THE EFFECT OF SOIL TREATMENT ON THE ACCUMULATION

OF IONS BY SEVERAL CROPS

by

KENNETH McALPINE PRETTY

AN ABSTRACT

Submitted to the School for Advanced Graduate Studies of
Michigan State University of Agriculture and Applied Science
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Department of Soil Science

Approved by R. L. Cook

ABSTRACT

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Field studies were conducted over a two-year period to determine the effect of unbalanced soil fertility conditions on the growth and chemical composition of several crops grown on an infertile Kalamazoo sandy loam soil. Calcitic and dolomitic lime, phosphorus and potassium were applied singly and in combination to give a total of twelve treatments. Yield data and chemical composition were determined for timothy and soybean hay, as well as the mature grain of millet, soybeans, corn and wheat.

The content of the various nutrients in the soil following treatment was determined and related to the content of the same elements in the plant. In addition, the manganese, total nitrogen and crude ash content of the various crops was determined.

Phosphorus significantly increased the yields of soybean hay and millet in 1955, while potassium depressed the yield of soybean seed. In 1956 phosphorus applications increased the yield of winter wheat and potassium increased corn and millet yields. Both liming materials increased wheat yields in 1956, while only dolomitic lime increased the yield of corn. Calcitic lime increased timothy yields but dolomitic lime had a depressing effect.

In the majority of cases applying the various nutrients to the soil resulted in an increased content of that element in the plant. However, with the exception of phosphorus, the overall composition of seeds was not substantially changed. Timothy and soybean plants showed an appreciable increase in the content of calcium, magnesium and potassium when these elements were applied to the soil. The cation composition of soybean seed tended to remain more constant than any other crop studied.

The sodium, nitrogen and crude ash contents of plants were not substantially or consistently altered by soil treatment. However, there was a tendency for lime applications to increase the nitrogen content, and phosphorus and potassium fertilization to increase the crude ash. Calcitic and dolomitic lime reduced the manganese content of all crops.

The potassium-magnesium interaction in plants was the most important relationship determining changes in cation content. Potassium applications usually depressed magnesium accumulation and vice versa. However, these changes did not occur in equivalent amounts. The total cation content was increased or decreased by magnesium and potassium fertilization, depending on the extent of the interaction and the relative quantities of the two ions in the plant tissue. Due to these interactions changes in cation ratios in the plants were not necessarily related to changes in the same ratios in the soil.

Changes in the composition of various plant species as a result of soil treatment can be caused by a number of factors, including the relative activity of the ions on the soil colloid, the varying cation exchange capacities of roots, the presence of specialized absorption sites or ion-carrier mechanisms, and the effect of climate on the physiological processes of the plants. Seeds apparently possess specialized absorption mechanisms by which certain ions can be selectively excluded.

The extent to which the recorded differences in crop composition may be a true index of nutritive value has not been determined

and the possibility of significant changes in more important, undetermined constituents is recognized.

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Department of Soil Science

TO MY PARENTS

whose unfailing interest and constant
encouragement have been a great
source of inspiration, these
results are affectionately
dedicated

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INTRODUCTION

The existence of all life, plant, animal or human, is dependent, directly or indirectly, upon the soil. Plants rely on the soil for the nutrients, moisture, aeration and support necessary for them to grow and reproduce. Animals and man utilize these plants for food, and hence are dependent on the soil to supply their sustenance in sufficient quantity and quality to support normal growth and development.

The importance of determining the extent to which the chemical composition or nutritive value of a plant can be changed by manipulation within the environment is evident. Although the magnitude of such changes is important from a nutritional standpoint, the factors governing these variations are of even greater significance. If it can be ascertained that plant composition can be substantially and consistently altered, and if the conditions responsible for such changes can be properly evaluated, then certain cause and effect relationships can be established which are applicable to a given environmental complex.

Under normal conditions nutritional diseases caused by deficient or toxic levels of mineral elements in the diet do not occur. This is particularly true in human nutrition where the food consumed represents plant material grown in widely separated areas of the country or the world, and hence under very diverse soil and climatic conditions. Nutritional disorders

of animals are perhaps more commonplace due to the restricted area from which they derive the majority of their feed. Certain locations are known to be deficient in one or more essential nutrients, thus causing a characteristic upset in normal metabolic and physiological processes. The incidence of goiter in the Mid-west as a result of low iodine levels in soils and plants is an example of such a mineral deficiency induced disorder. Cobalt, calcium and phosphorus deficiencies of animals in the United States, as well as selinium toxicity, have been related to the available levels of these elements in the soil. Consequently, any fundamental studies on dietary deficiencies must begin with plants and the soil upon which they were grown.

The chemical composition of a plant is a reflection of the environment in which it is grown, together with limitations imposed by the genetic constitution and uniformity of protoplasmic composition of species or varieties. The external environment of the plant is influenced by such factors as climate, plant competition, stage of maturity, soil type and level of available nutrients, as well as many other complex physical, chemical and biological relationships.

This study was undertaken to further examine the effect of unbalanced fertility levels in the soil on the growth of agriculturally important plant species, and more particularly, on the accumulation of mineral elements by these crops. An extensive study, recently concluded, indicated that the change in chemical composition of plants grown under field conditions as a result of

fertilizer application was not great (Duncan, 1955a). However, this experiment was conducted under conditions of balanced high and low soil nutrient levels as indicated by soil tests. Other research work showed that plant composition could be changed by unbalanced soil fertility under conditions of controlled greenhouse environment (Power _et al_, 1955).

The above studies failed to show the effects of wide variation in soil nutrient content upon the chemical composition of plants grown under the complex, variable environment of field conditions. Consequently, this was the primary objective of the present investigation. More specifically, it was designed to determine the influence of calcium, magnesium, phosphorus and potassium fertilization, singly and in combination, on the nutritive value of several crop species, insofar as this value can be assayed by chemical composition of the plant. A further, and more fundamental objective, was to determine certain basic relationships which are operative in establishing variations in plant composition so that these results might be of value in interpreting data from similar studies in the future.

LITERATURE REVIEW

The literature dealing with the effect of various chemical, physical and biological relationships on the accumulation of mineral elements by economic plants is voluminous. A complete discussion of all of the factors influencing the nutrient content of such plants is outside of the scope of this manuscript. Comprehensive reviews of previous work relating plant growth and composition to environment have been presented by Gauch (1957), Shaw (1952), Truog (1951) and Stout and Overstreet (1950).

Many factors contribute to the final yield and composition of a plant. Each factor, acting individually, may have an almost insignificant effect. However, the sum total of all components, and particularly the combinations of these factors, will result in a plant which is the product of its environment.

Among the factors known to have a profound influence on the growth, development, and composition of plants are (a) the soil, its chemical, physical and biological characteristics, both in its natural state and as altered by management, (b) the plant, its genetic and physico-chemical constitution, its stage of maturity, and its manipulation within the environment, and (c) the climate, that is, temperature and rainfall as it affects the soil substrate and the plant itself. Truog (1951) aptly commented "The soil is, indeed, an intricate dynamic system, and to understand how a fertile soil may function as a well nigh perfect

medium for plant growth requires much study and considerable imagination." Beeson (1947) stated, "When one considers the complexity of the biological system under which we produce our food crops, one will recognize as natural the variable results obtained by the superimposition of a fertilizer on a set of soil conditions." Similar statements could be made concerning the complexity of the plant factor.

That soils do differ widely in their ability to supply nutrients, and hence to support optimal plant growth, is an universally accepted fact. Recently, considerable effort has been devoted to studying fundamental differences between soils as they affect the nutrient supplying power of the soil. Studies by Chu and Turk (1949), Mehlich and Colwell (1943), and by Marshall and his associates (1950, 1951), indicate that the clay fraction is most important in determining the availability of ions. Attention has been given to the interaction of different soil colloids with such other properties as base saturation and exchange capacity. Emphasis has also been placed on the relative bonding energies of the various ions.

Mattson (1948) has stated the relationship between availability of ions and clay mineral type as follows, "If two soils having different cation exchange capacities (due to different acidoid content or strength) contain the same proportion of a monovalent and divalent ion, the soil with the higher exchange capacity should yield its monovalent ions more readily and its divalent ions less readily." An example of this relationship is

the often observed fact that potassium is absorbed more readily by plants from the 2:1 mineral colloids than from the 1:1 clays (Mehlich and Reed, 1948).

The ionic associations on the exchange complex have an important bearing on nutrient availability to plants. Marshall and his associates (1950, 1951) have demonstrated that the replacement of H+ ions on a soil colloid by calcium or magnesium increases the activity of a given amount of exchangeable potassium. The selection of ions by plants is more closely related to the active portions in the soil than to the total exchangeable amounts. Hence changing the ionic atmosphere by the application of nutrients in the form of fertilizers or other soil amendments could be expected to exert a considerable influence on ion availability to plants.

The concept of a static soil solution serving as the sole source of nutrients has been discarded by most soil scientists. Marshall (1951) has pointed out some of the shortcomings of this belief. Since that time other workers have contributed to the idea that the exchangeable ions must be looked upon as being the immediate source of cationic plant nutrients in most soils (Mehlich and Coleman, 1952).

It must be realized, however, that the ions in solution, or those retained on the clay and organic matter complexes by exchange mechanisms, are by no means the only source of nutrients. If this were so, soils would rapidly become depleted of nutrient reserves so that ion accumulation and growth by plants would

cease. Graham and Albrecht (1952) and Steward and Volk (1946) have reported studies on the release and subsequent uptake of potassium from nonexchangeable sources. Lawton and co-workers (1956 and 1958) have reported the uptake of phosphate from insoluble or weakly soluble sources applied to soils.

Certain physical relationships in soils can affect the absorption of nutrients, although the extent of this effect may vary with the plant and ions under study. Withrow (1951), in a review of the effect of light on the mineral nutrition of plants, has stated, "Light is not known to play any direct role indispensable for the absorption, movement, or metabolism of the mineral nutrients. Although light rarely strikes the absorbing surface of plants, that is, the roots, there may be an indirect effect resulting from the temperature rise concomitant with the absorption of light and from the basic photochemical reactions occurring in plants, such as photosynthesis, chlorophyll synthesis, photomorphogenesis, and photoperiodism."

Apart from a favorable soil reaction and an adequate supply of essential nutrients, the soil factors associated with an adequate supply of all essential nutrients are (a) a favorable supply of water, (b) adequate oxygen, (c) favorable temperature, and (e) friability or looseness of the soil so that roots are not restricted in their free growth and development (Page and Bodman, 1951). Although these factors may be most noticeable in terms of crop yields, differences in ion accumulation have been noted.

Cartter and Hopper (1942) reported results of a regional study with soybeans in which high temperature increased the calcium content of the seed produced by a given variety. Hoagland and Broyer (1936) and Broyer and Overstreet (1940) conducted experiments with excised barley roots in which they were able to show that potassium accumulation increased with increasing temperature, up to a maximum. However, in all of these studies, particularly those conducted in a soil medium with intact plants, any effects which temperature may have had on the solubilization of nutrients in the soil, on the ion absorption mechanism of the root interface, and on the translocation and utilization of the nutrients within the plant, cannot be readily separated.

Soil moisture is one of the variables in plant growth in the field which affects the absolute activities of cations and probably their ratios to one another (Peterson and Krackenberg, 1954). Richards and Wadleigh (1952) suggested that under conditions of adequate nutrient supply, plants that are limited in growth by a relatively low level of soil moisture will have a higher content of mineral nutrients than plants under comparable fertility but not limited in growth by moisture supply. Daniel and Harper (1934) noted that the calcium content of grasses and alfalfa grown under different fertilizer conditions in Oklahoma decreased and the phosphorus content increased during periods of high rainfall. When effective rainfall was low the reverse was true. Freeland (1936, 1937) indicated that soil moisture, through

its effects on transpiration rates, affected the rate of potassium uptake by corn, beans and sunflowers.

The influence of soil aeration on plant growth and nutrient absorption has been reviewed by Russell (1952). Lawton (1945) noted that the order of reduction in nutrient absorption by corn from Clyde silt loam soil because of restricted aeration was $K > Ca > Mg > N > P$. Cline (1957) studied oxygen diffusion rate as an important factor in soil aeration and nutrient absorption by peas.

Stubblefield and DeTurk (1940), in reporting results of their studies on the effect of seasonal conditions on the composition of corn, oats, and wheat, have stated "Weather conditions exert a pronounced effect, with the result that crops grown on the same plot in succeeding years may vary as much in chemical composition as crops grown on different plots."

Plants differ in their abilities to absorb nutrients from a given medium. Much of this difference in plant species has been attributed to variations in cation exchange capacity of the plant roof surfaces (Mehlich and Drake, 1955; Elgabaly and Wiklander, 1949). Drake, Vengris and Colby (1951) have listed the exchange capacities of the roots of many mono- and dicotolydenous plants showing a range from 30.4 to 10.5 m.e./100 grams oven-dry tissue for the former and from 94.0 to 25.0 for the latter. McLean and Baker (1953) made activity measurements of Na, K and Ca-saturated roots of several plant species, and from this calculated the mean free bonding energy of the cations. Plant roots with

relatively high cation exchange capacities had bonding energies for calcium which were more than double the bonding energies for potassium. Using roots of low cation exchange the bonding energy of calcium was about 50 percent of the value with higher cation exchange roots, whereas potassium was held with about 80 percent of the energy of the higher exchange roots.

The significance of these studies on the ability of plants to absorb or exclude ions has been the subject of extensive research and speculation. Epstein and Hagen (1952) postulated the presence of ion-binding compounds generated by metabolic processes, these compounds being specific for certain ions.

Mattson (1948) has used the Donnan principle to help explain the differences in monovalent and divalent cation absorption by colloids of high and low cation exchange capacity. According to his theory, the higher the cation exchange capacity of roots, the greater is the relative absorption of divalent over monovalent ions, since the activity of the divalent cation is inserted as the square root in the Donnan distribution.

Elgabaly and Wiklander (1949) pointed out that the root and soil colloids compete for cations, so that the cation uptake by the plant depends upon the relative exchange capacities of the root and soil. However, as Mattson has stated, it is only when nearly all of the cations exist in an exchangeable state and the plant root colloids must compete with soil colloids for these cations by exchange that the Donnan distribution will be reflected in the composition of plants. By an increase of free electrolytes, the inequalities of the Donnan distribution of ions will be evened out.

Although the prediction of cation content in plants appears promising under conditions of limited root extensions, substantial failures may be encountered with field-grown plants where the proportions and concentrations of cations vary widely in different zones of root penetration (Mehlich and Drake, 1955).

Other factors, intimately associated with physiological differences between plant species, may be operative in determining the rate and extent of ion accumulation. Newton (1923) suggested that the observed species differences in cation ratios are a function of the capacities of their root systems to produce carbon dioxide. Calcium accumulation was especially favored by release of carbon dioxide. Broyer (1951) has pointed out various hereditary limitations to ion accumulation by plant species. Collander (1941) also conducted numerous experiments to illustrate that the extent of physicochemical processes may be predetermined by ancestral characteristics.

The age of the plant, stage of maturation and associated rate of metabolic activity, and translocation of absorbed ions are all of importance in determining ion accumulation (Broyer, 1951). Tyson (1930), working with sugar beets, found that the percentage of minerals in the plant was usually highest in the spring when the young plants were making most rapid growth, and lowest during the summer. Beeson (1941) also indicated that the nutritive elements generally attain maximum concentrations

during the early part of the life of the plant. Ulrich (1946) and Sayre (1948) noted a decreased potassium content of plant tissue as the growing season progressed.

Various authors have noted that certain plant parts have the ability to selectively exclude certain ions while accumulating relatively large amounts of the others. However, the specific mechanism for such selectivity remains to be elucidated. Loehwing (1951) indicated that in many annuals a large part of the mineral nutrients are absorbed early in the life of the plant. As the plant passes from the initial anabolic stage to the catabolic stage just preceding flowering, important changes may occur in the mineral nutrient levels. Along with the redistribution of ions there is commonly a low level of root carbohydrate supply associated with a low absorption activity at this stage of growth.

McMurtrey (1947) observed that the magnesium and phosphorus content of the reproductive organs of plants increased during ripening. Cooper, Paden and Gorman (1947) commented on the relatively small amount of calcium in the carbonaceous parts of plants such as seeds, roots and tubers, and noted that the amount of magnesium in these parts is nearly always greater than the amount of calcium. Wallace, Toth and Bear (1948) studied the location of sodium in various plants and found a tendency for it to be concentrated in conductive tissues. Beeson (1947), in his classic study on plant composition, has noted the variable elemental content of plant parts.

Depending on the intensity and the combination of various soil and plant factors already discussed, the application of one or more nutrient elements may have a variable effect on the chemical composition of plants grown. Naftel (1937), Bender and Eisenmenger (1941), Vlamis (1949) and MacLean (1956) all reported an increased content of calcium in a range of crop plants as a result of lime applications. On the other hand, Chambers and Gardner (1951) found that the content of calcium in wheat was almost unaffected by liming, although the total uptake of calcium was increased due, primarily, to increased plant size.

Beaumont and Snell (1935) obtained an increased content of magnesium in corn stover, oats (grain and straw), barley (grain and straw), millet and buckwheat as a result of magnesium application. No change was observed in rutabagas or Sudan grass. Taylor (1954) and Carolus (1935) also noted an increased magnesium content of plant tissue with increasing available supplies in the soil.

Lawton and Cook (1954), in a comprehensive review of the literature, have pointed out that the potassium content of crops is generally increased as the level of exchangeable potassium in the soil is increased by the use of fertilizer, provided the level of soil potassium initially present is not extremely high. Bear and Prince (1945) have reported luxury consumption of potassium by alfalfa, while Windham (1953) found that the potassium content of 19 vegetable crops was usually increased by generous

applications of potassium fertilizers, the extent of this increase being dependent on plant species.

There is ample evidence in the literature that the accumulation of many micro-nutrients by plants is closely related to available supplies in the soil. Epstein and Stout (1951) and Lyon and Beeson (1948) made their observations with manganese. Steckel et al (1949) observed that the manganese concentration in oat and soybean plants was increased by soil applications of manganese sulfate. Fujimoto and Sherman (1948) noted that plant absorption of manganese was decreased by the addition of lime to the soil, thereby depressing the level of available manganese.

Variations in the phosphorus content of plants due to phosphate applications have been less marked. Blair and Prince (1939) found only a slight increase in the total percent phosphorus in alfalfa with increasing phosphorus applications to the soil. Studies in Michigan by Williams (1955) showed that increasing rates of application of superphosphate tended to increase the total phosphorus content of sugar beets, field beans and wheat. Wedin et al (1956) found that phosphorus applications also increased the level of phosphorus in the plant.

Of perhaps even greater significance in plant composition is the effect which the soil application of one ion exerts on the availability and/or accumulation of another. Practically all possible relationships between ions have been reported at some time in the literature. However, only those interactions which are most widely accepted will be reported here.

Peterson and Krackenberger (1954), in summarizing the interrelations of bases in calcium absorption, stated that an increase in the supply of absorbable calcium or magnesium tends to decrease the absorption of potassium from a low potassium medium, although this effect is likely to be less marked than the reverse. Carolus (1938) noted that nitrogen-phosphorus-potassium fertilization reduced calcium and magnesium absorption. Adequate absorption of calcium, magnesium and potassium could only be obtained by calcium-magnesium-potassium fertilization. McCalla and Woodford (1935) also found that low potassium supplies markedly increased the calcium and magnesium content of wheat. Prince and co-workers (1947), in studying the release of magnesium from New Jersey soils, concluded that the most important single factor influencing the magnesium uptake by plants was the quantity of available potassium. As the potassium supply decreased the magnesium content of the plant increased, even when the plants were growing on a soil quite deficient in magnesium. Contrasting results on the influence of calcium levels on the uptake of magnesium have been presented by Carolus (1933) and Naftel (1937).

Increased phosphorus uptake as a consequence of magnesium applications to soils have been reported by several workers (Truog *et al*, 1947; Beeson, Lyon, and Barrontine, 1944). The presence of a positive correlation between the phosphorus and magnesium contents of plants, or between the efficiency of phosphate fertilizers and the supply of available magnesium, has been reviewed by Beeson (1941, 1946).

Among the basic cations absorbed, potassium, calcium, magnesium and sodium, it is often noted that a decreased absorption of one ion is approximately balanced by an increased absorption of another, so that the total equivalents of cations in plant tissue will remain essentially constant (Lucas and Scarseth, 1947; Shear et al, 1946; McCalla and Woodford, 1938; and van Itallie, 1938). However, these workers have admitted that there are certain exceptions to this rule.

There is also a tendency to maintain a cation:anion balance in plants (Bear, 1950; McCalla and Woodford, 1938). Apparently an excess absorption of either cations or anions by the plant is balanced by the changing content of organic acids within the plant so that the reaction of the plant sap remains essentially unchanged (Hoagland and Broyer, 1940). This metabolic change within the root during the absorption process occurs primarily in the concentration of the malic acid fraction (Jacobson and Ordin, 1954).

The effects of chemical composition and quality of crops on the health, growth and reproduction of animals or humans utilizing these crops has been extensively studied. Research conducted over a ten-year period by workers at the Michigan Agricultural Station failed to show any differences in the rate of growth, vigor, milk production or reproductive ability of matched herds of dairy cows fed on fertilized and unfertilized crops (Dexter et al, 1950; Duncan et al, 1952; Duncan, 1955b; Ward et al, 1955). Similarly, no differences were obtained in the growth of rats fed on the cow's milk (Cederquist and Ohlson, 1955). Analyses of the feedstuffs

used in these studies indicated that the composition of timothy hay was favorably influenced by fertilization, while the relatively small differences that occurred in the composition of soybeans, corn, wheat, oats and brome hay in any one year could not be attributed to fertilization (Duncan, 1955a). According to the concept of plant nutrition proposed by Shear, Crane and Myers (1946) these results may have occurred because lime and fertilizer applications only increased the intensity of nutrient supply, but had no effect upon the balance of nutrients in the soil. Subsequent studies on this same soil did show that unbalanced nutrient levels could cause changes in plant composition (Power, Swenson and Cook, 1955).

Although nutritional disorders can be induced by restricting the kinds of feed or the content of any particular element in the feed, deficiencies in the diets of man or domestic animals have not been of general consequence because of the relatively small requirements for many elements and the varied selection of foodstuffs generally available. Nevertheless, deficiencies or toxicities of one or more elements can occur in localized areas, particularly where domestic animals are confined to feed produced in those areas. The many nutritional disorders of animals as a result of nutrient deficiencies in the feed have been reviewed by Underwood (1956) and Morrison (1947).

EXPERIMENTAL METHODS

Field Studies

Field experiments were initiated on an extremely infertile Kalamazoo sandy loam soil in May of 1955 to determine the effect of unbalanced applications of calcium, magnesium, potassium, and phosphorus on the chemical composition and quality of several feed crops, namely, timothy hay, soybean hay, millet, wheat, corn and soybeans. With the possible exception of millet, these crops are commonly grown in Michigan and are widely used for livestock feed. In addition, corn, soybeans and wheat, or portions thereof, are of considerable importance in human nutrition.

The results of other experiments conducted on this same soil have already been cited (Dexter, 1950; Duncan, 1955; Power, et al, 1955). These experiments indicated that no extreme nutrient unbalance existed in the untreated soil but rather the nutrients were properly balanced at a very low level of fertility. Records showed that the experimental field had received very little fertilizer or lime for a period of at least twenty years. Some of the characteristics of the experimental soil are given in Table I.

A total of twelve treatments were used, each replicated three times. Each plot measured one rod by five rods. The twelve treatments were randomized across the width of the experimental area, while the six crops were randomized across the length of each block.

[illegible]

[illegible]

TABLE I

SOME PHYSICAL AND CHEMICAL CHARACTERISTICS OF SOIL STUDIED

Available Phosphorus (lb/acre)	24[a]
Percent Potassium Saturation	1.5
Percent Calcium Saturation	24.1
Percent Magnesium Saturation	3.8
Percent Sodium Saturation	1.8
Exchangeable Manganese (ppm)	94
Cation Exchange Capacity (m.e./100 grams)	5.75
Soil pH	5.2
Soil Series	Kalamazoo
Texture of Surface Soil	sandy loam
Type of Clay (predominant)	Illite[b]

[a]Values represent average of 20 samples from experimental area.

[b]Stolzy, L. 1954. Unpublished Ph. D. thesis, Michigan State College

Calcitic and dolomitic limestones, phosphorus and potassium were applied in all possible combinations. Four treatments received no lime. On the plots receiving lime, meal grade calcitic limestone, with a neutralizing value of 87 was applied in amounts equivalent to four tons per acre of pure calcium carbonate. Dolomitic limestone meal, with a neutralizing value of 106 was applied in equivalent amounts to a second series. The limestones contained 9 and 45 percent magnesium carbonate, respectively.

Treble superphosphate (45 percent P_2O_5) was applied at the rate of 1250 pounds per acre, while muriate of potash,(60 percent K_2O) was applied at the rate of 500 pounds per acre on those plots designated to receive these nutrients.

With the exception of the timothy plots, one-half of the fertilizer and lime was applied before plowing, while the other half was applied after plowing and worked into the top three or four inches of the soil. In addition, all plots received a uniform application of 40 pounds per acre of nitrogen in the form of urea prior to plowing.

As the original sod was timothy, one series of plots in each replicate was left unplowed to serve as the hay crop. The complete application of lime, phosphorus and potassium was made as a topdressing on these plots. All fertilizer and lime applications were made during the period May 20 to 30.

In 1956, considerably smaller quantities of lime and fertilizer were applied. Hydrated calcitic and dolomitic lime was applied to the appropriate plots in amounts equivalent to 1,000

pounds per acre. Treble superphosphate (45% P_2O_5) and muriate of potash (60% K_2O) were applied at the rate of 200 and 100 pounds per acre, respectively, to plots receiving these elements. All applications, with the exception of those on timothy plots, were made following plowing.

Table II includes a summary of the crop varieties or strains used in the experiments, together with the dates of planting and harvest.

Soil samples were taken from each plot in 1955 and 1956 at the time of crop harvest, or shortly thereafter. Each sample represented fifteen to twenty cores to a depth of six inches.

Laboratory Studies

Soil Analysis

The soil samples obtained from each plot were air-dried and screened through a 2-mm sieve. One hundred gram samples of soil from each of the three replications of each treatment were thoroughly mixed together and saved for composite soil analysis.

A mechanical analysis was made on the soil using the hydrometer method of Boyoucous (1936). Soil pH measurements were made on noncomposited samples, using a 1:1 soil-water ratio and a Beckman model H-2 glass electrode, line-operated pH meter.

Available phosphorus was estimated by the method of Bray (1945). The extracting solution consisted of 0.03 N ammonium fluoride in 0.025 N hydrochloric acid. A soil-extracting solution ratio of 1:50 was employed.

TABLE II

DATES OF PLANTING AND HARVEST OF EXPERIMENTAL CROPS IN 1955 AND 1956

Crop	Variety	Date of Planting		Date of Harvest	
		1955	1956	1955	1956
Timothy hay[a]	Unknown	----	----	June 28	July 2
Millet	Proso	June 16	June 21	Sept. 27	Oct. 6
Soybean hay	Blackhawk	June 4	June 2	Sept. 2	Aug. 29
Soybeans	Blackhawk	June 4	June 2	Nov. 5	Oct. 9
Corn	Michigan 351	June 4	June 2	Nov. 5	Oct. 20
Wheat[b]	Gennessee	Sept. 24	----	----	July 19

[a]Established sod

[b]Winter wheat planted in 1955 and harvested in 1956.

Exchangeable cations were removed from the soil by leaching with neutral, normal ammonium acetate. The method used was similar to that suggested by Peech (1948). Potassium, sodium, and calcium concentrations in the ammonium acetate extract were determined by using a Beckman model D.U. flame photometer. Magnesium was determined by a modification of the thiazole yellow technique outlined by Drosdoff and Nearpass (1948). Values for exchangeable manganese were obtained by the periodate procedure of Willard and Greathouse (1917).

Plant Analysis

The plant samples were oven dried at 60° C. and ground in a Wiley mill. Twenty-five gram samples of plant material from each replicate were composited and saved for subsequent analysis.

Crude ash determinations were made by the A.O.A.C. procedure (1945). Values for total nitrogen were also obtained by the A.O.A.C. Kjeldahl distillation method.

Two gram plant samples were wet digested with nitric and perchloric acid, diluted to a volume of 50 milliliters and saved for element analysis. Calcium, magnesium, potassium and sodium concentrations were determined using a Beckman model D. U. flame photometer. Phosphorus and manganese analyses were performed with the ammonium molybdate and periodate colorimetric procedures, respectively.

Interpretation of Results

Due to the scope of this investigation, and the number of analyses involved, it was deemed necessary to composite the soil and plant samples from the three replications. Such action precluded the possibility of statistical analysis of the data, with the exception of crop yields, for which results were available for each replicate.

An attempt was made to calculate correlation coefficients between soil levels of any one nutrient and the content of any or all constituents in the plant. Such a procedure was discarded, however, as being conducive to erroneous interpretation and conclusions. Changes in the nutrient level of the soil were relatively large compared to changes in plant composition. Hence, highly significant correlations were obtained in certain instances when even a cursory examination of the plant analysis data indicated that the magnitude of the changes in plant composition could not conceivably be statistically significant under conditions of normal biological variability.

Therefore, for the purposes of the present discussion, it is assumed that a variation in composition of approximately ten percent is of sufficient magnitude to warrant drawing conclusions regarding its causes and effects. Although such an assumption may be subject to criticism, it is considered to be supported by sufficient evidence in the field of soil fertility research so as

to serve as a basis for interpreting the present data in terms of qualitative and quantitative factors influencing the accumulation of ions by plants.

RESULTS

Soil Nutrient Content

The effect of soil treatment on the level of available nutrients in 1955 and 1956 is presented in Tables III and IV, respectively. These data represent an average of all six crop areas in 1955, and all except the wheat plots in 1956. These latter plots were omitted from the 1956 averages due to the fact that they had not received the final additions of lime and fertilizer.

Four tons of calcitic lime almost doubled the exchangeable calcium in the soil in 1955, while dolomitic lime gave less than a twenty percent increase. This is a reflection of not only the lower calcium content of the dolomitic lime, but also the lower solubility and subsequent slower dissolution of this material. This latter effect is even more evident when the exchangeable magnesium levels are compared. In spite of the fact that calcite contained only one-fifth as much magnesium as dolomite, it was equally effective in increasing the magnesium content of the soil. Both materials resulted in a threefold increase in exchangeable magnesium.

Potassium fertilization increased the exchangeable potassium in the soil by over 200 percent. Based on the rate of application, exchangeable potassium levels in the soil should have been increased

TABLE III

THE AVERAGE EFFECT OF LIME AND FERTILIZER TREATMENTS ON THE SOIL NUTRIENT LEVEL IN 1955

Treatment	Ca	Mg	K	Na	Pounds	P.P.M.	pH
	(percent saturation)				P/acre	Exch. Mn	
None	27.4[a]	3.7	2.0	1.1	26	63	5.2
P	29.5	3.4	2.0	1.3	144	64	5.1
K	24.0	3.1	4.4	1.4	31	75	5.2
PK	27.6	3.3	4.4	1.1	162	73	5.2
L_1[b]	42.4	11.5	1.8	1.2	28	47	5.7
L_1P	49.8	12.0	1.9	1.4	156	45	5.7
L_1K	42.5	11.2	4.2	1.3	26	46	5.8
L_1PK	47.0	11.7	4.1	1.4	155	48	5.8
L_2[c]	34.5	12.3	1.9	1.3	28	47	5.5
L_2P	35.2	10.7	1.8	1.3	152	50	5.5
L_2K	27.5	10.8	3.9	1.3	28	46	5.6
L_2PK	31.4	10.0	3.9	1.2	145	49	5.6

[a]Average of all crop areas

[b]Calcitic lime

[c]Dolomitic lime

TABLE IV

THE AVERAGE EFFECT OF LIME AND FERTILIZER TREATMENTS ON THE SOIL NUTRIENT LEVELS IN 1956

Treatment	Ca (percent saturation)	Mg	K	Na	Pounds P/acre	P.P.M. Exch. Mn	pH
None	31.3[a]	5.2	1.8	0.7	32	27	5.1
P	33.6	4.9	1.8	0.8	144	27	5.0
K	25.5	4.5	4.6	0.8	43	35	5.0
PK	29.7	4.5	4.9	0.9	176	36	5.1
L_1[b]	77.1	12.3	1.7	0.9	35	11	6.3
L_1P	74.6	11.8	1.8	1.0	156	12	6.4
L_1K	73.3	12.4	4.3	0.9	32	12	6.5
L_1PK	80.0	12.2	4.7	1.0	159	13	6.6
L_2[c]	51.4	40.3	1.8	0.9	30	9	6.5
L_2P	55.2	36.9	1.7	0.9	189	10	6.4
L_2K	47.5	37.6	4.0	1.0	32	11	6.3
L_2PK	51.0	39.6	4.1	0.8	158	11	6.3

[a] Average of all crop areas except wheat

[b] Calcitic lime

[c] Dolomitic lime

by about 400 percent. However, the difference between observed and expected values can be explained partly on the basis of plant removal and leaching, but more particularly by fixation of potassium in nonexchangeable forms.

Phosphorus applications resulted in a five to sixfold increase in the level of available phosphorus. Here again, fixation would account for difference between observed and expected values.

Exchangeable manganese levels in the soil were substantially decreased by lime applications. However, there was no difference between liming materials with respect to their influence on available manganese. Phosphorus and potassium had no effect on manganese availability. Also, the soil treatments had no influence on exchangeable sodium levels of the soil.

In 1956 exchangeable calcium values were 250 percent greater where calcitic lime had been used, and 75 percent higher where dolomitic lime was applied, as compared to unlimed plots. The use of dolomite resulted in a ninefold increase in exchangeable magnesium, while the values where calcite was applied were almost the same as the previous year. This large increase in calcium and magnesium levels in 1956 is primarily due to the use of hydrated lime which is more readily soluble than the coarser carbonates.

Phosphorus and potassium fertilizers were applied in 1956 in amounts calculated to maintain the previously established levels. Within the limits of plot variation, this aim was accomplished.

TABLE V

THE EFFECT OF LIME AND FERTILIZER ON VARIOUS CATION RATIOS IN THE SOIL

Ratio	Lime Treatment			Fertilizer Treatment	
	-Ca-Mg	+Ca-Mg	+Ca+Mg	-K	+K
			1955		
Ca/Mg	8.02	3.92	2.94	4.08	3.94
Ca/K	8.48	15.17	11.12	19.19	8.02
Mg/K	1.06	3.87	3.79	4.71	2.04
			1956		
Ca/Mg	6.33	6.30	1.33	2.90	2.77
Ca/K	9.21	24.36	17.67	30.42	11.52
Mg/K	1.45	3.87	13.30	10.49	4.16

Values for exchangeable manganese were consistently lower on all plots in 1956. This is probably due to changing oxidation-reduction conditions in the soil as influenced by tillage, cropping and climate. Due to this variability, it has been shown that the exchangeable manganese content of a soil is not necessarily a good index of the manganese nutrition of plants (Hoff and Mederski, 1958). However, liming the soil reduced the exchangeable manganese to one-third the original level.

Table V lists some of the cation ratios in the soil in 1955 and 1956. It is evident that rather wide ratios were established between the primary cations in the soil as a result of lime and potassium applications. However, the ratios were relatively constant for any series of treatments. This would indicate that the presence of a complementary ion or ions had no effect on other ratios. For example, the Ca/Mg ratio was not affected to any extent by potassium fertilization in either of the two years.

The significance of these ratios in the nutrition of plants will be discussed later.

Crop Yields

The yields of all crops were exceptionally low (Tables VI and VIII). This is a reflection of the very low fertility status of the area at the beginning of the experiment. Although soil test values indicated relatively large increases in the supply of available nutrients (Tables III and IV), response in terms of increased growth was not obtained. Such results suggest that the expected

TABLE VI

THE EFFECT OF SOIL TREATMENT ON THE YIELD OF SEVERAL CROPS GROWN IN 1955

Treatment	Tons per Acre		Bushels per Acre		
	Timothy hay	Soybean hay	Millet	Soybeans	Corn
None	0.97[a]	0.60	7.5	4.0	24.1
P	0.99	0.80	14.4	3.9	13.8
K	0.78	0.98	9.6	2.8	10.1
PK	0.71	0.97	11.4	2.8	10.3
L_1[b]	0.76	0.74	10.0	3.8	12.8
L_1P	0.70	1.05	14.2	4.2	13.6
L_1K	0.70	0.69	13.0	3.7	13.9
L_1PK	0.81	1.11	11.9	3.0	10.3
L_2[c]	0.72	0.55	9.2	2.9	23.6
L_2P	0.71	1.02	12.4	3.7	14.6
L_2K	0.71	0.62	9.6	2.9	17.1
L_2PK	0.80	0.97	18.5	3.2	14.8
L.S.D. (.05)	N.S.	0.36	5.8	N.S.	N.S.

[a]Average of three replications

[b]Calcitic lime

[c]Dolomitic lime

TABLE VII

ANALYSIS OF VARIANCE OF 1955 CROP YIELDS

Source of Variation	Degrees of Freedom	F Values Timothy hay	Soybean hay	Millet	Soybeans	Corn
Total	35	0.64	.	.		
Replications	2	0.64	3.91*	0.58	2.44	1.89
Treatments	11	0.83	2.52*	2.32*	0.97	1.59
Lime	2	1.73	0.74	0.51	0.87	1.78
Phosphorus	1	0.05	16.52**	12.47**	0.13	3.54
Potassium	1	0.74	1.80	0.82	4.94*	4.11
Lime x Phosphorus	2	0.10	1.85	1.78	0.55	0.39
Lime x Potassium	2	1.87	1.54	1.40	0.71	1.18
Phosphorus x Potassium	1	0.19	0.28	0.49	0.72	1.01
Lime x Phosphorus x Potassium	2	0.40	0.87	2.17	0.31	1.09
Error	22					

*Significant at 5% level

**Significant at 1% level

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productivity of an extremely infertile soil cannot be regained in one or two seasons, even with adequate applications of lime, phosphorus and potassium. Apparently a longer period of time is necessary to establish a balance among all growth factors in the soil, physical, chemical and biological. An indication of a trend toward this equilibrium is present as evidenced by the general increase in the yields of all crops in 1956 as compared to 1955. The growth of timothy is the single exception. Two factors probably contributed to the lower yields of timothy in 1956. First, the stand of timothy was poor so that greatly stimulated growth could not be expected. The application of large amounts of fertilizer and lime as a top-dressing also interfered with growth. This is evidenced by the depressed yields in 1956 as a result of the application of dolomitic lime. The hydrated lime remaining in contact with the grass no doubt depressed growth. The necessity of crossing the plots several times with heavy equipment, coupled with the relatively short period of time from date of application to time of harvest probably prevented any possible yield differences.

In 1955, timothy and corn yields showed no significant response to treatment (Table VII). However there was a distinct tendency for all treatments, except dolomitic lime alone, to decrease corn yields. Soybean hay yields were improved by the application of phosphorus, as were millet yields. Apparently the phosphorus aided in the vegetative development of the soybean plant but not in the production of seed. This is worthy of note

in view of the importance of phosphorus in the development of reproductive parts and its preferential absorption by many seeds.

Potassium depressed soybean yields in 1955. Based on observations made during the growing season this may have been due to a slightly lowered germination, coupled with increased competition from weeds.

All crops, except soybean hay and soybeans, showed some response to fertilization and liming in in 1956, although the type and extent of response varied with species (Table IX). Variations in timothy yields as a result of lime applications have already been pointed out. The lack of a response of soybeans to treatment was expected. This crop often fails to give increased yields as a result of direct fertilization.

Potassium increased the yield of millet and corn, especially the former. More vigorous growth resulted from potassium applications, which was in turn reflected in higher grain yields. Although the yields of straw and stover were not calculated, observations would lead to the conclusion that the percentage increase due to potassium fertilization would be comparable to that for the grain.

Corn and wheat yields increased with lime applications. Dolomitic lime increased corn yields while the calcitic lime did not, indicating that the magnesium supplied by the dolomite was primarily responsible for this effect. Both liming materials caused large increases in wheat yields, with no significant differences between sources. Here the correction of soil acidity

TABLE VIII

THE EFFECT OF SOIL TREATMENT ON THE YIELD OF SEVERAL CROPS GROWN IN 1956

Treatment	Tons per Acre		Bushels per Acre			
	Timothy hay	Soybean hay	Millet	Soybeans	Corn	Wheat
None	0.54[a]	1.09	13.3	6.9	29.0	7.7
P	0.71	1.16	17.4	10.0	34.0	14.9
K	0.44	1.31	19.2	7.8	32.5	8.6
PK	0.53	1.00	21.4	8.6	35.1	15.5
L_1[b]	0.62	1.11	14.7	7.9	30.2	16.0
L_1P	0.59	1.15	19.4	7.7	31.2	28.2
L_1K	0.60	1.09	22.8	11.0	34.0	12.9
L_1PK	0.64	1.37	22.6	10.5	36.3	26.0
L_2[c]	0.49	1.14	14.6	6.3	34.8	16.4
L_2P	0.47	1.13	17.7	7.0	37.4	28.2
L_2K	0.47	1.18	18.7	9.0	39.7	12.9
L_2PK	0.52	1.32	20.7	8.4	47.8	24.4
L.S.D. (.05)	N.S.	N.S.	N.S.	N.S.	5.8	9.5

Average of three replications

Calcitic lime

Dolomitic lime

TABLE IX

ANALYSIS OF VARIANCE OF 1956 CROP YIELDS

Source of Variation	Degrees of Freedom	F Values					
		Timothy hay	Soybean hay	Millet	Soybeans	Corn	Wheat
Total	35						
Replications	2	4.38*	8.05**	10.48**	11.01**	24.88**	1.49
Treatments	11	1.67	0.32	1.75	1.03	2.37*	5.06**
Lime	2	3.88*	0.08	0.96	1.28	6.48**	10.22**
Phosphorus	1	2.00	0.11	3.83	0.66	3.68	31.45**
Potassium	1	0.91	0.58	11.87**	3.49	6.55*	0.99
Lime x Phosphorus	2	1.17	0.53	0.03	0.62	0.32	0.84
Lime x Potassium	2	1.92	0.56	0.20	1.24	0.68	0.53
Phosphorus x Potassium	1	0.08	0.00	0.87	0.45	0.15	0.00
Lime x Phosphorus x Potassium	2	0.54	0.78	0.18	0.25	3.68	0.01
Error	22						

*Significant at 5% level

**Significant at 1% level

and/or the supply of available calcium were probably of greatest importance.

The only significant response to phosphorus applications was by the wheat crop. The average increase in yield per acre with phosphorus additions was 85 percent, indicating the tremendous importance of an adequate supply of available phosphorus in the nutrition of the wheat plant.

None of the interactions between supplied nutrients were statistically significant, indicating that insofar as crop yields were concerned the addition of one nutrient, within the range of amounts applied, did not influence the effectiveness of another.

Chemical Composition of Crops Studied

Timothy Hay

Figures 1, 2 and 3, and Table X, present a summary of the effect of soil treatment on the composition of timothy hay. It should be recalled that these fertilizer and lime applications were made on the surface of the established timothy sod. In both years these applications were made about one month prior to harvest.

In spite of the relatively short period of time involved, certain changes in composition of timothy occurred in 1955. Both liming materials increased the uptake of calcium and magnesium. As would be expected, based on the composition of the two limestones, calcitic limestone was most effective in increasing calcium accumulation while dolomitic limestone improved the uptake of

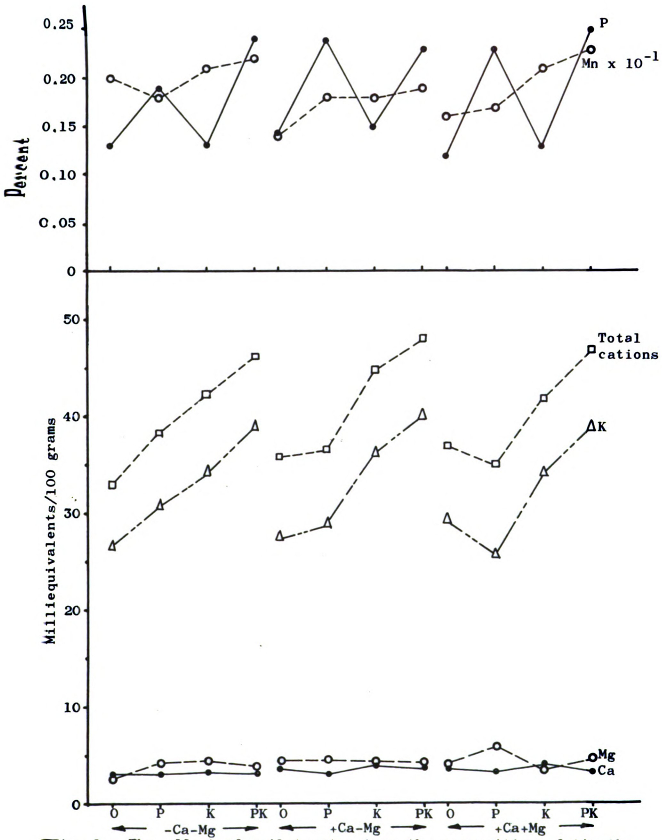

Fig. 1. The effect of soil treatment on the composition of timothy hay grown in 1955.

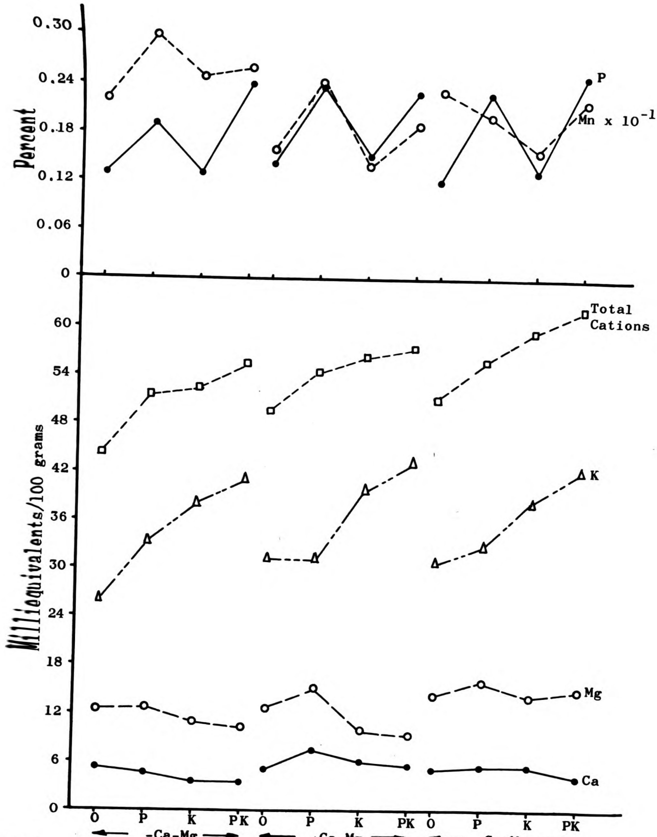

Fig. 2. The effect of soil treatment on the composition of timothy hay grown in 1956.

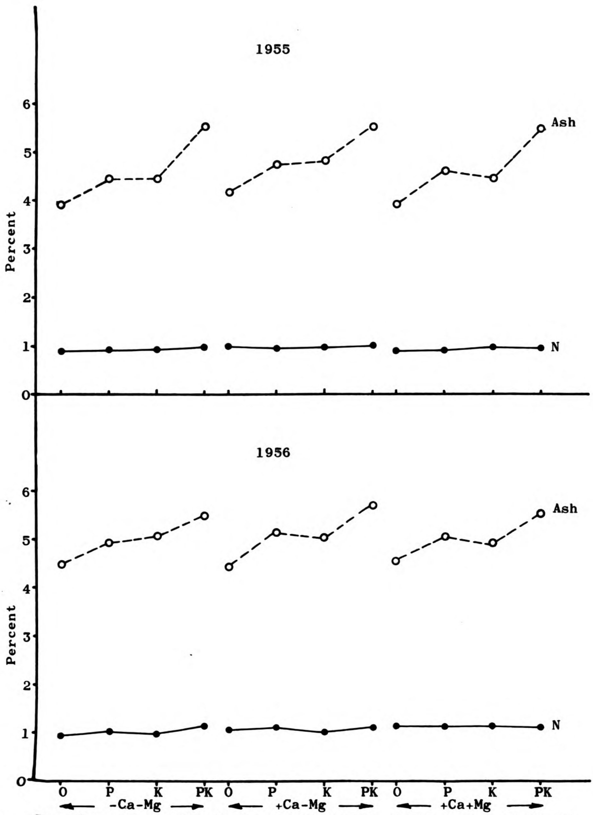

Fig. 3. The effect of soil treatment on the nitrogen and crude ash content of timothy hay grown in 1955 and 1956.

TABLE X

PERCENT CHANGE IN THE COMPOSITION OF TIMOTHY HAY AS A RESULT OF LIME AND FERTILIZER APPLICATIONS

Constituent	Ca-Lime	Mg-Lime	Phosphorus	Potassium
		1955		
Calcium	+13.4[a]	+10.2	- 9.9	+ 7.7
Magnesium	+14.6	+19.8	+16.8	- 2.8
Potassium	+ 1.4	- 2.0	+ 8.1	+31.8
Sodium	-24.3	-48.8	-12.7	+ 7.2
Total cations	+ 3.4[b]	- 0.6	+ 7.1	+25.3
Phosphorus	+ 9.8	+ 5.8	+72.9	+ 7.4
Manganese	-14.8	- 4.9	- 6.6	+20.3
Nitrogen	+ 5.9	+ 2.7	+ 3.2	+ 6.1
Crude ash	+ 4.8	+ 1.3	+17.8	+17.3
		1956		
Calcium	+39.1	+17.2	+ 2.5	-13.5
Magnesium	+ 0.6	+29.6	+ 5.4	-16.7
Potassium	+ 5.3	+ 5.8	+ 9.8	+30.5
Sodium	+ 2.9	+15.6	+ 1.6	+ 1.6
Total cations	+ 6.9	+12.4	+ 7.6	+12.0
Phosphorus	- 3.4	- 3.4	+45.4	- 3.0
Manganese	-29.1	-21.3	+21.8	- 9.8
Nitrogen	+ 4.5	+ 7.9	+ 5.9	+ 1.7
Crude ash	+ 2.2	+ 1.0	+11.8	+10.9

[a]Percent increase or decrease compared to unlimed or unfertilized treatments.

[b]Calculated from the sum of the milliequivalents of calcium, magnesium, potassium and sodium.

magnesium to the greatest extent. Both materials also tended to increase the uptake of phosphorus and decrease the accumulation of manganese. Here again, the trend was most noticeable with the calcitic limestone. This is no doubt due to the greater proportion of fine material in the calcitic lime, resulting in a more rapid dissolution and conversion to the ionic form. Even under conditions of equal particle size, dolomite is somewhat more resistant than calcite (Beacher et al, 1952).

The accumulation of sodium was greatly decreased by lime treatment, particularly dolomite. However, due to the very low content of sodium in the tissue this was not reflected in the overall uptake of cations. The uptake of the other monovalent cation, potassium, was unaffected by soil treatment. Since the potassium was applied in a water soluble form it was immediately available for plant absorption. Thus it would be expected that the lime treatment would not exert any substantial effect on the uptake of this nutrient during the comparatively short period of one month.

Of all the nutrients applied, phosphorus was the one most effective in increasing the content of that particular ion in the plant. On the average, plants receiving applied phosphorus contained 72.9 percent more phosphorus than untreated plants. In view of the surface application, and the immobile nature of phosphorus in the soil, this accumulation is worthy of note. Three factors probably contributed to this immediate response. First, the form of phosphorus used (treble superphosphate) is largely water

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soluble and hence was available for immediate utilization. Secondly, there was not sufficient time for soil fixation to occur, particularly with such a high rate of application (1250 pounds per acre). If the fertilizer had been mixed with the soil, fixation probably would have proceeded at a faster rate. Thirdly, there were no doubt a number of absorbing roots close to the surface of the soil, so that the phosphorus ions did not have time to move any appreciable distance before absorption occurred.

Phosphorus increased the uptake of magnesium and phosphorus, which contributed to an increase in the crude ash content. Potassium absorption was also increased to a certain extent by phosphorus applications to the soil. It is possible that the inclusion of phosphorus resulted in more vigorous root growth, thus increasing cation accumulation.

Potassium applications to the soil resulted in a substantial increase in potassium concentration in the plant. At the same time, the uptake of other cations was essentially unchanged so that the increase in total bases was almost entirely due to potassium, Potassium also accounted for a considerable increase in the content of crude ash and manganese. However, the manganese content was subject to appreciable variability so that this observation is of questionable significance.

The data for the composition of timothy hay grown in 1956 shows several inconsistencies when compared to the 1955 data. Calcitic lime increased the uptake of calcium even more than it did in 1955. This was probably due to the longer period of time

during which the lime was able to react with the soil, coupled with the use of hydrated lime in 1956, thus increasing the water soluble and exchangeable calcium in the soil. This conclusion was borne out by the soil analysis data. Similar statements can also be made regarding the dolomitic lime, with a subsequent increase in the content of magnesium.

The calcitic lime did not increase the uptake of magnesium in 1956 as it did the previous year. This can be accounted for on the basis of a considerable increase in the content of exchangeable calcium in the soil while the level of exchangeable magnesium was almost the same. This wider Ca/Mg ratio in the soil was then reflected in a wider Ca/Mg ratio in the plant.

The magnesium content of all samples was several times higher in 1956 compared to 1955. No plausible explanation can be offered for this observed phenomenon. Differences in climate and other cultural practices, such as nitrogen fertilization, may have contributed to this increase. The total nitrogen content of the forage was similarly increased, which appeared to be unrelated to soil treatment.

Liming the soil again reduced the uptake of manganese. The accumulation of manganese by the plant was closely related to soil levels of manganese, although the decrease in uptake as a result of lime applications was not nearly proportional to the decrease in exchangeable manganese in the soil. No doubt the plant secured soluble manganese from sources other than that adsorbed on the exchange complex.

Although phosphorus applications increased the phosphorus content of the timothy, the increase was considerably lower than for the previous year. During the intervening time interval a considerable portion of the phosphorus was probably fixed in a form unavailable to the plant, even though this fixation was not reflected in the soil tests. Manganese uptake was improved by phosphorus applications, although this trend was most noticeable on unlimed plots.

Potassium fertilization again accounted for a substantial increase in the content of total bases in the plant. However, the change was less noticeable than in 1955 for several reasons. First, high potassium levels in the soil and in the plant reduced the uptake of calcium, and more particularly magnesium. Secondly, increased magnesium uptake as a result of magnesium fertilization accounted for a greater proportion of the increase in total cation content. The fact remains, however, that heavy applications of potassium fertilizer exerted the greatest effect on cation accumulation, both in terms of ratio and absolute quantities. At any particular potassium level there was a marked tendency for the sum of the other cations to equal a constant.

Soybean Hay

As seen in Figures 4 and 5, the cation content of soybean plants was approximately three times that of timothy hay, indicating that this plant removed many more nutrients from the soil than did the timothy.

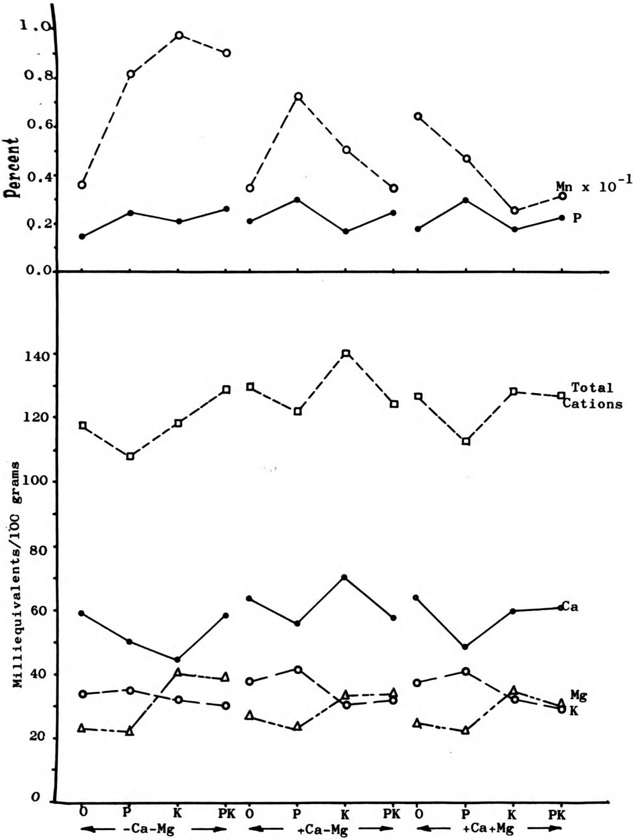

Fig. 4. The effect of soil treatment on the composition of soybean hay grown in 1955.

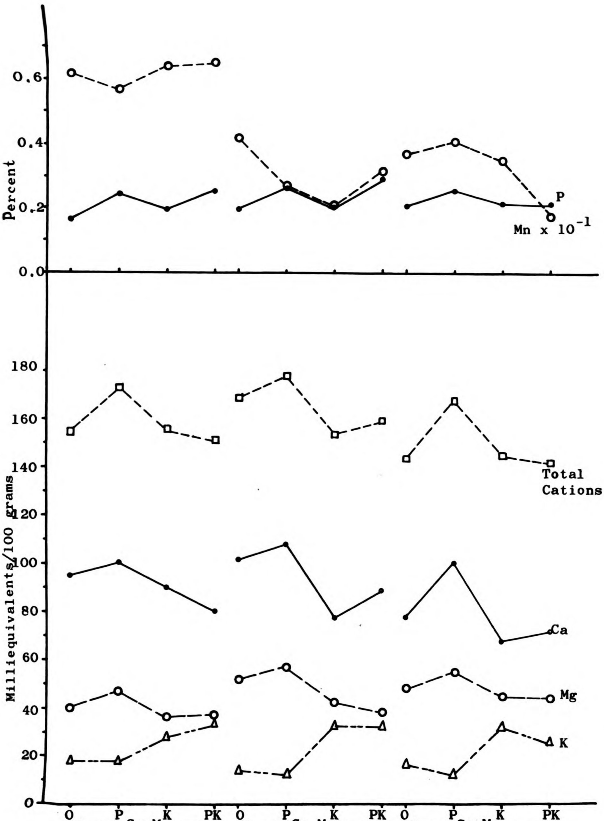

Fig. 5. The effect of soil treatment on the composition of soybean hay grown in 1956.

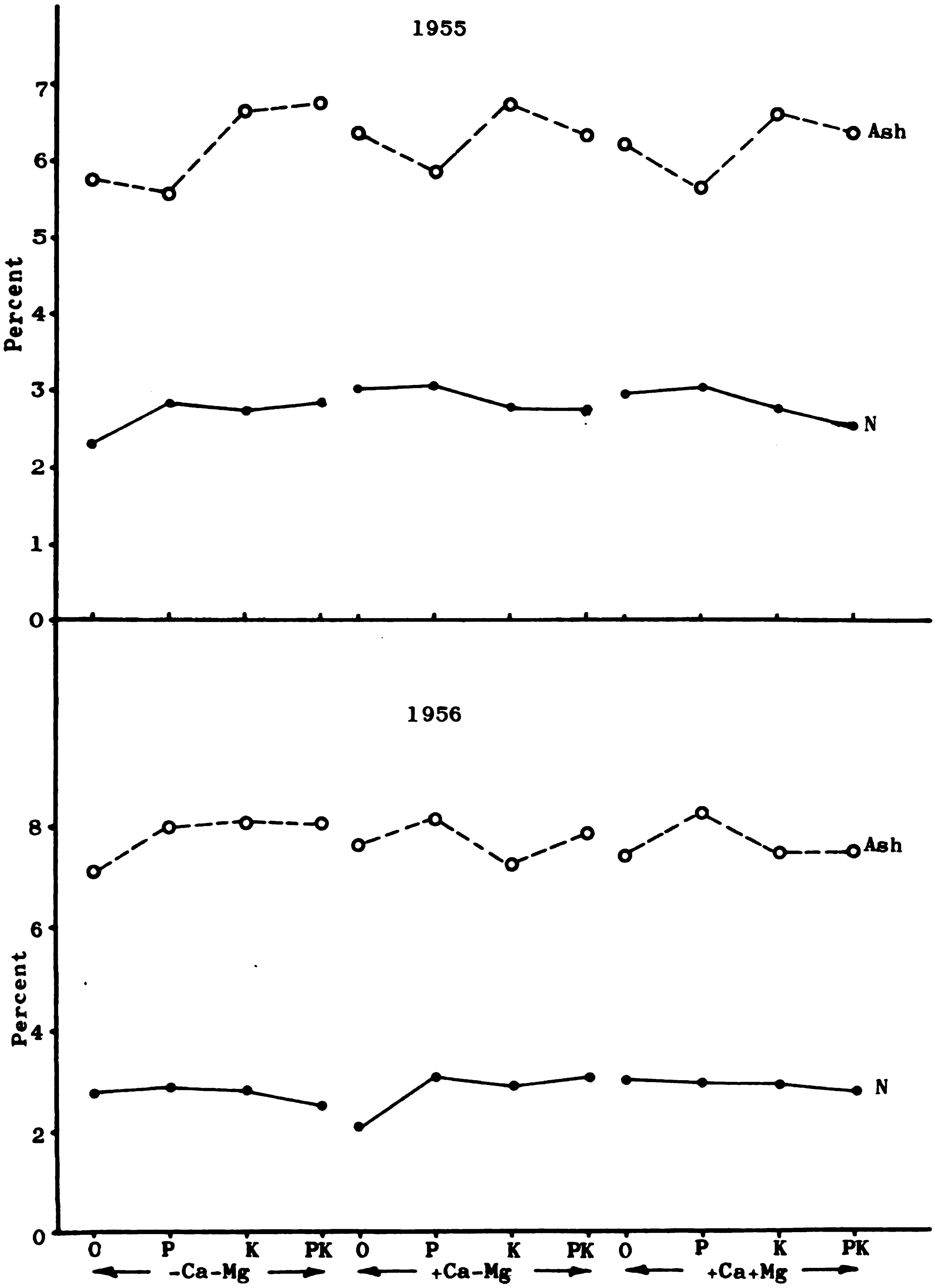

Fig. 6. The effect of soil treatment on the nitrogen and crude ash content of soybean hay grown in 1955 and 1956.

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TABLE XI

PERCENT CHANGE IN THE COMPOSITION OF SOYBEAN HAY AS A RESULT OF LIME AND FERTILIZER APPLICATIONS

Constituent	Ca-Lime	Mg-Lime	Phosphorus	Potassium
		1955		
Calcium	+16.1[a]	+ 9.1	- 8.3	+ 2.9
Magnesium	+12.0	+10.7	+ 2.8	-12.5
Potassium	- 6.3	- 9.2	- 6.4	+47.7
Sodium	+ 5.9	+16.9	- 5.4	0.0
Total cations	+ 8.9[b]	+ 4.7	- 4.7	+ 7.0
Phosphorus	+ 6.9	+ 2.3	+44.0	- 6.5
Manganese	-36.8	-44.3	+16.1	- 1.8
Nitrogen	+ 8.9	+ 5.5	+ 3.1	- 5.2
Crude ash	+ 2.5	+ 0.5	- 4.6	+ 5.8
		1956		
Calcium	+ 0.7	-14.8	+10.8	-19.3
Magnesium	+17.3	+18.7	+ 5.4	-18.6
Potassium	- 6.0	-11.5	- 5.4	+99.0
Sodium	- 8.5	-23.7	- 5.6	0.0
Total cations	+ 3.9	- 5.7	+ 5.5	- 8.0
Phosphorus	+10.5	+ 2.3	+29.0	+ 2.2
Manganese	-50.8	-47.1	- 8.8	-11.7
Nitrogen	+10.5	+ 5.9	- 1.8	- 4.1
Crude ash	- 0.8	- 1.5	+ 6.9	+ 0.5

[a]Percent increase or decrease compared to unlimed or unfertilized treatments.

[b]Calculated from the sum of the milliequivalents of calcium, magnesium, potassium and sodium.

Both liming materials were more effective in increasing the calcium and magnesium content of soybean plants in 1955 than they were in increasing the uptake of these same elements by timothy (Table XI). As already indicated, this is related to the length of time from date of application to harvest, and the low solubility of limestone. The uptake of calcium was somewhat proportional to the concentration of calcium in the two materials and the level of exchangeable calcium in the soil. Hence, the increase in calcium ion accumulation was only one-half as great with dolomitic lime compared to calcitic lime. Both materials gave small, almost identical, increases in magnesium uptake. This, too, was reflected in similar soil levels of available magnesium.

Lime applications reduced the uptake of potassium to a slight extent. The concentration of manganese in the plant was also reduced considerably by lime treatment. On the other hand, sodium uptake was increased by lime treatment, although in terms of absolute amounts, the increase was small.

Phosphorus in the plant was closely correlated with available soil phosphorus. Manganese absorption also appeared to be increased by phosphorus applications. Small, but probably insignificant decreases in calcium, potassium and sodium uptake accompanied phosphorus accumulation.

Potassium fertilization resulted in almost a 50 percent increase in the concentration of this ion in the plant. Part of this increased potassium uptake was counteracted by a decline in magnesium absorption. This is in agreement with the work of

Prince et al (1947) who noted that the quantity of available potassium in the soil was the most important single factor influencing the magnesium uptake of plants. Potassium also decreased the nitrogen content of the soybean forage (Figure 6). This appeared to be an indirect effect confounded with lime treatments. In the absence of lime, potassium did not decrease the nitrogen content of soybean hay.

In 1956 calcitic lime failed to increase calcium uptake but did improve magnesium accumulation. This increase in magnesium concentration was almost equal to that obtained with dolomitic lime. There is no apparent reason for these conflicting results. Calcitic lime also increased the uptake of nitrogen and phosphorus, probably due to its effect in increasing the pH, thus creating a more suitable environment for nitrogen fixing bacteria and a more desirable soil reaction for phosphorus solubility. Truog (1951) has shown that phosphorus availability is higher on neutral to slightly acid soils than on those which are strongly acid.

The increased absorption of magnesium as a result of applying dolomitic lime occurred at the expense of calcium and potassium uptake. However, the total reduction in cation accumulation was almost 17 milliequivalents per 100 grams, while the increase in magnesium uptake amounted to only 7.5 milliequivalents.

As in the case of timothy, applied phosphorus resulted in a smaller increase in the phosphorus content of the tissue in 1956 samples. However, it also decreased the accumulation of calcium in the plant.

The potassium concentration in the soybean plants was almost doubled in 1956 as a result of potassium fertilization. This effect was coupled with a substantial decrease in the calcium and magnesium content, so that the total cation concentration was reduced by the presence of high amounts of potassium in the soil. This was in contrast to the large increases in the cation content of timothy hay attributable to potassium applications to the soil, with a subsequent increase in potassium absorption.

Millet Grain

Data for the composition of millet as influenced by lime and fertilizer treatments are graphically shown in Figures 7, 8 and 9. It is evident that millet, like many other seeds, is very low in calcium so that small changes in the content of this element may be relatively large when expressed as a percentage of the total. In 1955 neither of the limestone materials changed the calcium content, but both gave about a fifty percent increase in magnesium (Table XII). This is no doubt a reflection of the selective exclusion of calcium by the millet seed. As observed with other crops, lime applications depressed the accumulation of manganese substantially. Total cation content was also increased by about one-third, primarily as a result of increased magnesium in the seed.

Phosphorus applications to the soil were less effective in increasing the phosphorus content of the tissue than they were in the other crops previously discussed. Small increases in the

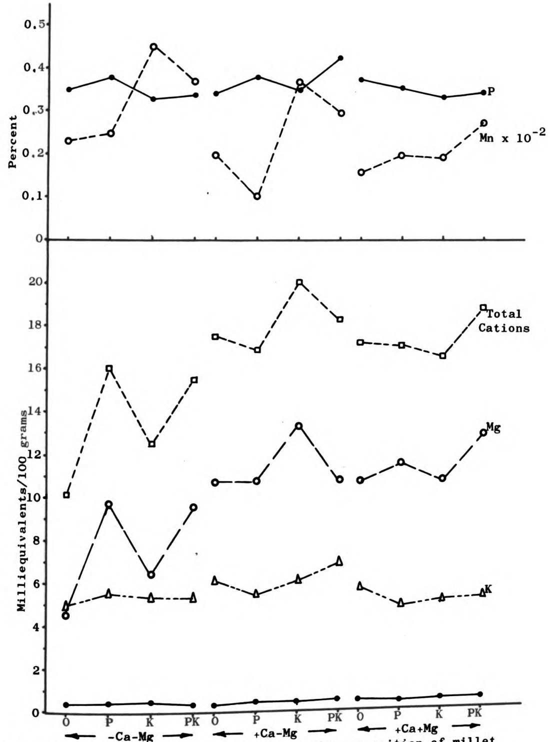

Fig. 7. The effect of soil treatment on the composition of millet grain grown in 1955.

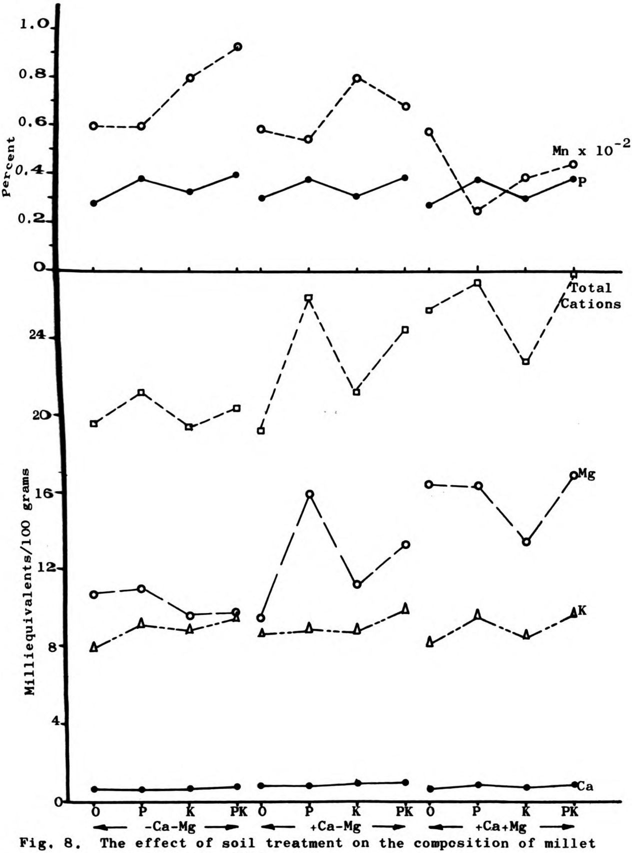

Fig. 8. The effect of soil treatment on the composition of millet grain grown in 1956.

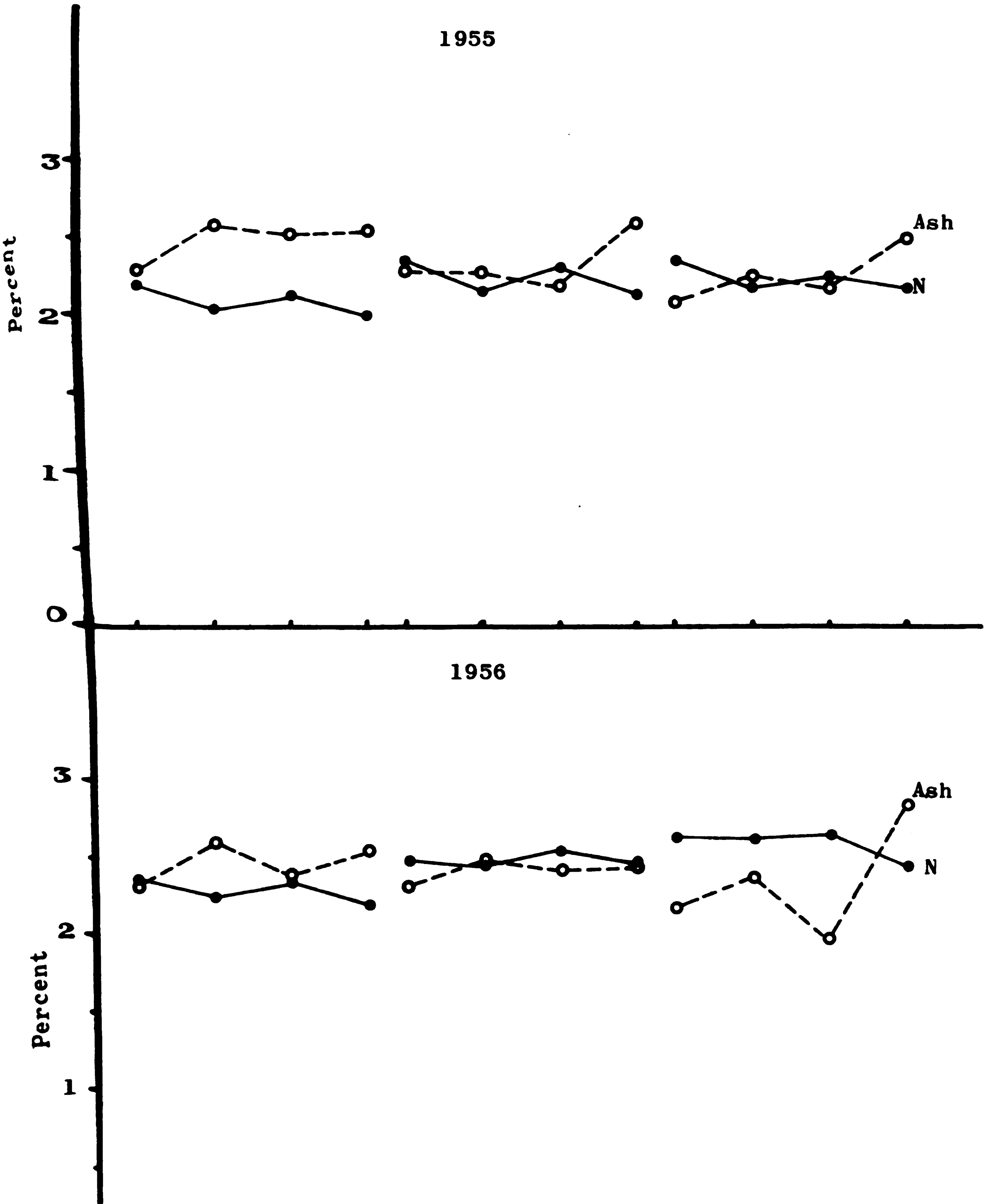

Fig. 9. The effect of soil treatment on the nitrogen and crude ash content of millet grain grown in 1955 and 1956.

TABLE XII

PERCENT CHANGE IN THE COMPOSITION OF MILLET GRAIN AS A RESULT OF LIME AND FERTILIZER APPLICATIONS

Constituent	Ca-Lime	Mg-Lime	Phosphorus	Potassium
		1955		
Calcium	- 3.7[a]	- 2.7	+ 6.7	+ 4.1
Magnesium	+50.1	+51.1	+15.2	+ 9.7
Potassium	+15.5	- 0.9	- 0.4	+ 4.0
Sodium	- 8.5	+ 4.2	+ 2.6	+ 2.6
Total cations	+33.9[b]	+28.4	+ 9.1	+ 7.3
Phosphorus	+ 7.1	+ 2.3	+ 7.2	- 1.4
Manganese	-25.2	-35.4	- 6.7	+72.6
Nitrogen	+ 6.7	+ 6.7	- 7.0	- 2.3
Crude ash	- 6.4	- 9.2	+ 8.8	+ 5.2
		1956		
Calcium	+20.3	+ 4.0	+14.6	+ 1.6
Magnesium	+21.8	+52.5	+17.4	- 7.5
Potassium	+ 2.5	+ 1.0	+11.7	+ 6.0
Sodium	- 1.6	+ 0.8	+ 2.4	- 7.5
Total cations	+13.1	+27.6	+30.5	- 2.0
Phosphorus	- 0.9	- 3.7	+26.8	+ 4.5
Manganese	-14.1	-43.4	-11.0	+24.4
Nitrogen	+ 8.7	+13.1	- 3.6	- 1.2
Crude ash	- 2.0	- 4.9	+12.3	+ 2.5

[a]Percent increase or decrease compared to unlimed or unfertilized treatments.

[b]Calculated from the sum of the milliequivalents of calcium, magnesium, potassium and sodium.

crude ash and calcium content, and an appreciable increase in magnesium uptake could also be attributed to phosphorus fertilization, with the net result that the total cation content of the millet seed was increased by almost ten percent.

Potassium applications did not affect the composition of the millet to any significant extent, with the exception of manganese, which was increased. The increased magnesium content of the tissue which had received potassium fertilization was contrary to observations with other crops.

The further application of lime in 1956 increased the uptake of calcium where the calcitic material was used. It should be remembered that the lime applied in 1956 was hydrated, thus a faster reaction in the soil and a subsequent increased uptake by the plant could be expected. Magnesium uptake was also increased by the calcitic lime, but not nearly to the extent it was in 1955.

Dolomitic lime again caused a fifty percent increase in the magnesium content of the millet. However, it had no effect in the accumulation of calcium, potassium or sodium. Both materials increased the nitrogen and total cation content of millet seed and decreased the manganese. Dolomite was most effective in bringing about these changes in composition. In both instances the increase in total cations was almost entirely due to the accumulation of additional magnesium, especially in view of the wide Mg/Ca ratio in millet.

In 1956 phosphorus applications to the soil increased the crude ash, calcium, magnesium, potassium and total cation content

of millet seed, apart from a substantial increase in the accumulation of the phosphate anion. Manganese concentration in the tissue tended to be reduced by phosphorus treatment.

The effect of potassium fertilization on the composition of millet grown in 1956 was similar to results obtained in 1955. There was a general lack of any consistent change in the content of the various plant constituents, with the possible exception of manganese which was increased. Whereas potassium tended to increase magnesium absorption in 1955, the reverse was true in 1956.

Soybean Grain

Table XIII shows that lime applications in 1955 did not change the composition of soybeans to any extent. Calcitic lime tended to decrease the content of most constituents, although this trend was very slight. Dolomitic lime had a similar effect, with the exception that magnesium and sodium contents were increased a small amount.

Phosphate applications to the soil also produced very little change in seed composition, aside from an increase in the phosphorus content and a decrease in the manganese content (Figure 10).

Potassium treatments increased the manganese and crude ash in the soybeans but had no other effect (Figures 10 and 12).

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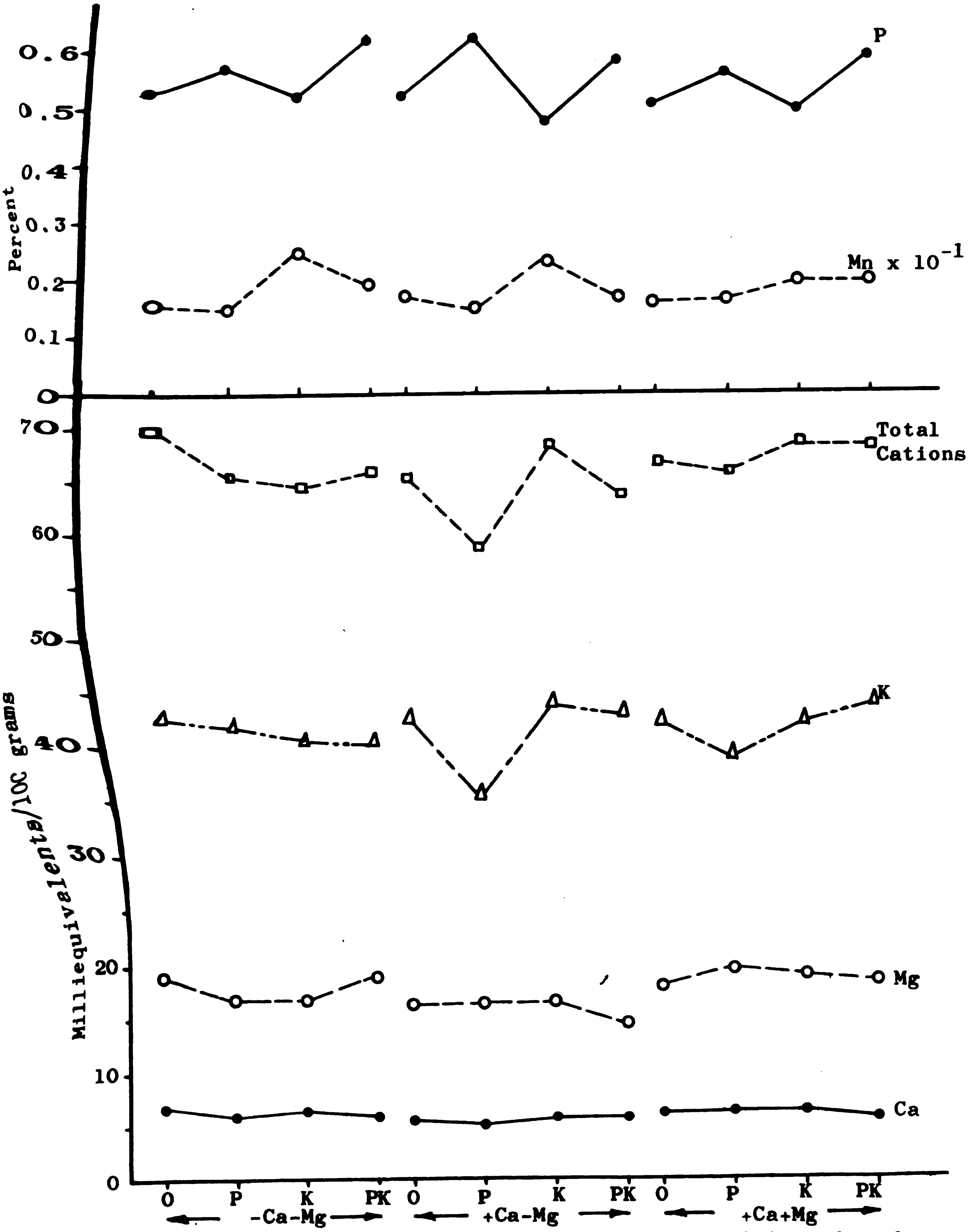

Fig. 10. The effect of soil treatment on the composition of soybean grain grown in 1955.

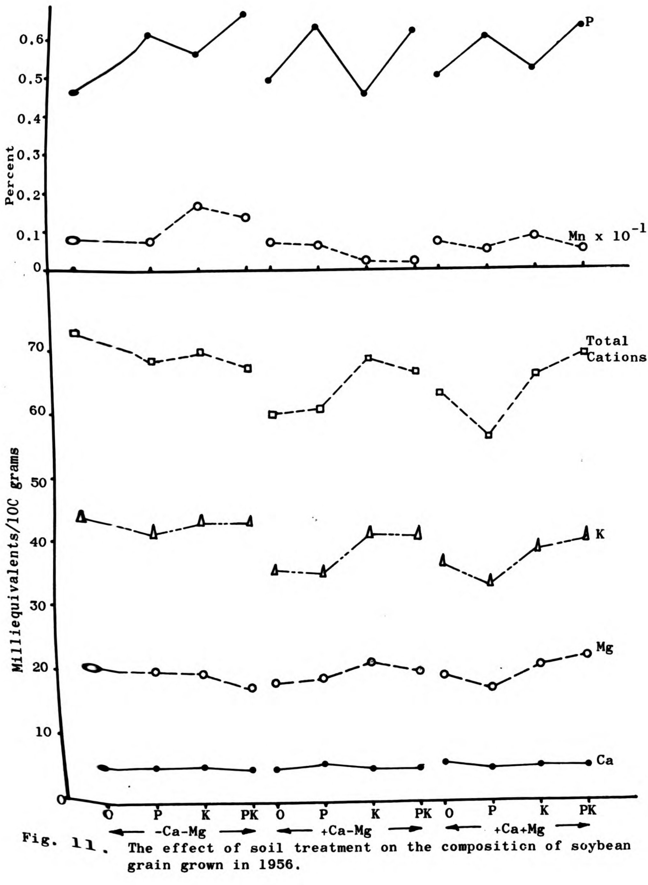

Fig. 11. The effect of soil treatment on the composition of soybean grain grown in 1956.

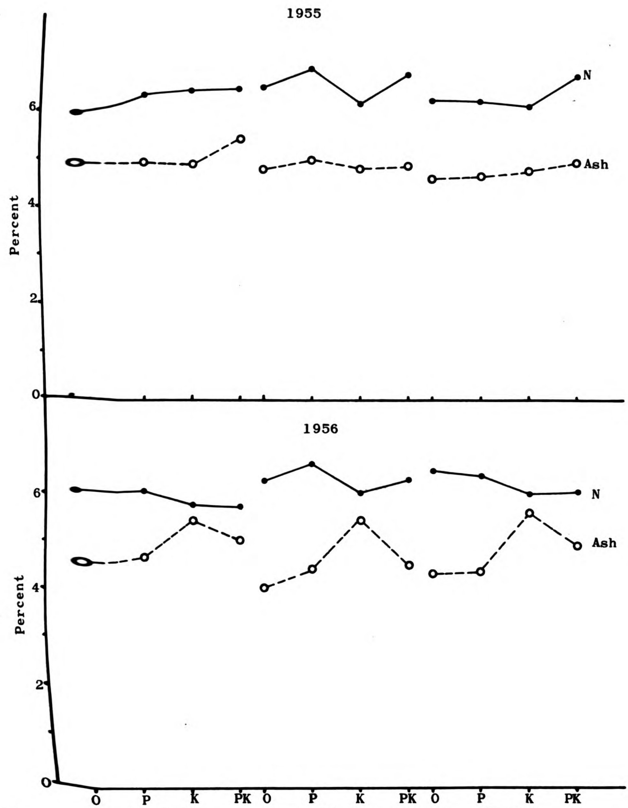

Fig. 12. The effect of soil treatment on the nitrogen and crude ash content of soybean grain grown in 1955 and 1956.

TABLE XIII

PERCENT CHANGE IN THE COMPOSITION OF SOYBEAN GRAIN AS A RESULT OF LIME AND FERTILIZER APPLICATIONS

Constituent	Ca-Lime	Mg-Lime	Phosphorus	Potassium
		1955		
Calcium	- 9.2[a]	- 3.6	- 5.1	- 0.8
Magnesium	- 8.1	+ 4.9	- 0.8	- 1.7
Potassium	- 0.2	+ 1.3	- 4.2	+ 4.2
Sodium	+ 2.9	+15.6	+ 1.6	+ 1.6
Total cations	- 3.2[b]	+ 1.9	- 3.3	+ 2.1
Phosphorus	- 1.3	- 3.6	+16.7	- 0.9
Manganese	- 4.3	- 5.1	-12.8	+26.8
Nitrogen	+ 4.3	+ 0.3	+ 5.5	+ 1.4
Crude ash	- 3.6	- 5.8	+ 3.3	+ 2.5
		1956		
Calcium	- 3.2	- 1.4	- 0.9	- 6.2
Magnesium	+ 0.4	+ 2.1	- 3.2	+ 7.0
Potassium	-10.8	-12.9	- 1.9	+ 9.7
Sodium	- 17.6	- 2.7	- 2.3	- 2.3
Total cations	- 7.0	- 7.5	- 2.2	+ 7.5
Phosphorus	- 4.4	- 1.7	+25.8	+ 4.6
Manganese	-61.9	-44.1	-15.0	+16.6
Nitrogen	+ 6.9	+ 5.7	+ 1.6	- 5.3
Crude ash	- 5.8	- 2.2	- 4.2	+16.9

[a]Percent increase or decrease compared to unlimed or unfertilized treatments.

[b]Calculated from the sum of the milliequivalents of calcium, magnesium, potassium and sodium.

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As shown by Figure 11 both liming materials decreased the accumulation of potassium and manganese in 1956. However, values for total calcium and magnesium in the plant were essentially unchanged.

Phosphorus and potassium had the same effect on composition in 1956 as in the previous year. The former increased the accumulation of phosphorus and decreased the manganese content while the latter increased the manganese and crude ash content. Potassium in the seed was also increased to a small extent by potash applications to the soil.

There was a marked tendency for the composition of the soybean grain to remain constant, particularly as far as the major cations were concerned. This trend was consistent for both years indicating that the soybean seed is not materially affected by unbalanced soil fertility levels.

Corn Grain

Corn grain is characterized by a small accumulation of cations, especially calcium. For this reason, small variations in composition, although not readily apparent, may be of very real importance in determining the nutritive value.

In 1955, liming the soil did not increase the accumulation of calcium in the corn grain (Figure 13). Magnesium absorption, however, was increased by applications of dolomitic lime, but not

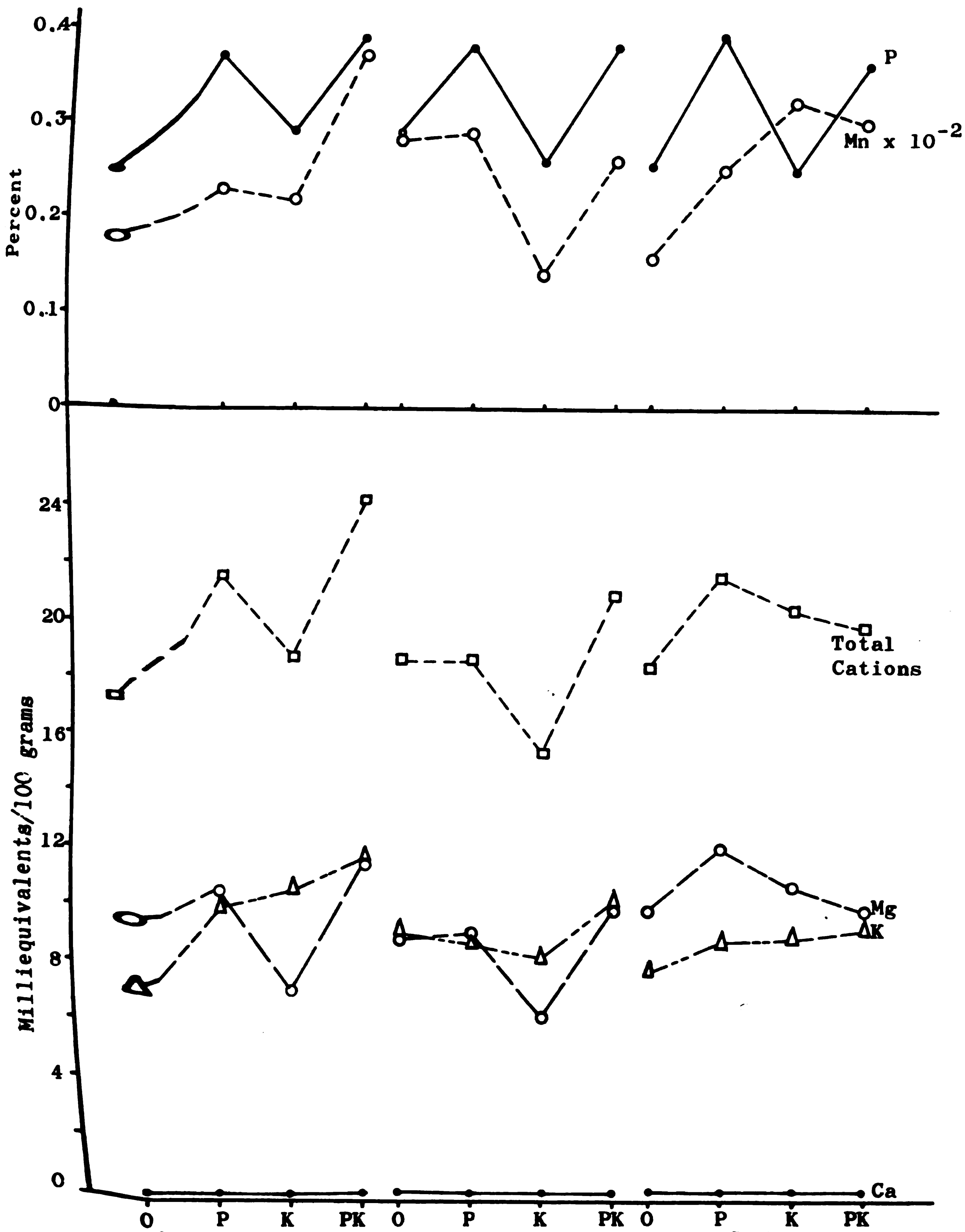

Fig. 13. The effect of soil treatment on the composition of corn grain grown in 1955.

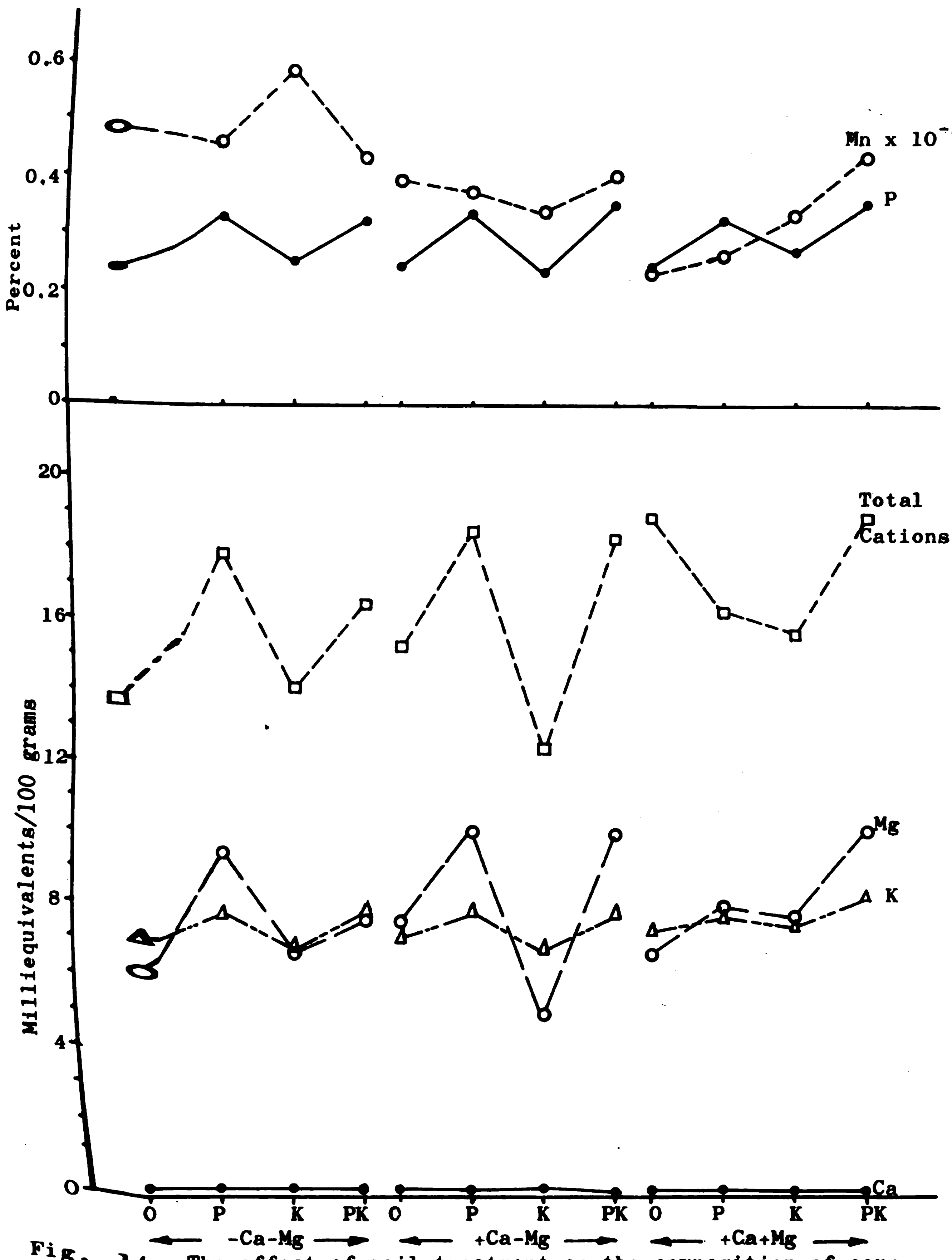

Fig. 14. The effect of soil treatment on the composition of corn grain grown in 1956.

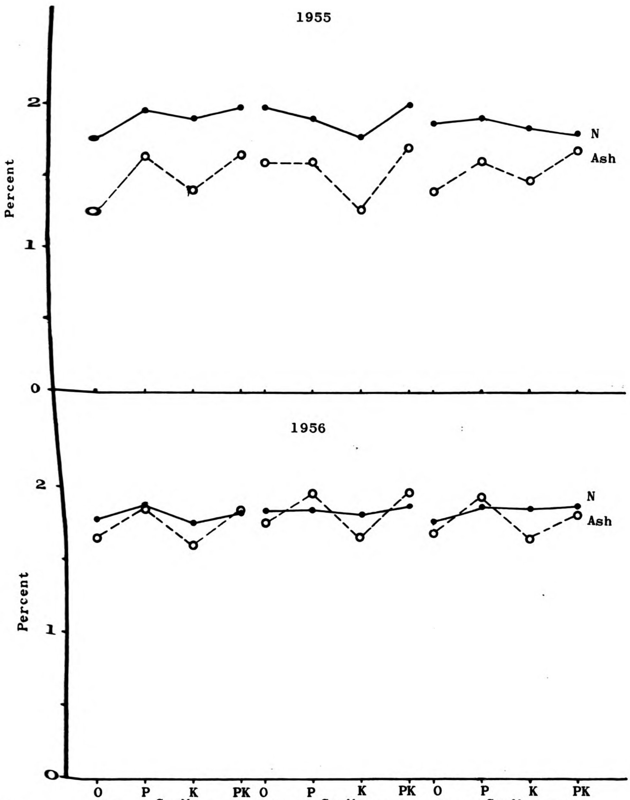

Fig. 15. The effect of soil treatment on the nitrogen and crude ash content of corn grain grown in 1955 and 1956.

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TABLE XIV

PERCENT CHANGE IN THE COMPOSITION OF CORN GRAIN AS A RESULT OF LIME AND FERTILIZER APPLICATIONS

Constituent	Ca-Lime	Mg-Lime	Phosphorus	Potassium
		1955		
Calcium	0.0[a]	- 2.4	- 3.0	- 3.0
Magnesium	-11.4	+ 9.9	+20.2	- 7.5
Potassium	- 7.8	-11.5	+13.7	+14.5
Sodium	-37.5	-55.7	-18.9	+28.4
Total cations	- 9.9	- 1.9	+16.1	+ 2.9
Phosphorus	+ 0.9	+ 1.5	+40.0	- 1.5
Manganese	- 2.8	+ 3.2	+30.4	+15.5
Nitrogen	+ 0.5	- 2.1	+ 3.2	- 1.1
Crude ash	+ 4.1	- 3.4	+18.0	+ 1.2
		1956		
Calcium	-11.1	-14.8	-11.5	- 4.0
Magnesium	+ 9.2	+ 8.3	+38.2	- 1.5
Potassium	- 0.9	+ 3.3	+11.8	+ 1.6
Sodium	- 1.7	0.0	+20.4	- 6.5
Total cations	+ 3.8	+12.4	+17.9	- 4.5
Phosphorus	+ 1.8	+ 3.5	+37.6	+ 3.9
Manganese	-23.2	-35.9	0.0	+14.5
Nitrogen	+ 1.6	+ 1.6	+ 2.7	0.0
Crude ash	+ 5.1	+ 1.7	+13.7	- 2.7

[a]Percent increase or decrease compared to unlimed or unfertilized treatments.

[b]Calculated from the sum of the milliequivalents of calcium, magnesium, potassium and sodium.

calcitic lime. Both materials reduced the potassium and sodium content. The net effect of adding lime to the soil was to cause an appreciable decrease in the measured cation content (Table XIV).

The applied phosphorus, aside from substantially increasing the phosphorus content of the grain, increased the accumulation of magnesium, potassium and manganese, but decreased sodium uptake. The total cation content of the grain was increased about 14 percent by phosphate fertilization. It is suggested that increased absorption of phosphorus may have stimulated the physiological processes in the grain in such a manner that the requirement for the other cations was similarly increased. The calcium content of the grain was not increased. Perhaps the element is selectively excluded by the corn grain.

Potassium fertilization increased the accumulation of potassium, sodium and manganese in the corn, but decreased the magnesium content to a slight degree. It is interesting to note, however, that the increase in potassium in the grain due to high levels of potassium in the soil was slightly less than the potassium accumulation due to phosphorus fertilization.

Figure 14 shows that the calcium in corn was actually reduced by lime applications in 1956. Although such a result might be expected when a high magnesium lime is used, it is contrary to expectations for a high calcium lime. This fact further leads to the conclusion that calcium is selectively excluded from corn grain. Apart from a small increase in the magnesium content and the usual

reduction in manganese, liming had no further effect on the composition of corn grown in 1956.

The effects of phosphorus applications on the chemical composition of corn grain grown in 1956 were very similar to those obtained in 1955. Phosphorus, potassium, magnesium, sodium, crude ash and total bases were all substantially increased in the kernels while calcium was decreased (Figures 14 and 15). The increase in the magnesium content was most striking. Total cations were increased by 18 percent as a result of phosphorus fertilization.

It is very evident that there was little change in chemical composition with the addition of potassium. Even when potassium was added singly the accumulation of this element remained unchanged. Whereas potassium decreased the content of calcium, and more particularly magnesium, in timothy and soybean plants, it had no effect on these two elements in corn. However, as in the previous year, potassium increased manganese uptake.

The data show that the sum of the cations in corn is not equal to a constant. Deviations of over 20 percent from the mean occurred.

Wheat Grain

Only one crop of wheat was grown. Plots which were limed and fertilized in the spring of 1955 were fallowed until autumn when the winter wheat crop was planted. Figures 16 and 17 present variations in plant composition as a result of soil treatment.

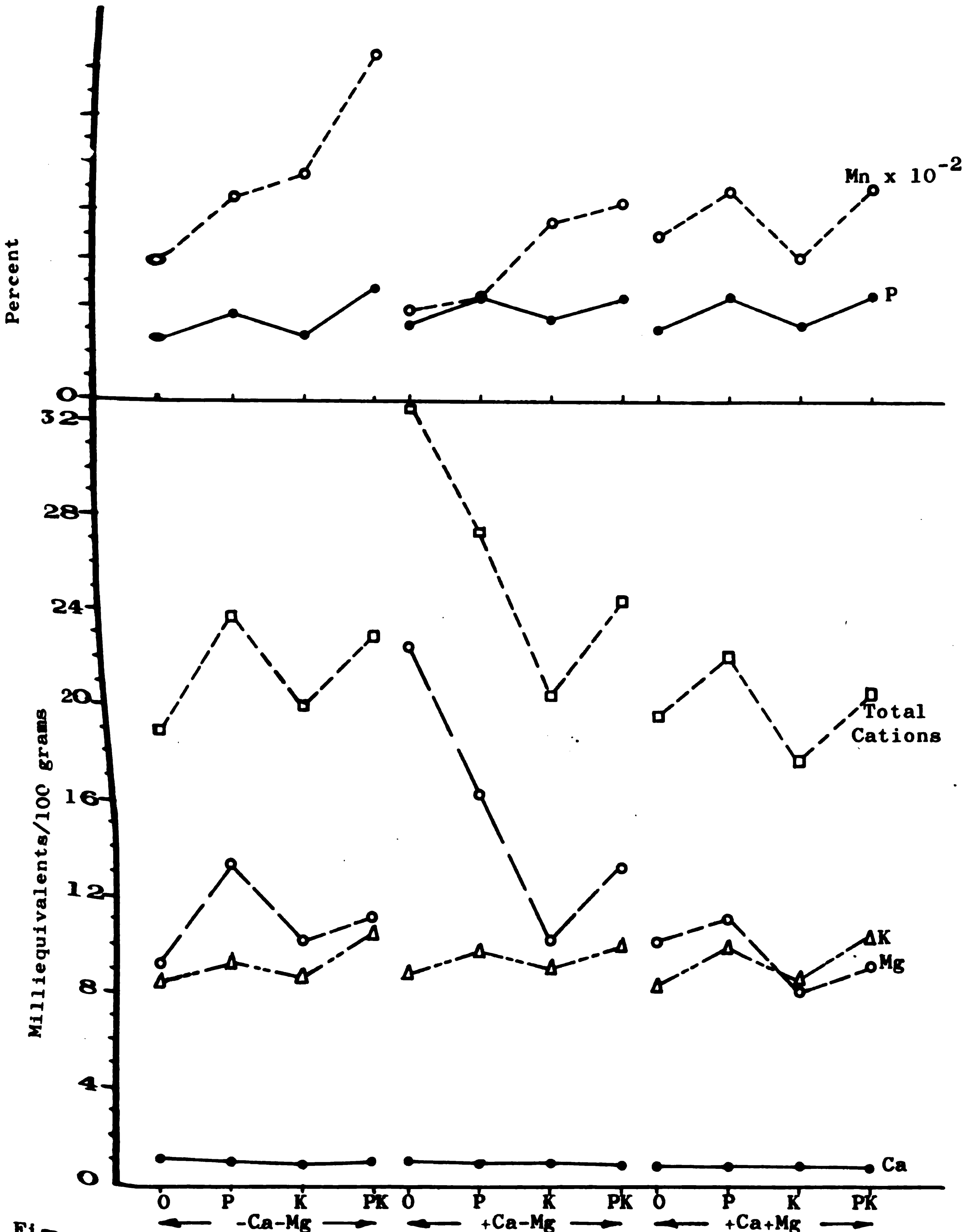

Fig. 16. The effect of soil treatment on the composition of wheat grain grown in 1956.

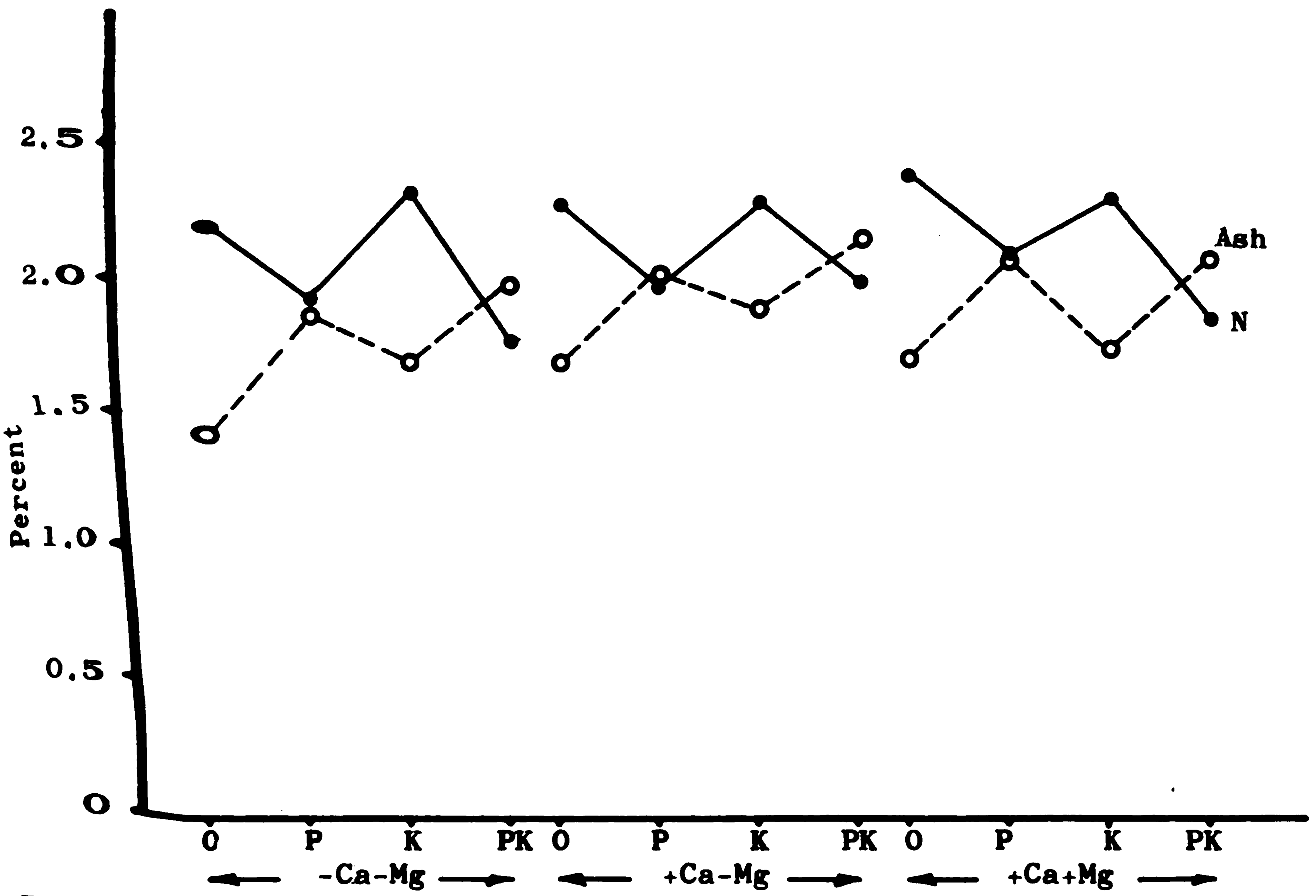

Fig. 17. The effect of soil treatment on the nitrogen and crude ash content of wheat grain grown in 1956.

TABLE XV

PERCENT CHANGE IN THE COMPOSITION OF WHEAT GRAIN AS A RESULT OF LIME AND FERTILIZER APPLICATIONS

Constituent	Ca-Lime	Mg-Lime	Phosphorus	Potassium
	1955-56[a]			
Calcium	- 6.6[b]	-18.5	- 4.3	- 8.2
Magnesium	+41.5	-11.7	+ 5.8	-24.6
Potassium	+ 2.1	+ 1.1	+14.9	+ 4.9
Sodium	-16.3	-18.7	- 2.7	- 2.7
Total cations	+21.8[c]	- 6.6	+ 9.0	-12.6
Phosphorus	+11.7	+ 8.7	+41.3	+ 8.0
Manganese	-37.5	-20.3	+35.6	+43.3
Nitrogen	+ 4.4	+ 5.8	-15.6	- 1.9
Crude ash	-10.9	+10.9	+27.2	+ 6.0

[a]Wheat planted in fall of 1955 and harvested in 1956.

[b]Percent increase or decrease compared to unlimed or unfertilized treatments.

[c]Calculated from the sum of the milliequivalents of calcium, magnesium, potassium and sodium.

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Table XV illustrates the average change in composition resulting from lime and fertilizer applications.

Calcitic lime increased the magnesium, phosphorus, crude ash and total cation content of the grain while reducing the accumulation of sodium and manganese. Calcium in the wheat was also slightly decreased. The largest increase in magnesium content occurred where calcitic lime was applied alone, or in combination with phosphorus. When combined with potassium there was no substantial increase in magnesium, indicating that potassium depressed the magnesium uptake.

Dolomitic lime had a similar effect on crude ash, phosphorus, sodium and manganese. However, in addition, this liming material decreased the calcium and magnesium contents, and thus the total cation content. No ready explanation can be given for these observed differences between liming materials.

Phosphorus applications to the soil, aside from increasing the phosphorus in the wheat, increased the crude ash, potassium, manganese and total cation content. However, total nitrogen in the grain was reduced by these treatments (Figure 17).

Potassium fertilization resulted in an increased uptake of manganese and a decrease in the magnesium and total cation content. Calcium was decreased to a small extent. It is evident from these data that heavy potassium fertilization of wheat had the same general effect on plant composition that was obtained with the other seed crops, millet, corn and soybeans.

Cation Ratios in Plants

The ratios, Ca/Mg, Ca/K and Mg/K in crops grown in 1955 and 1956 are presented in Tables XVI and XVII, respectively. These ratios should be compared to the same ratios calculated for the cations in the soil (Table V).

The ratios point out several important factors. Although differences in the ratios did occur with soil treatment, the ratios in the plant were not necessarily related to those found for soil nutrients. For example, the Ca/Mg ratios in millet, soybeans, corn and wheat were relatively constant irrespective of soil treatment. However, in the soil, three to fourfold variations occurred. Similar statements could be made regarding the Ca/K and the Mg/K ratios, although the latter is probably more closely correlated to soil values than either the Ca/Mg or Ca/K ratios.

This lack of a good relationship between the soil and plant ratios is the result of several fundamental facts. First, and probably most important, is the selective absorption of certain cations by different plant species and plant organs. This factor will be discussed more fully later. Secondly, a whole series of similar values can be obtained from entirely different experimental conditions. The complementary ion effect is relatively more important in determining final plant composition than it is in establishing the absolute level of associated cations in the soil solution or on the exchange complex. Too, with crops such as corn which are very low in one particular cation (calcium) a substantial percent increase or decrease in the content of that ion will not be reflected

TABLE XVI

THE EFFECT OF SOIL TREATMENT ON CERTAIN CATION RATIOS IN CROPS GROWN IN 1955

Ratio	Lime Treatment			Fertilizer Treatment	
	-Ca-Mg	+Ca-Mg	+Ca+Mg	-K	+K
			Timothy hay		
Ca/Mg	0.83[a]	0.84	0.76	0.74	0.84
Ca/K	0.10	0.11	0.11	0.12	0.09
Mg/K	0.12	0.13	0.14	0.16	0.11
			Soybean hay		
Ca/Mg	1.61	1.67	1.59	1.50	1.76
Ca/K	1.70	2.11	2.04	2.37	1.65
Mg/K	1.06	1.26	1.29	1.59	0.94
			Millet grain		
Ca/Mg	0.06	0.04	0.04	0.05	0.05
Ca/K	0.09	0 08	0.09	0.09	0.09
Mg/K	1.43	1.85	2.18	1.77	1.87
			Soybean grain		
Ca/Mg	0.35	0.35	0.32	0.34	0.34
Ca/K	0.15	0.14	0.14	0.15	0.14
Mg/K	0.43	0.40	0.45	0.44	0.41
			Corn grain		
Ca/Mg	0.03	0.03	0.02	0.03	0.03
Ca/K	0.03	0.03	0.02	0.03	p.03
Mg/K	0.98	0.94	1.22	1.16	0.94

[a]Calculated on the basis of milliequivalents per 100 grams.

TABLE XVII

THE EFFECT OF SOIL TREATMENT ON CERTAIN CATION RATIOS IN CROPS GROWN IN 1956

Ratio	Lime Treatment			Fertilizer Treatment	
	-Ca-Mg	+Ca-Mg	+Ca+Mg	-K	+K
			Timothy hay		
Ca/Mg	0.38[a]	0.52	0.34	0.40	0.41
Ca/K	0.13	0.17	0.14	0.18	0.12
Mg/K	0.34	0.33	0.42	0.46	0.29
			Soybean hay		
Ca/Mg	2.30	1.97	1.65	1.96	1.95
Ca/K	3.80	4.07	3.66	6.37	2.58
Mg/K	1.66	2.07	2.20	3.25	1.32
			Millet grain		
Ca/Mg	0.07	0.07	0.05	0.06	0.07
Ca/K	0.08	0.10	0.09	0.09	0.09
Mg/K	1.16	1.37	1.75	1.53	1.33
			Soybean grain		
Ca/Mg	0.28	0.27	0.28	0.30	0.26
Ca/K	0.13	0.14	0.15	0.15	0.13
Mg/K	0.46	0.52	0.54	0.51	0.50
			Corn grain		
Ca/Mg	0.03	0.03	0.04	0.03	0.03
Ca/K	0.03	0.03	0.04	0.03	0.03
Mg/K	1.11	1.06	1.01	1.07	1.04
			Wheat grain		
Ca/Mg	0.10	0.06	0.09	0.07	0.09
Ca/K	0.11	0.10	0.09	0.11	0.10
Mg/K	1.19	1.65	1.04	1.51	1.08

[a]Calculated on the basis of milliequivalents per 100 grams.

in the cation ratio when compared to an element which is accumulated in relatively large amounts.

Finally, a wide range of cation ratios in the soil and in the plant will result in the same final yield. This fact is supported by yield data in this experiment. Hence, it is still necessary to know the absolute levels of an ion in the soil and in the plant in order to interpret the significance of any particular ratio.

DISCUSSION

One of the primary purposes of this investigation was to determine the effect of unbalanced fertility levels in the soil on the chemical composition of several species of crops. It is known that species vary widely in their ability to accumulate ions depending on the stage of maturity of the plant, the type of ion studied and the part of the plant analyzed.

It will be noted from the data that timothy and soybean hay crops, in which the vegetative portions of the plant were analyzed, tended to accumulate all cations to a considerable extent when these nutrients were applied to the soil. Although the data are not consistent in all cases, it is evident that calcium, magnesium and potassium levels in the plant were directly related to available supplies in the soil. Only the magnitude of the increases varied.

On the other hand, the cation content of the seeds of various species, corn, millet, soybeans and wheat was only slightly affected by soil treatment. The notable exception is magnesium which was accumulated by millet and to a lesser extent by wheat and corn.

There is considerable evidence that seeds tend to maintain a relatively constant composition (Arnon and Hoagland, 1943; Norman, 1955). This conclusion is substantiated by the data in the present study. Duncan (1955a) drew similar conclusions from analyses of

a number of species. However, unlike the present investigation, he used balanced soil nutrient levels for plant growth.

The mechanism by which plants tend to exclude additional nutrients from reproductive organs beyond those quantities necessary for normal metabolic processes is not clear. However, Loehwing (1951) has suggested that it may be due to the formation and translocation of growth substances within the tissue during the initiation of the fruiting process.

Actively growing tissue, such as that present in an enlarging seed, requires adequate amounts of nutrients. The extent to which these nutrients are present in the vegetative tissue, or in the soil in an available form, will determine the ultimate size and numbers of seeds. If the nutrient supply in the vegetative portion is sufficient, considerable quantities of inorganic elements can be diverted to the reproductive organ, so that the additional requirement placed on the soil may not be great. This is particularly true of nitrogen, magnesium, phosphorus and potassium which are relatively mobile in the plant and can be reutilized. However, calcium is much less mobile in the plant than the above elements so that supplied for the last formed plant parts (i.e., reproductive organs) must come from the soil solution.

Phosphorus was accumulated by seeds more than any other element. Apparently the mechanism by which cations are excluded from reproductive parts is inoperative as far as anions are concerned, or at least it seems true for phosphorus. Seeds are usually higher in phosphorus than vegetative parts (Morrison, 1947).

However, much of this phosphorus is in the form of phytin which is not readily digested; hence many plant materials, although they may be rich in phosphorus according to their chemical analysis, are poor sources of phosphorus in the diet (Anderson, 1947).

Whether or not the additional phosphorus taken up by seeds is actually necessary for metabolic processes is open to conjecture. This hypothesis would presuppose that additional quantities of cations wculd also be required to satisfy the needs created by an increase in growth reactions. Albaum (1952), in outlining the role of phosphorus in the metabolism of plants, concluded that phosphorus probably affects growth by participating in a number of processes at the cellular level. These include respiration and the subsequent utilization of carbohydrates. If these reactions are interfered with due to a lack of phosphorus, secondary changes may occur such as inhibition of salt uptake, nitrification, and loss of chlorophyll.

In the present study, additional quantities of magnesium and potassium were absorbed by corn, millet, and wheat grain, along with increased phosphorus. Whether this is a direct effect resulting from increased respiration with a subsequent increase in ion accumulation is unknown. The lack of such a trend in soybean grain, and the absence of an additional calcium requirement in all seeds except millet, leaves the subject open to debate.

In general, all nutrient elements were increased in the vegetative portions of crops used when available levels in the soil were simultaneously increased. Hence, it is evident that the root does not possess the ability to selectively exclude ions, at least

to the degree that reproductive organs are capable. However, the magnitude of the change in composition varied with the species, thus leading to the conclusion that morphological and physiological differences in the species are important in determining ion accumulation. Such factors as cation exchange capacity of roots, permeability of root membranes, level of metabolic activity, and the innate requirement of the plant are just several of a host of possible causes for such observed phenomena. Since the study of such mechanisms was beyond the scope of this study the selection of a cause or causes would be rash speculation.

Macy (1936) developed the concept of a "critical percentage" of each essential nutrient in each kind of plant. Above this content "luxury consumption" occurs and below it there is a region of "poverty adjustment." In the region of poverty adjustment, that is, between a certain minimum nutrient percentage and the critical percentage, yield increases almost proportionately to the increase in percent nutrient content. Below this zone yield increases may occur with increasing nutrient supply while the percent content of that element remains essentially unchanged. Above this zone the reverse is true.

An attempt has been made to evaluate this concept with the present data. Table XVIII presents a summary of the effect of various nutrients on the content of that element in the plant as well as the effect of these nutrients on crop yields. It should be pointed out that these data are somewhat arbitrary and hence are subject to certain limitations in their interpretation. The

TABLE XVIII

A COMPARISON OF THE EFFECT OF LIME AND FERTILIZER TREATMENTS ON THE COMPOSITION AND YIELD OF SEVERAL CROPS

Crop	Plant Composition				Crop Yield			
	Ca	Mg	P	K	Ca	Mg	P	K
				1955				
Timothy hay	I[a]	I	I	I	U	U	U	U
Soybean hay	I	I	I	I	U	U	I	U
Millet grain	U	I	U	U	U	U	I	U
Soybean grain	U	U	I	U	U	U	D	U
Corn grain	U	I	I	I	U	U	U	U
				1956				
Timothy hay	I	I	I	I	U	U	U	U
Soybean hay	U	I	I	I	U	U	U	U
Millet grain	I	I	I	U	U	U	U	I
Soybean grain	U	U	I	U	U	U	U	U
Corn grain	D	U	I	U	U	I	U	I
Wheat grain	U	D	I	U	I	I	I	U

[a]I = increase, D = decrease, U = unchanged, compared to absence of of nutrient.

yields are reported as being increased, decreased or unchanged, based upon statistical analysis. The nutrient status of the plant is similarly reported. In the latter instance a ten percent change in composition was considered necessary to warrant the tabulation of an increase or decrease in that particular element.

It would appear from an examination of these data that the critical percentage of most nutrients had been reached, that is, where the content of an element increased with no appreciable increase in yield. There are, of course, notable exceptions such as the increase in the yield of soybean hay in 1955 as a result of phosphorus fertilization, accompanied by an increase in the phosphorus content of the tissue. Similar results were obtained with wheat. These observations are characteristic of the zone of poverty adjustment, where both yields and nutrient content increase. At the other extreme there are examples of a yield increase but no increase in nutrient content, as illustrated by the effect of phosphorus and potassium on the growth of millet in 1955 and 1956, respectively.

When one considers the absolute yields of these crops the fallacy of these conclusions is evident. All yields were extremely low indicative of nutrient starvation, at least for one element. It is more logical to conclude, therefore, that the nutrient contents, at least where no lime or fertilizer was applied, are actually minimal percentages, and that in most instances the zone where both yield and nutrient content increase was just being reached. It is possible, however, for an increase in nutrient

content to occur without an accompanying increase in yield. This is one of the greatest limitations to the use of total chemical analyses of plant tissue as an index of the soils supply of nutrients. Under conditions of unbalanced fertility one or more elements which are in short supply may restrict growth while the element which is in the soil in greatest amounts is utilized in luxury amounts by the plant. Too, a limited supply (or excess) of one nutrient may affect the quantity of another nutrient which is taken into the plant. This observation was made in the present investigation, particularly between magnesium and potassium. Another complicating factor is the tendency for many plants to show an almost normal content of a certain nutrient even if the supply is limited. The plant or plant part merely makes the amount of growth which the nutrient supply permits, keeping the chemical composition of the plant tissue almost constant (Cook and Millar, 1953). As seen in the present study, this is especially true of seeds.

Considerable evidence has accumulated supporting the hypothesis that cation uptake by plants is related to the percent base saturation of that particular element in the soil (Mehlich and Colwell, 1943, 1946; Mehlich, 1946). This is due to the fact that the availability of a cation is dependent on the activity of that ion adsorbed on the soil colloid (Marshall, 1948, 1951). The type of soil colloid is also a factor in determining the activity of an ion and hence its uptake by plants from a given system (Chu and Turk, 1949; Mehlich and Coleman, 1952).

Mehlich (1946) noted that the sum of the cations in a particular plant species grown on an illitic soil was a function of the base saturation of that soil. Data in this investigation do not bear out this relationship. Although there was a distinct tendency for the content of any particular cation to be related to the base saturation of that cation in the soil, the total cation content did not increase with increasing base saturation. Since calcium and magnesium are the ions primarily responsible for an increase in the percent base saturation of the soil, the failure of the relationship referred to by Mehlich to prevail in the present study is due to a general failure of the plants to take up additional calcium and magnesium with an increase in the availability of these cations in the soil. It should be pointed out, however, that the analysis of entire plants rather than specific parts might have shown entirely different results. A slight, though inconsistent, trend toward increased cation content of plant tissue was observed with increasing bases in the soil. Power (1954) obtained an increase in the total cation content of alfalfa, soybeans and oats with increasing percent base saturation in the soil.

Observed differences in the accumulation of nutrients by plants of several species have been attributed to variations in morphology and physiology of roots. Drake and his associates (1951) have related this phenomenon to differences in the cation exchange capacity of roots of varying species, while Graham and Baker (1951) paid particular attention to the quantity of exchangeable hydrogen absorbed on the root membranes. Hence these

H-ions associated with the root surface may be replaced by other cations. Plant roots also show the suspension effect and interact with neutral salts to develop exchange acidity, thus indicating the existence of a cation double layer associated with the root surface. However, these phenomena of absorption and release of various cations by plant roots are not directly dependent on root metabolism, since similar results have been obtained with living and ether killed roots at 0°C and 25°C (Williams and Coleman, 1950).

Cation exchange capacity measurements on the roots of a number of species have shown that this value decreases in the order soybeans > timothy > corn > millet > wheat (Drake et al, 1951). Mattson (1948) stipulated a cation distribution in which the outer layers of a high cation exchange capacity colloid would be more dilute or of lower concentration than a low exchange colloid. This greater dilution requires greater relative absorption of divalent than of monovalent cations, since the divalent cation is inserted as the square root in the Donnan distribution (K: $\sqrt{Ca}$). Thus the higher the cation exchange capacity, the greater is the relative absorption of calcium over potassium.

The data in this study bear out the general relationship. The average Ca/K ratio in soybean plants was approximately 2/1 while in timothy this same ratio was about 1/9. Even wider ratios were observed in millet, corn and wheat. However, the selective exclusion of calcium by some of these seeds makes further interpretation impossible.

The distribution of divalent and monovalent cations as a function of the cation exchange capacity of roots has perhaps been oversimplified. For example, McLean and Adams (1954) found that calcium was bound more strongly than potassium on both mono- and dicotolydenous roots. The strength of this bond was not necessarily related to the cation exchange capacity. However, these measurements were made in homoionic systems at 100 percent saturation which does not accurately characterize the normal root atmosphere.

The relative absorption of ions of different valence is also affected by the concentration of the ions in the soil and the type of colloid. When cations are at low concentration, divalent ions are absorbed in relatively greater amounts than monovalent ions from the soil colloid with increasing cation exchange capacity of the roots. However, at higher ionic concentrations the valence effect tends to disappear (Mehlich and Drake, 1955). Mattson (1948) concludes that it is only when nearly all the cations exist in an exchangeable state and the plant root colloids must compete with the soil colloids for these cations by exchange that the Donnan distribution will be reflected in the composition of plants. Thus, in this investigation, where high concentrations of cations were present in solution and in solid phase, as well as absorbed on the soil colloid, the Donnan distribution has limited application in explaining observed differences in the accumulation of cations by various plant species.

The specific mechanism by which cations and anions are accumulated by plants has been the subject of intensive investigation

by plant physiologists. The scope of these studies, and the number of theories advanced, necessarily restrict a discussion of the accumulation of ions to a most general one.

Most theories involve the concept of an ion-carrier mechanism (Lundegardh, 1955; Overstreet and Jacobson, 1952). A generalized scheme illustrating the concept of ion transport from the surrounding medium (o-level) to the interior of the cell (i-level) has been presented by Lundegardh (1955).

	Absorption	Translocation	Accumulation	
o-level	$M^+A^- + R^+ + R^- \longrightarrow$	$R^+A^- + M^+R^- \longrightarrow$	$R^+ + R^- + M^+A^-$	i-level

R^+ and R^- are the carrier groups and M^+ and A^- are the metallic cations and anions, respectively.

The extent to which metabolic energy is involved in ion accumulation is the subject of considerable debate. Lundegardh considers that the accumulation of a free salt needs only active accumulation of one of its ions. If ions are actively accumulated the acid HA will decompose the carrier complex MR, resulting in free salt MA and regenerated carrier HR capable of combining with new cations. The carriers R^+ and R^- may act as "absorption tracks" in transporting ions from the root surface into plant cells.

Lundegardh further considers that the Fe ion in respiratory enzymes affects the anion transport. As an electron moves outward along the enzyme system an anion is transported in the opposite direction. According to the reaction $4H^+ + 4e + O_2 = 2H_2O$ four

anions corresponding to four electrons should be transported for each molecule of oxygen consumed. Anions are therefore actively accumulated while cations are passively dragged into the cell via R^- carriers.

Overstreet and Jacobson (1952) made certain observations regarding the nature of ion carriers. They summarized these as follows: (a) ion carriers are intermediate metabolic products or closely related substances; (b) the carriers are not stable _in vitro_; (c) they undergo chemical alteration in the course of their carrier function; and (d) they probably function as chelated complexes.

Different rates of absorption of different ions of the same charge, the unequal rates of absorption of a cation and its associated anion, and the mutual reciprocal effect of ion pairs can partially be explained on the basis of the Lundegardh hypothesis. Jacobson _et al_ (1950) studied the interaction between H^+ and K^+. No absorption of K was observed if the K^+/H^+ ratio was less than 17. Competition between Na^+ and K^+ was interpreted as indicating a single binding compound for these two ions.

Overstreet, Jacobson and Handley (1952) studied the competition between Ca^+ and K^+. The presence of K^+ reduced the absorption rate of Ca^{++}, whereas the presence of Ca^{++} in certain concentrations reduced the rate of K^+ uptake and in other concentration ranges markedly increased K^+ absorption. They concluded that probably a single binding substance serves Ca^{++} and K^+; but in addition Ca^{++} is effective in the removal of the KR complex from the absorption

site. The results obtained by Epstein and Hagen (1952) are somewhat at variance with the above conclusions. Therefore the carrier substance HR may actually be a single compound with differing affinities for different cations or it may be a series of quite specific compounds.

These studies can be of value in interpreting variations in plant composition, particularly when complemented by the concepts of the distribution of ions between root and soil colloids. At low concentrations of a particular ion in the soil, and a balance between ions, normal accumulation occurs. As the concentration of a cation increases (e.g., potassium) the relative activity of the cation also increases in comparison to the other saturating ions. For ions which are bound by the same absorption site or binding compound an increase in activity of one will result in an increase in the uptake of this cation to the mutual repression of the complementary ion. This in turn is related to the cation of the roots. Monocotyledons, because of their low cation exchange capacity, and the presence of the Donnan distribution on roots, would tend to accumulate more potassium and sodium than calcium and magnesium, especially at low external concentrations. Conversely, dicotyledons would tend to accumulate calcium and magnesium and depress potassium absorption. The net effect of increasing the ion concentration in the external root environment is then a combination of several phenomena; (a) the activity of the ion on the soil colloid, (b) the activity of the ion on the root colloid and the competition between ions for sites on the absorption mechanism. A further complicating factor is the possibility of an

absorbed ion enhancing or depressing the removal of other ion-carrier complexes from the absorption site. Based on these facts an approximate, though imperfect relationship between the percent saturation of a particular cation in the soil and the content of that nutrient in the plant should result. The present data bear out this relationship in a general way within the limits possible in such a heterogeneous environment.

Many authors have referred to the presence of rather definite cation ratios in plants. Among these studies have been those by Mehlich and Reed (1948) on Ca/K and Ca/Mg ratios, and by Stanford et al (1942) on the Ca+Mg/K ratio. As already pointed out these ratios are of value in predicting ion accumulation and pointing out the competition between ions insofar as absorption is concerned. However, plants will grow over a wide range of cation ratios. This is evidenced by the wide variations in the Ca/Mg, Ca/K, and Mg/K ratios reported in Table V, with very little difference in plant growth. If the ratio widens or narrows to the point where one ion is present in deficient amounts then changes in growth will result. For the most part, the ratios obtained in the present investigation were not sufficiently varied to result in any appreciable differences in plant growth. Consequently, such ratios must be interpreted in only a general sense. Ulrich (1952), in discussing the nutrient balance concepts of Shear et al (1946, 1948), has pointed to the impossibility of maintaining a single nutrient at a specified concentration within a plant. It would seem more expedient to study the effect of nutrient relationships of

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on growth until such time as the specific role of each nutrient in plant metabolism has been sufficiently elucidated.

Bear (1950), Van Itallie (1938), and Bear and Prince (1945) have pointed to the presence of a rather constant total cation content in plants, together with a similar constant cation:anion ratio. However, they hasten to explain that these constant ratios are only found under conditions of balanced or normal soil fertility. Data presented in this thesis would support this general conclusion insofar as seeds are concerned, even with severely unbalanced soil fertility. However, if composition of the entire plant is considered, the cation content was not a constant. As phosphate was the only anion determined, it is difficult to draw any conclusions on the constancy of the cation:anion ratio. Based on the data available, it would appear that the cation:anion ratio did not approach a constant value under the conditions of this experiment.

An excess absorption of cations compared to anions is overcome by the production of organic acids, particularly malate (Jacobson and Ordin, 1954; Hoagland and Broyer, 1940). Thus the reaction of the cellular contents remains essentially the same. Similarly, an excess of anions absorbed is compensated by a proportional reduction in the organic acid content. Where the activities of cations and anions are similar, almost equal quantities of each will be absorbed from a given system. However, if the activity of the anion exceeds that of the cation, additional quantities of anion will be absorbed with a proportionate decline

in malic acid concentration, presumably to serve as metabolite in the tricarboxylic acid cycle (Lundegardh, 1955).

Unfortunately, no evidence is available in the present study to confirm or refute this conclusion. Presumably potassium chloride would result in an increased uptake of both ions due to similar activities. Calcium and magnesium carbonates, because of the low activity of the bicarbonate ion, would result in an excess of these cations in the cells, with a subsequent increase in the organic acid content of the tissue. In a polyionic environment, such as that experienced under field conditions, variations in organic acid content are doubtless much less than those found in homionic systems in the laboratory.

The extent to which the chemical composition of a plant is an index of the nutritive value of that plant is questionable. Certainly the content of phosphorus, calcium, magnesium and manganese can be of value in interpreting composition in terms of nutritive value. Nitrogen may or may not be included, as the quality of the nitrogen in terms of amino acids is often of greater significance than the total nitrogen content (Morrison, 1947). With the possible exception of phosphorus, it may be concluded that the nutritive value of seeds as measured by chemical composition is not materially affected by unbalanced soil fertility levels. However, vegetative plant parts are subject to wider variations so that unbalanced soil fertility conditions can alter the plant as far as feeding value is concerned. The extent of this effect can only be ascertained accurately by biological assay.

Feeding trials with rats were conducted to determine the effect of soil treatment on the nutritional value of corn and soybeans.[1] No differences in animal growth were observed, but variations in the Ca:P ratio of bones could be related to differences in the Ca:P ratio of the feed. However, no feeding trials were conducted to determine the effect of changing the composition of timothy and soybean hay on the nutritive value of these crops.

[1]Rutherford, B. Elaine, and Pretty, K. M. 1958. Unpublished data.

SUMMARY AND CONCLUSIONS

Field and laboratory studies were conducted in 1955 and 1956 to determine the effect of unbalanced soil fertility on the growth and nutritive value of several crops, as assessed by yields and chemical composition. Relatively large amounts of calcitic and dolomitic limestone, phosphorus and potassium were applied in all combinations to an extremely infertile Kalamazoo sandy loam soil. Vegetative portions of timothy and soybeans, and the mature seed of millet, soybeans, corn and wheat were harvested for yield data and the determination of chemical composition.

The results obtained from these investigations may be summarized as follows:

1. Crop yields were increased by some soil treatments depending on the plant species. Calcitic limestone increased the yields of timothy hay and wheat in 1956 while dolomitic limestone increased corn and wheat yields. Phosphorus applications increased soybean hay and millet yields in 1955 and wheat yields in 1956. Potassium depressed the yield of soybeans in 1956 and increased the yield of millet and corn in 1956.

2. It is concluded that crop yields on this soil cannot be increased to normal values within a two-year period, even with balanced nutrient applications. The calcium, magnesium and potassium contents of timothy and soybean hay were generally increased by the application of these nutrients to the soil. However, seed

crops increased only in magnesium as a result of the same soil treatments.

3. Phosphorus applications to the soil substantially and consistently increased the phosphorus content of all crops grown.

4. Lime applications greatly decreased the exchangeable manganese content of the soil and the total manganese in plant tissue. However, the manganese content of the crops was not directly related to the exchangeable manganese levels in the soil.

5. There was a distinct tendency for phosphorus and potassium to increase the manganese content of plants although considerable variation occurred between 1955 and 1956.

6. Lime applications had no appreciable effect on phosphorus accumulation by plants. Calcitic limestone did not affect the potassium content of crops but dolomitic lime reduced the potassium content of wheat, corn, soybean hay and soybean seed.

7. The application of phosphorus increased the total cation content of corn, and the 1956 millet crop, as well as the crude ash content of timothy hay, millet, corn and wheat. Phosphorus also increased the magnesium content of millet, corn and timothy hay.

8. Magnesium contents were generally decreased by potassium fertilization, especially in wheat, soybean hay and the 1956 timothy hay crop. Calcium levels were depressed in 1956 by potassium applications to timothy and soybean hay.

9. The Mg/K ratio was the most important factor determining the total cation content of crops. An increase in the content of

one did not result in an equivalent decrease in the other, so that the total cation content increased or decreased depending on the proportionate uptake of each ion. There was no tendency toward a constant cation content except in soybean grain.

10. Sodium, nitrogen and crude ash levels in the plant were not consistently affected by any soil treatment. However, there was a tendency for lime applications to increase the nitrogen content of the crops and for phosphorus and potassium to increase the crude ash.

11. The total cation content of the plants was not closely related to soil pH or percent base saturation, but was primarily affected by Mg/K relationships.

12. A comparison between crop yields and plant composition failed to show a definite relationship between the two.

13. It is concluded that plant composition, although closely related to the availability or percent saturation of the soil colloid by any particular ion, is also affected by the cation exchange capacity of the roots, the balance between nutrients and the competition between ions for sites on the absorption or ion-carrier mechanism.

14. Due to the exclusion of certain ions by an as yet unknown mechanism, the cation composition of reproductive parts of plants was not appreciably changed by unbalanced soil fertility conditions. The composition of vegetative plants can be substantially altered by similar conditions.

15. The extent to which soil treatment altered the nutritive value of the crops studied through a change in undetermined constituents is a question of great magnitude. The importance of the variations in plant composition herein reported in the nutrition of animals and man is also open to debate.

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APPENDIX

TABLE XIX

THE EFFECT OF FERTILIZER AND LIME TREATMENTS AND CROP GROWN ON THE SOIL NUTRIENT CONTENT

Treatment	Ca	Mg	K	Na	P	Exch. Mn	pH
	(percent saturation)				(lbs/A)	(ppm)	
				Timothy hay - 1955			
None	26.7	3.7	1.8	1.3	22	66	5.4
P	23.4	3.7	1.9	1.7	191	71	5.2
K	25.7	3.1	5.4	1.3	22	71	5.3
PK	26.9	3.8	5.7	1.3	210	74	5.2
L_1[a]	40.6	9.4	1.6	1.2	18	64	5.6
L_1P	44.6	7.3	1.5	1.5	170	63	5.7
L_1K	38.9	8.3	5.6	1.3	27	64	5.5
L_1PK	42.0	9.7	5.1	1.5	189	64	5.6
L_2[b]	25.7	5.9	1.6	1.6	28	53	5.4
L_2P	34.5	5.6	1.4	1.5	193	58	5.4
L_2K	19.7	5.6	5.5	1.1	22	55	5.3
L_2PK	27.8	5.7	5.1	1.1	153	61	5.4
				Soybean hay - 1955			
None	30.2	4.2	1.8	1.1	25	53	5.2
P	28.7	3.3	1.6	1.0	133	52	5.1
K	22.9	3.8	4.5	1.3	33	81	4.9
PK	26.3	3.1	3.7	1.4	160	79	5.0
L_1[a]	48.7	14.1	1.8	1.2	28	39	5.9
L_1P	58.8	12.7	2.2	1.6	153	51	5.7
L_1K	43.5	10.1	4.0	1.7	24	51	5.7
L_1PK	43.1	10.8	3.8	1.7	155	55	5.6
L_2[b]	34.2	11.1	1.7	1.1	17	48	5.6
L_2P	35.6	10.4	2.0	1.3	148	51	5.5
L_2K	27.5	10.4	3.4	1.1	19	44	5.6
L_2PK	35.4	10.3	3.0	1.7	133	47	5.5

[a]Calcitic lime

[b]Dolomitic lime

TABLE XIX (Cont.)

Treatment	Ca (percent saturation)	Mg	K	Na	P (lbs/A)	Exch. Mn (ppm)	pH
			Timothy hay - 1956				
None	28.2	7.5	1.9	0.6	23	41	5.2
P	33.7	7.7	2.1	0.6	187	39	5.1
K	22.6	7.5	6.9	0.8	40	47	5.2
PK	27.1	5.7	6.4	0.8	224	50	5.0
L_1[a]	85.9	7.7	1.6	0.7	27	29	6.0
L_1P	67.1	7.5	1.4	0.6	178	26	6.0
L_1K	68.9	9.6	6.2	0.8	24	30	6.0
L_1PK	81.7	7.0	6.5	0.9	214	36	6.1
L_2[b]	49.7	48.7	1.9	0.8	20	23	6.1
L_2P	50.8	30.4	1.5	0.7	290	24	6.0
L_2K	49.4	44.0	4.8	0.7	28	22	6.0
L_2PK	48.0	36.9	5.7	0.7	214	27	6.0
			Soybean hay - 1956				
None	32.0	3.3	1.9	0.6	33	30	5.0
P	31.3	3.3	1.5	0.6	135	26	4.9
K	25.4	2.8	3.6	0.7	38	38	4.9
PK	27.1	4.0	4.6	0.7	158	35	5.0
L_1[a]	61.9	9.9	1.4	0.9	36	10	6.4
L_1P	73.7	11.5	1.7	1.0	145	11	6.3
L_1K	61.2	10.3	3.8	0.9	31	10	6.2
L_1PK	79.3	11.0	3.4	1.0	130	8	6.5
L_2[b]	52.9	40.9	1.8	0.7	37	6	6.4
L_2P	59.5	38.8	1.8	0.7	143	8	6.2
L_2K	44.5	29.9	4.0	0.6	32	9	6.1
L_2PK	50.8	32.2	4.0	0.7	143	6	6.3

TABLE XIX (Cont.)

Treatment	Ca	Mg	K	Na	P	Exch. Mn	pH
	(percent saturation)				(lbs/A)	(ppm)	
			Millet grain - 1955				
None	33.3	3.8	1.8	1.1	25	65	5.3
P	35.9	4.3	2.0	0.9	143	71	5.2
K	26.1	3.5	3.7	1.3	37	74	5.2
PK	28.7	3.3	3.4	1.0	152	71	5.2
L_1	45.2	11.5	1.7	0.9	35	49	5.7
L_1P	44.9	11.8	1.6	1.2	163	36	5.7
L_1K	48.9	11.8	3.7	1.1	27	40	5.8
L_1PK	56.8	13.7	3.5	1.2	168	44	5.8
L_2	37.1	14.4	1.6	1.0	40	49	5.6
L_2P	38.3	11.5	1.3	0.8	164	49	5.7
L_2K	32.5	11.1	3.0	1.0	28	40	5.8
L_2PK	32.7	11.3	3.5	1.1	158	46	5.6
			Soybean grain - 1955				
None	22.0	3.1	2.1	0.9	28	67	5.2
P	29.2	3.1	2.3	1.1	148	68	5.3
K	23.2	2.6	4.0	1.3	27	72	5.0
PK	26.7	2.8	4.2	0.7	158	70	5.2
L_1	37.9	9.7	1.8	1.2	24	43	5.5
L_1P	48.7	13.4	1.7	1.3	155	44	6.0
L_1K	37.3	13.6	4.4	0.9	29	46	5.9
L_1PK	51.6	13.4	5.0	1.2	192	41	5.9
L_2	34.5	12.7	1.9	1.1	27	47	5.7
L_2P	34.2	10.4	1.8	1.1	145	50	5.7
L_2K	29.2	14.4	3.4	1.1	29	52	5.7
L_2PK	27.8	10.4	4.5	0.7	158	49	5.7

TABLE XIX (Cont.)

Treatment	Ca (percent saturation)	Mg (percent saturation)	K (percent saturation)	Na (percent saturation)	P (lbs/A)	Exch. Mn (ppm)	pH
			Millet grain - 1956				
None	29.6	3.8	1.8	0.7	33	28	5.0
P	35.1	4.2	1.8	0.7	124	29	5.0
K	28.2	3.8	4.9	0.7	46	44	5.0
PK	32.7	4.7	5.5	0.9	168	45	4.9
L_1	74.4	16.0	2.4	1.0	35	11	6.1
L_1P	80.7	16.2	2.5	1.1	145	10	6.5
L_1K	77.2	9.9	4.2	0.9	40	7	6.5
L_1PK	85.6	13.6	4.4	1.0	150	9	6.5
L_2	50.8	38.4	1.8	0.7	28	7	6.4
L_2P	59.5	45.9	1.9	1.1	173	8	6.2
L_2K	45.6	34.3	3.6	0.8	33	10	6.2
L_2PK	53.6	44.7	3.4	0.7	169	9	6.5
			Soybean grain - 1956				
None	35.5	5.9	2.1	0.9	32	23	5.2
P	37.2	3.8	2.1	0.8	130	27	5.1
K	25.0	3.5	4.0	0.7	46	29	5.0
PK	32.7	4.5	4.1	0.9	163	30	5.1
L_1	82.8	10.4	1.9	1.0	42	6	6.4
L_1P	75.8	7.3	1.7	1.1	155	8	6.5
L_1K	80.7	11.5	3.9	0.9	31	7	6.6
L_1PK	74.4	11.7	4.4	1.0	160	7	6.6
L_2	52.2	33.6	1.7	1.0	32	5	6.6
L_2P	51.8	25.7	1.7	1.0	184	5	6.5
L_2K	49.4	34.3	3.9	1.4	39	8	6.5
L_2PK	51.5	38.4	3.7	1.0	145	8	6.5

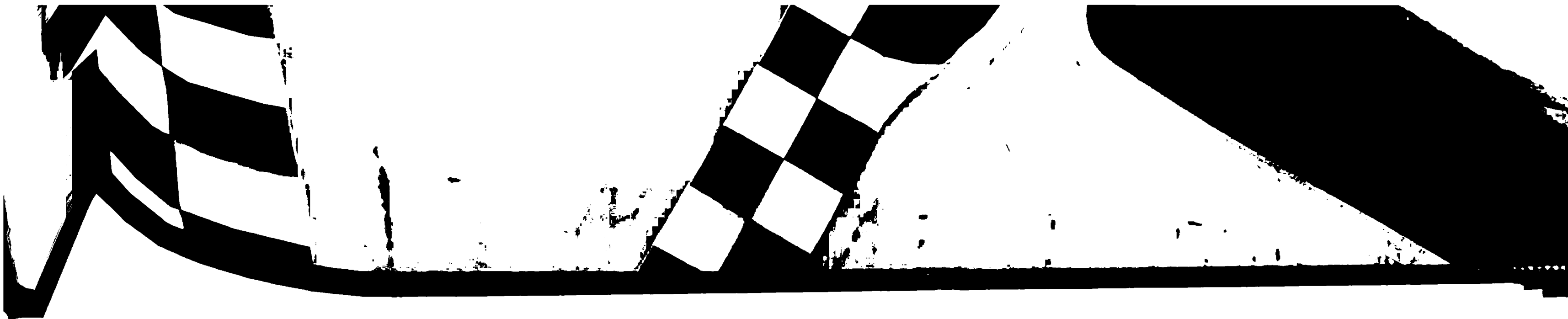

TABLE XIX (Cont.)

Treatment	Ca	Mg	K	Na	P	Exch. Mn	pH
	(percent saturation)				(lbs/A)	(ppm)	
			Corn grain - 1955				
None	23.2	3.1	2.1	1.1	24	55	5.1
P	26.7	2.3	1.7	1.2	100	46	5.0
K	22.9	2.1	5.7	1.5	29	75	5.0
PK	28.1	2.3	5.0	1.4	142	59	5.1
L_1	40.0	13.7	1.7	1.2	24	29	5.6
L_1P	49.6	14.8	2.1	1.3	145	29	5.7
L_1K	45.8	12.9	4.1	1.4	21	25	5.5
L_1PK	50.4	12.7	4.2	1.3	103	31	5.8
L_2	39.7	15.7	2.6	1.7	27	35	5.3
L_2P	37.4	15.7	2.5	1.5	136	37	5.4
L_2K	28.4	11.8	4.7	1.5	30	32	5.4
L_2PK	32.5	12.9	3.9	1.2	129	31	5.4
			Fallow - 1955				
None	29.0	4.5	2.6	1.0	32	75	5.3
P	33.0	3.7	2.3	1.9	148	78	5.2
K	23.2	3.7	3.3	1.7	35	76	5.2
PK	29.0	4.3	4.2	1.3	152	84	5.2
L_1	42.0	10.8	2.3	1.5	38	58	5.7
L_1P	52.2	11.8	2.1	1.4	148	46	5.9
L_1K	39.1	10.4	3.3	1.5	28	49	5.9
L_1PK	38.3	9.7	3.1	1.4	125	52	5.8
L_2	35.9	13.9	2.2	1.1	27	52	5.7
L_2P	31.3	10.8	2.0	2.0	128	58	5.6
L_2K	27.8	10.3	3.3	3.3	39	54	5.7
L_2PK	32.1	10.3	3.5	3.5	138	59	5.6

TABLE XIX (Cont.)

Treatment	Ca (percent saturation)	Mg	K	Na	P (lbs/A)	Exch. Mn (ppm)	pH
			Corn grain - 1956				
None	31.3	5.7	1.5	0.9	40	13	5.3
P	30.6	5.6	1.6	1.1	143	14	5.3
K	26.4	4.9	3.7	1.1	44	18	5.2
PK	28.7	4.5	3.8	1.1	168	19	5.2
L_1	80.5	17.4	1.2	1.0	35	6	6.6
L_1P	75.8	16.5	1.7	1.0	155	4	6.7
L_1K	78.3	20.5	3.4	1.0	32	6	6.6
L_1PK	79.1	17.9	5.0	1.0	143	6	6.7
L_2	51.3	47.8	1.7	1.2	32	5	6.9
L_2P	54.2	43.5	1.6	1.0	153	5	6.5
L_2K	48.8	45.6	3.7	1.3	30	5	6.6
L_2PK	50.9	45.7	3.7	0.9	117	5	6.7
			Wheat grain - 1956				
None	30.6	6.3	2.4	0.9	29	46	5.0
P	34.1	7.0	1.9	0.9	120	39	5.1
K	21.6	3.1	2.7	1.0	36	37	5.0
PK	27.1	3.7	3.9	1.0	150	43	5.0
L_1	50.1	16.2	2.0	1.0	29	14	5.6
L_1P	55.0	16.5	1.7	0.8	125	13	6.0
L_1K	49.4	16.5	3.1	1.1	31	14	5.9
L_1PK	45.2	11.7	2.9	1.0	106	15	5.7
L_2	41.0	18.3	1.7	0.7	33	19	5.7
L_2P	39.7	17.2	1.4	0.8	160	15	5.7
L_2K	36.9	21.2	2.4	0.6	33	13	6.0
L_2PK	36.9	23.1	2.6	0.7	130	9	5.8

TABLE XX

THE EFFECT OF SOIL TREATMENT ON THE CHEMICAL COMPOSITION OF CROPS STUDIED

Treatment	Ca	Mg	K	Na	Total	P	Mn	N	Ash
	(m.e./100 grams)					(percent)			
				Timothy hay - 1955					
None	3.1	2.6	26.8	0.40	32.9	0.13	0.020	0.90	3.94
P	3.1	4.2	30.7	0.38	38.4	0.19	0.018	0.92	4.47
K	3.3	4.4	34.1	0.39	42.2	0.13	0.021	0.92	4.48
PK	3.0	3.9	38.9	0.43	46.2	0.24	0.022	1.00	5.56
L_1 [a]	3.5	4.4	27.4	0.33	35.6	0.14	0.014	0.97	4.16
L_1P	3.1	4.4	28.8	0.24	36.5	0.24	0.018	0.96	4.78
L_1K	3.9	4.3	36.2	0.41	44.8	0.15	0.018	0.97	4.84
L_1PK	3.7	4.2	40.0	0.23	48.1	0.23	0.019	1.06	5.55
L_2 [b]	3.5	4.1	29.2	0.19	37.0	0.12	0.160	0.91	3.98
L_2P	3.2	5.9	25.7	0.21	35.0	0.23	0.170	0.94	4.65
L_2K	4.0	3.5	34.1	0.22	41.8	0.13	0.210	1.01	4.51
L_2PK	3.1	4.6	38.9	0.20	46.8	0.25	0.230	0.98	5.52
				Soybean hay - 1955					
None	59.4	34.2	23.5	0.14	117.2	0.15	0.036	2.30	5.76
P	50.6	35.5	22.4	0.09	108.6	0.25	0.082	2.84	5.59
K	45.0	32.4	40.6	0.13	118.1	0.21	0.098	2.75	6.65
PK	58.8	30.8	39.1	0.11	128.8	0.26	0.091	2.83	6.75
L_1 [a]	63.8	38.0	27.1	0.12	129.0	0.21	0.035	3.02	6.37
L_1P	56.3	42.1	23.4	0.13	121.9	0.30	0.073	3.08	5.86
L_1K	70.6	36.0	33.5	0.12	140.1	0.17	0.051	2.80	6.76
L_1PK	57.5	32.7	33.7	0.13	124.0	0.25	0.035	2.77	6.37
L_2 [b]	63.8	38.0	24.9	0.13	126.7	0.18	0.065	2.98	6.23
L_2P	48.8	40.9	23.0	0.15	112.9	0.30	0.048	3.08	5.66
L_2K	60.0	32.9	35.0	0.14	128.0	0.18	0.026	2.74	6.61
L_2PK	60.6	35.3	31.2	0.13	127.2	0.23	0.032	2.51	6.38

[a] Calcitic lime

[b] Dolomitic lime

TABLE XX (Cont.)

Treatment	Ca	Mg	K	Na	Total	P	Mn	N	Ash
	(m.e./100 grams)					(percent)			
				Timothy hay - 1956					
None	5.5	12.7	26.0	0.18	44.4	0.17	0.022	0.95	4.50
P	4.9	12.9	33.7	0.16	51.7	0.23	0.030	1.06	4.90
K	3.9	11.2	37.3	0.16	52.6	0.18	0.025	1.03	5.05
PK	3.6	10.7	41.0	0.19	55.5	0.24	0.026	1.13	5.49
L_1[a]	5.2	13.0	31.3	0.18	49.7	0.17	0.016	1.06	4.45
L_1P	7.8	15.0	31.4	0.15	54.4	0.25	0.024	1.14	5.16
L_1K	6.1	10.2	39.9	0.20	56.4	0.14	0.014	1.01	5.04
L_1PK	5.8	9.6	43.2	0.18	57.8	0.23	0.019	1.15	5.75
L_2[b]	5.2	14.8	31.1	0.19	51.3	0.16	0.023	1.13	4.59
L_2P	5.6	17.2	33.0	0.23	56.0	0.24	0.020	1.12	5.09
L_2K	5.6	14.5	39.3	0.18	59.6	0.16	0.016	1.15	4.92
L_2PK	4.6	15.1	42.6	0.20	62.5	0.23	0.022	1.10	5.55
				Soybean hay - 1956					
None	95.0	40.9	18.4	0.14	154.4	0.17	0.062	2.73	7.01
P	106.9	47.3	18.0	0.09	172.3	0.25	0.057	2.85	7.96
K	90.6	36.5	28.1	0.13	155.3	0.20	0.064	2.79	8.05
PK	80.0	37.5	33.5	0.11	151.1	0.26	0.065	2.54	8.05
L_1[a]	101.9	51.9	14.4	0.11	168.3	0.20	0.042	2.08	7.59
L_1P	107.5	57.1	12.7	0.11	177.4	0.27	0.027	3.05	8.15
L_1K	77.5	42.7	32.7	0.10	153.0	0.21	0.021	2.89	7.21
L_1PK	88.1	38.6	32.3	0.11	159.1	0.29	0.032	3.03	7.87
L_2[b]	78.1	48.3	16.6	0.08	143.1	0.21	0.037	3.00	7.37
L_2P	100.0	55.0	12.5	0.10	167.6	0.26	0.041	2.91	8.27
L_2K	67.5	45.0	32.0	0.09	144.6	0.21	0.035	2.92	7.46
L_2PK	71.9	44.2	25.6	0.09	141.8	0.22	0.018	2.72	7.49

TABLE XX (Cont.)

Treatment	Ca	Mg	K	Na	Total	P	Mn	N	Ash
	(m.e./100 grams)					(percent)			
				Millet grain - 1955					
None	0.45	4.6	5.0	0.11	10.2	0.35	0.0023	2.21	2.31
P	0.54	9.8	5.6	0.11	16.1	0.38	0.0025	2.05	2.60
K	0.51	6.5	5.4	0.13	12.5	0.33	0.0045	2.14	2.53
PK	0.45	9.6	5.4	0.12	15.6	0.34	0.0037	2.00	2.56
L_1	0.40	10.8	6.2	0.11	17.5	0.34	0.0020	2.35	2.29
L_1P	0.48	10.8	5.5	0.11	16.9	0.38	0.0010	2.16	2.29
L_1K	0.46	13.4	6.1	0.10	20.1	0.35	0.0037	2.30	2.19
L_1PK	0.54	10.8	6.9	0.11	18.3	0.43	0.0030	2.13	2.59
L_2	0.49	10.8	5.8	0.12	17.2	0.38	0.0016	2.35	2.11
L_2P	0.45	11.6	4.9	0.13	17.1	0.36	0.0020	2.17	2.27
L_2K	0.46	10.8	5.2	0.12	16.6	0.34	0.0020	2.26	2.18
L_2PK	0.50	12.9	5.3	0.13	18.8	0.35	0.0028	2.17	2.50
				Soybean grain - 1955					
None	6.8	19.1	43.2	0.18	69.3	0.53	0.017	5.94	4.81
P	6.1	17.0	42.4	0.16	65.7	0.57	0.016	6.31	4.93
K	6.3	17.2	40.9	0.16	64.6	0.52	0.025	6.41	4.91
PK	6.1	19.1	40.8	0.19	66.2	0.62	0.019	6.46	5.40
L_1	5.8	16.5	43.0	0.18	65.5	0.52	0.017	6.47	4.78
L_1P	5.4	17.7	35.8	0.15	59.1	0.63	0.016	6.89	4.99
L_1K	5.9	17.7	44.6	0.20	68.4	0.48	0.024	6.14	4.81
L_1PK	5.9	14.6	43.5	0.18	64.2	0.58	0.017	6.75	4.84
L_2	6.0	18.2	42.7	0.19	67.1	0.51	0.016	6.21	4.62
L_2P	6.4	19.8	39.6	0.23	66.0	0.56	0.016	6.20	4.66
L_2K	6.5	19.1	42.8	0.18	68.6	0.49	0.020	6.11	4.78
L_2PK	5.5	18.8	44.4	0.20	68.9	0.60	0.020	6.73	4.92

TABLE XX (Cont.)

Treatment	Ca	Mg	K	Na	Total	P	Mn	N	Ash
	(m.e./100 grams)					(percent)			
Millet grain - 1956									
None	0.74	10.8	7.9	0.12	19.6	0.28	0.0060	2.36	2.34
P	0.76	11.1	9.2	0.15	21.2	0.38	0.0060	2.26	2.60
K	0.73	9.6	8.9	0.13	19.4	0.33	0.0080	2.34	2.39
PK	0.76	9.8	9.7	0.13	20.4	0.40	0.0093	2.20	2.55
L_1	0.79	9.6	8.7	0.14	19.2	0.31	0.0059	2.48	2.32
L_1P	0.97	16.0	9.0	0.13	26.1	0.38	0.0055	2.47	2.48
L_1K	0.84	11.3	8.9	0.12	21.2	0.31	0.0080	2.54	2.42
L_1PK	1.00	13.4	10.0	0.13	24.5	0.38	0.0058	2.48	2.45
L_2	0.71	16.5	8.2	0.13	25.5	0.28	0.0058	2.64	2.18
L_2P	0.84	16.3	9.6	0.13	26.9	0.38	0.0025	2.62	2.37
L_2K	0.71	13.4	8.6	0.12	22.8	0.30	0.0039	2.66	1.97
L_2PK	0.85	16.8	9.7	0.11	27.5	0.38	0.0044	2.44	2.86
Soybean grain - 1956									
None	5.5	20.8	43.8	0.18	70.3	0.46	0.0080	6.09	4.61
P	5.7	20.6	41.9	0.19	68.4	0.61	0.0080	6.16	4.77
K	5.9	20.3	43.5	0.23	69.9	0.56	0.173	5.84	5.52
PK	5.4	18.0	43.5	0.15	67.1	0.66	0.143	5.80	5.12
L_1	5.4	18.5	36.0	0.15	60.1	0.49	0.0070	6.34	4.16
L_1P	6.1	19.3	35.5	0.15	61.1	0.63	0.0068	6.70	4.51
L_1K	5.1	21.9	41.6	0.14	68.7	0.45	0.0020	6.09	5.56
L_1PK	5.2	20.3	40.9	0.18	66.6	0.62	0.0023	6.37	4.63
L_2	6.1	19.6	36.8	0.20	62.7	0.50	0.0073	6.55	4.41
L_2P	5.2	17.7	33.6	0.19	56.7	0.60	0.0055	6.47	4.49
L_2K	5.4	21.4	39.2	0.16	66.2	0.52	0.0083	6.08	5.68
L_2PK	5.5	22.7	40.9	0.18	69.3	0.63	0.0055	6.12	5.01

TABLE XX (Cont.)

Treatment	Ca	Mg	K	Na	Total	P	Mn	N	Ash
	(m.e./100 grams)					(percent)			
				Corn grain - 1955					
None	0.27	9.6	7.2	0.26	17.3	0.25	0.0018	1.75	1.24
P	0.31	10.8	10.2	0.35	21.7	0.37	0.0023	1.95	1.63
K	0.29	7.3	10.8	0.47	18.9	0.29	0.0022	1.89	1.40
PK	0.31	11.7	11.9	0.39	24.3	0.39	0.0037	1.97	1.64
L_1	0.33	9.1	9.1	0.24	18.8	0.29	0.0028	1.97	1.59
L_1P	0.28	9.3	9.0	0.15	18.7	0.38	0.0029	1.88	1.59
L_1K	0.29	6.4	8.5	0.36	15.6	0.26	0.0014	1.77	1.27
L_1PK	0.28	10.1	10.4	0.17	21.0	0.38	0.0026	1.98	1.69
L_2	0.30	10.1	8.0	0.16	18.6	0.28	0.0016	1.86	1.38
L_2P	0.27	12.2	9.0	0.17	21.6	0.39	0.0025	1.91	1.60
L_2K	0.30	10.9	9.1	0.19	20.5	0.25	0.0032	1.83	1.47
L_2PK	0.28	10.1	9.4	0.13	19.9	0.36	0.0030	1.78	1.67
				Wheat grain - 1956					
None	1.19	9.3	8.5	0.12	19.1	0.26	0.0059	2.19	1.43
P	1.04	13.4	9.4	0.11	24.0	0.36	0.0085	1.93	1.88
K	0.94	10.3	8.8	0.12	20.2	0.28	0.0095	2.34	1.69
PK	1.04	11.3	10.6	0.14	23.1	0.47	0.0145	1.78	1.98
L_1	1.04	22.6	8.9	0.11	32.7	0.32	0.0038	2.29	1.71
L_1P	1.00	16.4	9.9	0.10	27.4	0.44	0.0044	1.98	2.05
L_1K	0.98	10.3	9.2	0.11	20.6	0.34	0.0075	2.30	1.81
L_1PK	0.91	13.4	10.1	0.09	24.5	0.43	0.0083	2.01	2.17
L_2	0.88	10.3	8.5	0.11	19.8	0.30	0.0068	2.41	1.73
L_2P	0.88	11.3	10.0	0.11	22.3	0.43	0.0088	2.10	2.10
L_2K	0.88	8.2	8.7	0.09	20.7	0.32	0.0060	2.32	1.75
L_2PK	0.79	9.3	10.5	0.09	18.9	0.44	0.0090	1.88	2.16

TABLE XX (Cont.)

Treatment	Ca	Mg	K	Na	Total	P	Mn	N	Ash
	(m.e./100 grams)					(percent)			
				Corn grain - 1956					
None	0.28	6.2	7.1	0.11	13.7	0.23	0.0048	1.80	1.67
P	0.27	9.6	7.9	0.13	17.9	0.33	0.0046	1.89	1.87
K	0.25	6.8	6.9	0.12	14.1	0.25	0.0058	1.77	1.62
PK	0.28	7.8	8.3	0.12	16.5	0.32	0.0043	1.84	1.86
L_1	0.29	7.7	7.2	0.09	15.3	0.24	0.0039	1.85	1.77
L_1P	0.20	10.2	7.9	0.15	18.5	0.33	0.0037	1.86	1.97
L_1K	0.28	5.2	6.9	0.12	12.5	0.23	0.0034	1.83	1.67
L_1PK	0.19	10.1	7.9	0.11	18.3	0.35	0.0040	1.89	1.98
L_2	0.23	6.8	7.4	0.12	18.9	0.24	0.0023	1.79	1.70
L_2P	0.24	8.1	7.8	0.14	16.3	0.32	0.0026	1.88	1.95
L_2K	0.24	7.8	7.6	0.09	15.7	0.26	0.0033	1.87	1.67
L_2PK	0.21	10.2	8.4	0.13	18.9	0.35	0.0043	1.88	1.84