange complex, particularly those of potassium and calcium.

Blair et al. (5) found that yields of crops as influenced by magnesium additions depended not only on the individual crop, but also upon the soil type on which they were grown. Snap beans, tomato, and cabbage yields were increased on sandy soils by the additions of magnesium, while on heavier soils, little, no increase, or even a decrease in yield occurred.

Mehlich and Reed (30) showed that large soil additions of calcium or potassium reduced the uptake of magnesium. Increasing the magnesium in the soil augmented the magnesium concentration in the plant, lowered the potassium slightly, and appreciably decreased the calcium concentration.

Magnesium deficiency has been reported on the organic soils of Michigan by Harmer (19), and Davis and McCall (15). Johnson (23), working with celery on the organic soils of Michigan, found that magnesium deficiency could be controlled by broadcast application of magnesium sulfate at a rate of two to four tons one week before transplanting. It was found that for mature susceptible varieties of celery 0.07 - 0.13 per cent magnesium of the aboveground portion was indicative of magnesium deficiency symptoms and when this was raised to 0.14 per cent or above, no symptoms developed.

METHODS AND MATERIALS

Greenhouse experiments. In order to evaluate the effect of magnesium applications on the dry weight and chemical composition of several crops, thirteen Michigan soils representing different soil types, and varying over a wide range of texture, organic matter, pH, exchange capacity, and base status were used in this study. Three different crops, soybeans, millet, and wheat were grown under three levels of added magnesium, namely, 60, 120, and 240 pounds MgO per acre and without magnesium fertilization. Each treatment was replicated three times.

The soils were procured from farmer's fields from 13 different locations in southern Michigan. Samples were taken from two different depths, 0-6 inches and 6-12 inches, respectively. The bulk samples were air-dried and passed through $\frac{1}{4}$ inch sieve and were mixed thoroughly. Two gallon glazed porcelain pots were used as containers, the soils being placed in each pot on a volume basis rather than on a weight basis, due to the fact that the soils show such a wide range in texture. The sample taken from the 6-12 inches layer of each soil was placed in each pot to a height of three inches, on top of which five inches of the surface soil was added after being thoroughly mixed with the fertilizers. The object of incorporating the subsoils in this study was not only to get a soil volume more similar to the feeding volume of the crops in the field, but also to bring in a soil layer which may be of importance in supplying magnesium to the specific crops grown.

<u>Fertilizer treatments</u>. All fertilizer applications were made on volume basis, only the first five inches of the soil being taken into consideration in all the computations, except in the case of Houghton muck, where the plow depth of seven inches was taken into consideration, as no subsoil was included in the series under this soil.

1. Blanket applications: Nitrogen was applied as $(NH_4)_2SO_4$ at a rate of 40 pounds N per acre. Additional applications at a rate of 50 pounds of nitrogen were made for each successive crop.

Phosphorus was applied as $Ca(H_2PO_4)_2.H_2O$ at a rate of 200 pounds P_2O_5 per acre.

Manganese was added as $MnSO_4.H_2O$ at a rate of 100 pounds per acre.

Copper and zinc were applied as the sulfates at rates of 20 and 10 pounds per acre, respectively.

Boron was added as $Na_2B_4O_7.10H_2O$ at a rate of 10 pounds per acre.

Molybdenum was added as $(NH_4)_6Mo_2O_{24}.4H_2O$ at a rate of 1 pound per acre.

2. Magnesium was the experimental variable, and this element was added at rates of 0, 60, 120, and 240 pounds of MgO, equivalent to 0, 36, 72, and 144 pounds of Mg per acre. These quantities under the four treatments expressed as milligrams of magnesium per pot amounted to 0, 197, 394, and 788 milligrams, respectively. The magnesium was added as Sul-Po-Mag, $MgSO_4.K_2SO_4$, a water-soluble double salt of potash-magnesia, containing 18.5 per cent MgO and 22.4 per cent K_2O. Potassium was present in the 240-MgO series of the soils to the extent of 185 pounds per acre, and consequently, the levels of potassium in the 0-MgO, 60-MgO, and 120-MgO series were brought

up to the same level as in the 240-MgO series by adding appropriate amounts of K_2SO_4. These additions of potassium were designed to keep the added potassium at the same level in all the series, so that magnesium would not be thrown out of balance.

Irrigation. Each soil was adjusted to an optimum moisture content as calculated from the moisture equivalent percentage. At regular intervals throughout the experiment, an attempt was made to maintain this moisture level of each soil by adding a uniform quantity of distilled water.

Cultural methods. Soybeans, millet, and wheat were grown in succession on the same soils between June 25, 1955, and November 30, 1955. Soybeans were grown in the period from June 25 to August 4, 1955; millet from August 6 to September 21, 1955; while wheat was grown from September 21 to November 30, 1955. Only wheat had to be provided with artificial illumination, as light conditions were far from satisfactory at this time.

Soybeans (Richland variety). Twelve seeds were planted in each pot, but the seedlings were eventually thinned down to 4 per pot. The plants were in excellent condition during the growth period, except for the fact yellowish-brown spots appeared on the lower leaves of all plants growing on the lighter soils. Plants in the 120-MgO and the 240-MgO series did not develop these symptoms to an appreciable extent. The yellowish-brown spots were probably the result of boron toxicity.

Millet. Twenty seeds were sown in each pot; plants were thinned down to 8 in each pot.

Wheat (spring wheat - Illinois 120). Twenty-five seeds were planted in each pot; the number of plants per pot was brought to 8. Although growth was good at the beginning, poor light conditions during the latter part of the experiment hampered heading of the plants to some extent.

After the harvest of the final crop, composite samples were taken from each of the soils according to fertilizer treatment. No attempt was made to remove the roots of any crop. Consequently, calculations for fixation or release of magnesium after cropping are subject to this possible error.

Preparation of plant materials. The plant material of each pot in each of the three crops was dried in paper bags for 3 days at 70° C., weighed, and ground separately. Each sample was thoroughly mixed before chemical analyses were made. The triplicates were not combined for analyses.

Laboratory Procedures

Soils. The thirteen soils used in this study were analyzed for pH, organic matter, sand, silt, and clay, exchange capacity, and exchangeable bases. Exchangeable potassium, calcium, and magnesium were determined both at the beginning, as well as at the end of the experiment.

Soil reaction was determined by the glass electrode, using a 1:1 soil to water ratio.

Exchange capacity was determined by the neutral normal ammonium acetate method described by Peech (32). Total exchangeable bases were determined according to the method of Bray and Wilhite (10).

Exchangeable potassium, calcium, and magnesium were determined on the leachates from the ammonium acetate extractions of the soils using the Beckman DU flame spectrophotometer (23).

Per cent organic matter was determined by the well-known dry combustion method as outlined by Piper (33).

Per cent sand, silt, and clay were estimated by using the hydrometer method of Bouyoucos (8).

Analyses of plant materials. One gram samples of the dry plant materials were first moistened with 1:1 sulfuric acid, then dried on a hot plate, followed by drying in an oven at 105° C. The dried samples were then ignited in a muffle furnace, first at 200° C, with the temperature being ultimately raised to 600° C. The samples were maintained at this temperature for 10-12 hours to insure complete combustion of all the carbonaceous matter. The ash was taken up in 3 ml. of concentrated hydrochloric acid, and this solution boiled over a gentle flame for one minute, after which it was filtered through a Whatman No. 42 filter paper. The residue was washed repeatedly with hot water, and the filtrates were made up to a volume of 200 ml. with distilled water.

Calcium and magnesium in these ash extracts were determined with the Beckman DU flame spectrophotometer, equipped with a photomultiplier. The source of fuel for the flame was hydrogen burned in the presence of oxygen. The instrumental conditions used for the determination of calcium and magnesium are set out in the following table:

Conditions	Elements Determined	
	Calcium	Magnesium
Wave length	4227 A°	2852 A°
Phototube resistor	No. 2	No. 2
Phototube	Blue	Blue
Selector	0.1	0.1
Slit	0.01	0.06
Sensitivity		
a. Instrument panel	variable	variable
b. Photomultiplier	No. 4	Full
Zero suppression	1.0	1.0

The standard curves for the Beckman flame photometer were reproducible from day to day, provided the same conditions were used. Due to too many electrical fields, and other mechanical disturbances in the neighborhood of the instrument, fluctuations of the gross luminosity were caused, which had to be rectified with new slit settings, and whenever this was done, it was necessary to establish a new standard curve. A slit width of 0.06 mm. with a top standard of 100 p.p.m. Mg at 2852 A° wavelength eliminated all interferences from other ions present in the solution. Sodium added in concentrations ranging from 5 to 50 p.p.m. to the calcium standards, did not seem to interfere with calcium.

Potassium was determined on the Perkin-Elmer flame photometer, Model. 52 A. The conditions for this flame photometer varied from time to time, and new settings had to be made frequently.

TABLE I

SOME PHYSICAL AND CHEMICAL CHARACTERISTICS OF THE THIRTEEN MICHIGAN SURFACE SOILS USED IN THIS STUDY

Soil Type	Location (County)	pH[1]	Organic[2] Matter Percent	% Sand	% Silt	% Clay[3]
Thomas sandy loam	Tuscola	7.4	11.20	60.0	24.4	15.6
Kalkaska sand	Oceana	6.0	0.90	94.0	2.2	3.8
Oshtemo loamy sand	Shiawassee	7.4	0.92	85.0	10.2	4.8
Emmet sandy loam	Oceana	6.3	1.65	62.0	30.2	7.8
Plainfield loamy sand	Kalamazoo	6.3	1.02	86.0	9.2	4.8
Fox sandy loam	Kalamazoo	6.2	2.32	60.0	30.2	9.8
Warsaw loam	Kalamazoo	5.6	5.80	36.0	42.2	21.6
Isabella silt loam	Kent	6.5	1.95	24.0	54.4	21.6
Brookston clay loam	Saginaw	6.7	5.06	44.0	25.4	31.6
Miami sandy loam	Clinton	6.8	2.20	75.0	12.2	12.8
Kent clay loam	Muskegon	7.2	1.82	40.0	28.4	31.6
Wisner clay loam	Tuscola	8.1	3.65	32.0	30.4	37.6
Houghton muck	Clinton	6.2	----	----	----	----

1 Determined by glass electrode

2 Dry combustion method

3 Hydrometer method of Bouyoucos

RESULTS AND DISCUSSION

Greenhouse Study

Partial Physical and Chemical Analyses of Soils

Data of specific properties for the thirteen soils as they were collected from the field are shown in Tables I and II. Included in Table I are reaction values of the soils, their organic matter contents, and sand, silt, and clay contents expressed on a per cent basis. Of the twelve mineral soils obtained, one was a sand, two were loamy sands, four were sandy loams. It should be noted that the texture of the soils, which ranged from sand to clay loam, affected the extent to which the various cations were removed from the soils, movement of water within the soils, soil temperature, soil aeration, and the microbiological activity of the soil.

The pH values of the original soils varied from 5.6 for Warsaw loam to 8.1 for Wisner clay loam.

Organic matter content of the mineral soils expressed on per cent basis ranged from 0.90 for Kalkaska sand to 11.2 for Thomas sandy loam.

Clay contents varied between 3.8 per cent for Kalkaska sand to 37.6 per cent for Wisner clay loam.

In Table II, values are given for exchange capacity, total exchangeable bases, and exchangeable calcium, magnesium, and potassium contents of the surface and subsoil at the start of the experiment. The exchange capacity of the mineral soils from the 0-6 inch layer varied between 1.68 milliequivalents per 100 grams for Oshtemo loamy sand to 28.52 milliequivalents for Thomas

TABLE II

SOIL REACTION, EXCHANGE CAPACITY, TOTAL EXCHANGEABLE BASES, AND EXCHANGEABLE MAGNESIUM, CALCIUM, AND POTASSIUM OF THE SOILS AT THE START OF THE GREENHOUSE STUDY

Soil Type	Depth in Inches	pH	Exchange Capacity M.e. Per 100 Gms.	Total Exchangeable Bases M.e. Per 100 Gms.	Exchangeable Cations M.e. Per 100 Gms.			Mg Saturation Per Cent
					Mg	Ca	K	
Thomas sandy loam	0 - 6	7.4	28.52	26.50	5.75	18.90	0.18	20.16
	6 - 12	7.4	25.30	21.26	3.50	14.32	0.09	13.83
Kalkaska sand	0 - 6	6.0	2.10	1.61	0.41	0.65	0.08	19.52
	6 - 12	5.7	3.52	1.82	0.25	0.34	0.05	7.10
Oshtemo loamy sand	0 - 6	7.4	1.68	7.05	0.90	6.13	0.16	53.57
	6 - 12	6.7	8.72	9.95	1.97	6.53	0.13	22.59
Emmet sandy loam	0 - 6	6.3	7.56	6.35	0.92	3.50	0.06	12.17
	6 - 12	6.3	6.80	5.10	0.74	2.72	0.08	10.88
Plainfield loamy sand	0 - 6	6.3	3.20	2.40	0.74	1.81	0.06	23.12
	6 - 12	6.8	2.48	3.52	1.10	1.50	0.05	44.35
Fox sandy loam	0 - 6	6.2	8.52	7.10	1.06	3.90	0.15	12.44
	6 - 12	5.6	10.31	8.60	1.93	6.10	0.16	18.72
Warsaw loam	0 - 6	5.6	15.56	11.20	2.06	7.40	0.13	13.24
	6 - 12	5.1	12.36	8.80	1.81	5.24	0.14	14.64
Isabella silt loam	0 - 6	6.5	10.48	8.15	1.93	6.50	0.13	18.41
	6 - 12	5.7	8.36	8.05	1.93	4.89	0.12	23.08
Brookston clay loam	0 - 6	6.7	20.10	16.30	3.61	11.35	0.23	17.96
	6 - 12	6.8	12.68	18.54	6.59	11.47	0.19	51.97
Miami sandy loam	0 - 6	6.8	8.88	9.05	2.71	6.13	0.12	30.52
	6 - 12	5.8	10.00	8.12	3.90	4.30	0.13	39.00
Kent clay loam	0 - 6	7.2	15.48	14.15	1.89	11.10	0.30	12.21
	6 - 12	6.8	12.48	18.31	8.14	9.00	0.30	65.22
Wisner clay loam	0 - 6	8.1	14.10	22.60	2.30	20.45	0.13	16.31
	6 - 12	8.0	10.00	27.83	5.34	21.34	0.17	53.40
Houghton muck	0 - 6	6.2	131.00	125.60	22.00	74.58	0.62	16.79

sandy loam. The high cation exchange capacity value for the latter soil is due to its high organic matter content. The exchange capacity of the subsoils from the 6-12 inch layer ranged from 3.52 milliequivalents per 100 grams for Oshtemo loamy sand to 25.30 milliequivalents for Thomas sandy loam. A general positive relationship between the cation exchange capacity, organic matter, and clay contents of the mineral soils is apparent. Houghton muck had a high exchange capacity of 131 milliequivalents per 100 grams of air dry soil.

The content of exchangeable magnesium of the mineral soils from the 0-6 inch layer varied between 0.41 milliequivalents per 100 grams for Kalkaska sand to 3.61 for Brookston clay loam. The subsoils contained exchangeable magnesium from 0.25 milliequivalents per 100 grams for Kalkaska sand to 8.14 milliequivalents for Kent clay loam. In general, the subsoils contained more exchangeable magnesium than the surface soils, the exceptions being Thomas sandy loam, Kalkaska sand, Emmet sandy loam, and Plainfield loamy sand. The exchangeable magnesium, calcium, and potassium contents of Houghton muck were 22.00, 74.58, 0.62 milliequivalents per 100 grams, respectively. The magnesium saturation of these soils varied from a low of 7.10 per cent for Kalkaska subsoil to a high of 65.22 per cent for Kent clay loam subsoil. The values for per cent magnesium saturation of these soils furnish a partial index to the magnesium-supplying powers of these soils. Of the surface soils, all thirteen soils had more than 10 per cent of their exchange capacity satisfied by magnesium. Of the thirteen subsoils, all but one soil, namely, Kalkaska, had more than 10 per cent of the exchange capacity satisfied by magnesium. It is also evident that there is no correlation between magnesium saturation percentage and soil reaction in the case of these thirteen soils.

TABLE III

THE EXCHANGEABLE MAGNESIUM, CALCIUM, AND POTASSIUM CONTENT OF SOIL SUPPLIED WITH VARYING AMOUNTS OF MAGNESIUM AT THE CONCLUSION OF THE EXPERIMENT

Soil Type	Exchangeable Cations in M.e. Per 100 Grams of Soil											
	0-MgO[1]			60-MgO			120-MgO			240-MgO		
	Mg	Ca	K	Mg	Ca	K	Mg	Ca	K	Mg	Ca	K
Thomas sandy loam	3.65	12.15	0.17	3.86	12.30	0.17	3.96	10.80	0.15	4.01	12.30	0.15
Kalkaska sand	0.04	0.15	0.06	0.42	0.10	0.06	1.75	0.18	0.05	2.28	0.20	0.05
Oshtemo loamy sand	1.75	6.70	0.07	2.28	6.00	0.07	2.58	5.70	0.06	2.92	5.60	0.06
Emmet sandy loam	1.75	3.90	0.06	2.28	3.70	0.05	2.58	3.50	0.05	3.28	3.25	0.05
Plainfield loamy sand	0.73	1.50	0.05	0.73	1.70	0.05	2.92	1.45	0.05	2.92	1.45	0.05
Fox sandy loam	2.92	5.60	0.11	2.96	4.80	0.09	3.13	4.90	0.09	3.13	4.20	0.09
Warsaw loam	1.75	7.00	0.09	2.92	6.80	0.09	2.92	6.80	0.09	3.78	6.70	0.09
Isabella silt loam	3.60	6.00	0.10	4.96	5.50	0.09	4.96	4.90	0.09	4.88	5.10	0.09
Brookston clay loam	6.66	17.88	0.25	6.66	17.70	0.27	5.88	17.75	0.26	5.28	17.75	0.24
Miami sandy loam	5.88	12.10	0.09	5.88	12.10	0.09	5.00	12.38	0.09	6.67	10.88	0.09
Kent clay loam	6.25	16.13	0.23	7.29	15.88	0.22	7.92	15.63	0.23	8.50	15.50	0.23
Wisner clay loam	4.04	19.38	0.23	4.17	20.13	0.23	5.63	21.50	0.23	5.67	21.80	0.23
Houghton muck	3.33	21.50	0.28	13.75	21.50	0.28	14.08	21.50	0.28	14.33	21.50	0.28

[1]Refers to pounds of MgO applied on an acre basis as sulfate of potash-magnesia

The exchangeable calcium of the surface layer of mineral soils ranged from 0.34 milliequivalents per 100 grams for Kalkaska sand to 20.45 milliequivalents for Wisner clay loam. The Ca+Mg ratio of the original soils ranged from 1.1 for Kent subsoil to 8.9 for Wisner surface soil.

The exchangeable potassium content of the mineral soils ranged from 0.05 milliequivalents per 100 grams for Kalkaska sand to 0.3 milliequivalents for Kent clay loam.

Data of the exchangeable magnesium, calcium, and potassium contents of the soils at the end of the greenhouse experiment are listed in Table III. The amount of exchangeable magnesium at the end was found to be generally slightly higher than that found at the beginning of the experiment in all the four series, namely, 0-MgO, 60-MgO, 120-MgO, and 240-MgO. It is possible that this increase may have come from the subsoils, and also from added magnesium. In Fox sandy loam, magnesium at the end of the experiment at the 0-MgO level was higher than at the start of the experiment, even though the subsoil was lower in exchangeable magnesium. The same was true for Isabella, Brookston, Miami, and Emmet soils. In cases where the exchangeable magnesium is higher at the end than at the beginning, it is likely that magnesium has been released from the soils as a result of cropping. And where exchangeable magnesium at the end is lower than at the beginning, it is probable that the exchangeable magnesium has been reduced by cropping or added magnesium has been fixed by the soil.

Yields of Crops on Different Soils

Data presented in Tables IV through VI show the dry weight yields of soybeans, millet, and wheat, respectively, grown on the thirteen soils in the greenhouse, while in Tables VII through IX is listed the per cent increase

TABLE IV

DRY WEIGHT YIELDS OF SOYBEANS GROWN IN THE GREENHOUSE ON THIRTEEN MICHIGAN SURFACE SOILS SUPPLIED WITH VARYING AMOUNTS OF MAGNESIUM

Soil Type	Dry Weight Yields of Plants, Gms. Per Pot				F Values[2]	L.S.D.	
	0-MgO[1]	60-MgO	120-MgO	240-MgO		5%	1%
Thomas sandy loam	30.21	28.78	30.35	29.80	1.48		
Kalkaska sand	23.91	22.70	31.53	22.91	2.09		
Oshtemo loamy sand	26.56	28.10	26.33	25.00	1.78		
Emmet sandy loam	19.81	21.18	23.43	23.03	0.47		
Plainfield loamy sand	18.90	17.45	21.00	20.36	4.38		
Fox sandy loam	28.30	24.21	21.61	22.82	4.01		
Warsaw loam	24.20	23.82	23.96	21.90	3.29		
Isabella silt loam	24.28	24.70	25.82	27.46	0.60		
Brookston clay loam	33.09	31.10	30.06	26.02	9.66*	1.04	1.55
Miami sandy loam	28.83	29.43	32.76	31.56	6.43*	0.79	1.17
Kent clay loam	25.40	27.43	24.36	27.16	1.83		
Wisner clay loam	26.52	26.63	26.26	27.53	0.47		
Houghton muck	25.23	23.48	22.73	24.20	4.34		

1 Refers to pounds of MgO applied on an acre basis as sulfate of potash-magnesia

2 From analysis of variance data

* Significance at 5% level
All values are the mean of three replications

TABLE V

DRY WEIGHT YIELDS OF MILLET GROWN IN THE GREENHOUSE ON THIRTEEN MICHIGAN SURFACE SOILS SUPPLIED WITH VARYING AMOUNTS OF MAGNESIUM

Soil Type	Dry Weight Yields of Plants, Gms. Per Pot				F Values[2]	L.S.D.	
	0-MgO[1]	60-MgO	120-MgO	240-MgO		5%	1%
Thomas sandy loam	11.86	10.90	10.76	11.33	0.52		
Kalkaska sand	5.06	3.93	13.03	9.83	8.54*	5.02	7.60
Oshtemo loamy sand	11.10	8.85	8.35	11.26	4.95*	2.34	3.54
Emmet sandy loam	5.45	7.83	7.35	8.66	2.63		
Plainfield loamy sand	9.95	7.33	7.73	7.53	6.42*	1.66	2.46
Fox sandy loam	6.58	5.32	3.80	4.56	3.69		
Warsaw loam	8.76	9.00	9.92	8.40	1.56		
Isabella silt loam	6.50	6.03	5.20	7.93	0.68		
Brookston clay loam	6.65	5.51	3.93	9.92	10.74**	2.71	4.10
Miami sandy loam	10.56	10.98	8.76	8.13	0.93		
Kent clay loam	8.23	10.46	5.26	8.26	8.81*	2.49	3.77
Wisner clay loam	6.53	4.35	5.74	7.01	4.03		
Houghton muck	15.90	22.00	23.56	23.50	11.30**	3.78	5.73

1 Refers to pounds of MgO applied on an acre basis as sulfate of potash-magnesia

2 From analysis of variance data

* Significance at 5% level

** Significance at 1% level

All values are the mean of three replications

TABLE VI

DRY WEIGHT YIELDS OF WHEAT GROWN IN THE GREENHOUSE ON THIRTEEN MICHIGAN SURFACE SOILS SUPPLIED WITH VARYING AMOUNTS OF MAGNESIUM

Soil Type	Dry Weight Yields of Plants, Gms. Per Pot				F Values[2]	L.S.D.	
	0-MgO[1]	60-MgO	120-MgO	240-MgO		5%	1%
Thomas sandy loam	7.13	6.23	4.60	4.80	1.33		
Kalkaska sand	4.30	3.60	4.60	3.80	1.28		
Oshtemo loamy sand	6.86	7.56	6.80	6.73	0.30		
Emmet sandy loam	4.96	5.40	4.73	4.86	0.54		
Plainfield loamy sand	3.53	4.40	3.86	4.63	1.39		
Fox sandy loam	5.40	5.00	5.40	5.46	0.16		
Warsaw loam	4.60	4.93	3.30	3.33	13.23**	0.80	1.20
Isabella silt loam	6.60	5.86	5.06	5.93	1.67		
Brookston clay loam	4.80	4.90	6.56	5.13	3.08		
Miami sandy loam	6.13	5.63	4.66	5.70	1.96		
Kent clay loam	4.96	7.40	6.96	6.80	25.30**	0.74	1.13
Wisner clay loam	5.46	5.86	5.13	3.83	2.32		
Houghton muck	5.33	5.76	5.66	8.63	1.30		

1 Refers to pounds of MgO applied on an acre basis as sulfate of potash-magnesia

2 From analysis of variance data

** Significance at 1% level

All values are the mean of three replications

or decrease in yields of soybeans, millet, and wheat, respectively, due to applications of 60, 120, and 240 pounds of MgO per acre. The pattern of yield response in each of the three crops is shown graphically in Figures 1 through 13. Results of the yield responses of the three crops for each soil are presented below:

Thomas sandy loam. Data shown in Tables IV and V and in Figure 1 for yields of soybeans and millet grown on Thomas sandy loam indicate there was no response from added magnesium. The same is true for the dry weight yields of wheat as shown in Table VI and Figure 1. Moreover, the dry weight yields of wheat plants tended to be depressed, as magnesium additions were increased. Since this soil contained more magnesium in the surface layer than any soil except Houghton muck, it is quite likely that no growth response could be expected.

Kalkaska sand. Increases in dry weight of soybeans from added magnesium were not significant, although the 120-MgO series showed a 28.9 per cent increase in dry weight over the checks, as shown in Table IV. Data for yield increases in millet were found to be significant for this soil as shown in Table V. The greatest dry weight yields and most vigorous plants were found in the 120-MgO series. No yield responses from added magnesium for wheat were noted. This soil contained less than 0.5 milliequivalents of magnesium in both the surface and subsoil of the original samples, although magnesium saturation was slightly less than 20 per cent in the surface soil. However, since crop yields were equal to those found with most of the soils, greater response to magnesium might have been expected.

Oshtemo loamy sand. There was no significant response in yields of soybeans or wheat to magnesium treatments applied to this soil as shown in Tables IV and VI. However, a significant decrease in yield was found for millet when the 120-MgO level was compared with the 0-MgO treatments. No explanation can be given for the apparent depression in growth when such a condition was not evident with the 240-MgO level.

Emmet sandy loam. No significant response in yields of soybeans, millet, or wheat is evident according to data in Tables IV, V, and VI. This soil contained 0.92 and 0.74 milliequivalents magnesium in the original surface and subsoils, respectively, and had a magnesium saturation of 12.17 per cent in the surface layer. Yield increases from added magnesium might be expected from this soil. However, as shown in Tables IV, V, and VI, crop yields on this soil are distinctly lower than those obtained on other soils. It is possible that the decreased yield is due to physiological disorders brought about by additions of large amounts of magnesium.

Plainfield loamy sand. No response from added magnesium was noted in the yields for soybeans or wheat as shown in Tables IV and VI. There was a significant decrease in dry matter produced by millet. The surface and subsoil in this case contained 0.74, and 1.10 milliequivalents exchangeable magnesium, respectively, per 100 grams, although the magnesium saturation of the surface soil was 23.12 per cent. However, as in the case of Emmet sandy loam, here also crop yields fall far below those obtained on most other soils. This situation is rather strange, because one would expect a favorable yield response to magnesium additions by a light-textured soil like Plainfield loamy sand, provided no other nutrient is a limiting factor in growth.

Fox sandy loam. There was no significant increase in yields of soybeans, millet, or wheat from added magnesium, as shown in Tables IV, V, and VI. This soil contained 1.06 and 1.93 milliequivalents exchangeable magnesium in the surface and subsoils, respectively, and, in fact, there was an increase in the exchangeable magnesium content of the soil at the end of the experiment, particularly in the 0-MgO series. However, crop yields were similar to those obtained from most other soils.

Warsaw loam. No significant increase in yields of soybeans or millet was obtained from added magnesium as shown in Tables IV and V. There was a significant decrease in dry weight of wheat plants, as shown in Table VI. The surface layer of this soil contained 2.06 milliequivalents exchangeable magnesium per 100 grams, and had a magnesium saturation of 13.24 per cent. It is likely that there would not be any growth response to added magnesium. In the case of wheat, a peculiar nutritional disorder set in, with the plants becoming lean, spiny, and yellowish, and most plants withered off. This condition was responsible for the depressed yields.

Isabella silt loam. There was no significant increase in dry matter production from added magnesium for soybeans, millet, or wheat, as shown in Tables IV, V, and VI. The surface and subsoil both contained 1.93 milliequivalents of exchangeable magnesium per 100 grams of soil, with a magnesium saturation of 18.41 per cent in the surface layer. If values above 15 per cent magnesium saturation are considered adequate, then no yield increases would be expected from soluble magnesium added to this soil.

Brookston clay loam. A significant decrease in yields of soybeans grown on this soil was obtained when the highest rate of magnesium was applied, as seen in Table IV. Millet yields were significantly increased by magnesium, as shown in Table V, while the data in Table VI show that there was no significant increase in yields of wheat from any rate of added magnesium. Since this soil contained 3.61 and 6.59 milliequivalents of exchangeable magnesium content per 100 grams of soil in the surface and subsoil layers, respectively, and the respective magnesium saturation values were 17.96 and 51.97 per cent, any response to added magnesium would be unlikely. However, no explanation can be given for the significant increases in millet yields on this soil.

Miami sandy loam. Magnesium additions brought about significant increases in the yield of soybeans as shown in Table IV, while for millet and wheat, no significant response is recorded in Tables V and VI. This soil has an exchangeable magnesium content of 2.71 milliequivalents per 100 grams in the surface layer and 3.90 milliequivalents in the subsoil, and the magnesium saturation values are 30.52 per cent and 39.00 per cent, respectively. It is quite likely that no growth response could be anticipated. This situation is true for millet and wheat yields obtained on this soil. However, the soybean crop, which is quite responsive to magnesium additions, does show significant increases in yields from added magnesium on this soil.

Kent clay loam. Dry weight yields of soybean plants were not significantly increased, as shown in Table IV. However, magnesium additions significantly increased the yields of millet and wheat, as seen in Tables V and VI. This soil had 1.89 milliequivalents of exchangeable magnesium per 100 grams of soil in the upper six inches, and a magnesium saturation per cent of 12.21. It is rather likely that millet and wheat, which have a shallower root system than soybeans, would show significant response to added magnesium.

TABLE VII

THE EFFECT OF INCREASING RATES OF ADDED MAGNESIUM ON THE YIELD AND UPTAKE OF MAGNESIUM BY SOYBEANS GROWN ON SOME MICHIGAN SURFACE SOILS

Soil Type	Percent Increase in Dry Weight from Added Magnesium			Percent Increase in Magnesium Uptake from Added Magnesium		
	60-MgO[1]	120-MgO	240-MgO	60-MgO	120-MgO	240-MgO
Thomas sandy loam	- 4.7	+ 0.40	- 1.30	00.00	+ 12.50	- 12.50
Kalkaska sand	- 5.02	+ 28.90	- 4.20	+ 6.60	+ 66.60	+ 20.00
Oshtemo loamy sand	+ 6.04	- 0.84	+ 7.90	+ 18.20	00.00	- 18.20
Emmet sandy loam	+ 7.07	+ 18.20	+ 17.70	+ 14.30	+ 28.60	+143.00
Plainfield loamy sand	- 7.90	+ 11.10	+ 7.40	- 7.14	+ 28.60	+ 28.60
Fox sandy loam	- 14.50	- 23.70	- 19.40	- 8.80	- 21.50	- 8.80
Warsaw loam	- 1.60	- 1.30	- 9.50	- 16.90	- 5.20	- 18.20
Isabella silt loam	+ 2.05	+ 6.20	+ 12.70	+ 16.50	+ 3.30	+ 17.60
Brookston clay loam	- 6.00	- 7.50	- 21.40	- 7.50	- 7.50	- 8.30
Miami sandy loam	- 2.10	+ 13.50	+ 9.40	+ 16.40	+ 8.20	+ 8.20
Kent clay loam	+ 7.90	- 4.70	+ 6.70	+ 19.04	+ 10.47	+ 6.70
Wisner clay loam	- 0.40	- 2.60	+ 3.40	00.00	- 8.90	+ 8.90
Houghton muck	- 6.70	+ 9.92	+ 3.60	- 5.40	00.00	+ 5.40

[1] Refers to pounds of MgO applied on an acre basis as sulfate of potash-magnesia
All values are the mean of three replications
Positive values indicate increase
Negative values indicate decrease

TABLE VIII

THE EFFECT OF INCREASING RATES OF ADDED MAGNESIUM ON THE YIELD AND UPTAKE OF MAGNESIUM BY MILLET GROWN ON SOME MICHIGAN SURFACE SOILS

Soil Type	Percent Increase in Dry Weight from Added Magnesium			Percent Increase in Magnesium Uptake from Added Magnesium		
	60-MgO[1]	120-MgO	240-MgO	60-MgO	120-MgO	240-MgO
Thomas sandy loam	- 7.60	- 9.30	- 4.20	- 2.60	- 2.60	+ 18.40
Kalkaska sand	- 2.50	+ 15.60	+ 8.80	+ 21.90	+ 15.60	- 43.70
Oshtemo loamy sand	- 20.70	- 22.80	+ 0.80	- 13.30	- 26.60	- 13.30
Emmet sandy loam	+ 44.40	+ 37.00	+ 61.10	+214.20	+514.20	+442.80
Plainfield loamy sand	- 26.20	- 22.20	- 24.20	+ 3.40	+ 10.34	- 17.24
Fox sandy loam	- 19.60	- 42.40	- 31.80	- 5.90	- 23.50	00.00
Warsaw loam	+ 3.40	+ 13.80	+ 1.15	- 11.76	+ 35.30	- 11.76
Isabella silt loam	- 3.00	- 20.00	+ 21.50	+ 33.30	- 6.60	+ 66.60
Brookston clay loam	- 16.60	- 40.90	+ 51.50	+ 15.40	- 7.69	+146.10
Miami sandy loam	+ 4.70	- 17.10	- 22.80	+ 36.30	- 3.03	- 12.12
Kent clay loam	+ 26.80	- 28.00	- 00.00	+ 50.00	- 25.00	+ 15.00
Wisner clay loam	- 32.30	- 12.30	+ 7.70	- 28.60	- 9.52	- 33.30
Houghton muck	+ 40.10	+ 49.70	+ 50.30	+ 70.00	+ 21.60	+ 86.60

[1] Refers to pounds of MgO applied in an acre basis as sulfate of potash-magnesia
All values are the mean of three replications
Positive values indicate increase
Negative values indicate decrease

TABLE IX

THE EFFECT OF INCREASING RATES OF ADDED MAGNESIUM ON THE YIELD AND UPTAKE OF MAGNESIUM BY WHEAT GROWN ON SOME MICHIGAN SURFACE SOILS

Soil Type	Percent Increase in Dry Weight from Added Magnesium			Percent Increase in Magnesium Uptake from Added Magnesium		
	60-MgO[1]	120-MgO	240-MgO	60-MgO	120-MgO	240-MgO
Thomas sandy loam	- 12.60	- 35.20	- 32.30	+ 15.40	- 26.90	- 19.20
Kalkaska sand	- 20.90	+ 7.00	- 11.60	- 20.00	+ 22.00	+160.00
Oshtemo loamy sand	+ 5.90	00.00	- 1.40	- 15.30	00.00	00.00
Emmet sandy loam	+ 10.20	- 4.00	- 2.00	+ 87.50	+125.00	+100.00
Plainfield loamy sand	+ 25.70	+ 8.60	+ 31.40	+116.60	+100.00	+133.30
Fox sandy loam	+ 5.70	Nil	Nil	+ 50.00	+ 75.00	+200.00
Warsaw loam	+ 6.50	- 21.70	- 28.30	+ 11.10	- 22.20	- 44.40
Isabella silt loam	+ 12.10	- 24.20	- 10.60	+ 62.50	00.00	+ 25.00
Brookston clay loam	+ 2.10	+ 35.40	+ 6.20	+ 75.00	+100.00	+ 50.00
Miami sandy loam	- 8.20	- 24.60	- 6.50	+ 40.00	- 10.00	- 20.00
Kent clay loam	+ 51.02	+ 40.80	+ 38.80	+ 83.30	+ 50.00	+ 50.00
Wisner clay loam	+ 7.40	- 5.50	- 29.60	+ 33.30	+ 11.10	+ 11.10
Houghton muck	+ 5.50	+ 3.70	+ 50.00	+127.20	+ 90.90	+181.80

[1] Refers to pounds of MgO applied on an acre basis as sulfate of potash-magnesia
All values are the mean of three replications
Positive values indicate increase
Negative values indicate decrease

The subsoil has an exchangeable magnesium content of 8.14 milliequivalents per 100 grams, and thus, soybeans with a deeper-feeding root system would not show any significant growth response.

Wisner clay loam. No significant response from added magnesium was noted for the dry matter production of soybeans, millet, or wheat, as indicated in Tables IV, V, and VI. This soil contained 2.30 milliequivalents per 100 grams of exchangeable magnesium, and a magnesium saturation of 16.31 per cent in the surface layer. With adequate calcium and magnesium in the exchangeable form in this soil, a significant growth response would not be expected.

Houghton muck. There was no significant increase in the dry weight yield of soybeans or wheat, as shown in Tables IV and VI. However, magnesium additions produced a significant increase in yields of millet, as shown in Table V. This soil has more exchangeable magnesium than any other soil used in this study, and it is quite likely that no growth response by added magnesium could be expected. However, no explanation can be offered for the significant yield response in the case of millet.

Uptake of Magnesium by the Three Crops

From the yield data in Tables IV, V, and VI, and the magnesium content of the various crops in Tables XIII, XIV, and XV, the uptake of magnesium can be calculated in terms of milligrams per pot. This information is presented graphically in Figures 1 through 13. Per cent increase in uptake of magnesium for each crop, due to added magnesium, is reported in Tables VII through IX. Results on the uptake of magnesium by soybeans, millet, and wheat are presented.

Soybeans. Magnesium contents of soybeans expressed as milligrams per pot ranged from 70 in Plainfield loamy sand to 160 in Thomas sandy loam on the O-MgO series. As for the 60-MgO series, the magnesium concentration ranged from 65 milligrams per pot in Plainfield loamy sand to 160 in Thomas sandy loam. In most soils, with the exception of Fox sandy loam, Brookston clay loam, and Houghton muck, there was an increase in the uptake of magnesium by soybeans upon addition of the soluble magnesium salt. In Isabella silt loam, a 100 per cent increase in the uptake of magnesium by soybeans at the 60-MgO level was recorded. At the 120-MgO level, in only Thomas sandy loam, Kalkaska sand, Emmet sandy loam, Plainfield loamy sand, and Houghton muck, was a further increase in the uptake of magnesium by this crop found over that in plants from the 60-MgO treatment. In Oshtemo loamy sand and Isabella silt loam was noted an actual decrease in magnesium uptake at the 120-MgO level. Crops in the 240-MgO series showed an increase in magnesium uptake only when grown in Emmet sandy loam, whereas for soybeans in all the other soils, there was little or no increase in magnesium uptake, and in some soils, magnesium uptake was actually depressed.

In general, it is evident that magnesium in soybeans tended to increase at the 60-MgO and 120-MgO levels in the soils, while at the 240-MgO level, magnesium uptake was depressed. No correlation was found to exist between uptake of magnesium by the crops and yield response.

Millet. Data as given in Table IV show that the magnesium content in millet grown in the different soils ranged from 7 milligrams per pot for Emmet sandy loam to 60 milligrams for Houghton muck. In the 60-MgO series, increases in magnesium uptake by millet were obtained with Kalkaska sand, Emmet sandy loam, Isabella silt loam, Brookston clay loam, Miami sandy loam, and

TABLE X

THE MAGNESIUM AND POTASSIUM CONTENTS OF SOYBEANS GROWN IN THE GREENHOUSE ON SOME MICHIGAN SURFACE SOILS SUPPLIED WITH VARYING AMOUNTS OF MAGNESIUM

Soil Type	Nutrient Content in M.e. per 100 Gms. Dry Matter											
	0-MgO[1]			60-MgO			120-MgO			240-MgO		
	Mg	K	Mg/K	Mg	K	Mg/K	Mg	K	Mg/K	Mg	K	Mg/K
Thomas sandy loam	44.75	28.70	1.56	46.66	28.70	1.62	48.83	28.35	1.72	39.42	27.69	1.42
Kalkaska sand	25.66	29.23	0.88	29.42	42.05	0.70	35.25	33.33	1.06	35.25	36.05	0.98
Oshtemo loamy sand	37.16	34.36	1.08	39.17	34.87	1.12	35.50	33.23	1.07	32.50	32.56	1.06
Emmet sandy loam	29.54	33.84	0.87	31.66	26.82	1.18	35.50	25.31	1.40	35.25	30.59	1.08
Plainfield loamy sand	31.08	39.74	0.78	31.00	48.97	0.63	34.42	48.46	0.71	34.66	50.50	0.69
Fox sandy loam	30.16	28.36	1.06	32.66	31.43	1.04	30.83	35.64	0.86	34.16	41.79	0.82
Warsaw loam	26.66	52.05	0.51	31.66	46.66	0.68	29.83	44.61	0.67	34.16	43.08	0.79
Isabella silt loam	31.08	25.80	1.20	35.25	23.23	1.52	30.42	25.40	1.19	31.92	31.54	1.01
Brookston clay loam	30.25	35.90	0.84	29.75	32.82	0.91	30.92	32.64	0.95	35.25	37.43	0.94
Miami sandy loam	39.16	29.49	1.33	44.16	30.51	1.45	36.92	31.54	1.17	38.33	30.00	1.28
Kent clay loam	36.08	35.64	1.01	38.00	31.10	1.22	39.66	28.20	1.40	34.16	29.74	1.15
Wisner clay loam	42.00	26.82	1.56	41.33	26.92	1.53	39.00	28.42	1.37	44.41	30.51	1.45
Houghton muck	39.16	59.56	0.66	47.66	49.23	0.97	54.00	54.51	0.99	53.42	52.56	1.01

[1] Refers to pounds of MgO applied on an acre basis as sulfate of potash-magnesia
All values refer to the mean of three replications

TABLE XI

THE MAGNESIUM AND POTASSIUM CONTENTS OF MILLET GROWN IN THE GREENHOUSE ON SOME MICHIGAN SURFACE SOILS SUPPLIED WITH VARYING AMOUNTS OF MAGNESIUM

Soil Type	Nutrient Content in M.e. per 100 Gms. Dry Matter											
	0-MgO[1]			60-MgO			120-MgO			240-MgO		
	Mg	K	Mg/K	Mg	K	Mg/K	Mg	K	Mg/K	Mg	K	Mg/K
Thomas sandy loam	26.66	44.10	0.60	28.58	43.49	0.66	29.00	45.13	0.64	27.75	45.90	0.60
Kalkaska sand	4.66	55.64	0.08	8.33	68.20	0.12	23.58	24.69	0.95	15.25	29.23	0.52
Oshtemo loamy sand	11.00	51.02	0.21	12.33	63.07	0.19	10.66	68.20	0.15	9.42	51.79	0.18
Emmet sandy loam	10.66	53.84	0.19	23.58	66.66	0.50	36.33	39.69	0.91	36.08	30.85	1.16
Plainfield loamy sand	23.83	32.82	0.72	34.60	38.97	0.88	34.25	35.90	0.95	26.50	45.90	0.58
Fox sandy loam	21.92	47.18	0.46	25.16	60.00	0.42	28.16	70.27	0.40	30.83	68.66	0.45
Warsaw loam	17.16	50.25	0.34	14.00	69.49	0.28	19.27	48.46	0.39	15.16	54.36	0.28
Isabella silt loam	19.66	62.56	0.31	27.75	67.95	0.57	23.33	51.28	0.45	26.33	40.51	0.65
Brookston clay loam	16.08	44.10	0.36	23.16	55.13	0.42	26.50	57.18	0.46	27.00	61.79	0.44
Miami sandy loam	26.00	44.35	0.58	34.00	51.02	0.66	30.08	60.25	0.59	29.00	60.51	0.48
Kent clay loam	20.50	54.87	0.37	23.58	53.66	0.43	24.58	50.25	0.48	23.00	55.64	0.41
Wisner clay loam	26.75	55.38	0.48	29.58	65.64	0.45	28.00	59.74	0.47	17.16	54.36	0.31
Houghton muck	30.83	28.20	1.09	38.92	35.90	1.08	25.92	39.13	0.66	39.66	41.10	0.96

[1] Refers to pounds of MgO applied on an acre basis as sulfate of potash-magnesia
All values refer to the mean of three replications

TABLE XII

THE MAGNESIUM AND POTASSIUM CONTENTS OF WHEAT GROWN IN THE GREENHOUSE ON SOME MICHIGAN SURFACE SOILS SUPPLIED WITH VARYING AMOUNTS OF MAGNESIUM

Soil Type	Nutrient Content in M.e. per 100 Gms. Dry Matter											
	0-MgO[1]			60-MgO			120-MgO			240-MgO		
	Mg	K	Mg/K	Mg	K	Mg/K	Mg	K	Mg/K	Mg	K	Mg/K
Thomas sandy loam	30.66	52.30	0.59	40.16	53.07	0.75	33.83	56.56	0.59	37.41	51.61	0.73
Kalkaska sand	10.50	59.74	0.17	13.83	64.69	0.21	29.50	45.63	0.64	27.33	81.79	0.33
Oshtemo loamy sand	15.92	62.31	0.26	16.92	62.56	0.27	16.66	64.36	0.26	16.66	57.18	0.29
Emmet sandy loam	12.83	49.23	0.26	22.75	42.56	0.53	30.50	33.59	0.91	27.00	49.23	0.55
Plainfield loamy sand	16.33	57.18	0.28	24.66	51.02	0.48	26.50	41.69	0.63	25.08	39.13	0.64
Fox sandy loam	8.33	50.77	0.16	10.92	51.61	0.21	11.58	55.20	0.21	17.16	52.13	0.32
Warsaw loam	15.92	50.77	0.31	16.66	47.4	0.35	19.12	38.28	0.50	12.00	57.43	0.21
Isabella silt loam	12.08	57.94	0.21	17.75	54.87	0.32	12.42	64.61	0.19	14.92	60.51	0.24
Brookston clay loam	8.16	76.66	0.10	12.08	83.84	0.14	12.88	79.49	0.16	10.75	77.33	0.14
Miami sandy loam	13.16	58.72	0.22	21.33	61.79	0.37	15.50	58.72	0.26	12.08	62.31	0.19
Kent clay loam	10.50	74.10	0.14	12.08	66.92	0.18	10.75	72.56	0.15	11.33	77.33	0.15
Wisner clay loam	12.92	66.92	0.19	17.50	75.90	0.23	16.92	76.66	0.22	21.83	72.56	0.30
Houghton muck	27.92	42.05	0.66	32.00	42.38	0.75	28.00	44.35	0.63	29.42	38.72	0.76

[1] Refers to pounds of MgO applied on an acre basis as sulfate of potash-magnesia
All values refer to the mean of three replications

Houghton muck. As for the 120-MgO and 240-MgO series, the uptake of magnesium was about the same as for the 60 pounds per acre treatment on all soils except for Emmet sandy loam, Brookston clay loam, and Houghton muck soils. In some soils, even a decrease was found, as shown in Figures 1 through 13.

For this crop also, no correlation was obtained between the magnesium content of the plant and yield response.

Wheat. The quantity of magnesium in wheat varied between 7 milligrams per pot for Fox sandy loam to 21 milligrams for Houghton muck on the 0-MgO series. As for the 60-MgO, 120-MgO, and 240-MgO applications, there was no appreciable increase in magnesium uptake by the crop, due to added magnesium, as can be seen in Figures 1 through 13.

Relation Between the Various Cations in the Three Crops

The three basic cations, calcium, magnesium, and potassium, and their proper physiological balance influence the quality and quantity of plant growth. Although each cation has a specific function in the plant, there are some physiological functions that are performed in common by these cations. Variations in the amounts of these three cations within a certain range may not affect the quality and quantity of plant growth, but any extreme change that results from a luxury consumption of one cation will be reflected in the growth and composition of the crop. Several investigators have shown that when the individual content of plants is expressed on an equivalent basis, the sum of the equivalents tends to be constant.

TABLE XIII

THE MAGNESIUM AND CALCIUM CONTENTS OF SOYBEANS GROWN IN THE GREENHOUSE ON SOME MICHIGAN SOILS SUPPLIED WITH VARYING AMOUNTS OF MAGNESIUM

Soil Type	Nutrient Content in M.e. per 100 Gms. Dry Matter											
	0-MgO[1]			60-MgO			120-MgO			240-MgO		
	Mg	Ca	Mg/Ca	Mg	Ca	Mg/Ca	Mg	Ca	Mg/Ca	Mg	Ca	Mg/Ca
Thomas sandy loam	44.75	36.00	1.24	46.66	35.00	1.33	48.83	39.50	1.23	39.42	35.00	1.12
Kalkaska sand	25.66	21.40	1.19	29.42	18.40	1.60	35.25	21.50	1.64	35.25	17.30	2.03
Oshtemo loamy sand	37.16	30.00	1.24	39.17	29.30	1.33	35.50	27.30	1.30	32.50	25.90	1.25
Emmet sandy loam	29.54	27.05	1.09	31.66	27.10	1.16	35.50	29.30	1.21	35.25	29.70	1.18
Plainfield loamy sand	31.08	21.98	1.41	31.00	21.50	1.45	34.42	21.71	1.59	34.66	18.36	1.89
Fox sandy loam	30.16	33.65	0.90	32.66	31.50	1.03	30.83	27.36	1.12	34.16	28.20	1.21
Warsaw loam	26.66	31.70	0.84	31.66	31.61	1.00	29.83	32.30	0.92	34.16	31.61	1.08
Isabella silt loam	31.08	29.95	1.04	35.25	31.50	1.12	30.42	29.91	1.02	31.92	28.30	1.13
Brookston clay loam	30.25	28.30	1.07	29.75	28.23	1.05	30.92	26.25	1.17	35.25	26.25	1.34
Miami sandy loam	39.16	28.73	1.36	44.16	30.28	1.45	36.92	29.48	1.25	38.33	27.28	1.40
Kent clay loam	36.08	31.00	1.16	38.00	29.46	1.29	39.66	27.96	1.42	34.16	28.25	1.21
Wisner clay loam	42.00	34.33	1.22	41.33	33.58	1.23	39.00	34.25	1.14	44.41	36.12	1.23
Houghton muck	39.16	27.40	1.43	47.66	28.43	1.67	54.00	26.60	2.03	53.42	25.00	2.14

[1] Refers to pounds of MgO applied on an acre basis as sulfate of potash-magnesia
All values refer to the mean of three replications

TABLE XIV

THE MAGNESIUM AND CALCIUM CONTENTS OF MILLET GROWN IN THE GREENHOUSE ON SOME MICHIGAN SOILS SUPPLIED WITH VARYING AMOUNTS OF MAGNESIUM

Soil Type	Nutrient Content in M.e. per 100 Gms. Dry Matter											
	0-MgO[1]			60-MgO			120-MgO			240-MgO		
	Mg	Ca	Mg/Ca	Mg	Ca	Mg/Ca	Mg	Ca	Mg/Ca	Mg	Ca	Mg/Ca
Thomas sandy loam	26.66	5.75	4.63	28.58	5.88	4.86	29.00	5.45	5.32	27.75	5.91	4.69
Kalkaska sand	4.66	4.78	0.95	8.33	3.91	2.13	23.58	5.00	4.71	15.25	3.16	4.83
Oshtemo loamy sand	11.0	4.70	2.30	12.33	5.08	2.42	10.66	4.82	2.21	9.42	5.20	1.81
Emmet sandy loam	10.66	4.96	2.14	23.58	5.00	4.72	36.33	5.75	6.32	36.08	5.90	6.12
Plainfield loamy sand	23.83	5.41	4.40	34.60	5.65	6.12	34.25	5.60	6.12	26.5	4.56	5.81
Fox sandy loam	21.92	5.25	4.17	25.16	4.91	5.12	28.16	4.91	5.74	30.83	4.25	7.25
Warsaw loam	17.16	4.40	3.90	14.00	4.50	3.11	19.27	4.20	4.59	15.16	3.80	3.99
Isabella silt loam	19.66	4.41	4.45	27.75	4.38	6.33	23.33	4.08	5.72	26.33	4.65	5.66
Brookston clay loam	16.08	4.51	3.56	23.16	4.70	5.55	26.50	4.96	5.34	27.00	4.66	5.79
Miami sandy loam	26.00	4.81	5.41	34.00	4.33	7.85	30.08	4.00	7.52	29.00	3.25	8.92
Kent clay loam	20.50	5.75	3.56	23.58	3.28	7.19	24.58	5.02	4.90	23.00	4.65	4.95
Wisner clay loam	26.75	5.90	4.53	29.58	5.88	5.03	28.00	5.03	5.57	17.16	4.63	3.71
Houghton muck	30.83	5.40	5.71	38.92	5.11	7.62	25.92	4.50	5.76	39.66	5.46	7.26

[1] Refers to pounds of MgO applied on an acre basis as sulfate of potash-magnesia
All values refer to the mean of three replications

TABLE XV

THE MAGNESIUM AND CALCIUM CONTENTS OF WHEAT GROWN IN THE GREENHOUSE ON SOME MICHIGAN SOILS SUPPLIED WITH VARYING AMOUNTS OF MAGNESIUM

Soil Type	Nutrient Content in M.e. Per 100 Gms. Dry Matter											
	0-MgO[1]			60-MgO			120-MgO			240-MgO		
	Mg	Ca	Mg/Ca	Mg	Ca	Mg/Ca	Mg	Ca	Mg/Ca	Mg	Ca	Mg/Ca
Thomas sandy loam	30.66	11.20	2.74	40.16	12.90	3.11	33.83	11.55	2.93	37.41	10.90	3.43
Kalkaska sand	10.50	6.30	1.65	13.83	5.30	2.61	29.50	11.55	2.55	27.33	5.91	4.62
Oshtemo loamy sand	15.92	6.60	2.41	16.92	6.65	2.54	16.66	6.75	2.47	16.66	7.80	2.14
Emmet sandy loam	12.83	6.80	1.89	22.75	8.05	2.82	30.50	7.25	4.20	27.00	7.60	3.55
Plainfield loamy sand	16.33	5.98	2.73	24.66	7.30	3.37	26.50	7.55	3.51	25.00	6.25	4.01
Fox sandy loam	8.33	5.96	2.81	10.92	6.00	1.82	11.58	5.70	2.03	17.16	6.18	2.78
Warsaw loam	15.92	7.18	2.22	16.66	8.55	1.94	19.12	8.30	2.30	12.00	6.03	1.99
Isabella silt loam	12.08	5.93	2.04	17.75	7.05	2.52	12.42	5.00	2.48	14.92	6.31	2.36
Brookston clay loam	8.16	6.86	1.19	12.08	6.83	1.77	12.88	6.20	2.08	10.75	6.20	1.73
Miami sandy loam	13.16	6.10	2.16	21.33	7.05	3.03	15.50	5.86	2.65	12.08	5.60	2.16
Kent clay loam	10.50	6.70	1.57	12.08	8.15	1.48	10.75	7.03	1.53	11.33	7.30	1.55
Wisner clay loam	12.92	8.40	1.54	17.50	7.40	2.36	16.92	7.01	2.41	21.83	7.50	2.91
Houghton muck	27.92	13.30	2.10	32.00	11.20	2.86	28.00	10.60	2.64	29.42	10.50	2.80

[1]Refers to pounds of MgO applied on an acre basis as sulfate of potash-magnesia
All values refer to the mean of three replications

Tables X, XI, XII contain data for magnesium and potassium expressed as milliequivalents per 100 grams of dry matter, and the Mg:K ratios for soybeans, millet, and wheat, respectively. In Tables XIII, XIV, and XV are reported values for the magnesium and calcium expressed as milliequivalents per 100 grams of dry matter, and the Mg:Ca ratios for soybeans, millet, and wheat, respectively. A discussion of the experimental results on this aspect for each crop is presented below:

Soybeans. The amount of magnesium in soybeans for the 13 soils where no magnesium was applied ranged from 25.66 milliequivalents per 100 grams of dry matter for Kalkaska sand to 44.75 milliequivalents for Thomas sandy loam. The potassium contents varied between 26.82 milliequivalents per 100 grams of dry matter for Wisner clay loam to 59.56 milliequivalents for Houghton muck. The Mg:K ratios in soybeans varied between 0.66 for Houghton muck to 1.56 for Thomas sandy loam. The amount of calcium in soybeans grown on the different soils ranged from 21.40 milliequivalents per 100 grams of dry matter for Kalkaska sand to 36.00 milliequivalents for Thomas sandy loam. The Mg:Ca ratios in soybeans varied between 0.84 for Warsaw loam to 1.43 for Houghton muck.

In the 60-MgO series, the amount of magnesium in soybeans ranged from 29.42 milliequivalents per 100 grams of dry matter for Kalkaska sand to 47.66 milliequivalents for Houghton muck. The amount of potassium ranged from 23.23 milliequivalents per 100 grams of dry matter for Isabella silt loam to 49.23 milliequivalents for Houghton muck. The Mg:K ratios varied between 0.63 for Plainfield loamy sand to 1.62 for Thomas sandy loam. It can be seen from Figure 1 that potassium content of soybeans was greatly increased as magnesium application to the soil was increased. Calcium in soybeans grown in soils treated with 60 pounds of magnesium expressed as the oxide ranged from 18.40 milliequivalents per 100 grams of dry matter for Kalkaska sand to 35.00 milliequivalents for Thomas sandy loam, as shown in Table XIII. The Mg÷Ca ratios of this crop ranged from 1.00 for Warsaw loam to 1.67 for Houghton muck.

In the 120-MgO series, the amount of magnesium in soybeans varied between 29.83 milliequivalents per 100 grams dry matter for Warsaw loam to 54.00 for Houghton muck, as seen in Table X. The potassium content ranged from 25.31 milliequivalents per 100 grams dry matter for Emmet sandy loam to 54.51 milliequivalents for Houghton muck. The Mg÷K ratios varied between 0.67 for Warsaw loam to 1.72 for Thomas sandy loam. The amount of calcium in soybeans on this series ranged from 21.50 milliequivalents per 100 grams dry matter for Kalkaska sand to 39.50 milliequivalents for Thomas sandy loam. The Mg÷Ca ratios varied between 0.92 for Warsaw loam to 2.03 for Houghton muck.

In the 240-MgO series, the content of magnesium in soybeans ranged from 32.50 milliequivalents per 100 grams of dry matter for Oshtemo loamy sand to 53.42 milliequivalents for Houghton muck. The amount of potassium content ranged from 27.69 milliequivalents per 100 grams of dry matter for Thomas sandy loam to 52.56 milliequivalents for Houghton muck. The Mg÷K ratios varied between 0.69 for Plainfield loamy sand to 1.42 for Thomas sandy loam. The content of calcium in soybeans on the 240-MgO series ranged from 17.30 milliequivalents per 100 grams of dry matter for Kalkaska sand to 36.12 milliequivalents for Wisner clay loam. The Mg÷Ca ratios ranged from 1.12 for Thomas sandy loam to 2.14 for Houghton muck.

In summarizing the nutrient composition of soybeans grown on the different soils in the 0-MgO, 60-MgO, 120-MgO, and 240-MgO series, it was found that the magnesium content initially increased with added magnesium, and then decreased when 120 and 240 pounds of MgO were applied. The content of potassium increased appreciably as the rate of magnesium application was increased. So far as the uptake of calcium is concerned, a gradual decrease in calcium content occurred as the amount of added magnesium was increased.

Millet. The amount of magnesium in millet on the 0-MgO series varied between 4.66 milliequivalents per 100 grams of dry matter for Kalkaska sand to 30.83 milliequivalents for Houghton muck. The amount of potassium varied between 28.20 milliequivalents per 100 grams dry matter for Houghton muck to 62.56 milliequivalents for Isabella silt loam. The Mg÷K ratios ranged from 0.08 for Kalkaska sand to 1.09 for Houghton muck. The content of calcium in millet on this series varied between 4.40 milliequivalents per 100 grams of dry matter for Warsaw loam to 5.90 milliequivalents for Wisner clay loam. The Mg÷Ca ratios ranged from 0.95 for Kalkaska sand to 5.71 for Houghton muck.

In the 60-MgO series, the amount of magnesium in millet ranged from 8.33 milliequivalents per 100 grams of dry matter for Kalkaska sand to 38.92 for Houghton muck. The amount of potassium varied between 35.90 milliequivalents per 100 grams of dry matter for Houghton muck to 69.49 milliequivalents for Fox sandy loam. The Mg÷K ratios ranged from 0.12 for Kalkaska sand to 1.08 for Houghton muck. The calcium content varied between 3.28 milliequivalents per 100 grams of dry matter for Kent clay loam to 5.88 milliequivalents for Wisner clay loam. The Mg÷Ca ratios ranged from 2.13 for Kalkaska sand to 7.85 for Miami sandy loam.

On the 120-MgO series, the magnesium content in millet varied between 10.66 milliequivalents per 100 grams of dry matter for Oshtemo loamy sand to 36.33 milliequivalents for Emmet sandy loam. The potassium content ranged from 24.69 milliequivalents per 100 grams of dry matter for Kalkaska sand to 68.20 milliequivalents for Oshtemo loamy sand. The Mg÷K ratios in this crop ranged from 0.15 for Oshtemo loamy sand to 0.95 for Kalkaska sand and Plainfield loamy sand. The amount of calcium varied between 4.00 milliequivalents per 100 grams of dry matter for Miami sandy loam to 5.75 milliequivalents for Emmet sandy loam. The Mg÷Ca ratios ranged from 2.21 for Oshtemo loamy sand to 7.52 for Miami sandy loam.

On the 240-MgO series, the amount of magnesium in millet varied between 9.42 milliequivalents per 100 grams of dry matter for Oshtemo loamy sand to 39.66 milliequivalents for Houghton muck. The amount of potassium varied between 29.23 milliequivalents per 100 grams of dry matter for Kalkaska sand to 68.66 milliequivalents for Fox sandy loam. The Mg÷K ratios varied between 0.28 for Warsaw loam to 1.16 for Emmet sandy loam. The calcium content of millet on this series ranged from 3.16 milliequivalents per 100 grams of dry matter for Kalkaska sand to 5.91 milliequivalents for Thomas sandy loam. The Mg÷Ca ratios ranged from 1.81 for Oshtemo loamy sand to 8.92 for Miami sandy loam.

The above data of the magnesium, calcium, and potassium contents and their ratios in millet indicate that the quantity of potassium was increased to a very great extent as magnesium application to the soil increased. The high potassium content of the plants seems to be associated with low yields. The Mg÷Ca ratios are very wide, very low amounts of calcium being absorbed in comparison to the amounts of magnesium absorbed by millet. It is a well known fact that magnesium cannot replace calcium in the nutrition of plants and the rather low absorption of calcium by millet may account for the low yields.

<u>Wheat</u>. On the 0-MgO series, the amount of magnesium absorbed by spring wheat plants varied between 8.16 milliequivalents per 100 grams of dry matter for Brookston clay loam to 30.66 milliequivalents for Thomas sandy loam. The amount of potassium found in the same crop ranged from 49.23 milliequivalents per 100 grams of dry matter for Emmet sandy loam to 76.66 milliequivalents for Brookston clay loam. The Mg÷K ratios of the plant tissue ranged from 0.10 for Brookston clay loam to 0.66 for Houghton muck. The calcium content of wheat on this series ranged from 5.93 milliequivalents per 100 grams of dry matter for Isabella silt loam to 13.30 milliequivalents for Houghton muck. The Mg÷Ca ratios ranged from 1.65 for Kalkaska sand to 2.81 for Fox sandy loam.

On the 60-MgO series, the magnesium content of wheat plants varied from 12.08 milliequivalents per 100 grams of dry matter for Kent clay loam to 40.16 milliequivalents for Thomas sandy loam. The amount of potassium ranged from 42.38 milliequivalents per 100 grams of dry matter for Houghton muck to 69.49 milliequivalents for Warsaw loam. With this crop the Mg÷K ratios ranged from 0.14 for Brookston clay loam to 0.75 for Houghton muck. The amount of calcium ranged from 5.30 milliequivalents per 100 grams of dry matter for Kalkaska sand to 12.90 milliequivalents for Thomas sandy loam. The Mg÷Ca ratios varied from 1.48 for plants grown on Kent clay loam to 3.11 for those grown on Thomas sandy loam.

On the 120-MgO series, the amount of magnesium in wheat plants varied between 10.75 milliequivalents per 100 grams of dry matter for Kent clay loam to 33.83 milliequivalents for Thomas sandy loam. The potassium content varied between 33.59 milliequivalents per 100 grams of dry matter for Emmet sandy loam to 79.49 milliequivalents for Brookston clay loam. Magnesium to potassium ratios of from 0.15 to 0.91 were found for Kent clay loam and Emmet sandy loam, respectively. The amount of calcium varied between 5.00 milliequivalents per 100 grams of dry matter for Isabella silt loam to 11.55 milliequivalents for Thomas sandy loam. The Mg+Ca ratios in this crop ranged from 1.53 for Kent clay loam to 4.20 for Emmet sandy loam.

On the 240-MgO series, the amount of magnesium in wheat varied between 10.75 milliequivalents per 100 grams of dry matter for Brookston clay loam to 37.41 milliequivalents for Thomas sandy loam. The quantity of potassium varied between 38.72 milliequivalents per 100 grams dry matter for Houghton muck to 81.79 milliequivalents for Kalkaska sand. The Mg+K ratios ranged from 0.14 for Brookston clay loam to 0.76 for Houghton muck. The amount of calcium varied between 5.91 milliequivalents per 100 grams of dry matter for Kalkaska sand to 10.90 milliequivalents for Thomas sandy loam. The Mg+Ca ratios ranged from 1.55 for Kent clay loam to 4.62 for Kalkaska sand.

As in the case of millet, the increase in the uptake of potassium as increasing amounts of magnesium were added to soils appears to have caused decreased yields. Further, calcium absorption was depressed below the level of magnesium, and this probably resulted in physiological disturbances, which account for the low yields and even a depression of growth on some soils.

TABLE XVI

THE TOTAL MAGNESIUM-SUPPLYING POWER AND THE FIXATION OR RELEASE OF MAGNESIUM BY SOILS OF THE GREENHOUSE STUDY AS AFFECTED BY VARYING AMOUNTS OF ADDED MAGNESIUM AND CROPPING BY SOYBEANS, MILLET, AND WHEAT

Soil Type	0-MgO Series[1]			60-MgO Series		
	Magnesium Removed by 3 Crops[2]	Difference in Magnesium Before and After Cropping[3]	Fixation or Release of Magnesium Per Pot[4]	Magnesium Removed by 3 Crops	Difference in Magnesium Before and After Cropping	Fixation or Release of Magnesium Per Pot
	mgms.	mgms.	mgms.	mgms.	mgms.	mgms.
Thomas sandy loam	224	1949	-1725	227	2919	-2692
Kalkaska sand	113	Nil	+ 113	125	202	- 491
Oshtemo loamy sand	143	970	+1113	158	1413	+1571
Emmet sandy loam	85	810	+1660	117	1153	+1270
Plainfield loamy sand	105	30	+ 75	108	207	+ 99
Fox sandy loam	123	1893	+2016	115	1776	+1891
Warsaw loam	103	300	- 197	125	593	+ 718
Isabella silt loam	114	2380	+2494	217	2790	+3007
Brookston clay loam	137	4980	+5117	133	4863	+4996
Miami sandy loam	177	3380	+3557	215	3213	+3428
Kent clay loam	131	4130	+4261	169	5013	+5182
Wisner clay loam	164	1780	+1944	161	1713	+1874
Houghton muck	218	2924	-2706	262	2914	-2652

TABLE XVI continued

Soil Type	120-MgO Series[1]			240-MgO Series		
	Magnesium Removed by 3 Crops[2]	Difference in Magnesium Before and After Cropping[3]	Fixation or Release of Magnesium Per Pot[4]	Magnesium Removed by 3 Crops	Difference in Magnesium Before and After Cropping	Fixation or Release of Magnesium Per Pot
	mgms.	mgms.	mgms.	mgms.	mgms.	mgms.
Thomas sandy loam	236	2024	-2024	166	2376	-2210
Kalkaska sand	183	659	- 476	121	991	-1100
Oshtemo loamy sand	140	1576	+1716	116	1584	+1700
Emmet sandy loam	160	1286	+1446	224	1574	+1798
Plainfield loamy sand	134	2066	+2200	128	1684	+1812
Fox sandy loam	100	2749	+1849	132	1367	+1499
Warsaw loam	103	396	+ 499	111	804	+ 919
Isabella silt loam	116	3366	+3482	140	2804	+3044
Brookston clay loam	131	3826	+3957	148	2814	+2962
Miami sandy loam	196	2076	+2272	181	3494	+3675
Kent clay loam	140	5416	+5026	144	5604	+5748
Wisner clay loam	151	3026	+3117	170	2684	+2854
Houghton muck	241	2758	-2517	300	3322	-3022

[1]Refers to pounds of MgO applied on an acre basis as sulfate of potash-magnesia

[2]Mg removed by three crops per pot

[3]For exchangeable Mg in soils before and after cropping refer Tables II and III, respectively

[4]Positive values indicate release; negative values indicate fixation

CHEMICAL ANALYSES OF SOILS AT THE END OF THE GREENHOUSE STUDY

Magnesium fixation or release in different soils. The exchangeable potassium, calcium, and magnesium contents of the greenhouse soils after cropping are presented in Table III. These data indicate that exchangeable magnesium after cropping was slightly higher than that of the surface soil at the start of the experiment, as shown in Table II. It is difficult to tell whether this increase was entirely due to release from non-exchangeable sources or to a mixing of the surface and subsoil increments at time of sampling at the end of the experiment. It is also likely that some magnesium may have remained in the roots not harvested.

The data in Table XVI refer to the total amount of magnesium removed by soybeans, millet, and wheat, the difference in magnesium in the soils before and after cropping, and fixation or release of magnesium expressed as milligrams per pot in all the four series, namely, 0-MgO, 60-MgO, 120-MgO, and 240-MgO.

The values for the "difference in magnesium before and after cropping" were calculated as follows:

The quantity of exchangeable soil magnesium before cropping plus the amount of magnesium added per treatment, minus the exchangeable soil magnesium after the harvest of the three crops.

The colums headed, "Fixation or release of magnesium per pot" show positive and negative values, indicating both release and fixation. The values for magnesium fixation or release in the different soils are obtained from the following relation:

Amount of exchangeable magnesium in the soils at the beginning of the experiment plus the amount of magnesium added per treatment, minus the total amount of magnesium removed by the three crops, plus the amount of magnesium left in the soil at the end of the experiment.

Several criteria can be used for evaluating the need of soils in general for magnesium fertilization. These are, the absolute yields without added magnesium, the response of crops on the application of magnesium to the soil, the content of exchangeable magnesium of the original soils, and the extent to which their reserve magnesium is released.

In the 0-MgO series, where no magnesium was added, three soils, namely, Thomas sandy loam, Warsaw loam, and Houghton muck, fixed magnesium. The soils on the 0-MgO series can be arranged in order based on the total amount of magnesium removed by all three crops: Thomas sandy loam, Houghton muck, Miami sandy loam, Wisner clay loam, Oshtemo loamy sand, Brookston clay loam, Kent clay loam, Fox sandy loam, Isabella silt loam, Kalkaska sand, Warsaw loam, and Emmet sandy loam.

As regards the ability of the soils to release magnesium, the soils can be arranged in the following order based on the greatest or lowest amounts of magnesium released: Brookston clay loam, Kent clay loam, Miami sandy loam, Isabella silt loam, Fox sandy loam, Wisner clay loam, Emmet sandy loam, Oshtemo loamy sand, and Kalkaska sand.

The soils in the order of increasing fixation of magnesium on the 0-MgO series are: Warsaw loam, Thomas sandy loam, and Houghton muck.

In the 60-MgO, 120-MgO, and 240-MgO series, three soils, Thomas sandy loam, Kalkaska sand, and Houghton muck fixed magnesium, the last soil showing the highest fixation of all the soils in the three series.

The greatest release of magnesium occurred with Brookston clay loam, followed by lower values from Kent clay loam, Wisner clay loam, Isabella silt loam, and finally lowest values from the coarse textured soils.

SUMMARY AND CONCLUSIONS

This study was undertaken in order to evaluate the magnesium-supplying powers of some Michigan soils for certain crops. Twelve mineral soils and one organic soil, representing different soil types, were used in a pot culture experiment.

Magnesium was the only fertilizer element varied. Four rates of this element corresponding to 0, 60, 120, and 240 pounds of MgO were applied on an acre basis as Sul-Po-Mag, a water-soluble, double sulfate of potash-magnesia. All other nutrients, including nitrogen, phosphorus, potassium, and certain micronutrients, were added at what was believed to be optimum rates.

Soybeans, millet, and wheat were grown as the test crops. Yield and chemical composition of the crops were determined. The plants were analyzed for potassium, calcium, and magnesium. The last two elements were determined on the Beckman DU flame spectrophotometer, while potassium was analyzed on the Perkin-Elmer flame spectrophotometer.

The soils were analyzed for pH, per cent organic matter, per cent sand, silt, and clay, exchange capacity, total exchangeable bases, and exchangeable magnesium, calcium, and potassium at the start of the experiment. Exchangeable magnesium, calcium, and potassium were determined on the soils after cropping.

Yield of soybeans was significantly increased in only one of thirteen soils, a Miami sandy loam, while in Brookston clay loam, soybean yields were significantly decreased due to magnesium additions.

Yield of millet was significantly increased using three soils - Kalkaska sand, Brookston clay loam, and Houghton muck, while a significant decrease in yield was found using Oshtemo loamy sand, Plainfield loamy sand, and Kent clay loam.

A significant increase in wheat yield was registered in only one soil, namely, Kent clay loam, while the growth of wheat on Warsaw loam was significantly decreased upon use of supplemental magnesium.

Results of chemical analysis of the three crops showed that, in general, magnesium uptake increased only up to the 120-MgO level in all soils except Emmet sandy loam, Warsaw loam, and Houghton muck. Increasing amounts of magnesium reduced uptake of magnesium beyond the 120-MgO level, but in contrast, increases in the uptake of potassium were found for most of the soils, especially in the case of millet and wheat. The increase in potassium uptake was associated with decreased crop yields.

The Mg÷K ratios for a given crop were not very consistent for the different magnesium treatments in the case of most soils. Particularly the Mg÷Ca ratios in millet and wheat were very wide. It appears that supplemental additions of calcium to the soil would have been of decided benefit to these crops, as it is recognized that excessive amounts of magnesium without calcium might reduce crop yields. It has also been recognized that if magnesium exceeds calcium in plants by a very wide margin, toxic conditions result, which, in turn, would affect growth. This point emphasizes the importance of the proper balance of these three cations in the soil.

With the soils used in this study, no magnesium deficiency was noted. Neither were visual symptoms of toxicity apparent. However, the total amount of magnesium removed by the three crops was only a small fraction of the quantity of exchangeable magnesium in the original soils. The yield data, especially indicate that an application of 240 pounds of MgO as the sulfate was too high. It seems likely that all the soils used in this study had adequate amounts of exchangeable magnesium, and it is apparent that much response to added magnesium would not be forthcoming. Since these soils were collected from farmer's fields, it is possible that some had received dolomitic limestone, it would be necessary to conduct further experiments on a wide range of soil types, where exchangeable magnesium was known to be low, in order to show magnesium deficiency with Michigan soils. Since the total amount of magnesium removed by the three crops was only a small fraction of the quantity of exchangeable magnesium in the original soils, it would be necessary to increase the cropping period.

The following conclusions can be made from this investigation:

1. No visible magnesium deficiency was found in several field crops grown on the soils used in this greenhouse study.

2. There was no definite correlation between the dry matter production of crops and the exchangeable magnesium content of the soils studied.

3. The increased uptake of magnesium by plants did not necessarily indicate increased yields in all cases.

4. The uptake of potassium was markedly influenced by supplemental magnesium, the larger the amount of magnesium in the soil, the higher was the content of plant potassium, especially in the case of millet and wheat.

5. Response to applications of magnesium was influenced by its ratio to other cations in the exchange complex, especially those of calcium and potassium.

6. There was no cation constancy relationships in the crops as grown.

7. It is likely that 60 to 80 pounds of MgO in the form of a soluble salt is adequate to meet the magnesium needs of crops.

8. The ideal amount of exchangeable magnesium of a soil has been suggested to be equivalent to about 10 per cent of the total exchange capacity. In this study it was found that most of the soils had exchangeable magnesium far in excess of this amount, hence, any response to applications of magnesium in the soluble form would be unlikely.

9. Magnesium fixation occurred only in three soils, namely, Thomas sandy loam, Kalkaska sand, and Houghton muck, the first and the last soils showing high fixation values. All other soils released magnesium, the largest release occurring in the heavier soils. It is possible that some magnesium remained in the roots of the crops, especially the final one, and on this basis, the values for release might be even higher than recorded.

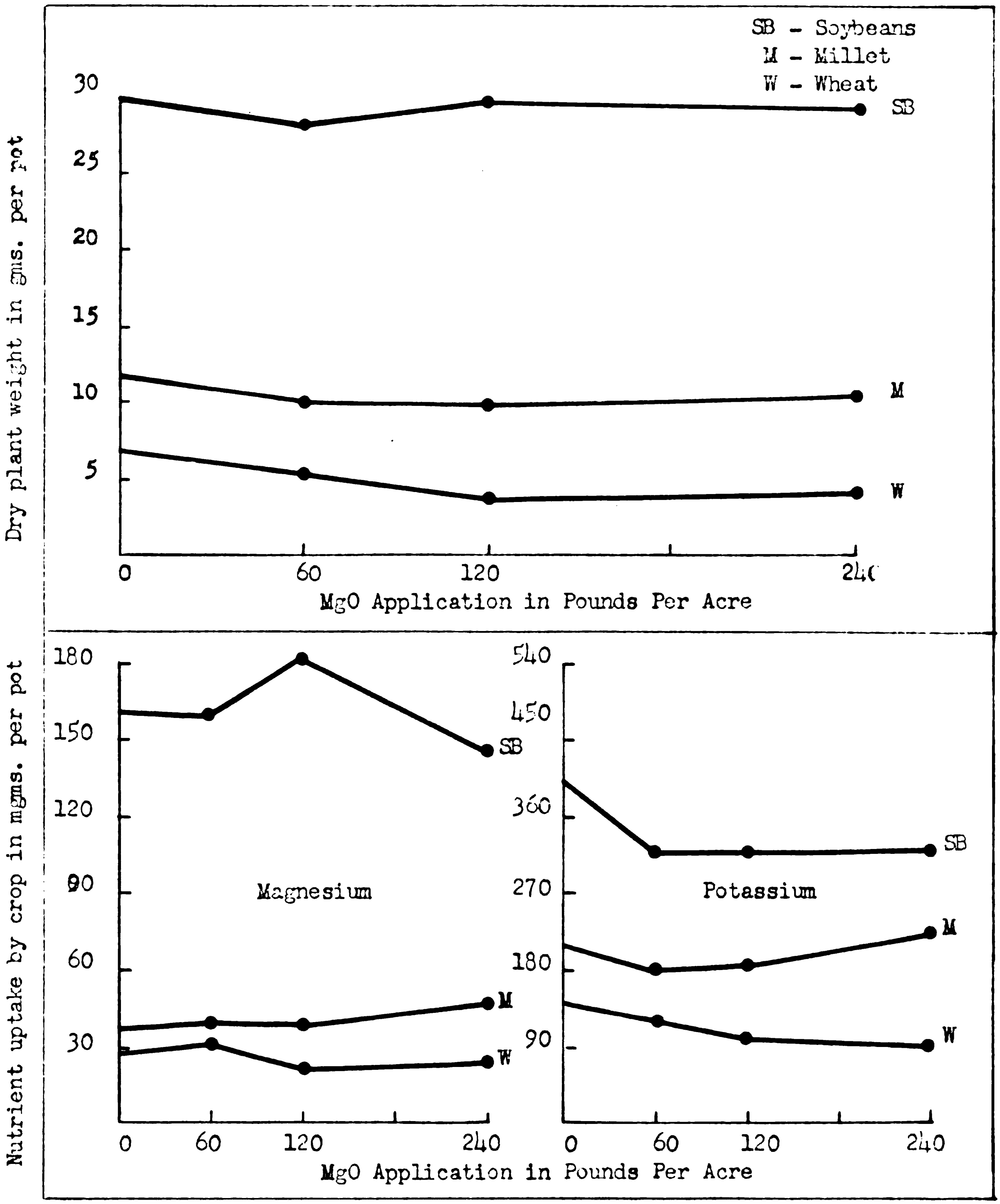

Fig. 1. The effect of varying amounts of added Magnesium on the yield and uptake of Magnesium and Potassium by soybeans, millet, and wheat grown on Thomas sandy loam.

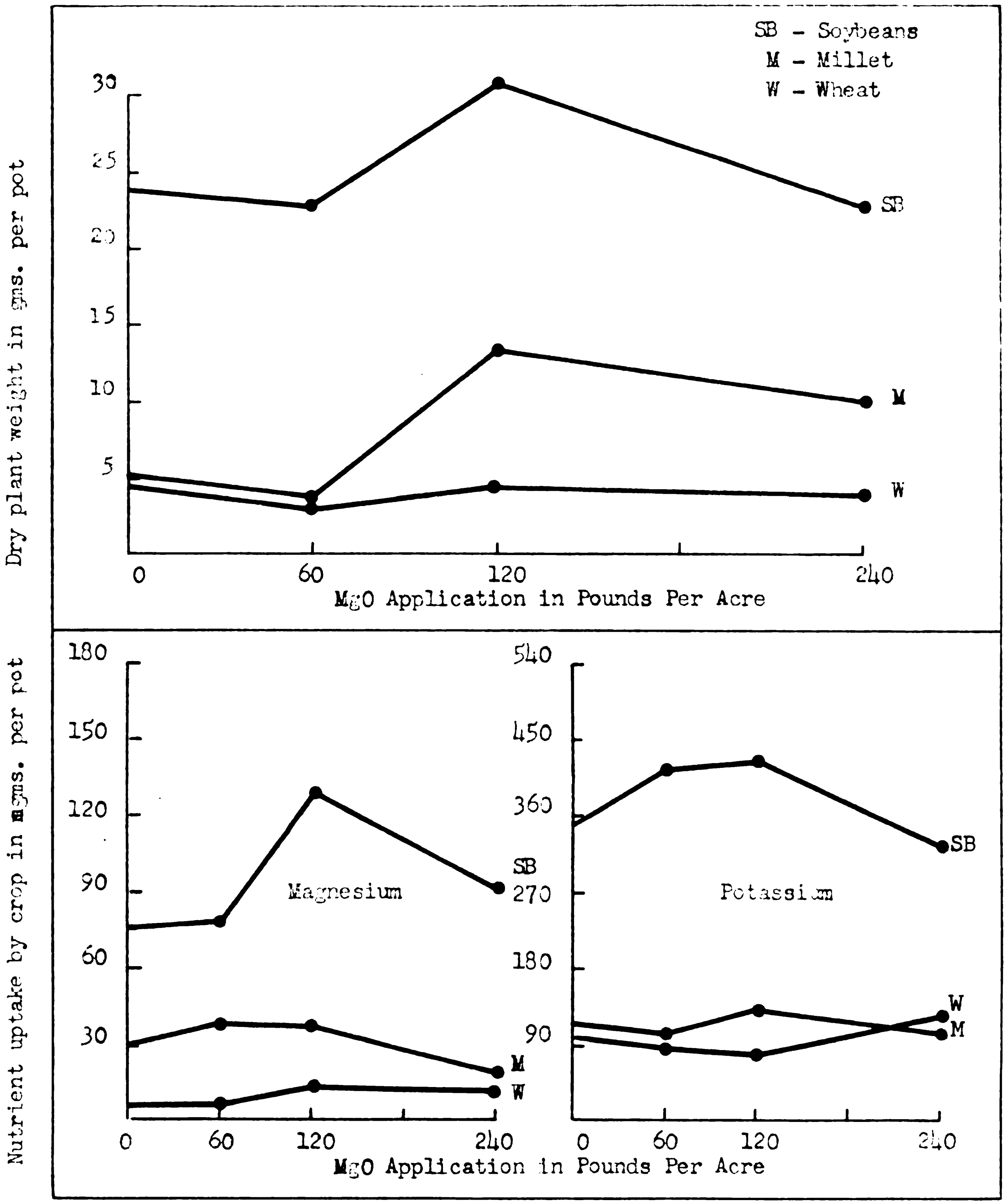

Fig. 2. The effect of varying amounts of added Magnesium on the yield and uptake of Magnesium and Potassium by soybeans, millet, and wheat grown on Kalkaska sand.

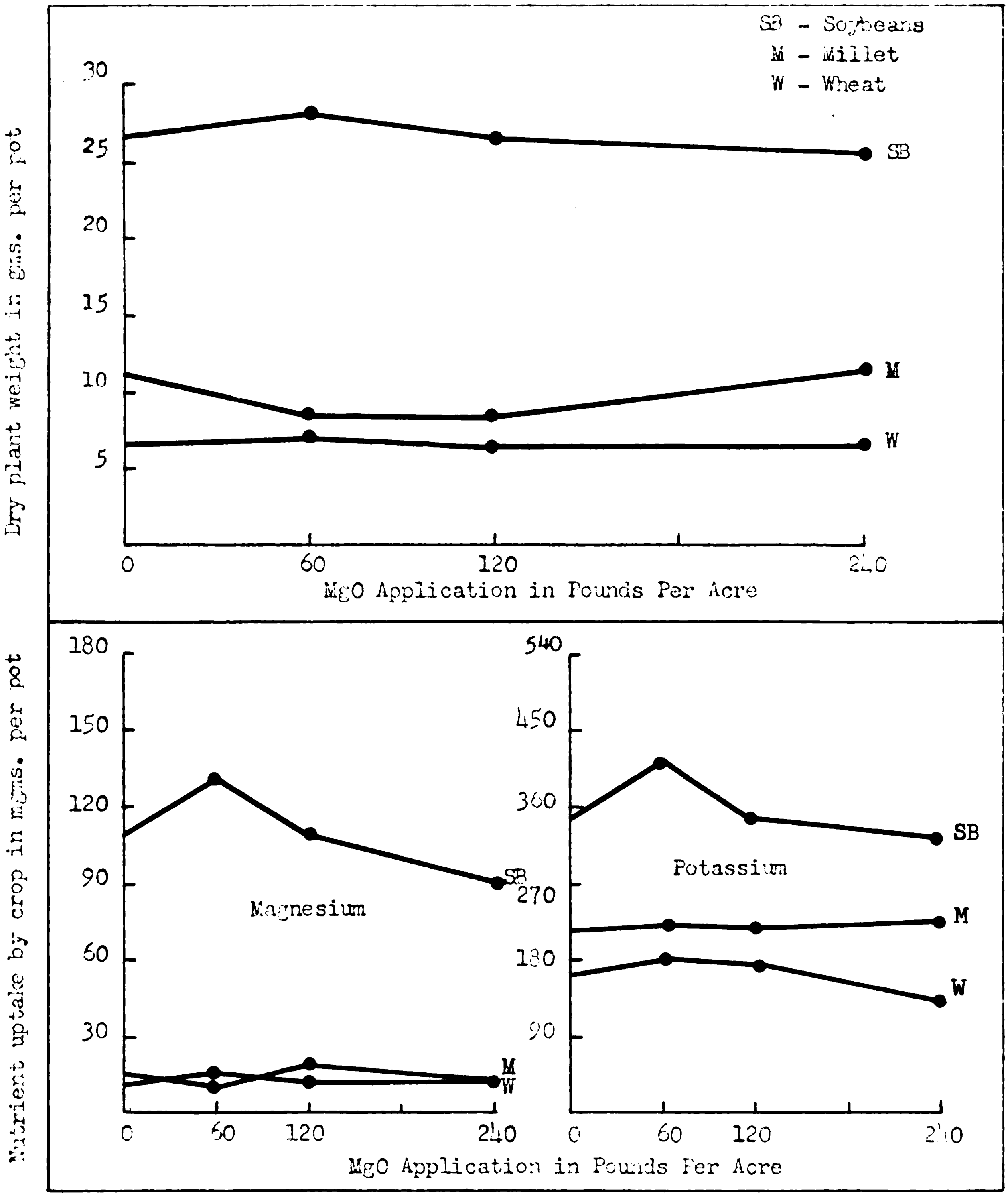

Fig. 3. The effect of varying amounts of added Magnesium on the yield and uptake of Magnesium and Potassium by soybeans, millet, and wheat grown on Oshtemo loamy sand.

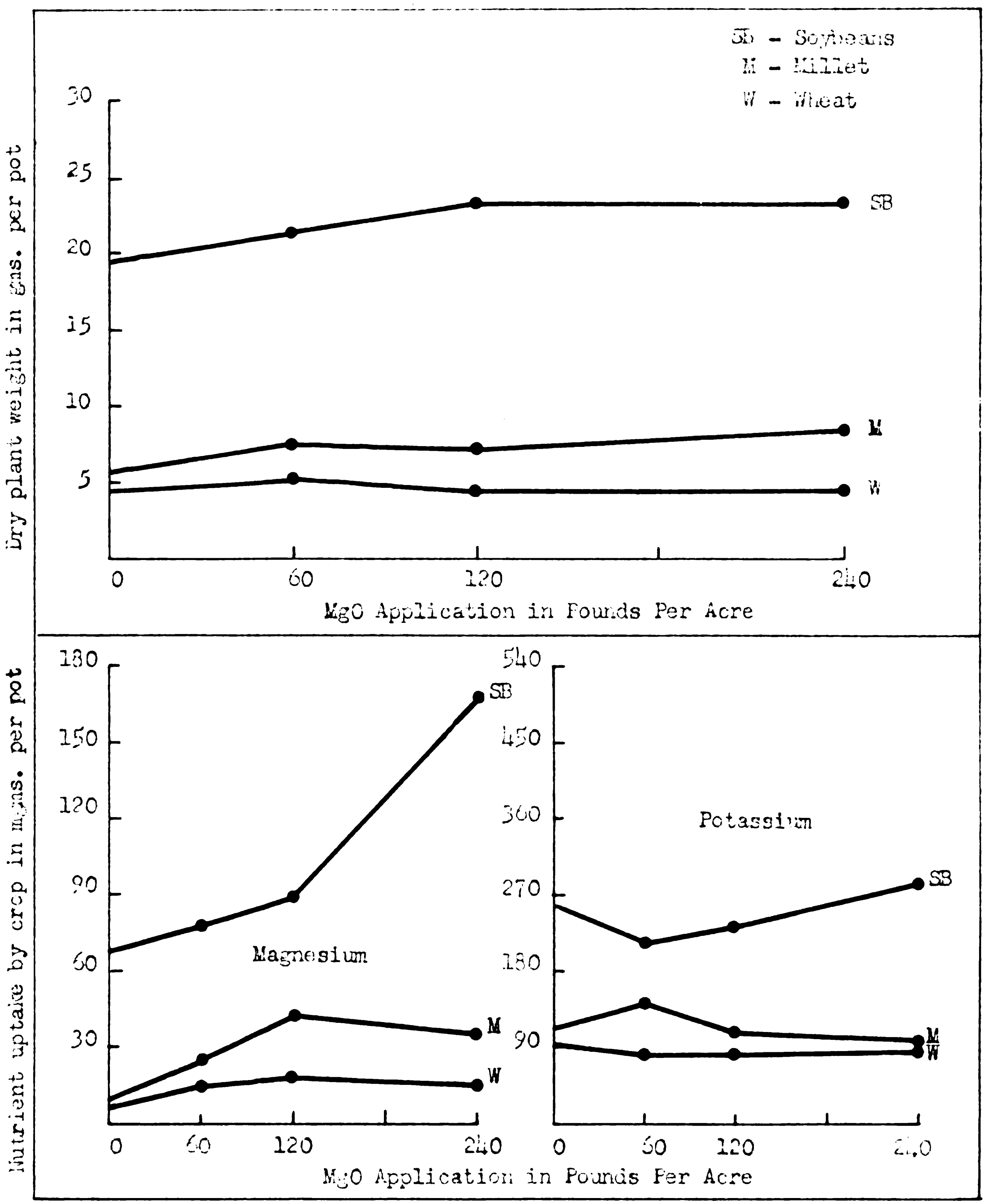

Fig. 4. The effect of varying amounts of added Magnesium on the yield and uptake of Magnesium and Potassium by soybeans, millet, and wheat grown on Emmet sandy loam.

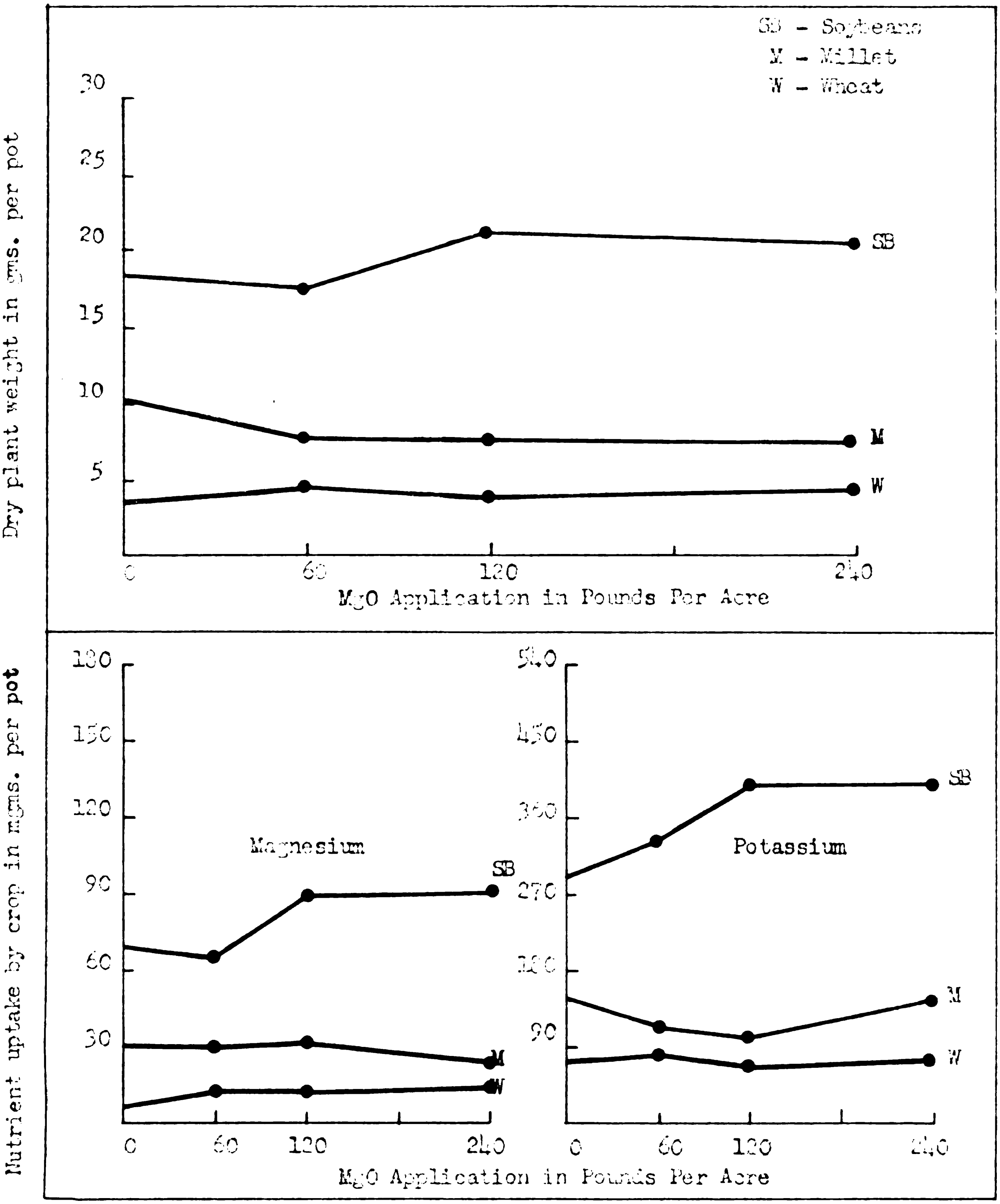

Fig. 5. The effect of varying amounts of added Magnesium on the yield and uptake of Magnesium and Potassium by soybeans, millet, and wheat grown on Plainfield loamy sand.

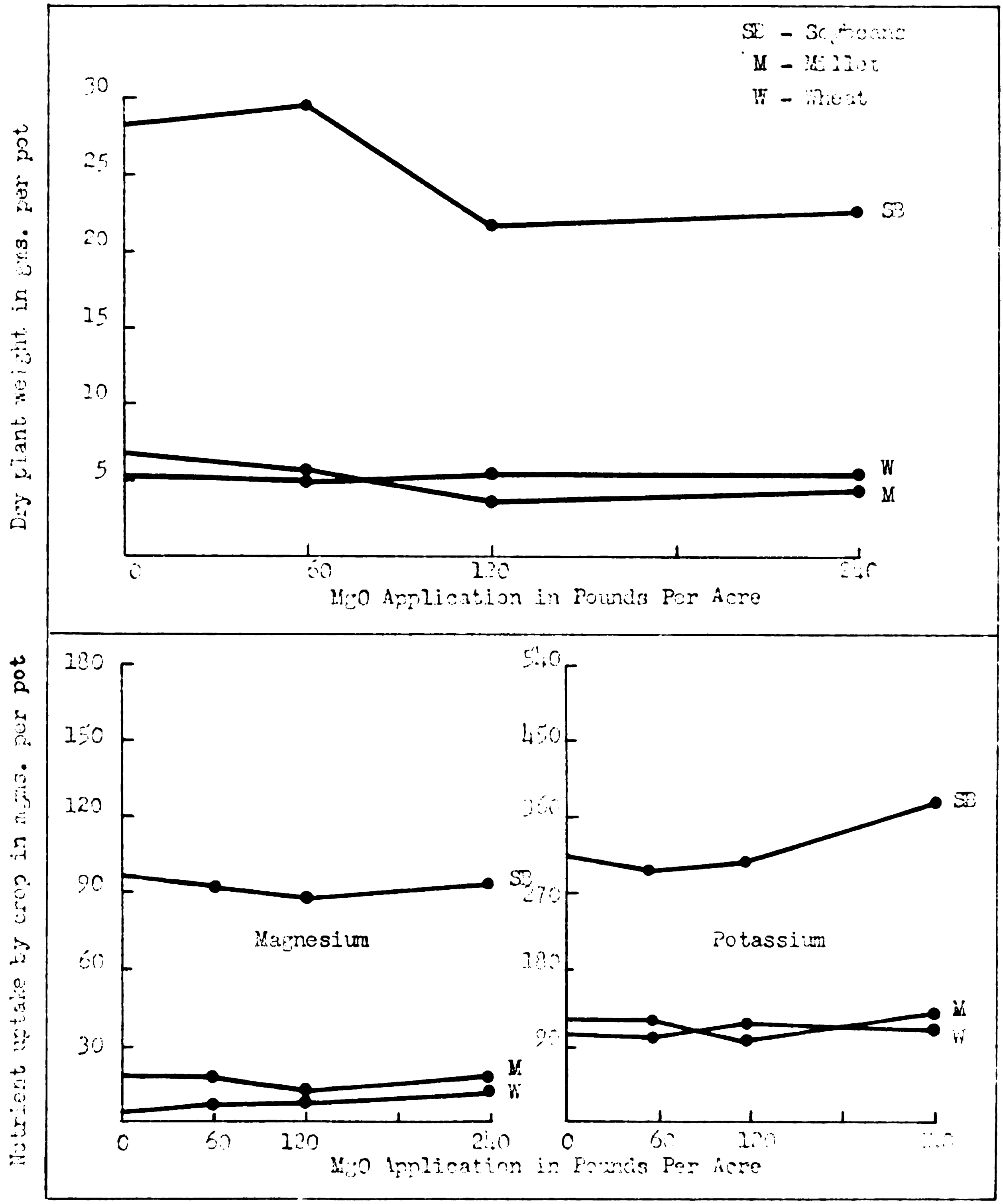

Fig. 6. The effect of varying amounts of added Magnesium on the yield and uptake of Magnesium and Potassium by soybeans, millet, and wheat grown on Fox sandy loam.

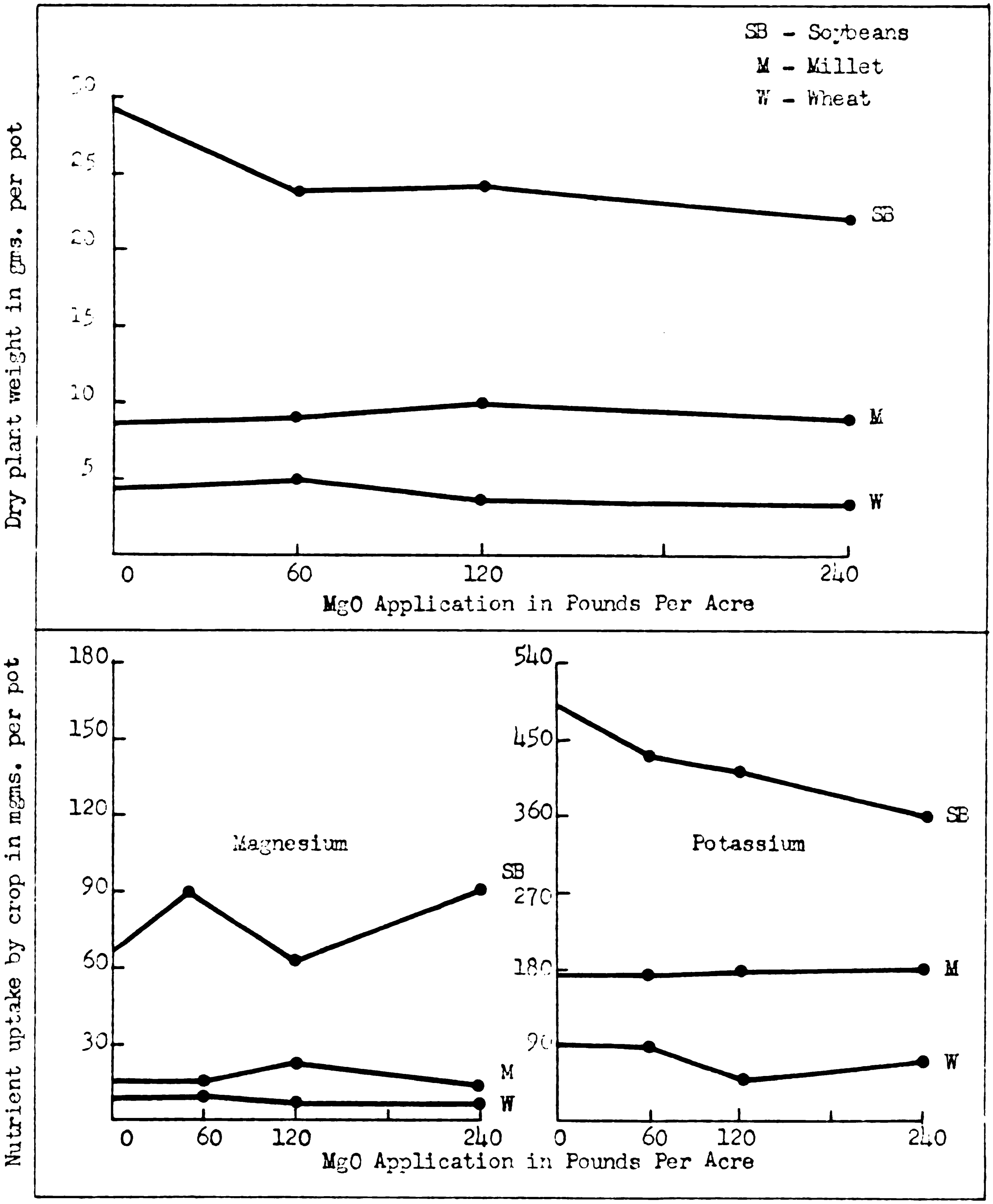

Fig. 7. The effect of varying amounts of added Magnesium on the yield and uptake of Magnesium and Potassium by soybeans, millet, and wheat grown on Warsaw loam.

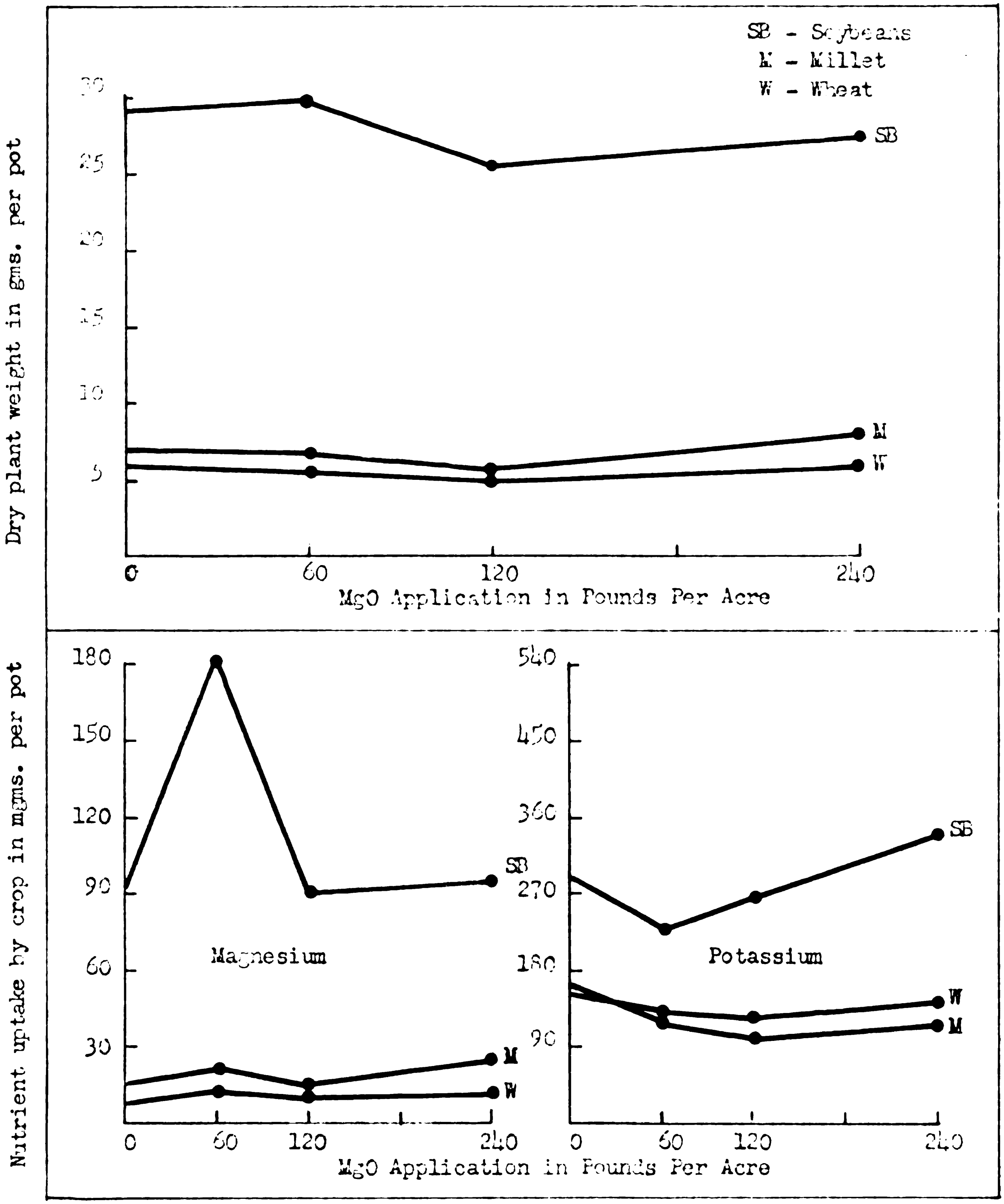

Fig. 8. The effect of varying amounts of added Magnesium on the yield and uptake of Magnesium and Potassium by soybeans, millet, and wheat grown on Isabella silt loam.

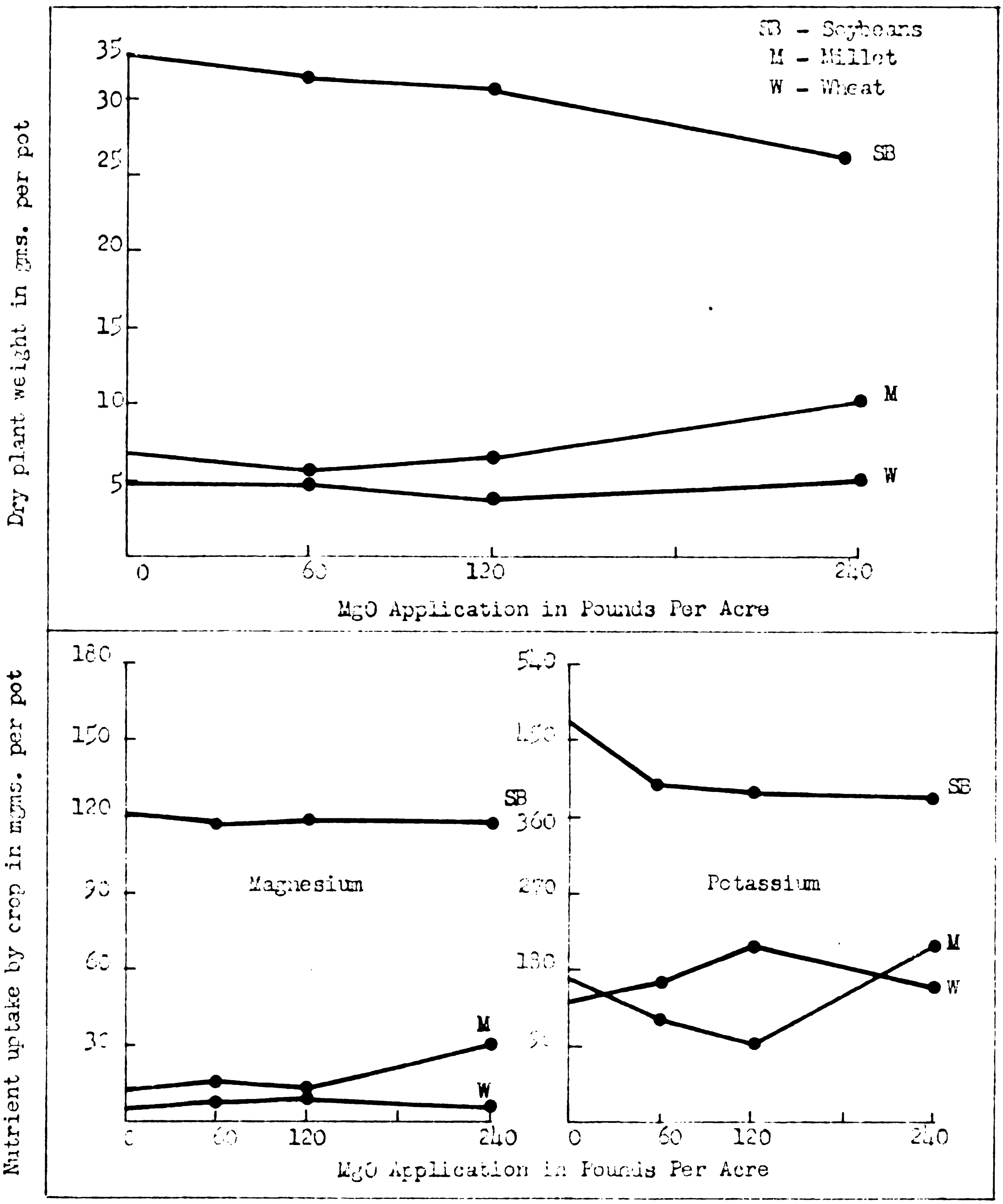

Fig. 9. The effect of varying amounts of added Magnesium on the yield and uptake of Magnesium and Potassium by soybeans, millet, and wheat grown on Brookston clay loam.

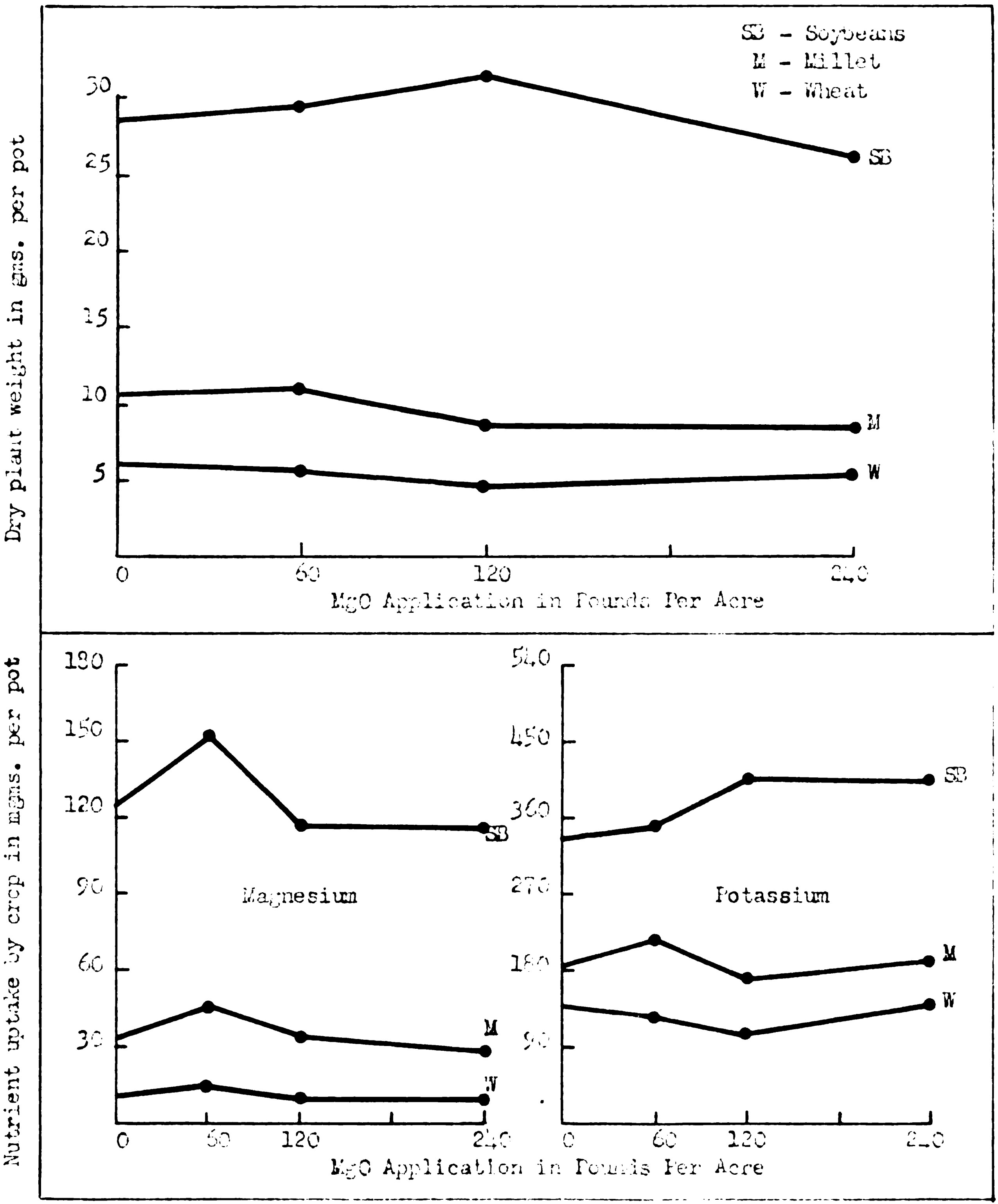

Fig. 10. The effect of varying amounts of added Magnesium on the yield and uptake of Magnesium and Potassium by soybeans, millet, and wheat grown on Miami sandy loam.

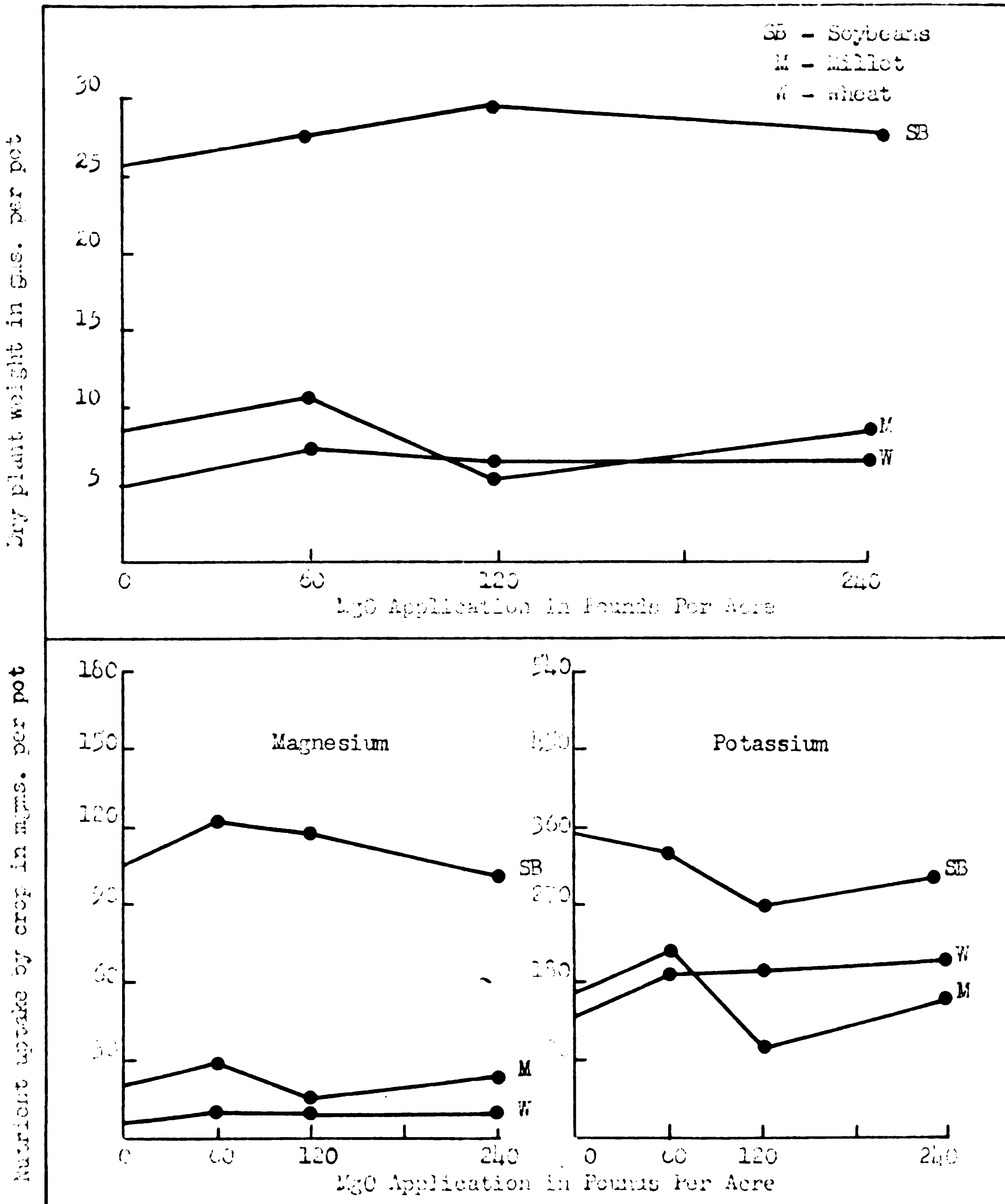

Fig. 11. The effect of varying amounts of added Magnesium on the yield and uptake of Magnesium and Potassium by soybeans, millet, and wheat grown on Kent clay loam.

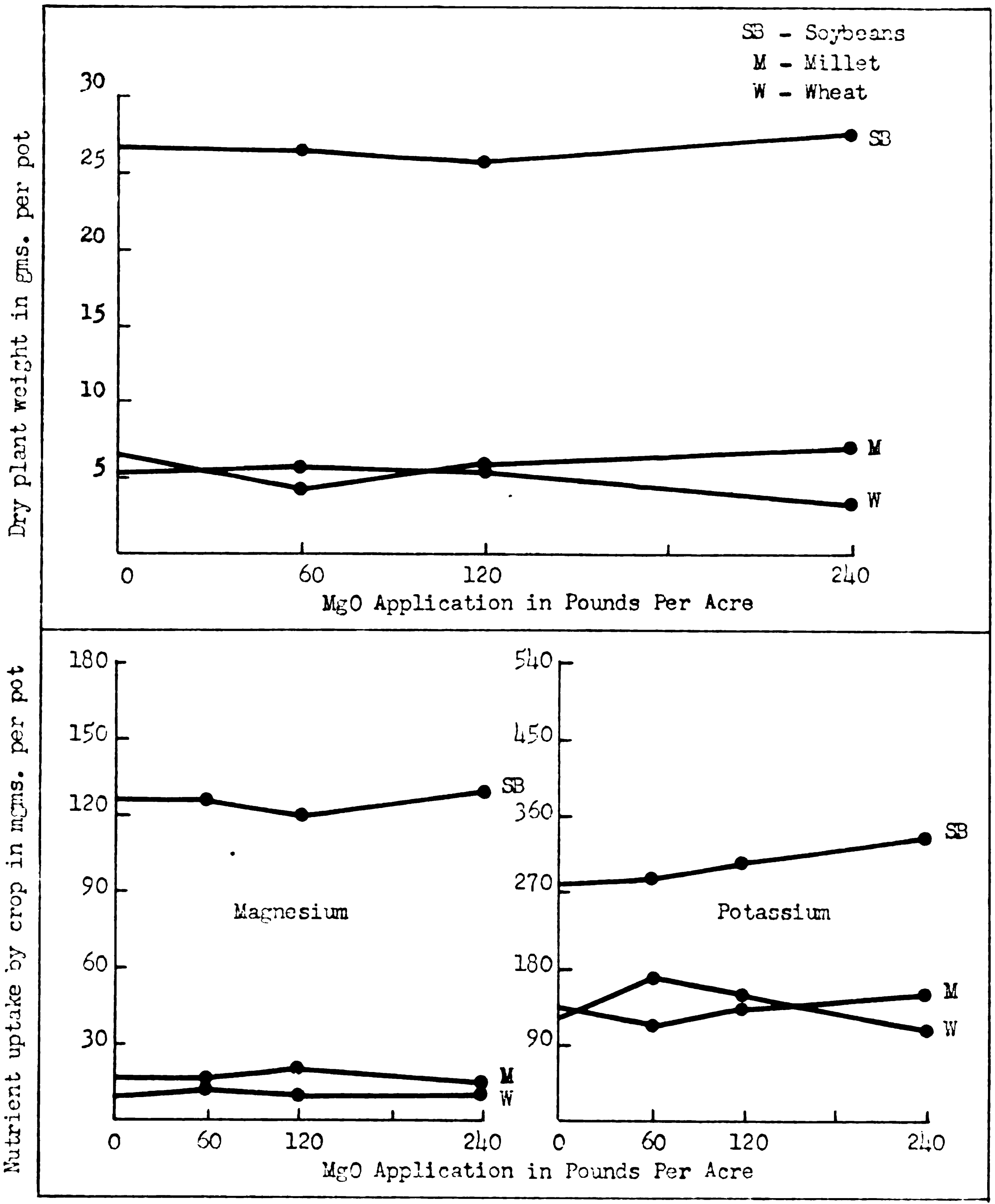

Fig. 12. The effect of varying amounts of added Magnesium on the yield and uptake of Magnesium and Potassium by soybeans, millet, and wheat grown on Wisner clay loam.

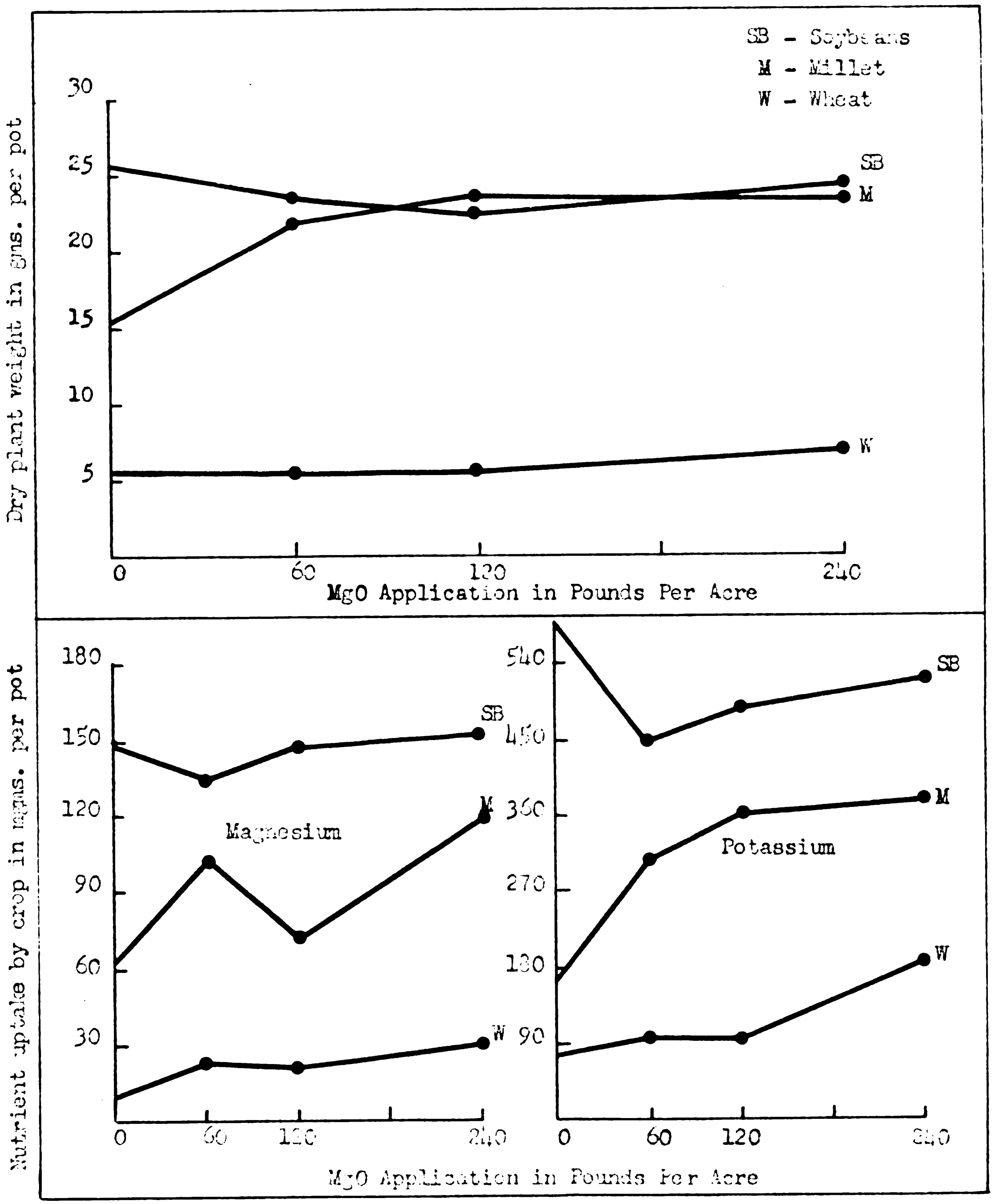

Fig. 13. The effect of varying amounts of added Magnesium on the yield and uptake of Magnesium and Potassium by soybeans, millet, and wheat grown on Houghton muck.

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