EFFECT OF FERTILIZERS ON PHOSPHORUS AVAILABILITY AND EXCHANGEABLE CALCIUM, POTASSIUM, AND MAGNESIUM IN SOIL FERTILITY PLOTS ON HILLSDALE SANDY LOAM

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INTRODUCTION

It has been long recognized that soils are often unproductive because the amount of available phosphorus is inadequate for optimum growth of the crop. Numerous investigations have revealed that certain soils have the power to fix relatively large quantities of phosphorus and hold it comparatively unavailable for higher plant nutrition.

Farmers being confronted with this problem, have endeavored to alleviate these conditions by treating their soils with varying amounts of phosphate fertilizers. Some treatments have given satisfactory crop response, others gave no significant increase in yield. If the soil is deficient in available phosphorus, why is there no crop response to phosphate fertilizer treatments on some soils? This is the problem that presented itself and during the past few years has been under almost continuous study by numerous investigators.

The writer is aware of the numerous reciprocal effects caused by fertilizer materials on both the solubility in the soil and absorption in plants. In this study, it has been the effort of the writer to show the relations of these reciprocal effects produced by continuous fertilization on the available phosphorus, and replaceable* potassium, calcium, and magnesium in the soil. The use of fertilizers to increase the mineral content of soils and plants as discussed in the United States Department of Agriculture Year Book (48) reveals that the mineral composition of crops can be affected only within certain limits. An increase of one constituent is offset by the decrease of another. Too

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*The terms "exchangeable" and "replaceable" have been used interchangeably throughout this study.

great an excess, as well as too great a deficiency, of a particular nutritive element brings with it an injury to the crop which is reflected in lowered vitality and diminished yield. Somewhere between the limits of excess and deficiency for the different essential elements--nitrogen, phosphorus, potassium, calcium, magnesium, sulphur, iron, etc.--is the optimum range of the well-balanced or harmonious mixture of nutrients which will be found to vary according to the nature of the soil, variety of crop, supply of water, amount of sunshine, and numerous other environmental conditions.

This chemical equilibrium in soils between the available nutrients is the determining factor for a productive or unproductive crop. The median between the limits of excess and deficiency has been established by Spurway* in his studies on plant nutrients in greenhouses.

In this study, both the direct and indirect reciprocal effects have been considered in an effort to explain the reasons for increase and decrease in the replaceable cations of the soil and the consequent crop response.

Any factors which cause a change in the cation equilibrium; increased or decreased absorption of cations by plants; efficient or inefficient utilization of cations within the plant; or increased liberation from or fixation of cations in the difficult available form tend to effect the amounts of replaceable bases in the soil and the consequent crop response. It was from this point of view that this study was conducted.

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REVIEW OF LITERATURE

During the past few years a number of workers have studied the relationships between soil reaction and fertilizer needs. This work has been confined in many cases to European soils.

Niklas and Hock (32), using the Neubauer method, found that only 25 per cent of the soils having a pH below 4.5 gave a phosphoric acid value above 8 mgms. and nearly 50 per cent were below 4 mgms. In the alkaline soil regions, however, nearly 50 per cent of the soils showed values above 8 mgms. and only 21 per cent less than 4 mgms.

Sekara (41) found that, in general, both very acid and very alkaline soil were more deficient in phosphorus than neutral soils. For potassium, acid soils were found to be more deficient than neutral soils while alkaline soils were relatively well supplied.

Schmitt (40) obtained Neubauer results for phosphorus that were lower on both acid and alkaline soils than on neutral soils. Larger amounts of available potash were found in neutral and alkaline soils.

Goy (17), using the Neubauer method, found that in general potash deficiency increased with increase of soil acidity.

Kling and Engels (23) tested 166 soils by means of the Neubauer method and found that either very acid or very alkaline soils were much more likely to be deficient in available phosphoric acid and very acid soils in available potash.

Gourley and Smock (16) in a survey of Ohio orchard soils found a low available phosphorus supply in the acid soils of eastern and central Ohio and a relatively large supply in the less acid soils of northwestern Ohio.

Recent studies have been made in relation to the available phosphorus and potassium contents of surface soils and subsoils and the conseqeunt crop productivity. Much of the work on this problem in recent years has been confined largely to pot test and field observations. Because of the large amount of work involved in such tests only a relatively few soils have been investigated.

Millar (28, 29, 30), from work with several soil types, concluded that the poor growth of corn in soil from A_2 and B horizons is due very largely to a lack of available nutrients and that very large quantities, particularly of phosphorus, must be added to satisfy the adsorptive capacity of the soil and make plant growth commensurate with that obtained when surface soil is used.

McMiller (27) used alfalfa in pot tests to show that certain Minnesota subsoils which previously had been found "raw" towards innoculated legumes were rendered as productive as the corresponding surface soils when soluble phosphorus and potassium fertilizers were added.

Lipman (24) questioned the existence of humid subsoils which were sterile towards inoculated legumes and denied that lack of phosphoric acid or potash could be the cause of such unproductivity.

In order to determine the efficiency of added phosphorus and potassium fertilizers to soils, many investigations have been conducted to obtain data concerning the fixation capacities of soils. Recent work has shown that a number of factors are important in determining the fixation capacities of soils. Probably the most important of these are soil reaction, amount and composition of soil colloids and the amounts of organic matter, active silicon and iron and aluminum compounds present.

In general, for phosphorus, it appears that increased fixation capacity of the soil accompanies very acid soil reactions, the presence of large amounts of soil colloids, low silica-sesquioxide ratios of the soil colloids and the presence of large quantities of active iron and aluminum compounds. Decrease in fixation capacity may be expected with neutral or slightly acid soil reactions, low colloidal contents, high silica-sesquioxide ratios, and the presence of only small amounts of active iron and aluminum compounds and relatively large amounts of active silica and organic matter.

For potassium fixation much less information is available regarding either its prevalence or the mechanism through which it takes place. Even the effect of lime, which has been intensively studied, is still a disputed question. However, it is generally agreed that when potassium in solution is added to soils it readily and rapidly combines with the exchange material of the soil and is held in less soluble but exchangeable and plant available forms. It has been suggested that in time a part of this exchangeable potassium is changed to non-exchangeable and available forms, the rapidity and completeness of the change varying greatly with different soils. In these processes, the reaction of the soil and the amount and composition of the colloidal material present appear to be important factors.

Davis (6), on the basis of his work with Hawaiian soils, stated that phosphate fixation in soils may occur through three processes:

1. Formation of insoluble phosphates through reaction with soluble bases, such as calcium, magnesium, iron, aluminum and manganese.

2. Adsorption on colloidal surfaces.
3. Slow diffusion out of the soil solution and into some of the amorphous solids of the soil where it combines with substances such as hydrated oxides of iron and aluminum to form complex compounds.

Davis found, that, even after removal of the readily soluble substances, the soil possessed high phosphorus fixing power and believed that little phosphorus is fixed in Hawaiian soils as insoluble phosphates or by absorption by soil colloids.

Heck (19) states that, if the ratio of active calcium to active iron and aluminum is high, phosphorus fixation will be largely in the form of calcium phosphates and so readily available to plants. If the reverse is true, fixation will be largely as iron and aluminum compounds which are difficultly available. On the basis of solubility, it was found that phosphorus was fixed in a Miami silt loam largely as calcium phosphates, in a more acid Carrington silt loam less as calcium phosphate and more as iron and aluminum phosphates, and in two Hawaiian laterites largely as basic forms of iron and aluminum phosphates. Although reaction and the presence of active calcium are ordinarily important factors, in the laterites they are overshadowed by the presence of large quantities of hydrated oxides of iron and aluminum.

Ayres (3), in a study of phosphorus fixation in Hawaiian soils found that the degree of fixation was characteristic for a given locality. In general, lowland soils showed a lower phosphate fixing capacity than upland soils and surface soils lower than subsoils. A general correlation existed between the degree to which fixation occurred in soils and the availability therein of applied phosphates.

Weiser (50) found relatively high phosphorus fixation capacities for Vermont soils. Fixation was increased by exposure of the fertilizer to large amounts of soil. It was considered as due chiefly to compounds of iron and aluminum. Certain hydrated oxides and precipitated salts fixed especially large amounts of phosphorus. On the other hand certain silicates, minerals and organic matter reduced fixation. Lime likewise increased the ability of crops to recover applied phosphorus.

Scarseth and Tidmore (39) studied phosphorus fixation by soil colloids. Availability of the native phosphorus in the four types of soil colloids used varied directly as the silica-sesquioxide ratio, being less available in soils with red colloids than in soils with grey colloids. Phosphate fixation capacity of the colloid was inversely proportional to the silica-sesquioxide ratio. The lower the silica-sesquioxide ratio, the smaller was the influence of the degree of calcium saturation on the amount of phosphorus fixed by the colloid. The more acid the soil colloid the greater was the recovery of added phosphorus.

Gile (15) studied the effect of different colloidal soil materials on the efficiency of superphosphate. He concluded that the degree to which the colloid was saturated with phosphorus, the silica-sesquioxide ratio, effect of colloid on the pH of the medium and the content of organic matter seemed important in determining relative efficiency of superphosphate.

Volk (48), in an extensive study of potash fixation in soils, found that rapid fixation in a non-replaceable form was caused by alternate wetting and drying. For the four soils investigated, the ultra-clay fraction contained the lowest percentage of potash but was by far the most active in fixation. Fixation was influenced by the nature as well as the amount of soil colloids present. Sodium carbonate and calcium hydroxide both increased fixation. Synthetic mixtures of alumnia gel, silica gel, calcium hydroxide and sand did not fix potash. Mineralogical, chemical and X-ray analyses of Hagerstown silt loam soil, a part of which had received 5,000 lbs. of muriate of potash over a period of 50 years, led to the conclusion that a portion of the added potash became fixed in the soil in the form of muscovite.

McGeorge (26), in a comparison of calcareous and non-calcareous soils having the same amount of replaceable potassium, found higher values for water soluble potassium with the non-calcareous soils while Neubauer values were higher with the calcareous soil. Calcareous soils were found to contain a larger part of their potassium adsorbed by non-crystalline colloids, either in the form of synthetic zeolite-like compounds or iso-clectric precipitates.

Many investigators have attempted to correlate the size of particles to the availability of phosphorus in rock phosphates.

DeTurk and Sears (10) found no marked differences with material of different fineness used on soil in greenhouse cultures.

Ames and Kitsuta (1) obtained increased phosphorus absorption by plants from the more finely ground rock phosphate.

Rauscher (36), using the Neubauer method and several different types of rock phosphate, found it necessary to consider each type separately. With certain types of material particle size exerted an important influence on the phosphorus absorption, this being especially true with the hard phosphates. With the soft phosphates, phosphorus absorption was greater but much less influenced by differences in particle size than with the hard phosphates.

There appears to be no pronounced or consistent increase in availability with decrease in particle size.

Early investigations revealed evidence of reciprocal effects of nitrogen, phosphorus, and potassium additions on the absorption of phosphorus and potassium. In addition to its direct effects on plant growth and development, any nutrient added to the soil may have important indirect effects on the utilization of the other nutrients present. Occasionally these indirect effects are fully as important as the direct ones. In explanation of the effect of one nutrient on the utilization of another several possibilities are suggested:

1. Changes in solubility relationships in the medium upon which the plant is growing.
2. Influence on absorption by the plant.
3. Effects on efficiency of utilization within the plant.

Soil reaction and concentration and nature of the cations in the soil solution and the exchange complex of the soil have been suggested as the principal factors determining the availability of phosphorus and potassium. From this it is to be expected that any treatment that influences either of these factors will affect the availability of these two plant foods.

Thomas (43, 44) studied the reciprocal effects of a number of materials on both solubility in soils and absorption by plants. Addition of monocalcium phosphate to Hagerstown silty clay loam soil increased the amounts of iron and aluminum in the soil solution, addition of sodium nitrate and potassium sulfate increased the amount of phosphorus in solution and both monocalcium phosphate and potassium sulfate increased the concentration of sodium in solution. Potassium additions increased absorption of both nitrogen and phosphorus by apple trees. In fact, a significant increase in the absorption of phosphorus occurred only after the addition of nitrogen or potassium or both. This was true whether or not phosphorus was added.

Fudge (14) investigated the effect of a number of nitrogenous fertilizers on phosphorus and potassium availability. Such material may affect both soil reactions and nature and concentration of cations present in the soil complex. Acid-forming materials, such as ammonium sulfate, ammonium nitrate, Leuna-saltpeter and urea, increase soil acidity and the concentration of hydrogen ions. Acid forming fertilizers caused a marked decrease in phosphate availability. For potassium, their effect was to increase the water soluble forms but to decrease the potentially available supply.

Thornton (45), in his observation on phosphorus absorption by corn and potato plants found that potassium additions increased the absorption of both nitrogen and phosphorus. A higher concentration of inorganic phosphorus within the plant often was found where relatively large applications of muriate of potash had been made. This was true whether or not growth responses to the potash additions could be observed and regardless of the initial phosphate level in the plant. In many cases the phosphorus values were increased more by the addition of potassium alone than by the addition of phosphorus alone.

The ability of soils to supply potassium to crops is a result of many processes. The total replaceable potassium content of a soil is so closely correlated with crop response to added potassium that its measure can be used in estimating the potassium needs of crops. Replaceable potassium is in equilibrium with a form of non-replaceable potassium or "difficultly replaceable" potassium which in turn is assumed to be in equilibrium with the potassium minerals. Reducing the replaceable potassium induces release of potassium from the "difficultly replaceable" form while increasing it induces "fixation" in this form.

Bray (4), in his study of the equilibrium between the replaceable bases and the soil water has found that the ability of a given plant under field conditions to secure replaceable potassium is conditioned by the extent and nature of its rooting system, the amount of replaceable bases present, the degree of saturation with bases, their relative ease of replacement, the electrolyte concentration of the soil water and numerous other factors. He has devised the equation below in order to show the relationship of these factors to the equilibrium of the replaceable bases in the soil water.

$$B_{1S} = C_{B1} \cdot \frac{f_1B_1}{f_2B_2 + f_3B_3 + --- + f_nB_n} \cdot \sqrt{\frac{B_1 + B_2 + --- + B_n}{E}}$$

Where B_{1S} = the amount of B_1 in solution.

B_1, B_2, etc. = replaceable bases.

f_1, f_2, etc. = factors for relative ease of replacement for B, B_1, etc.

E = Base-exchange capacity.

C_{B1} = constant for B_1 for the given conditions.

All expressed in milliequivalents per 100 grams of soil.

For dilute HCl (0.005N) good constants were obtained as follows: $C_K = 1.7$; $C_{Mg} = 1.0$; $C_a = 0.7$. Applied to Hoagland and Martin's data (21) for potassium removed in a 2:1 soil-water extraction the equation gave a C_K of 0.12 for their conditions.

Factors for ease of replacement were calculated by assuming calcium to have a value of one. The percentages of the replaceable magnesium and replaceable potassium released were then divided by the percentage of the replaceable calcium released, giving factors as follows: $f_K = 2.3$; $f_{Mg} = 1.7$; and $f_{Ca} = 1.0$ for the experiment.

The equilibrium expressed by this equation controls the release and movement of the replaceable potassium (and other bases) thru the soil. Any increase in calcium or magnesium will give two opposite effects. It will tend to decrease the potassium in solution in that the potassium in solution is inversely proportional to the sum of the other replaceable bases times their ease of replacement factors. At the same time it will tend to increase the release of potassium by increasing the degree of saturation with bases. Since the latter is a square root function, the actual result is a decrease in K release. This is contrary to the conclusion of Jenny and Ayers (22) who believe that potassium release will be greater when the replaceable calcium is increased by liming.

The relatively slow rate of movement of the strongly adsorbed ions, such as K, PO_4, Ca, Mg, Mn, through the soil is in striking contrast to the mobility of the relatively unadsorbed ions, notably nitrates. This situation gives rise to two distinct types of zones from which plants feed or absorb nutrients. The one, for the strongly adsorbed ions has a relatively short radius immediately around the roots or root hairs, with untapped areas occurring between these "root surface feeding zones" within the root system of the plant. When these "root surface zones" interpenetrate, competition for the adsorbed ions occurs between the individual root hair surfaces of the same or different plants.

Spurway (42), in his study of the factors influencing the solubility of soil-superphosphate mixtures found that additions of potassium fertilizers increased the solubility of phosphorus.

Owens (33) has reported increased absorption of phosphorus with the omission of potassium fertilization.

Hess (20) has reported increased solubility of phosphorus upon additions of potassium.

Willis, Et. At. (52), in their study with soybeans found that with an abundance of calcium a deficiency of magnesium does not limit absorption of phosphates. Their data do not indicate whether the phosphate absorbed under these conditions is efficiently utilized, but collateral evidence indicates that magnesium deficiency and phosphate deficiency have no mutual relationship.

Dunkle (12) in his studies of potash availability concluded that surface soils were definitely higher than subsoils in replaceable potassium and loss of top soil by erosion is a factor in increasing the need of applied potassium. The amount of replaceable potassium is related to the organic matter content of the soil. The rapid method for determining replaceable potassium compared favorably with the quantitative cobalti-nitrite method and is satisfactory for determining the general level of soil potassium. His analyses of leaves did not correlate with the replaceable soil potassium but in some cases gave indications of the effects of potash application which could not be detected by exchange analyses.

Richer and White (37) made extensive studies on available phosphorus and crop yields. As a result of these studies no correlation was found between the available phosphorus and crop yields in the comparison of plats receiving various carriers of phosphorus, such as superphosphate, rock phosphate, basic slag, and bone meal. Plats receiving double or triple amounts of superphosphate showed only small increases in the available phosphorus extracted. The available phosphorus of rock phosphate-treated plats was directly proportional to the amount applied, but it was many times higher than that of plats receiving superphosphate in equivalent amounts. After long continued use of phosphorus fertilizers the soil tends to approach a phosphorus equilibrium. When this equilibrium is approached, available phosphorus has a tendency to show an excellent correlation with crop yield.

Daniels and Harper (8), in their studies of the relationships between total calcium and phosphorus in mature prairie grass in Oklahoma found that these grasses make a good growth on both acid and basic soils and often on soils very low in easily soluble phosphorus, base exchange calcium, and organic matter.

The correlation coefficient for the comparison between total calcium in the grass and the exchangeable calcium in the soil was 0.50 ± .09 and the correlation between the available phosphorus in the soil and the total phosphorus in the grass was 0.35 ± .11. It was found that a slight positive correlation existed between the total calcium in the plant and exchangeable calcium in high calcium soils. No data were obtained that would indicate that plants growing in soil low in base exchange calcium would also be low in this element. A slight positive correlation occurred between the total phosphorus in the grass and the easily soluble phosphorus. A slight negative correlation occurred when the plants were collected from soils containing less than 10 p.p.m. of available phosphorus. From their data, they concluded that a single plant food element in the soil will not give an accurate indication as to the amount of that element which will be found in the plant.

Dorman and Coleman (11) made greenhouse studies of available phosphorus using cotton and sagrain. They found that cotton and sagrain failed to respond to phosphate application on soils containing 15 p.p.m. or more available phosphorus, which indicated that under southern conditions crops do not require large quantities of phosphorus. Most southern soils do not contain 15 p.p.m. available phosphorus and require phosphorus, but application should be made without determining the available phosphorus present. It is believed that when nitrogen and potassium are limited and phosphorus fixation is at a minimum, phosphate recommendations for cotton and sorghum may be made on the following basis: Soils containing less than 6 p.p.m. available phosphorus require liberal applications, those containing from 6 to 15 p.p.m. require light applications, but those containing more than 15 p.p.m. require very little or no phosphorus.

Parker and Truog (34) concluded from their compilation of analyses secured from different sources that a rather close relationship existed between the calcium and nitrogen content of plants, while potassium, phosphorus and magnesium do not bear this close relationship.

Daniel (7), in his studies on magnesium content of grasses and legumes found that the calcium-magnesium ratios varied in mature grasses and legumes from 1.10 to 5.46, the phosphorus-magnesium ratios from 0.09 to 2.42, and the nitrogen-magnesium ratios from 2.09 to 22.06. He found that the magnesium content of legumes decreased as plants matured.

Mitchell, Warner, and Morrow (31) found that phosphorus in fertilizers decreased the calcium and magnesium content of oats and increased the phosphorus content of oats, grass hay, and soybean hay. Wide variation in phosphorus content of feeds was found in different parts of the country.

Ames, Boltz, and Stenius (1), in their investigation on composition of wheat, found that the character of wheat is changed more by seasonal influences than by the differences in soils or fertilizer treatments. Their investigations revealed that a high starch content was associated with a high phosphorus content and a low protein content and that the ratio of phosphorus to nitrogen in wheat stands in the same order as that of phosphorus to nitrogen in the soil.

Lockett (25), in his study on nitrogen and phosphorus changes in the decomposition of rye and clover at different stages of growth found that the soil microbes engulf a considerable amount of organic and inorganic phosphorus in their microbial cells. He has pointed out that this fixation of phosphorus is important from the point of view of supplying available phosphorus for plant nutrition. If the phosphorus were liberated immediately in the soil, a large portion might become fixed in forms which are unavailable to higher plants.

Eschenhagen (13) applied the Neubauer's method for the study of the nutrient contents of the soil and found that with increasing amounts of potassium the dry weight of plants follows the action law of the growth factors. He concluded the amount of potassium absorbed by plants, depends not only on the amount of potassium available in the soil but also on all other growth factors. It is pointed out that the absorption of potassium is controlled by the concentration of the potassium solution in the soil and does not depend on the lack of available potassium. He showed that the Neubauer method can be used only within certain limits.

Densch and Hunnius (9), in their extensive investigation of the influence of the soil-water content on the yield, on the grain-straw ratio, and on the phosphorus nutrition of oats at various times in growth period, have concluded the following:

1. A long period of drought caused a decrease in straw yield but did not show the bad effect on grain formation until early part of July.
2. Phosphoric acid is taken up by the oats until the panicles appear and under favorable moisture condition the whole amount is available for grain formation.
3. Even if the period of drought ends during the stretching period, the plant is able until the panicle formation to take up as much potassium as when under continual favorable moisture conditions.

4. Oats take up nitrogen even after the panicle formation, under favorable moisture conditions, and the nitrogen nutrition lasts until near their ripening.

The minimum supply of readily available phosphorus which suffices for plant growth varies depending upon the crop, climate, and soil involved. Crops with a long growing period can get along with a lower supply than those with a shorter growing period, because the long growing period makes possible the utilization of a greater amount of the difficultly available phosphorus. A climate which makes possible a long growing period has a similar effect. As a consequence, fairly good crops of corn can apparently be produced in the South on soils whose readily available phosphorus supply would be entirely inadequate in the North.

Unquestionably, a higher amount of readily available phosphorus than 75 to 85 pounds per acre in the plowed layer for the heavier, and better soils, and 50 pounds for the sandy soils will further tend to increase yields in many cases. All biological activities of soils are greatly stimulated by a liberal supply of readily available phosphorus. The economics involved must, however, be taken into consideration. Where land values and crop prices are relatively high, it will be economical to farm with higher amounts of readily available phosphorus than where the reverse conditions hold. In sections when the land is devoted to the production of vegetable and truck crop production, it is often desirable to have 150 pounds or more per acre of readily available phosphorus in the plowed layer. In most cases it is not practical and of no avail to supply the soil with readily available phosphorus beyong the point where climatic conditions, such as amount or distribution of rainfall, limit the yield.

DESCRIPTION OF SOIL PLATS STUDIED

This experiment was conducted on a Hillsdale sandy loam. The whole area involved was exceptionally level and uniform for that type of soil. The pH determinations on the soil samples ranged from 5.2 to 6.4. The plow layer consisted of a grayish-brown sandy loam, underlain by a 20-inch layer of pale-yellow fine-granular friable clay loam ranging from 18 to 24 inches in thickness. The substratum had a pervious sandy clay, which was moderately stony and gravelly in places with separate layers and pockets of sand, clay, and gravel.

The humus content was not very high but the amount was sufficient to impart a light-brown color. The subsurface layer was moderately retentive of moisture and is permeable and penetrable to a depth of several feet.

Diagrammatic Layout of Plats

7A	8A	9A	10A	11A	12A
7	8	9	10	11	12
1A	2A	3A	4A	5A	6A
1	2	3	4	5	6

Plate 1

A View of the Phosphorus Series

Seeded to Alfalfa and Brome

Plate 2

A View of the Phosphorus Series

Seeded to Alfalfa and Brome

Plate III

Wheat and Barley on the Phosphorus Series

Plate IV

A View of the Phosphorus Series

EXPERIMENTAL WORK

The soil on which this experiment was conducted is classified as Hillsdale sandy loam and the whole area involved was exceptionally level and uniform for that type of soil. There are 24 duplicate plats comprising 0.0409 acres each. The soil being acid in reaction, was given a uniform application of 2 tons of limestone per acre. In each set of duplicates there was one plat which received lime only. All other plats got a uniform application of urea, KCl, and $CaSO_4$. Only the phosphorus treatments varied and the acre application of this element is given in Table **1** . During the years of 1933, 1934, 1935, 1936, 1937, and 1939, the plats grew barley, timothy, wheat, oats, barley, timothy, and wheat respectively. Regular fertilizer applications were made in spring for barley and in September for wheat. The first sampling after phosphorus applications was made in 1933, 1934, and again in 1937 and 1939. Soil samples were taken in late October or early November each year after time for applying fertilizer for wheat. Twenty borings 1.5 inches in diameter and 6.5 inches deep were taken from as many spots uniformly distributed over the plat. These were put together, dried, sifted through a 20-mesh screen, thoroughly mixed, and stored for analysis.

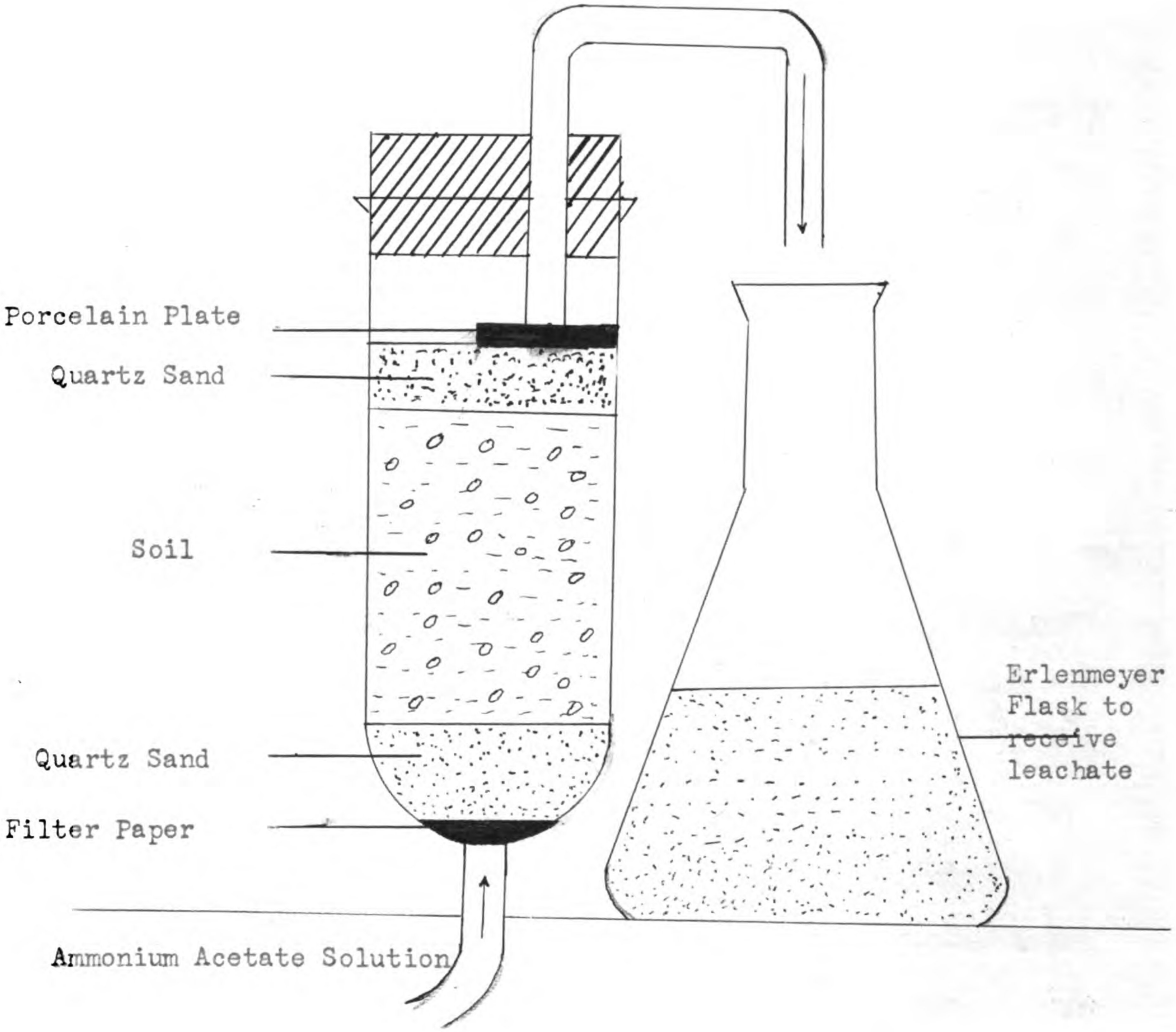
It is quite probable that some of the differences might be due to inaccuracy in sampling, but it is also quite likely that many of them are due to soil differences despite the fact that the soil seemed very uniform. Enough samples were not taken to calculate the error due to method of sampling.

The A plots were not started until 1933. Each original plot was divided in half and the new division was given the symbol of A. To each of these A plots a uniform treatment of Urea, KCl, and $CaSO_4$ was applied. In each set of duplicates there was only one plot which received lime only.

ANALYTICAL PROCEDURES

The soil samples which were analyzed had been previously dried, sifted through a 20-mesh screen, thoroughly mixed and stored for analysis. The soil samples were oven-dried at 105° C. for several days before beginning the analysis. The samples were then placed in a dessicator to cool and later weighed accurately to two decimal places.

The soil samples were placed in percolator tubes and leached according to the method recommended by Russel (38). The percolation was allowed to continue 8 to 10 hours with the leachate passing dropwise into an Erlenmeyer flask.


Porcelain Plate
Quartz Sand
Soil
Quartz Sand
Filter Paper
Ammonium Acetate Solution
Erlenmeyer Flask to ~~receive~~ receive leachate

DISPLACEMENT OF BASES

Twenty-five grams of the oven-dried soil (weighed out to two decimal places) was placed in the percolation tubes and firmly packed so that the leaching solution came into contact with the entire sample. The soil was leached for about 8 hours with normal ammonium acetate adjusted to a pH of 7.0. After the 500 ml. of normal ammonium acetate had percolated through the soil, the excess ammonium acetate was removed by passing 300 ml. of a 50 per cent methanol through the sample. The ammonia that remained in the soil after this treatment was in the exchangeable form. The ammonium acetate leachate was then reserved for the determination of calcium, magnesium, and potassium.

DETERMINATION OF EXCHANGEABLE CALCIUM

After treating the soil with the neutral ammonium acetate solution, calcium, magnesium, and potassium ions were brought into solution as acetates. The ammonium acetate leachate was then transferred to a 600 ml. beaker and evaporated to dryness on the steam bath. 10 ml. of aqua regia was added and the evaporation continued until dry again. (This procedure was to remove any organic matter present in the leachate.) The acetates were then destroyed by general ignition. This was accomplished in the pyrex beaker in which the sample was evaporated to dryness, the rim of beaker being held and the lower portion exposed to the flame of a bunsen burner. The residue in it turned black at first, but became white as the ignition continued. The beaker and contents was then cooled to room temperature and 10 ml. of (1:1) HCl and 10 ml. of distilled water added. The beaker was then heated until the residue was completely dissolved. The solution was filtered through a Whatman No. 41 filter paper into a 250 ml. beaker. The filter paper was washed with hot water until 150 ml. of filtrate was obtained. At this point, the filter paper was discarded.

To the filtrate, was added 1 gram of ammonium chloride and 10 ml. of a saturated solution of ammonium oxalate. A few drops of methyl orange was added and the solution heated to boiling on a hot plate with a dropwise addition of concentrated ammonium hydroxide, while stirring until the solution became alkaline to methyl orange. The beaker was then placed on the steam bath and digested for 1 hour. This allowed the calcium oxalate to settle and solution to become clear. This solution was then filtered through a Whatman No. 40 filter paper. The beaker and filter paper was thoroughly washed with hot water until free of oxalates. The filtrate and washings was reserved for magnesium determination.

The filter paper and contents was returned to the beaker carefully. 100 ml. of boiling water and 10 ml. of 1:1 H_2SO_4 added to the beaker and the solution titrated with standardized $KMnO_4$ while still hot. The normality of $KMnO_4$ x 0.002004 = gms. Ca in 25 gms. of soil.

DETERMINATION OF EXCHANGEABLE MAGNESIUM

Concentrated HCl was added drop by drop to the filtrate from the calcium determination until the solution became slightly acid. Then 10 ml. of a 10% solution of dibasic ammonium phosphate was added and beaker cooled to 15° C. Then 30 ml. of concentrated NH_4OH with vigorous stirring, special care being taken not to touch sides of beaker with glass rod. The addition of the NH_4OH was added very slowly and with much care. The beaker was placed in a cool place to allow the precipitate to settle out.

The solution was filtered after all the precipitate had settled and then washed with a dilute solution of ammonia (1 part of concen. NH_4OH in 8 parts of water). Much care was taken to remove all precipitate from beaker by use of policeman.

The titration method of J. O. Handy (J. Amer. Chem. Soc., 1900, 22, pp. 31-39) was used to determine the magnesium ion present. After the precipitate was thoroughly washed and allowed to drain, the filter paper was opened and as much of the moisture as possible was removed by placing it on another dry filter paper. This process repeated several times removed most of the moisture. The filter paper was then dried in the air for 45 minutes to remove the free ammonia. The filter paper and precipitate was then placed in a dry beaker and 5 ml. of N/10 H_2SO_4 and 3 drops of methyl orange added to the beaker also. The whole contents of the beaker was then diluted to 100 ml. with water and titrated with N/10 NaOH solution to a clear yellow color. 1 ml. x N/10 H_2SO_4 = 0.001216 gm. of magnesium.

DETERMINATION OF REPLACEABLE POTASSIUM

The replaceable potassium in the soil was determined by the volumetric cobaltinitrite method described by C. S. Piper (J. So. Chem. Ind., 1934, 53, pp. 392-396T). The following reagents were used in making the determinations:

Glacial Acetic Acid

Sodium Chloride Solution.--A filtered saturated solution.

Sodium Nitrite Solution.--35 gm. of sodium nitrite was dissolved in water, and made up to 100 ml. and filtered.

Cobalt Nitrate Solution.--20 gm. of cobalt nitrate, $Co(NO_3)_2 \cdot 6\ H_2O$, was dissolved in water and then made up to 100 ml. and filtered.

For washing the precipitate a saturated solution of potassium sodium cobaltinitre was used. This was previously prepared by adding about 0.3 gm. of potassium sodium cobaltinitrite to a liter of distilled water and shaking at intervals for an hour, and then filtering through an 11 cm. Buchner funnel of unglazed porcelain. Since this filtrate is somewhat unstable, it was always used within ½ to 1 hour. The color decreases noticeably in 1 hour and disappears completely within 2-3 hours. The supply of potassium sodium cobaltinitrite was prepared by precipitating a potassium chloride solution with sodium cobaltinitrite in the presence of sodium chloride. The precipitate was then collected, washed several times with water and dried by washing with alcohol and ether.

The filtrate and washings from the magnesium determination was made just acid by adding a few drops of HCl and then evaporated to dryness on a steam bath. The HCl acted as an agent in destroying any substances present other than the potassium salt. After the filtrate had reached dryness, the residue was dissolved in 1.5 ml. of glacial acetic acid and 10 ml. of saturated sodium chloride which was added to the beaker in that order, and, after 10 minutes, 5 ml. of sodium nitrite solution was added. The contents of the beaker was stirred thoroughly until all soluble substances were dissolved. After a further 5 to 10 minutes, but not longer, 5 ml. of cobalt nitrate solution was added, the addition was made very rapidly, with constant stirring from a pipette with an extra large jet. After a thorough stirring for 40-60 seconds the beaker was covered and left over night in a cool place.

The supernatant liquid was then decanted through a 10 ml. Gooch crucible charged with asbestos. The asbestos was previously digested with acidified permanganate and then with an excess of oxalic acid; it was then transferred to the crucible, using a rubber-tipped stirring rod, and washed five times with 10 ml. portions of a freshly prepared saturated solution of potassium sodium cobaltinitrite.

A measured volume of standard $KMnO_4$, N/20, about 5 ml. in excess of the quantity required, was pipetted into a beaker, diluted to 150 ml., and 5 ml. of concentrated H_2SO_4 added. The crucible and precipitate was then added, the solution stirred, and heated just to the boiling point. It was then removed from the flame, and after 5 minutes a small excess of N/20 oxalic acid solution was added. The beaker and contents was then reheated nearly to the boiling point, and the titration completed with N/20 $KMnO_4$ until a stable pink color first appeared. Blank determinations were carried out to correct for the small amounts of potassium invariably present in the reagents used. The reagents used were considered satisfactory since the blank titration did not exceed 0.5 ml. of N/20 $KMnO_4$ solution. The presence of ammonium as an impurity in the cobalt nitrate used in the determination leads to a very serious error. Great care was used to eliminate this possible error.

The potassium was calculated from the equation:

K_2O in mgm. = permanganate value x 0.354 + (permanganate value)^2 x 0.00034.

The permanganate value being the amount of potassium permanganate, expressed as ml. of N/20 solution, required to oxidize the precipitate. This equation takes into consideration the change in composition of the precipitate as the quantity of potassium increases.

DETERMINATION OF READILY AVAILABLE PHOSPHORUS

The determinations of readily available phosphorus in these soil samples were made by use of the Truog laboratory method. Truog (46) has suggested the designations readily available and difficultly available be used rather than available and unavailable in speaking of the phosphorus of the soil in relation to its availability to plants.

The following reagents were used in making the phosphorus determinations:

Ammonium molybdate-sulfuric acid solution.--25 grams of ammonium molybdate was dissolved in 200 ml. of water and heated to 60°C. and filtered. 280 ml. of arsenic-and phosphorus-free concentrated sulfuric acid (approximately 36 N) was diluted to 800 ml. After both solutions had cooled, ammonium molybdate solution was added to the sulfuric acid solution slowly with shaking. This solution was diluted to exactly 1,000 ml. after cooling to room temperature. This produced a 10 N sulfuric acid solution containing 2.5 grams of ammonium molybdate per 100 ml.

Stannous chloride solution.--25 grams of $SnCl_2 \cdot 2H_2O$ was dissolved in 1,000 ml. of dilute (10% by volume) HCl solution. The solution was then filtered and stored in a bottle with a side opening near the bottom, arranged with a glass stopcock for delivering the solution in drops.

The solution was protected from the air by floating a layer of white mineral oil about 5mm. thick over the surface.

Sulfuric acid solution for extraction.--A stock solution of exactly N/10 H_2SO_4 was prepared by titrating against a standard alkali. Convenient volumes of 0.002 N H_2SO_4 were prepared from the stock solution by dilution. In order to buffer the solution, 3 grams of $(NH)_2SO_4$ per liter was added to the solution to produce a pH of 3 in the final solution.

Standard phosphate solution.--0.2195 gm. of recrystallized potassium-dihydrogen-phosphate was dissolved and diluted to 1,000 ml. This solution contained 50 p.p.m. of phosphorus which was too concentrated for use directly. A second stock solution was made taking 50 ml. This second stock solution contained 5 p.p.m. and was used in making the standard solution for comparison.

To make this standard solution 5 ml. of the second stock solution was diluted to 95 ml. with distilled water and 4 ml. of the ammonium molybdate-sulfuric acid solution added and mixed thoroughly. Six drops of stannous chloride was added with a thorough shaking. The solution was then diluted to 100 ml. with a vigorous shaking the solution was ready for use. It contained 0.25 p.p.m. of phosphorus. After standing 10 to 12 minutes the standard starts to fade, and a drop more of stannous chloride would then be added to bring the full color back which would again be permanent for 10 to 12 minutes.

In developing the color it was absolutely necessary to maintain the concentration of acid secured according to the directions, since in a less acid solution ammonium molybdate itself gives the blue color with stannous chloride, and in a more acid solution phosphate fails to give its full color.

EXTRACTION AND DETERMINATION OF THE PHOSPHORUS

From the sample of oven-dried soil, 2 grams of 20 mesh soil was placed in a 750 ml. Erlenmeyer flask together with 400 ml. of N/2000 H_2SO_4. The flask and contents was then placed in the shaking apparatus for a 30 minute agitation. At the end of this period, the solution was filtered through a ss. 589 filter paper. The filtrate was discarded until it came through perfectly clear. 50 ml. of this clear filtrate was placed in a 200 ml. Erlenmeyer flask, and 2 ml. of ammonium molybdate-sulphuric acid solution added with a thorough shaking. A blue color developed after this treatment, the intensity depending on the concentration of phosphorus ion in the solution. A standard phosphorus solution was treated similarly. The unknown solution was compared with the standard solution within a few minutes in the colorimeter.

Calculation of available phosphorus in pounds per acre in the plowed layer was as follows:

The 50 ml. of unknown solution used in the analysis represented 50/400 x 2/1 or 1/4 gram of soil. If the standard contains 0.25 p.p.m. of phosphorus, and it takes say 40 ml. of standard to match the unknown, the amount of phosphorus in the soil will be equal to: 40/0.25 x 0.25/1 or 40 p.p.m. Since the plowed layer of mineral soils weighs approximately 2,000,000 pounds, the amount of available phosphorus per acre will be equal to 2 x 40 or 80 pounds per acre.

EXPERIMENTAL DATA

Table 1.--Rate of fertilizer application, amount of phosphorus per application and amount of available phosphorus in soil at different times, all on the acre basis.

Plot No.	Treatment		Lbs. available phosphorus in soil at different times						
	250 lbs per acre	Lbs added per application	*1933	1934	1935	1936	1937	1938	1939
1	3-8-10	8.73	40.7	42.4	36.0	35.8	32.0	34.0	37.3
2	0-0-0	0.00	38.9	39.4	34.7	34.7	29.3	28.8	25.6
3	3-16-10	17.46	53.6	58.9	46.6	45.8	42.8	45.4	39.5
4	3-32-10	34.92	69.6	105.8	77.8	68.0	69.5	85.6	50.0
5	3-48-10	52.38	113.9	135.5	125.1	99.8	118.7	136.1	59.1
6	3-0-10	0.00	28.5	26.4	26.2	27.1	22.0	20.2	34.1
10	3-8-10	8.73	47.8	49.4	47.8	43.0	40.1	36.5	36.4
11	0-0-0	0.00	45.4	41.6	40.9	44.5	34.7	32.7	24.6
12	3-16-10	17.46	66.5	79.3	68.5	57.0	58.3	61.1	40.1
7	3-32-10	34.92	61.9	66.3	67.7	85.2	62.7	69.8	41.6
8	3-48-10	52.38	100.7	110.5	117.0	97.7	106.5	115.0	60.1
9	3-0-10	0.00	33.5	34.1	29.2	33.2	28.2	26.9	35.2
1A	6-8-10	8.73	39.8	41.5	35.1	30.3	30.3	26.5	37.0
2A	3-0-0	0.00	39.5	37.7	35.4	32.3	30.2	27.0	36.6
3A	6-16-10	17.46	54.4	62.6	57.3	47.6	53.4	49.4	47.8
4A	6-32-10	34.92	77.6	99.9	89.8	58.5	79.5	100.5	57.2
5A	6-48-10	52.38	105.8	144.1	137.9	98.6	128.1	138.0	57.6
6A	6-0-10	0.00	37.5	39.1	34.3	31.2	32.0	26.0	36.9
10A	6-8-10	8.73	53.3	56.6	49.5	44.2	44.6	44.4	35.9
11A	3-0-0	0.00	48.4	51.4	47.3	41.1	43.9	42.9	36.3
12A	6-16-10	17.46	50.8	66.3	57.1	42.6	50.7	49.9	44.2
7A	6-32-10	34.92	67.7	90.9	75.5	58.7	70.5	84.9	59.9
8A	6-48-10	52.38	85.4	117.6	97.3	77.5	93.3	115.5	60.1
9A	6-0-10	0.00	29.1	26.5	25.0	23.1	21.9	25.1	36.3

* Indicates first samplings after phosphorus applications. Regular fertilizer applications were made in spring for barley and in September for wheat. Nitrogen only was added for other crops. Soil samples were taken in late October or early November each year after time for applying fertilizer for wheat.

Table 2.--The replaceable bases in soil samples from soil fertility plots in pounds per acre and milliequivalents per 100 grams of oven-dry soil.

Plot No.	Treatment 250 lbs./A	Calcium		Magnesium		Potassium		Phosphorous	
		M.e./ 100 gm. soil	Lbs./ acre	M.e./ 100 gm. soil	Lbs./ acre	M.e./ 100gm. soil	Lbs./ acre	M.e./ 100gm. soil	Lbs./ acre
1	3-8-10	4.34	1735.0	0.510	124.0	0.254	198.2	0.048	37.3
2	0-0-0	4.41	1763.2	0.296	71.9	0.222	173.6	0.033	26.6
3	3-16-10	4.25	1700.0	0.296	71.9	0.285	223.0	0.051	39.5
4	3-32-10	4.36	1745.0	0.210	51.2	0.263	205.8	0.064	50.2
5	3-48-10	4.82	1850.0	0.283	68.9	0.285	223.0	0.075	59.1
6	3-0-10	3.71	1484.0	0.412	100.0	0.263	205.8	0.044	34.1
10	3-8-10	4.82	1930.0	0.496	120.8	0.238	193.5	0.046	36.4
11	0-0-0	4.41	1763.2	0.424	103.2	0.236	184.1	0.032	24.6
12	3-16-10	4.78	1910.1	0.266	64.9	0.290	225.8	0.052	40.1
7	3-32-10	4.31	1720.0	0.296	71.9	0.259	202.1	0.053	41.6
8	3-48-10	5.82	2330.0	0.309	75.2	0.294	229.5	0.078	60.1
9	3-0-10	3.85	1540.0	0.412	100.0	0.261	204.0	0.045	35.2
1A	6-8-10	4.18	1670.0	0.424	103.2	0.224	175.0	0.047	37.0
2A	3-0-0	3.44	1372.0	0.595	145.0	0.234	183.1	0.047	37.0
3A	6-16-10	6.75	2700.0	0.266	64.9	0.246	192.0	0.061	47.8
4A	6-32-10	4.52	1808.0	0.338	82.5	0.242	189.4	0.073	57.3
5A	6-48-10	4.64	1855.0	0.595	145.0	0.309	241.8	0.074	57.6
6A	6-0-10	4.29	1715.0	0.496	121.0	0.277	176.9	0.047	37.0
10A	6-8-10	3.41	1365.0	0.412	100.0	0.282	220.0	0.046	35.9
11A	3-0-0	4.69	1875.0	0.740	180.0	0.226	176.0	0.046	35.9
12A	6-16-10	4.20	1680.0	0.539	131.2	0.246	192.0	0.057	44.2
7A	6-32-10	4.46	1785.0	0.730	177.9	0.244	191.1	0.077	59.9
8A	6-48-10	3.92	1570.0	0.611	148.9	0.276	216.0	0.077	59.9
9A	6-0-10	3.92	1570.0	0.595	145.0	0.264	207.5	0.046	36.3

Table 2a.--The average replaceable bases in soil samples from deuplicate soil fertility plots in pounds per acre and milliequivalents per 100 grams of even-dry soil.

Plot No.	Treatment 250 lbs./A.	Calcium		Magnesium		Potassium		Phosphorus	
		M.e./ 100 gm. soil	Lbs./ acre	M.e./ 100 gm. soil	Lbs./ acre	M.e./ 100gm soil	lbs./ acre	M.e./ 100gm soil	lb./ acre
2 & 11	0-0-0	4.41	1763.2	0.360	91.1	0.229	178.8	0.033	24.6
2A & 11A	3-0-0	4.05	1623.6	0.667	162.5	0.230	179.5	0.047	36.4
6 & 9	3-0-10	2.78	1512.8	0.412	100.0	0.262	204.9	0.044	36.1
6A & 9A	6-0-10	4.11	1641.2	0.545	133.0	0.271	192.9	0.047	36.6
1 & 10	3-8-10	4.58	1832.8	0.503	122.4	0.246	195.8	0.047	36.8
1A & 10A	6-8-10	3.70	1518.0	0.418	101.6	0.253	197.5	0.047	36.4
3 & 12	3-16-10	4.51	1804.8	0.281	68.4	0.287	224.4	0.053	39.8
3A & 12A	6-16-10	5.47	2191.2	0.402	98.1	0.246	192.0	0.059	46.0
4 & 7	3-32-10	4.33	1735.2	0.253	61.5	0.261	203.9	0.058	45.8
4A & 7A	6-32-10	4.49	1796.0	0.534	130.2	0.243	190.2	0.075	58.5
5 & 8	3-48-10	5.32	2130.0	0.296	72.1	0.289	226.2	0.076	59.6
5A & 8A	6-48-10	4.28	1712.8	0.603	146.9	0.292	226.9	0.075	58.8

Table 3.--Grain yields in pounds per acre on phosphorus series from 1933 to 1939 inclusive.

Plot No.	Treatment 250 lbs./A	*1933 Barley grain		1934 Timothy		1935 Wheat		1936 Oats	
		Bu.of grain	Lbs.of Straw	Bu.of grain	Lbs.of Straw	Bu.of grain	Lbs.of Straw	Bu.of Grain	Lbs of Straw
1	3-8-10	10.89	786	--	--	26.62	2759	37.60	1058
2	0-0-0	3.85	320	--	--	17.08	2045	28.14	755
3	3-16-10	8.00	555	--	--	24.68	2336	32.00	781
4	3-32-10	8.89	633	--	--	27.17	2435	31.20	930
5	3-48-10	7.11	519	--	--	25.03	2190	31.87	934
6	3-0-10	6.67	526	--	--	17.98	1991	32.00	879
1A	6-8-10	7.78	580	--	--	21.23	2253	35.74	956
2A	3-0-0	2.89	238	--	--	13.97	1734	38.14	806
3A	6-16-10	8.15	633	--	--	28.49	2771	32.67	845
4A	6-32-10	8.00	633	--	--	30.01	2763	33.34	939
5A	6-48-10	7.41	540	--	--	25.72	2386	32.94	1007
6A	6-0-10	7.63	644	--	--	21.64	2311	32.94	947
10	3-8-10	8.15	569	--	--	25.65	2526	35.07	977
11	0-0-0	3.85	320	--	--	17.84	2000	27.47	828
12	3-16-10	8.00	647	--	--	26.07	2502	32.67	917
7	3-32-10	8.22	558	--	--	25.44	2414	31.34	832
8	3-48-10	7.56	512	--	--	28.62	2638	31.87	900
9	3-0-10	6.81	512	--	--	20.05	2116	30.94	879
10A	6-8-10	4.52	452	--	--	27.93	2638	32.14	986
11A	3-0-0	2.89	238	--	--	20.88	2356	27.07	900
12A	6-16-10	7.11	590	--	--	30.49	3066	30.54	824
7A	6-32-10	6.22	462	--	--	26.90	2493	26.40	828
8A	6-48-10	7.56	526	--	--	31.80	2945	31.34	981
9A	6-0-10	4.00	384	--	--	21.43	2448	32.37	990

Table 3e :--Grain yields in pounds per acre on phosphorus series from 1933 to 1939 inclusive.

Plot No.	Treatment 250 lbs./A	*1937 Barley		1938 Timothy		*1939 Wheat	
		Bu.of grain	Lbs.of straw	Bu. of grain	Lbs. of straw	Bu. of grain	Lbs. of Straw
1	3-8-10	19.91	768	--	--	25.16	2329
2	0-0-0	7.29	384	--	--	19.62	1595
3	3-16-10	12.53	491	--	--	23.03	1988
4	3-32-10	14.22	574	--	--	24.45	2159
5	3-48-10	11.11	463	--	--	22.40	1886
6	3-0-10	13.42	559	--	--	19.42	1647
				--	--		
1A	6-8-10	18.31	789	--	--	23.46	2048
2A	3-0-0	8.53	435	--	--	19.05	1587
3A	6-16-10	16.96	666	--	--	24.31	1954
4A	6-32-10	16.36	740	--	--	25.45	2099
5A	6-48-10	13.07	563	--	--	25.16	2159
6A	6-0-10	20.09	952	--	--	23.74	2116
10	3-8-10	19.11	841	--	--	25.31	2065
11	0-0-0	6.58	405	--	--	19.90	1578
12	3-16-10	16.71	734	--	--	25.88	2031
7	3-32-10	14.94	623	--	--	25.59	2048
8	3-48-10	17.87	713	--	--	26.73	2235
10A	6-8-10	13.81	563	--	--	25.38	2201
11A	3-0-0	5.96	367	--	--	22.32	1860
12A	6-16-10	12.71	512	--	--	25.88	2009
7A	6-32-10	12.18	491	--	--	25.31	2193
8A	6-48-10	14.67	602	--	--	26.02	2193
9A	6-0-10	14.76	614	--	--	24.45	2116

Table 4.--Grain yields in pounds per acre on phosphorus series from 1933 to 1939 inclusive.[1]

Plot No.	Treatment 250 lbs./A	Barley	Wheat	Oats	Barley	Wheat
1	3-8-10	523	1597	1203	956	1510
2	0-0-0	185	1025	900	350	1177
3	3-16-10	384	1481	1024	601	1382
4	3-32-10	427	1630	998	683	1467
5	3-48-10	341	1502	1020	533	1356
6	3-0-10	320	1079	1024	644	1169
1A	6-8-10	373	1274	1144	879	1408
2A	3-0-0	139	838	900	409	1143
3A	6-16-10	391	1709	1045	815	1459
4A	6-32-10	384	1801	1067	785	1527
5A	6-48-10	356	1543	1084	627	1510
6A	6-0-10	366	1298	1054	964	1424
10	3-8-10	391	1539	1122	917	1519
11	0-0-0	185	1070	879	316	1194
12	3-16-10	384	1564	1045	802	1553
7	3-32-10	395	1526	1003	717	1535
8	3-48-10	363	1717	1020	858	1604
9	3-0-10	327	1303	990	845	1365
10A	6-8-10	217	1676	1028	648	1553
*11A	3-0-0	139	1253	866	286	1339
12A	6-16-10	341	1829	977	610	1553
7A	6-32-10	299	1614	845	585	1519
8A	6-48-10	363	1908	1003	704	1561
9A	6-0-10	192	1286	1033	708	1467

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[1] Acknowledgement is made to Mr. A. G. Weidemann, Research Assistant, for his compilation of tables in this study.

*Barley on plat 11A was destroyed by pheasants. Yield of duplicate plot was inserted here to facilitate averaging and totaling.

Table 4a.--The total average yield of wheat, oat, and barley grain and the total yield of grain and straw from duplicate plots of the phosphorus series 1933 to 1939, all on pounds per acre basis.

Plot No.	Treatment 250 lbs./A	Wheat	Oat	Barley	Total Yield of grain 1933-1939 inclusive	Total Yield of straw, excluding timothy 1933-1939 inclusive
2 & 11	0-0-0	1117	889	259	3541	5110
2A &11A	3-0-0	1143	883	343	3656	5261
6 & 9	3-0-10	1204	1009	534	4483	5881
6A & 9A	6-0-10	1369	1043	557	4896	6761
1 & 10	3-8-10	1541	1162	696	5638	7329
1A & 10A	6-8-10	1478	1086	524	5100	6737
3 & 12	3-16-10	1495	1034	543	5110	6491
3A & 12A	6-16-10	1637	1011	539	5364	6919
4 & 7	3-32-10	1540	1001	555	5191	6603
4A & 7A	6-32-10	1615	956	513	5213	6821
5 & 8	3-48-10	1545	1020	524	5157	6495
5A & 8A	6-48-10	1631	1028	513	5314	6936

Table 4b.--The total average yield of wheat, oat, and barley grain; and the total yield of straw and grain fromo plots grouped according to per cent P in the treatment.[1]

Plot No.	% P in fertilizer treatment 250 lbs./A	Wheat	Oat	Barley	Total yield of grain 1933-1939 inclusive	Total yeild of straw excluding timothy 1933-1939 inclusive
2,11, 2A,11A	checked	1208	956	398	4096	5603
1,10, 1A,10A	8%	1509	1124	610	5369	7033
3, 12, 3A,12A	16%	1566	1022	541	5237	6705
4,7, 4A,7A	32%	1577	978	534	5202	6712
5,8, 5A,8A	48%	1588	1024	518	5235	6665

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[1] The fertilizer treatment was applied at the rate of 250 pounds per acre.

Table 5.--Fertilizer treatment and the total average yield per treatment from 1933 to 1939 inclusive, all on the acre basis.

Plot No.	Treatment		Yields (1933-1939 inclusive)		
	250 lbs. per acre	Lbs. of P added per application	Total lbs of grain	Total lbs of straw (excluding Timothy)	Total lbs of grain and straw
1	3-8-10	8.73	5789	7700	13489
2	0-0-0	0.00	3637	5099	8736
3	3-16-10	17.46	4872	6151	11023
4	3-32-10	34.92	5205	6731	11936
5	3-48-10	52.38	4752	5992	10744
6	3-0-10	0.00	4236	5602	9838
10	3-8-10	8.73	5488	6978	12466
11	0-0-0	0.00	3644	5131	8775
12	3-16-10	17.46	5348	6831	12179
7	3-32-10	34.92	5176	6475	11651
8	3-48-10	52.38	5562	6998	12569
9	3-0-10	0.00	4730	6161	10891
1A	6-8-10	8.73	5078	6626	11704
2A	3-0-0	0.00	3429	4800	8229
3A	6-16-10	17.46	5419	6869	12288
4A	6-32-10	34.92	5564	7174	12738
5A	6-48-10	52.38	5090	6625	11715
6A	6-0-10	0.00	5106	6970	12076
10A	6-8-10	8.73	5122	6840	11962
11A	3-0-0	0.00	3883	5721	9604
12A	6-16-10	17.46	5310	7001	12311
7A	6-32-10	34.92	4862	6467	11329
8A	6-48-10	52.38	5539	7247	12785
9A	6-0-10	0.00	4686	6552	11238

Table 6.--Replaceable bases in pounds per acre in plowed layer and the total average yield of wheat, oat, and barley grain in pounds per acre from 1933-1939 inclusive.

Plot No.	Treatment 250 lbs./A		Pounds per acre in plowed layer			Yield(1933-1939 incl.) in total pounds per A.		
		P	K	Ca	Mg	Wheat	Oats	Barley
2	0-0-0	25.6	173.6	1763.2	79.1	1103	900	267
11	0-0-0	24.6	184.1	1763.2	103.2	1132	879	251
2A	3-0-0	36.6	183.1	1374.4	145.0	991	900	274
11A	3-0-0	36.3	176.0	1872.8	180.0	1296	1866	213
6	3-0-10	34.1	205.8	1484.8	100.0	1124	1024	482
9	3-0-10	35.2	204.0	1540.8	100.0	1284	1990	586
6A	6-0-10	36.9	176.9	1712.8	121.0	1361	1054	665
9A	6-0-10	36.3	207.5	1569.6	145.0	1377	1033	450
1	3-8-10	37.3	197.2	1735.2	124.0	1554	1203	739
10	3-8-10	36.4	193.5	1930.4	120.8	1529	1122	654
1A	6-8-10	37.00	175.0	1678.0	103.2	1341	1144	626
10A	6-8-10	35.9	220.0	1364.0	100.0	1615	1028	433
3	3-16-10	39.5	223.0	1698.4	71.9	1432	1024	493
12	3-16-10	40.1	225.8	1910.2	64.9	1559	1045	593
3A	6-16-10	47.8	192.0	2702.4	64.9	1584	1045	603
12A	6-16-10	44.2	192.0	1680.0	131.2	1691	977	476
4	3-32-10	50.0	205.8	1744.8	51.2	1549	998	555
7	3-32-10	41.6	202.1	1725.6	71.9	1531	1003	556
4A	6-32-10	57.2	189.4	1808.0	82.5	1664	1067	585
7A	6-32-10	59.9	191.1	1784.0	177.9	1567	845	442
5	3-48-10	59.1	223.0	1930.4	68.9	1429	1020	437
8	3-48-10	60.1	229.5	2329.6	75.2	1661	1020	611
5A	6-48-10	57.6	241.8	1856.0	145.0	1527	1054	492
8A	6-48-10	60.1	216.0	1569.6	148.9	1735	1003	534

DISCUSSION OF RESULTS

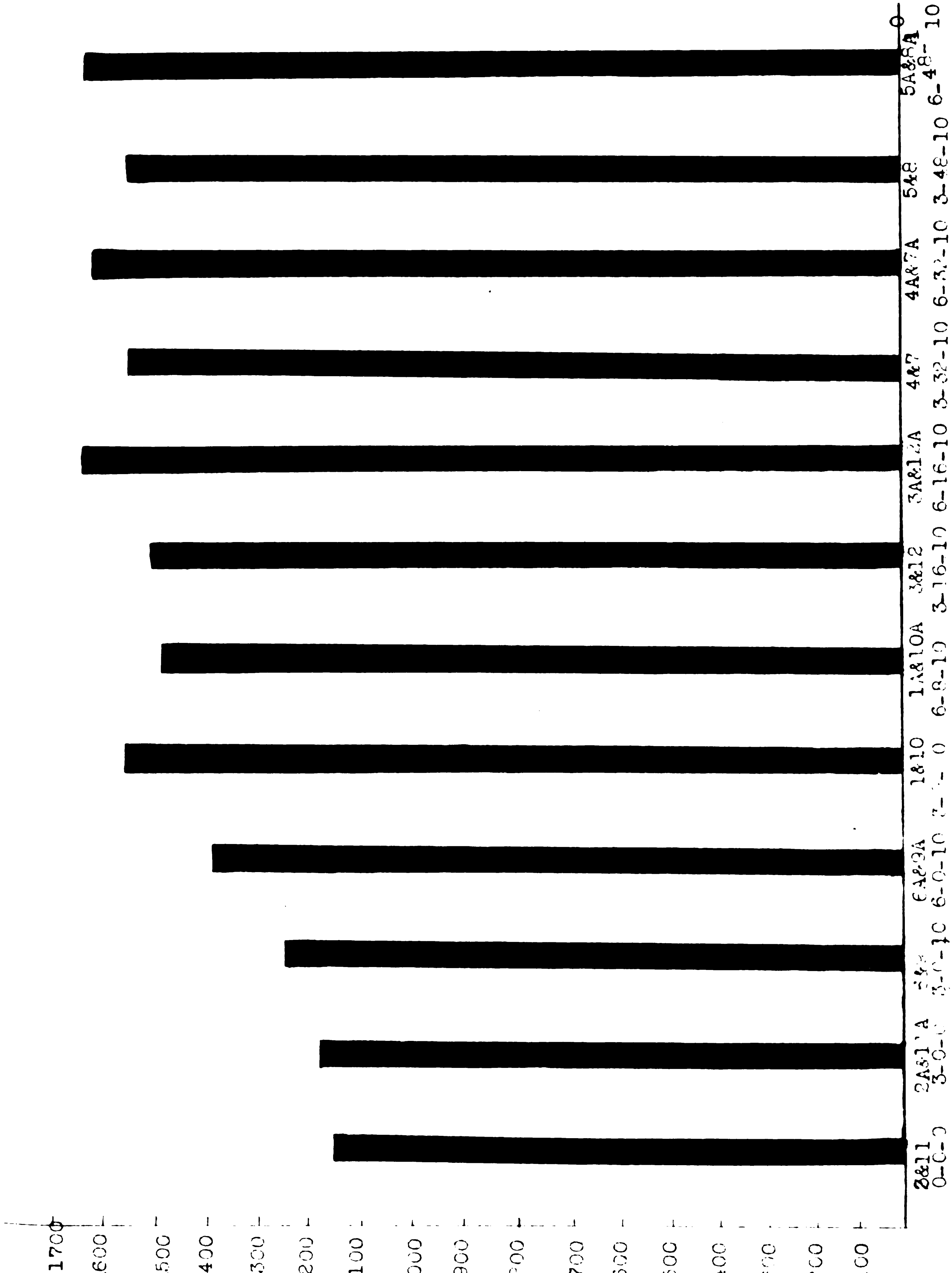
The tables given in the appendix of this study give the results obtained by Weidemann (50) in his studies with the phosphorus series at Michigan Agricultural Experiment Station, East Lansing, Michigan. The same results are presented by graphs (figure 1 to figure 8 inclusive) under the discussion of results.

Results With Wheat

From the data in Table 4a, the increase in average yield of plots 2A and 11A over plots 2 and 11 which were total check plots is not considered significant. It is quite apparent, however, that the 3-0-0 treatment caused a marked rise in the replaceable magnesium as shown by figure 6, and table 2a. The increase in yield on plots 6 and 9 over check plots 2 and 11 becomes significant with the 3-0-10 treatment. This treatment gave a marked increase in replaceable potassium accompanied by a decrease in replaceable calcium and magnesium. Treatment 6-0-10 on plots 6A and 9A gave a further increase in yield but here, too, the increase of percentage nitrogen in treatment caused an increase in replaceable magnesium and a decrease in the amount of replaceable potassium.

Plots 1 and 10 which received the 3-8-10 treatment gave a significant increase in yield over all plots receiving no phosphorus in their treatments. The 6-8-10 treatment on plots 1A and 10A gave a smaller yield than plots 1 and 10. The replaceable magnesium was further decreased with this treatment on plots 1A and 10A. The treatment of plots 3 and 12 with a 3-16-10 did not give a significant increase in

Figure 1.--Average wheat yield on duplicate plots in pounds per acre. (1933-1939 inclusive)



yield over plots 1A and 10A. There was a decided decrease in replaceable magnesium with the 3-16-10 treatment. The yield on plots 3A and 12A was significantly greater than the yield of wheat on plots 3 and 12. Data in figure 6 reveals a slight increase in the amounts of replaceable phosphorus, calcium, and magnesium but a decrease in the amount of available potassium.

The 3-32-10 treatment on plots 4 and 7 gave a smaller yield than plots 4A and 7A which received the 6-32-10 treatment. The increase of percentage nitrogen in treatment caused a significant increase in yield. The replaceable phosphorus, calcium and magnesium on plots 4 and 7 were decreased with the 3-32-10 treatment, but with an increase in amount of replaceable potassium. The 6-32-10 treatment on plots 4A and 7A gave the opposite effects, a marked decrease in replaceable potassium and an increase in replaceable phosphorus, calcium, and magnesium. These results do not verify the results obtained by Fudge (14) whose data show that an increase of nitrogen fertilizer to the soil caused a marked decrease in replaceable phosphorus while the water soluble potassium was decreased.

Plots 5A and 8A which received the 6-48-10 treatment gave a significant increase in yield over plots 5 and 8 treated with the 3-48-10. In this case the increase in percentage nitrogen caused a depression of available phosphorus and calcium accompanied by an increase in available potassium and magnesium. This data seems to verify the results obtained by Fudge (14).

From the data of Willis et. al. (52), no mutual relation was found between the magnesium deficiency and phosphorus deficiency but to observe the data in figure 6, it seems that those factors which caused a decrease in the amount of replaceable magnesium caused a similar decrease in the amount of replaceable phosphorus.

It was pointed out by Weidemann (50) that no relationship was found to exist between the amount of readily available phosphorus and phosphorus content of the wheat grain but a fairly consistent relationship was found to exist between the amount of readily available phosphorus in the soil and the phosphorus content of chaff and straw. It is the belief of the writer that any reciprocal factor which cause an increase in the absorption of phosphorus into the plant will result in a decrease in amount of replaceable phosphorus in the soil.

From the results obtained with wheat it is significant to note that the reciprocal effects caused by the fertilizer treatments tend to increase the yields when there is an increase in the amounts of replaceable phosphorus, calcium, and magnesium. It is apparent that the 6% nitrogen treatment gave the most beneficial results. From the practical and economical standpoint, it seems that the 6-16-10 treatment gave the best results for the 5-year period oh the Hillsdale sandy loam.

RESULTS WITH OATS

The highest oat yield was obtained on plots 1 and 10 which received the 3-8-10 treatment. Despite the continuous increase in the amount of phosphorus applied the average yield on the fertility plots did not give a significant increase in yield.

Plots 2 and 11 which were total check plots gave a higher yield than plots 2A and 11A which received the 3-0-0 treatment. With the exception of plots 4A and 7A, the yields for the rest of plots were not

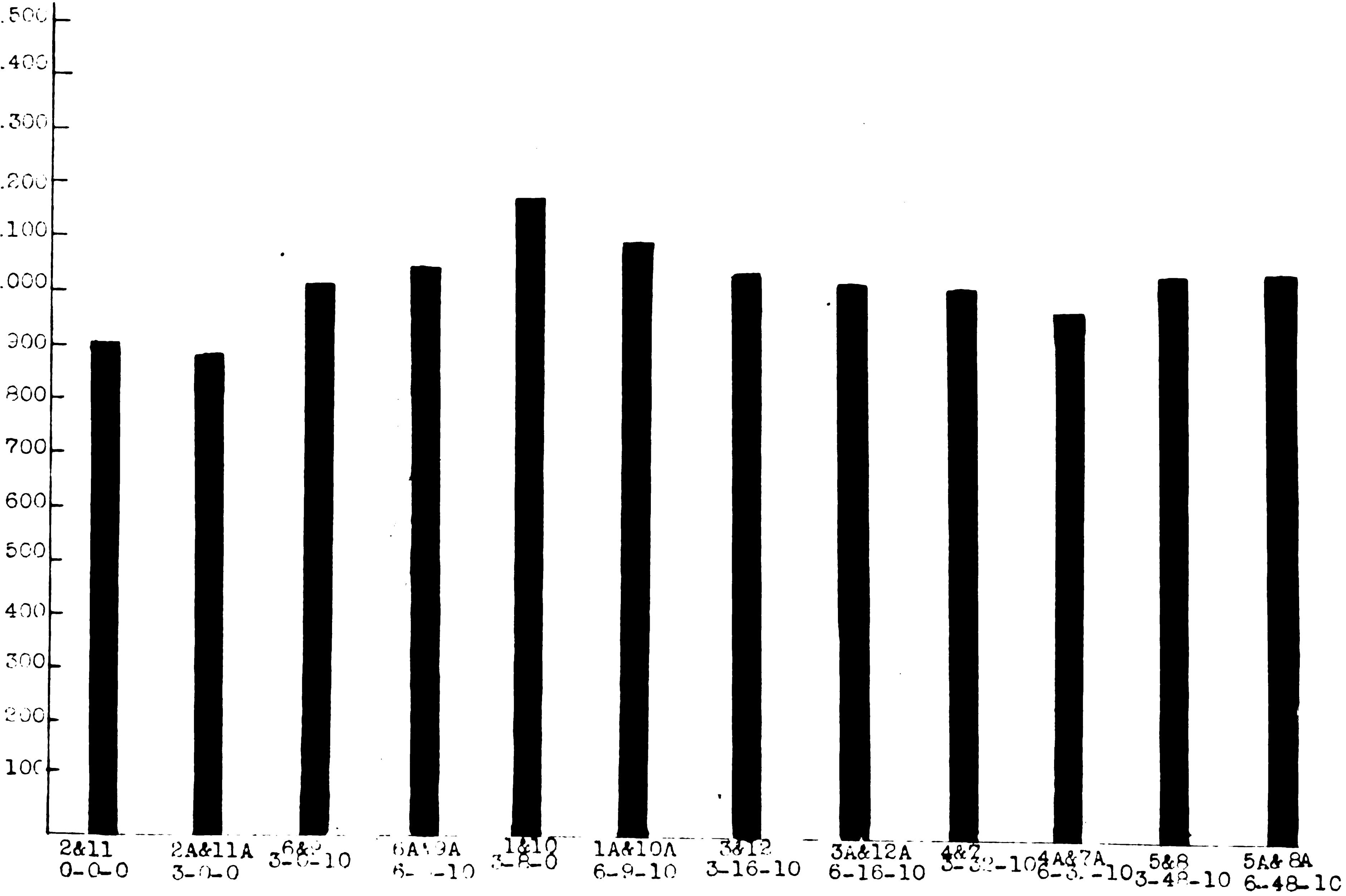


Figure 2.--Average oat yield on duplicate plots in pounds per acre. (1933-1939 inclusive)

significantly different. From the data of figure 6, the decrease in replaceable potassium appears to have been the limiting factor since there were increases in the other replaceable base on these two plots. This result tends to confirm the data presented by Bray (4) who found that any increase in the available calcium and magnesium gave a decrease in the amount of potassium in solution in that the potassium in solution is inversely proportional to the sum of other replaceable bases times their ease of replacement factors.

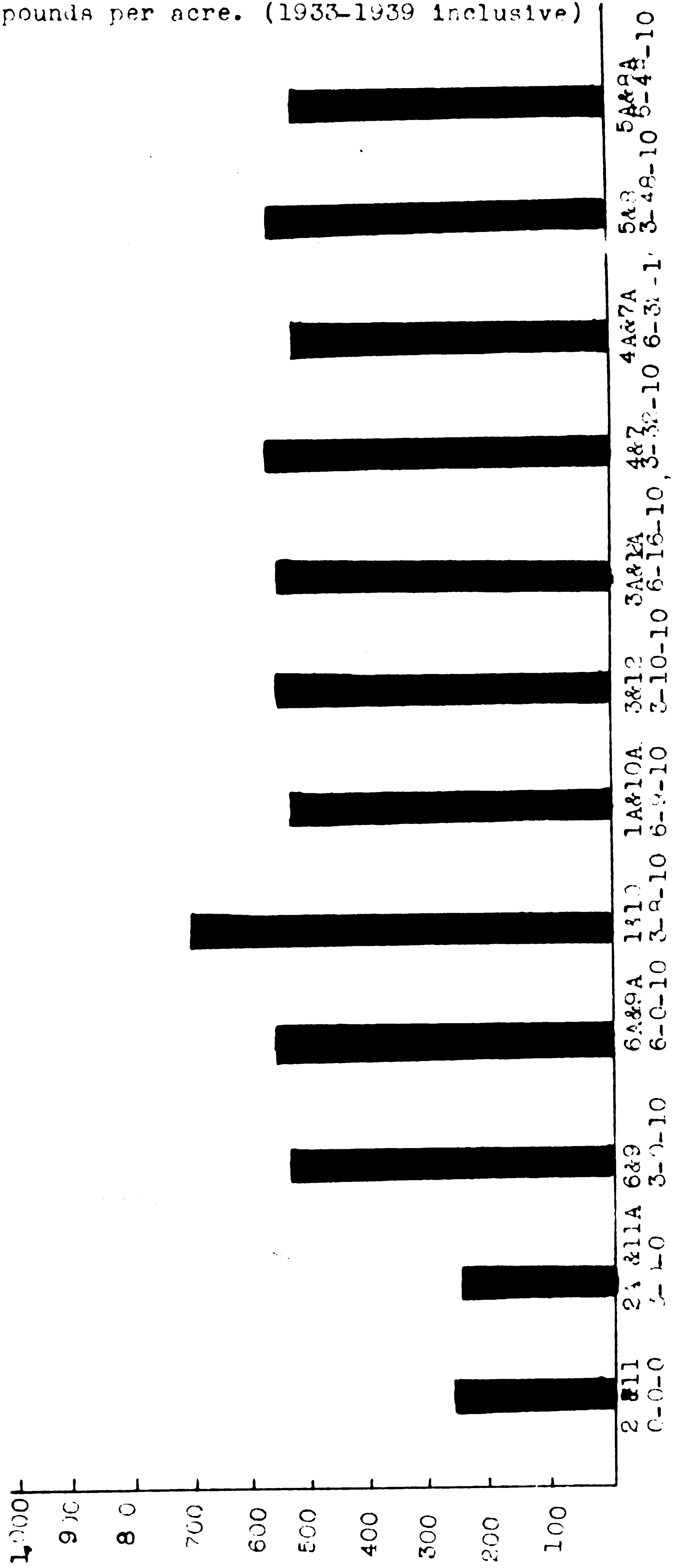
No relation was found to exist between the amount of phosphorus applied and the yield of oats. Weidemann (50) has shown that there was an increase in phosphorus content of grain due to increased application of phosphorus fertilizers. In case of chaff and straw the same relation held true between treatment and phosphorus content of this material as was found in the grain, although differences in phosphorus content due to treatment, or some other cause, were greater with chaff and straw than with grain.

For practical use of the data secured by this investigation, the writer believes it is more beneficial to use the 3-8-10 treatment on the Hillsdale sandy loam for the most economical production of the oat crop.

RESULTS WITH BARLEY

Observing the data presented in table 4a and figure 3, there was no significant difference in yield between the total check plots 2 and 11 and plots 2A and 11A receiving the 3-0-0 treatment; however, the 3-0-0 treatment did give a slight decrease in yield. There was a decrease in replaceable calcium and an increase in replaceable phosphorus,

Figure 3.--Average barley yeild on duplicate plots in pounds per acre. (1933-1939 inclusive)



potassium, and magnesium on plots 2A and 11A.

There was a marked increase in yield on plots 6 and 9 treated with the 3-0-10 fertilizer and plots 6A and 9A treated with the 6-0-10 fertilizer of the check plots 2 and 11 and plots 2A and 11A. Plots 6 and 9 showed a marked increase in amount of replaceable potassium but a decrease in the amounts of replaceable phosphorus, calcium, and magnesium. Plots 6A and 9A gave a slight increase in yield of barley over plots 6 and 9. Here the replaceable potassium was depressed with a consequent increase in available phosphorus, calcium, and magnesium.

Plots 1 and 10 receiving the 3-8-10 treatment, gave the highest yield. This treatment gave a slight increase in the amount of replaceable calcium with a consequent decrease in the amounts of available potassium and magnesium. The replaceable phosphorus showed no change. There were no significant increases in yields due to the increased amounts of phosphorus applied. This seems to verify the results obtained by Richer and White (37) who found no correlation between the available phosphorus and crop yield, but only after long continued use of phosphate fertilizer the soil tends to reach a phosphorus equilibrium. When this equilibrium is approached, available phosphorus has a tendency to show an excellent correlation with crop yield.

Figure 4.--The total yield of grain on duplicate plots in pounds per acre (Wheat, oats, barley 1933-193[illegible] inclusive)

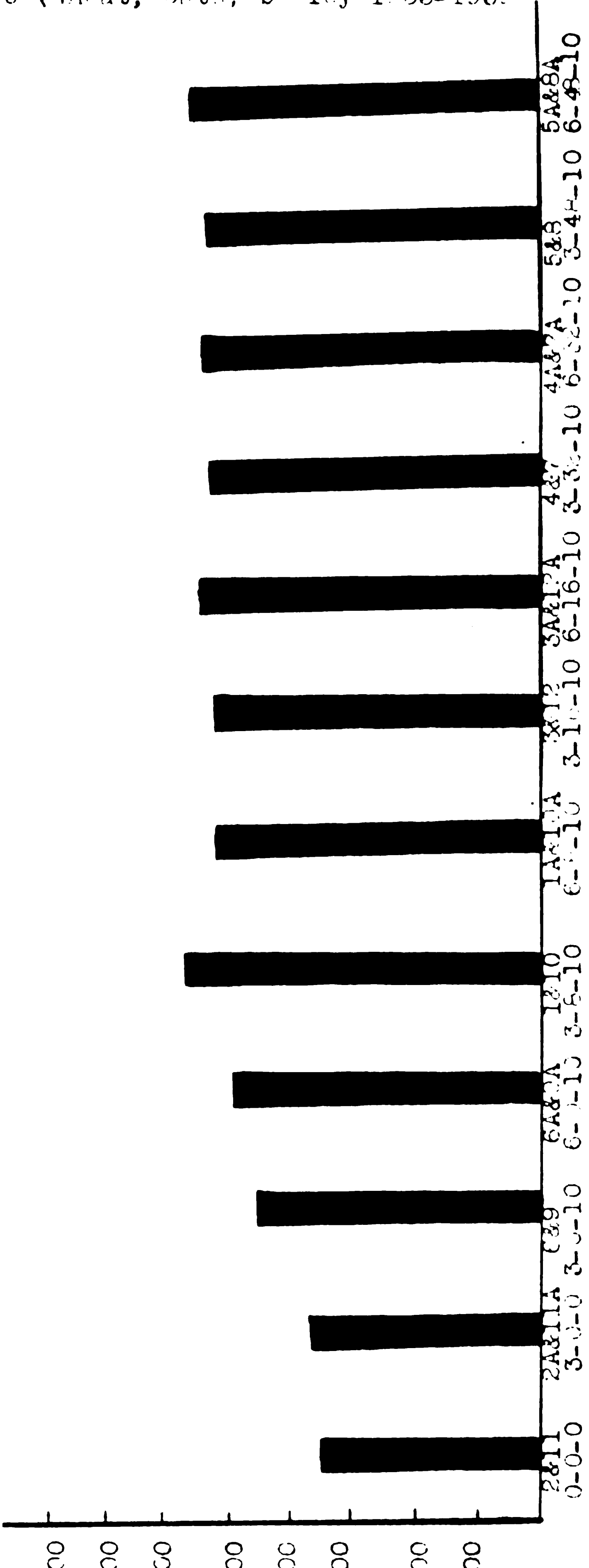


Figure 5.--The total yield of straw on duplicate plots in pounds per acre, (Wheat, oats, barley (1933-1939 inclusive)

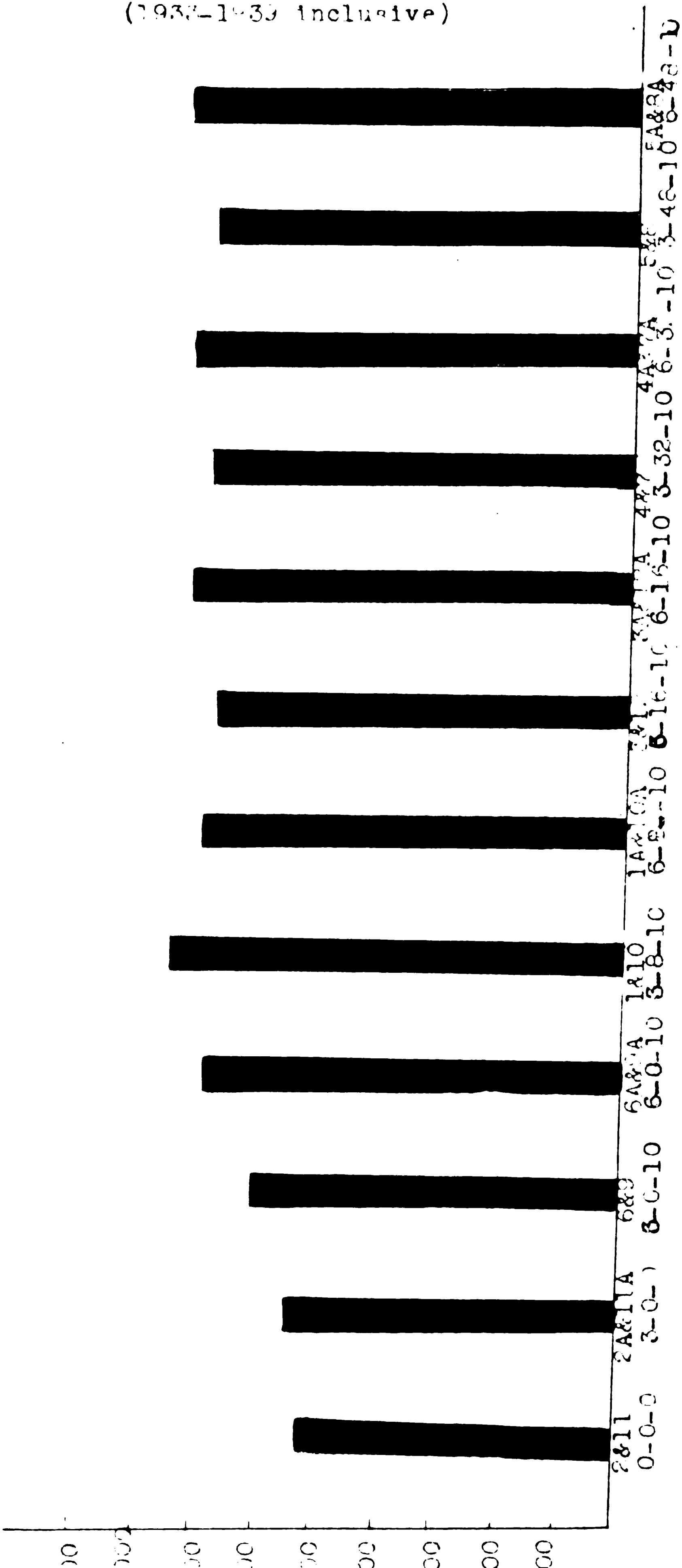


Figure6.--Relationship of replaceable bases in pounds per acre to the total yield of grain andstraw on duplicate plots

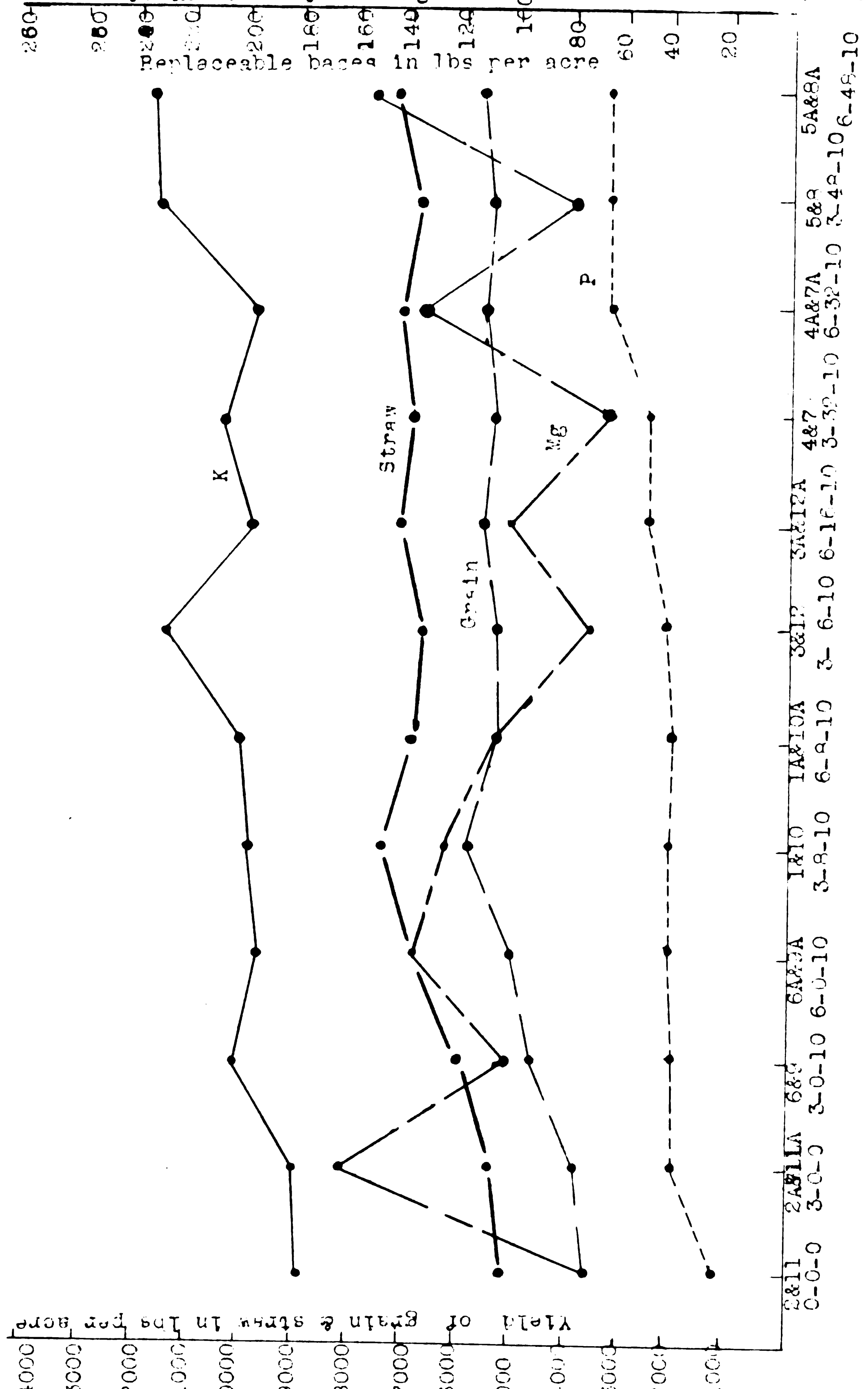


Figure 7.--Relationship of replaceable calcium in pounds per acre to the toal yield of grain and straw on duplicate plots in pounds per acre (1937-1939 inclusive)

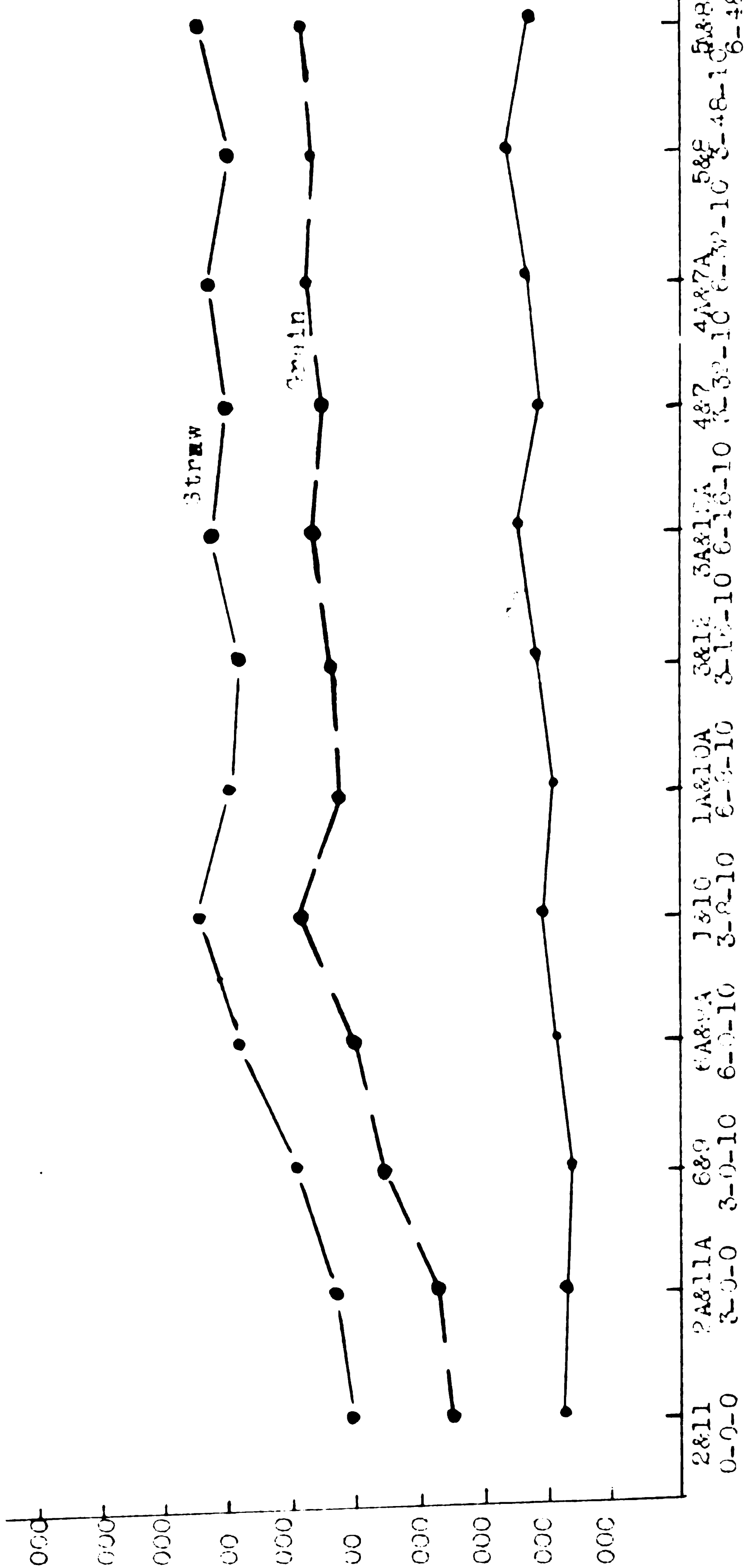


Figure 8.--Milliequivalents of replaceable bases per 100 grams of oven-dry soil from duplicate plots

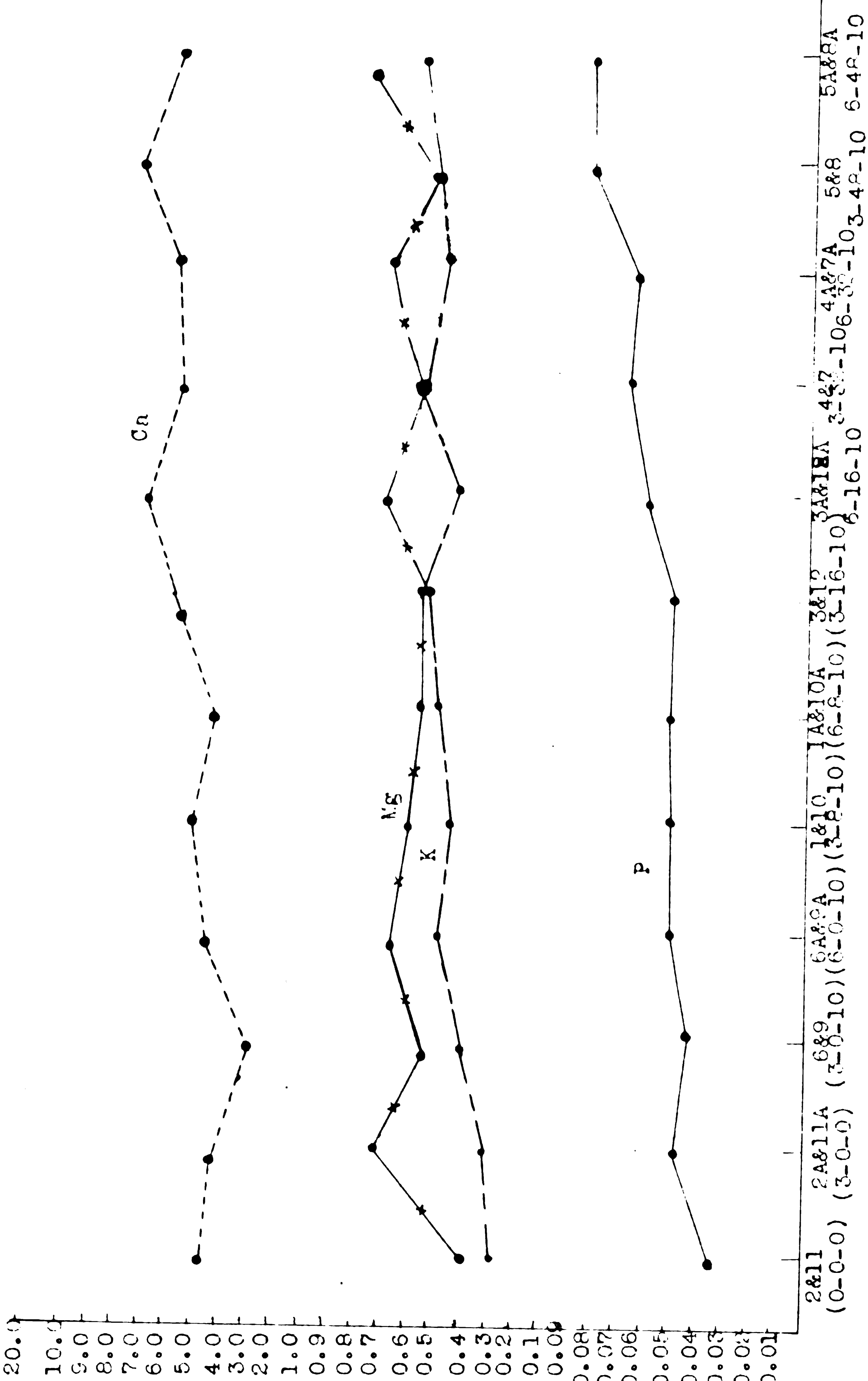


Figure 9.--Proportion of replaceable bases in pounds per acre of soil fertility plots with maximum and minimum yield of wheat and oats.

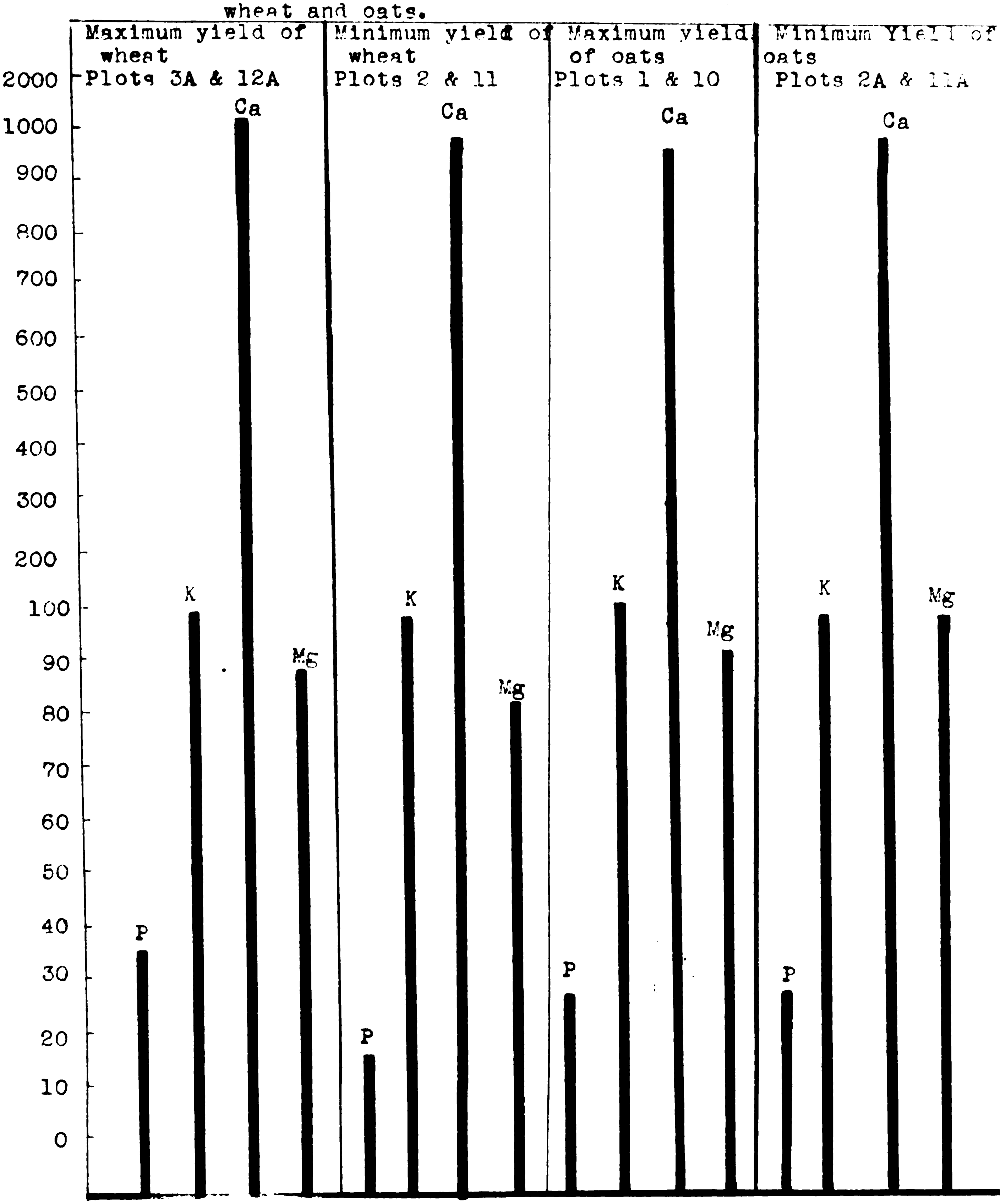
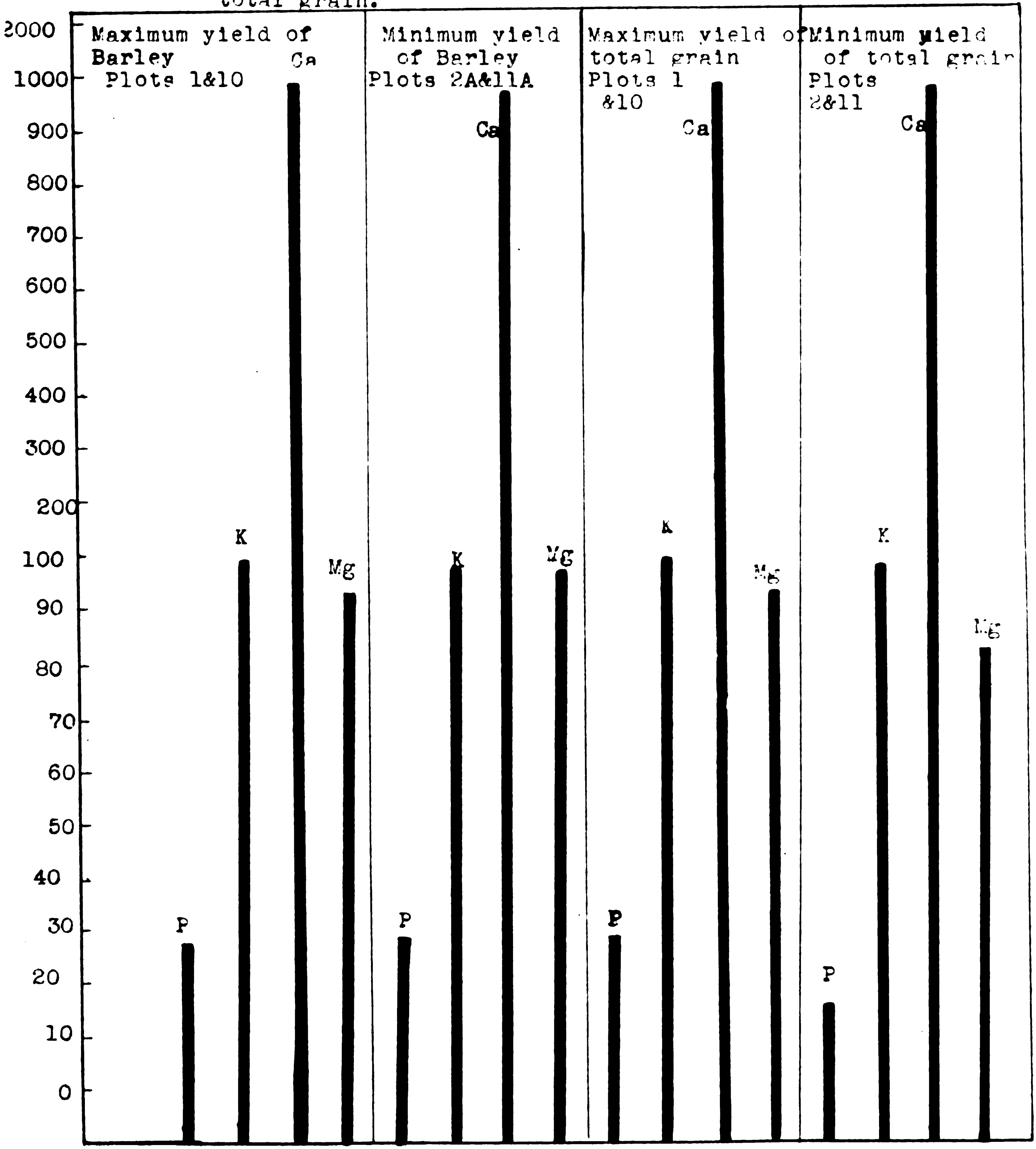


Figure 9a-- Proportion of replaceable bases in pounds per acre of soi fertility plots with maximun and minium yield of barleyand total grain.



SUMMARY AND CONCLUSIONS

1. The data obtained from this study did not reveal a consistent increase in yield of the crops grown due to the application of phosphorus in addition to the nitrogen and potassium. The efficiency of the added phosphorus treatments varied widely. Wheat was the only crop grown which showed a consistent increase in yield due to the application of phosphorus and in many cases this increase had no significance.
2. The untreated plots showed less available phosphorus than those plots receiving phosphorus treatments.
3. Those plots giving the largest amounts of replaceable phosphorus gave higher yields than plots with lower amounts of replaceable phosphorus.
4. The results indicated that increases in the amounts of replaceable phosphorus resulted in similar increases in amounts of available magnesium and calcium but a decrease in the amounts of replaceable potassium.
5. It was found that a decrease in the amounts of replaceable phosphorus resulted in similar decreases in replaceable magnesium and calcium but with an increase in the amounts of available potassium.
6. Decreases in the amounts of replaceable magnesium gave a decrease in yields of both grain and straw and also a decrease in amounts of replaceable phosphorus and calcium. A decrease in crop yield accompanied a decrease in the replaceable magnesium.

7. Increases in the amounts of available potassium resulted in a decrease in the amounts of replaceable phosphorus, calcium, and magnesium, this being accompanied by a decrease in crop yield. A decrease in the amount of available potassium gave an increase in the amounts of replaceable phosphorus, calcium and magnesium which was accompanied by a marked increase in crop yield.
8. No evidence was found which indicated any significant residual effects due to the phosphorus applications over a period of years.
9. The pH range of the soil was 5.2 to 6.4 and it is quite probable that a considerable portion of the phosphorus added in the fertilizer treatments has become fixed in a difficult available form. The amounts of available phosphorus on the plots as revealed by the analysis is not sufficient for a productive crop.
10. It is the belief of the writer that if the phosphorus applications are continued over a longer period of years the soil shall eventually reach a phosphorus equilibrium, and as this equilibrium is approached a more direct correlation between phosphorus applications and crop yield should be expected.

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