A CHEMICAL AND BIOLOGICAL STUDY OF THE RESIDUAL PHOSPHORUS OF HEAVILY FERTILIZED SOILS

By

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF TABLES (Continued)

LIST OF TABLES (Continued

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

INTRODUCTION

Phosphorus is added to soils in the form of fertilizers and organic residues to supply one of the essential elements of plant growth. The amount of phosphorus removed by crops and leaching is comparatively small. Considerable accumulation of phosphorus in soils has resulted in certain regions that have received heavy fertilization for many years. The purpose of the work reported here was to investigate some of the factors governing the availability for crop growth of accumulated or residual phosphorus. The means employed were the study of crop growth on various soils under greenhouse conditions and the chemical measurement of the extent of soil phosphorus utilization.

THEORY AND SCOPE OF THE INVESTIGATION

Methods for Determining Availability of Phosphorus

One means of determining the availability of soil phosphorus is the measurement of the response of plants grown under conditions where phosphorus is the limiting factor. In addition to time-honored plot and field tests, elaborate greenhouse and laboratory methods have been devised with this purpose in mind. Among these are the pot technique of Mitscherlich (41), the rye seedling method of Neubauer (45), and various microbiological procedures (38,46). Such methods are often expensive and time-consuming, although the Neubauer and microbiological tests are less so and, in addition, provide considerable control of environmental conditions. There are numerous references to these methods in the literature. The work of Thornton (62) with the Neubauer and that of Mehlich (38) with the microbiological procedures have been outstanding in this country.

A direct chemical estimation offers still greater simplicity and economy. There have been several such approaches made, although they have to be standardized by plant tests. This type of chemical method has evolved from the attempt to duplicate the solvent effects surrounding living plant roots in the soil. In 1845 Daubeny (14) suggested carbonic acid as a reagent to distinguish between more and less soluble nutrients. Dyer (21) introduced the terms "available" and "unavailable" to distinguish between these groups. He used one per cent citric acid as a solvent and found that the quantities of phosphate it dissolved were in the same order as the crop producing power of various soils.

The theoretical basis for the use of one per cent citric acid was that it approached in degree of acidity that of the cell sap and therefore it exerted a solvent action of the same order as root secretions in rendering phosphate soluble for assimilation. It is uncertain that the root possesses special excreting and dissolving properties other than that exerted by carbonic acid produced in respiration. Russell and Prescott (56) say not but other, more recent workers (8), have regarded it as a possibility. Whether empirical or not, one per cent citric acid found wide currency. This reagent has been joined by many others of the same type. These include solutions of inorganic or organic acids, salt solutions, or mixtures of these buffered to definite pH values. The phosphorus dissolved by such procedures is often called "readily available", "easily acid-soluble", "readily soluble", etc.

Similar results with respect to total phosphorus extracted are not obtained with any two of these reagents or with the same reagent under different conditions (28,29,57). But on a relative basis there is frequently good correlation among the results of different extraction methods themselves (54,69,72) and also between these results and the results of biological measurements (54,58,59). This is especially true on related soils receiving similar fertilizer treatments.

The limitations of such methods when applied to soils not meeting the requirements of close relationship or similar fertilization has received considerable attention. Thornton (62) states "that no extracting agent has been found which will give a true indication of availability to plants under all conditions." Hibbard (34) and Fraps and Fudge (25) have investigated the limitations of chemical methods for estimating phosphorus availability. Burd and Murphy (8) have discussed the problem. They hold that lack of correlation between plant growth and acid-extractable phosphate might be caused by plants possessing the property of absorption of ions such as phosphate without causing a shift in pH value of the soil solution such as would be caused by acid extraction. The mechanism postulated is that of a contact anion exchange without the intermediary of the soil solution between anions on the root surfaces for phosphate anions on mineral surfaces. Dean and Rubins (17), Overstreet (48), and Volk (66) have shown that such a mechanism is unlikely for anions. Another reason advanced by Burd and Murphy for the lack of correlation is the fact that extracting solutions produce greater shifts in pH values than occur naturally in soils and dissolve greater amounts of phosphate than would dissolve under field conditions. A third reason is held to be the presence of secondary reactions in which ions such as calcium dissolved by the extractant in turn precipitate phosphate.

The absorption of phosphate by plant roots prevents the occurrence of such secondary reactions.

Another way of viewing the picture is to presume that there are different chemical forms of phosphorus in soils. Their availability to the plant may fall in one order and their solubility in various extractants may fall in an entirely different order. For instance, it would be hazardous to compare the phosphorus availability of a calcareous soil with that of an acid soil by means of a single extracting solution. Entirely different types of extractants have been proposed for calcareous soils (13,35). A further instance occurs with soils fertilized with different phosphate carriers. Values for readily soluble phosphorus obtained on a soil fertilized with rock phosphate may be entirely out of line with those obtained on the same soil fertilized with superphosphate or other phosphorus carriers when the two are judged on the basis of crop response (53,59).

Another type of chemical approach has as its object the quantitative measurement of a definite soil phosphorus fraction or fractions. The hydroxyl ion has found application in many such methods. Several schemes have been proposed (15,16,26,27,71). They are based on the observation that organic phosphorus compounds, non-apatitic calcium phosphates, and inorganic phosphates associated with iron and aluminum are soluble in solutions of sodium hydroxide. Apatites are insoluble in this reagent but dissolve in sulfuric acid solution following alkali extraction. In addition, all soils contain considerable quantities of phosphorus of unknown combinations which are insoluble in the above reagents.

In these fractionation methods, the total phosphorus and the inorganic phosphorus in the alkali extract may be determined separately, thus giving organic phosphorus by difference. In the method of Chani (26,27) non-apatitic calcium phosphates are separated from phosphates associated with iron and aluminum by dissolving the former by means of extraction with dilute acetic acid prior to alkali extraction. The method of Bray and Dickman (3,20) employs fluoride solutions for fractionation. That of Fisher and Thomas (22) utilizes varying solubility rates of phosphorus compounds in buffered acid solutions at different pH ranges to effect a separation. The latter method dissolves fractionally forms of soil phosphorus.

In conjunction with soil phosphorus fractionation, methods have been devised to measure quantitatively a single phosphorus fraction--the portion that is immobilized or fixed in large quantities in acid soils. The mechanism of this retention has been the subject of considerable controversy. One group maintains that phosphorus undergoes chemical precipitation with iron and aluminum or the hydrous oxides of these elements (23,31,39). The opposing view is that such phosphates are held or adsorbed by means of an exchange reaction with hydroxyl ions on the surface of alumino-silicate clay particles (43,60,61). The subject has been reviewed by Midgeley (40). In any event, the quantitative measurement of this insoluble phosphorus, whether precipitated or adsorbed, has been considered to have agronomic implications (3,18,70). This phosphorus has also been termed "exchangeable". It has been established that such phosphorus is available for plant growth (12,37,43,70). The use of various reagents has been proposed for the displacement of this adsorbed or exchangeable phosphate. The hydroxyl, citrate, fluoride, and arsenate anions have been employed by Piper (52), Steele (60), Bray (3), and Dean (18), respectively.

The measurement of the capacity of the soil to fix phosphorus and the proportion of that capacity occupied by phosphorus (known as degree of saturation) have also been held to be important considerations when measuring the availability of soil phosphate (8,19,63,64). There is some analogy here to cation exchange. Burd and Murphy (8) hold that the adsorption capacity and the degree of saturation of the adsorbing complex (for phosphate) determines the phosphate accessible to plants by hydrolysis or anion exchange. Such phosphate, extractable by alkali, is held to be sharply distinct from the other source of phosphate for the plant, namely that soluble in acid (readily soluble phosphorus). For technical reasons they believe it is impossible to determine exactly the amount of the latter fraction but claim its value can be inferred from acid extractions plus a knowledge of the buffer capacity of the soil. According to Burd and Murphy (8) and to Bray and Kurtz (4), acid extraction procedures (for readily soluble or readily available phosphorus) are relatively ineffective in removing adsorbed or exchangeable phosphorus unless this fraction is present in large amounts. Dean and Rubins (19) also stress anion exchange capacity and degree of phosphorus saturation as factors to be considered, along with others, in determining phosphorus fertility of soils. They note that in acid soils phosphorus tends to accumulate in exchangeable form upon heavy fertilization. This is attended by a rise in readily soluble phosphorus. However, this could not be expected to hold for all types of soil.

The Accumulation of Phosphorus in Heavily Fertilized Soils

Some evidence has been published relative to the accumulation of phosphorus in soils receiving heavy and long-continued fertilizer applications (1,2,7,9,32,49,50). This accumulation has been appreciable with special crops such as tobacco, potatoes, and truck. Field experiments have been conducted relative to the value of this accumulated phosphorus to the plant (1,5,9,30,33,42,44,47,67,68). The concensus is that there is a decided carry-over in effect on new crops from previous heavy phosphate applications. Morgan and Jacobson (42) showed that white potatoes grown on old tobacco land in the Connecticut Valley did not respond to phosphate additions. Ware et. al. (68), found that high applications of phosphorus to white potatoes in South Alabama were of value to succeeding crops. Volk (67) found for cotton that "high rates of phosphorus application followed by low rates did not result in a distinct decrease in yield". Hawkins (30) reports the results of a cooperative study on white potatoes in which it was found that phosphate applications did not significantly increase yields in some soils where heavy applications had been made previously. This did not apply to all cases but the increase in yield of potatoes per pound of P_2O_5 applied was usually lower at locations where there were high amounts of residual phosphate in the soils. In a later report, Nelson and Hawkins (44) found that response to phosphate is related to the amount of readily soluble phosphorus in the soil and that the yield of potatoes from the first 80 pounds of phosphoric acid applied decreased as the amount of readily soluble phosphorus in the soil increased.

Application to the Present Study

The soils used in this study were surface soils from the Eastern Seaboard. They represented several soil types and are described in more detail in the section on results. They were, with minor exceptions, quite acid soils which had received heavy fertilization with commercial fertilizers and were presumed to have accumulated considerable quantities of residual phosphorus. On several of the sites from which these soils were taken, the results of field studies of the response of white potatoes to phosphate applications were available when the sampling locations were chosen (11,30). Data for response to various phosphate applications are given in table 2. These show that on many of the sampling sites little or no response was obtained to phosphate applications, indicating a high availability of residual phosphorus.

Several crops and cropping systems were used so that variations in residual phosphate utilization inherent in various plant species might be estimated. The crops were grown in the greenhouse under conditions which made it possible to account for all the phosphorus in the soil and in the plant.

The chemical procedures used to complement the crop growth studies in estimating phosphate availability were chosen to represent the two types of chemical approach already discussed. The method employed for readily soluble phosphorus was that of Truog (65), modified slightly to be better adapted for the use of the photoelectric colorimeter (51). This method involved the extraction of the soil with dilute (0.002N) sulfuric acid buffered at pH 3.0 with ammonium sulfate. Sodium hydroxide was used to determine exchangeable or adsorbed phosphorus. This reagent has been used by several workers for this purpose (8,52,55). It was extended to give values for organic phosphorus and apatitic phosphorus, the latter being the phosphorus soluble in acid following the alkali extraction. Some determinations of exchangeable or adsorbed phosphorus were made using the fluoride and the arsenate ions. The action of the fluoride, arsenate, and hydroxyl ions is believed to be alike in that an anion exchange is effected between them and adsorbed phosphorus.

An experiment with radioactive phosphorus was included so that an estimate of the efficiency of utilization of superphosphate could be made on soils whose fertility status had been established by the other methods described in this work. The technique used with the radioactive material is briefly described in the last part of the experimental section. The methods used for measuring phosphorus uptake from the applied fertilizer with radioactive phosphorus were those developed at the Bureau of Plant Industry, Soils, and Agricultural Engineering, United States Department of Agriculture, Beltsville, Maryland.

EXPERIMENTAL

Plant Growth Techniques

Crops. Several crops were grown on different soils in the greenhouse to provide information on variation among some different types of plants with regard to utilization of residual phosphorus and to make possible comparisons between plant growth and chemical tests of phosphorus availability. This was carried out in three different parts. The first part was concerned with evaluating the ability of some legumes and vegetables to remove residual phosphorus from soils which represented a variety of textural types:

A-1 *Lespedeza sericea* followed in some cases by hairy vetch

A-2 beets followed by hairy vetch

A-3 *Crotalaria retusa*

A-4 Slobolt lettuce.

A second part consisted of the measurement of residual phosphorus removed from heavily fertilized commercial potato soils by three different types of rotations:

B-1 legume rotation: hairy vetch-cowpeas-hairy vetch

B-2 vegetable rotation: beets-Slobolt lettuce-beets-Slobolt lettuce

B-3 grass rotation: rye grass-Sudan grass-rye grass.

In the third part, radioactive superphosphate was used to measure the utilization of phosphorus from soils. Slobolt lettuce was used as a test crop.

Containers. Small glazed pots were used in experiments A-1 and A-2. For the other work, number ten enamel-lined tin cans were employed. These were cut down to a height of four inches and then crimped to lend rigidity.

Soils. Two groups of soils were used in experiment A. The first group consisted of five soils, described in table 1. These were used in experiments A-1 and A-2. Six heavily fertilized soils from commercial white potato-producing areas, described in table 2, were used in experiments A-3 and A-4. The latter soils were the only ones used in the remainder of the experiments.

Preparation of Soil. For experiments A-1 and A-2, air-dry soil which had passed a 2-mm. sieve was used for crop growth. For the other experiments, the air-dry soils were passed through a screen having a quarter-inch mesh. In experiment B, the soils of replicate pots were composited and air-dried following each crop. After a weighed sample was removed for laboratory work the soil was redistributed for the following crop. In the experiment with radioactive superphosphate the six soils which had been cropped in experiment B-2 were compared with the corresponding six uncropped soils.

Fertilization. With the exception of phosphorus and liming, an attempt was made to maintain levels of all nutrients at a point optimum for crop growth at all times.

Chalk and magnesium carbonate were added to soils before seeding each crop at a rate estimated to give the soil a reaction approaching but not exceeding pH 5.5. Consideration was given to reaction, texture, exchangeable hydrogen, and cation exchange capacity in obtaining this estimate. The other nutrients were added, as a rule, in solution at intervals during the growth of the crops.

Radioactive Superphosphate. This material was prepared by E. J. Fox of the Bureau of Plant Industry, Soils, and Agricultural Engineering, United States Department of Agriculture, Beltsville, Maryland. The technique involved mixing 3.54 gm. of primary potassium phosphate containing 40 millicuries of radioactive phosphate with 49.11 gm. of Curacao phosphate rock and 62.9 gm. of 50.6 per cent sulfuric acid. The dried product weighed 90 gm. and contained 22.31 per cent phosphoric acid (P_2O_5). The quantity applied to the soil was equivalent to 200 pounds P_2O_5 per acre. This amounted to 0.2 gm. P_2O_5 per can with an activity of 0.4 millicuries. The phosphate, along with lime and other nutrients, was mixed with the soils before apportioning to replicate pots.

Experimental Design. Four replications were used with the five soils employed in experiments A-1 and A-2. Experiments A-3 and A-4 were run in duplicate. Four replications were used for each of the 12 soils in the work with radioactive superphosphate.

In experiment B each of the six soils was represented by six replications for each of the three cropping systems (B-1, B-2, B-3) making a total of 108 cans. The 36 cans for each crop (six soils by six replications) were randomized in the form of a 6 x 6 latin square. Six blocks were then made up consisting of corresponding columns from the three latin squares. The arrangement of sub-blocks was at random. A sample block is illustrated in figure 1.

Seeding. The seeding procedure followed in this work was to add the required amount of water to the pots or cans after first removing a small portion (about 200 gm.) of dry soil. The water required to bring the soil to the proper level for crop growth was determined by trial and error on an extra lot of each soil. After the water had soaked in, part of the dry soil was spread evenly over the surface to provide a good seed bed. After placing the seeds, the remainder of the dry soil was used to cover the seeds and then the pot or can was covered until emergence of the plant. The seeding plan for various crops is illustrated in figure 2. For the experiment with radioactive superphosphate, lettuce seeds were placed upon moist filter paper at 60° F. in diffuse light the afternoon prior to planting. Seeds showing hypocotyls the following afternoon were seeded eight per pot as illustrated (figure 2). The excess seeds were placed in vermiculite and used for the small amount of replanting that was required.

Culture of the Crops. In experiment A, no attempt was made to regulate the numbers of lespedeza or Crotellaria

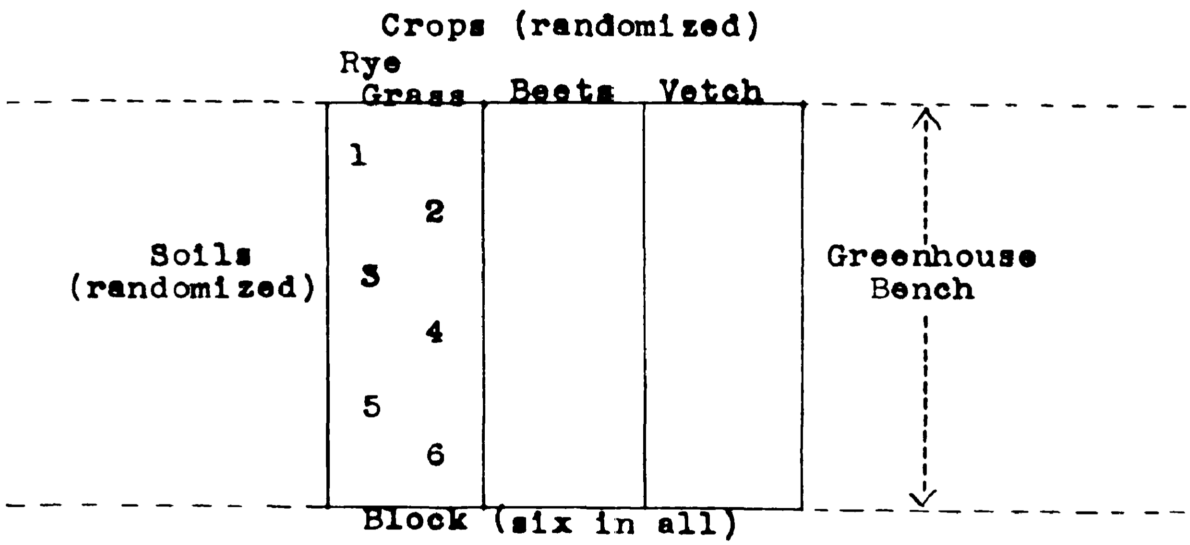

FIGURE 1. ARRANGEMENT OF CROPS AND SOILS FOR GREENHOUSE EXPERIMENT WITH HEAVILY FERTILIZED COMMERCIAL POTATO SOILS.

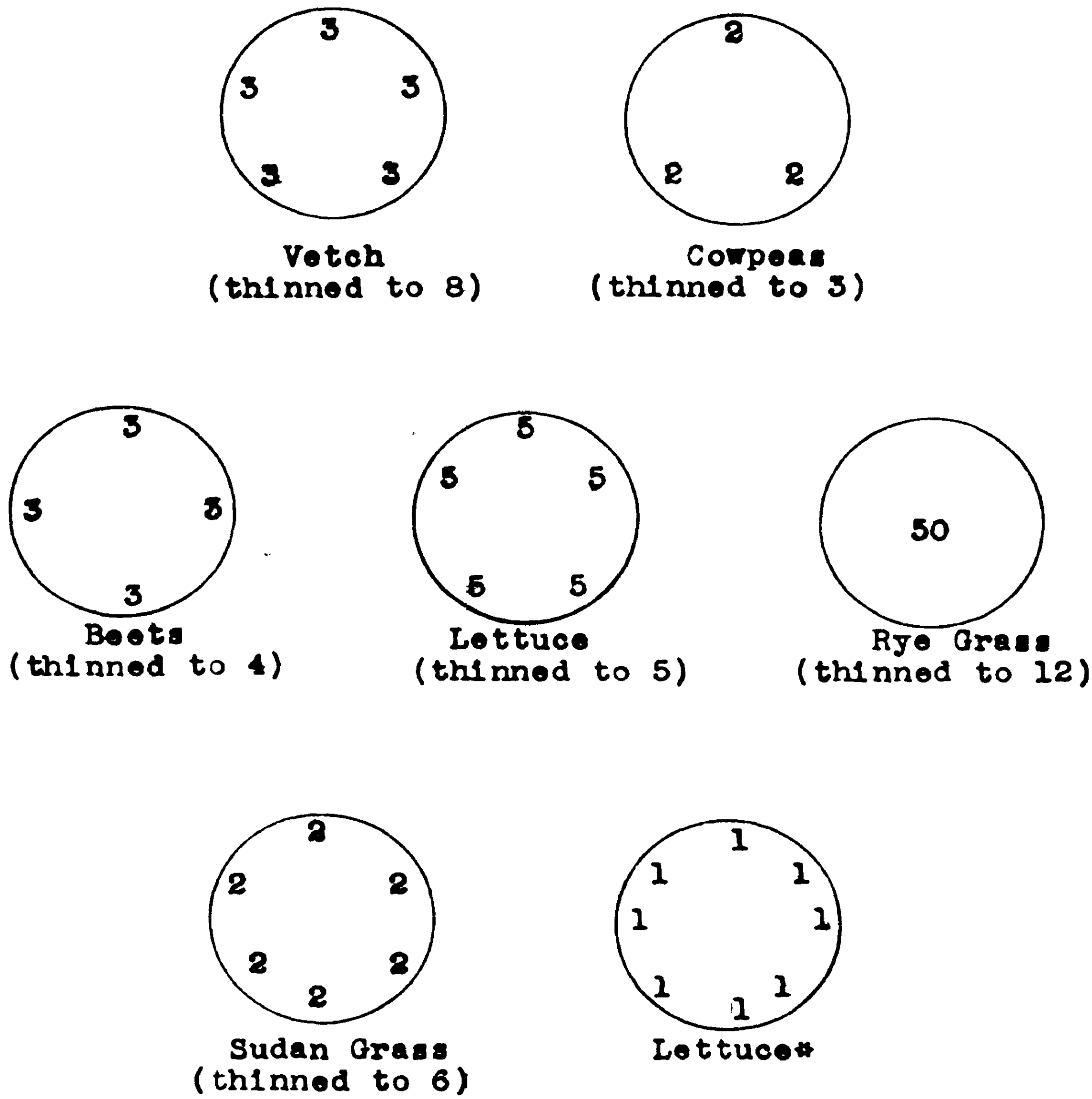

FIGURE 2. SEEDING PLAN FOR VARIOUS CROPS IN GREENHOUSE EXPERIMENTS.

*Experiment with radioactive superphosphate.

plants per pot. The remaining crops of experiment A and those of experiment B were thinned according to the data of figure 2. Two harvests were made of the lettuce which received radioactive superphosphate. Four plants were taken for the first harvest and the remaining four at the final harvest.

As previously stated, various nutrients were added in solution to the soils when deemed necessary during growth of the crops. All legumes were inoculated. Vetch and cowpeas were given support by means of stringsattached to glass rods set in the soil of the pots or cans. Aphids and thrip were controlled by nicotine fumigation. Red spider was controlled by spraying with "ENOR" at frequent intervals.

Harvest of Crops. Several cuttings were obtained from each seeding of lespedeza, vetch, rye grass and Sudan grass. For the other crops, one harvest was secured for each seeding. Dates of seeding, cuttings, and harvests are illustrated in figure 3.

Roots were harvested by removing the soil from a can and allowing it to dry for a few hours. The bulk of the soil was then worked away from the root mass which was then allowed to dry again for a few hours. Most of the remaining soil could then be removed. Roots were washed by placing on a sieve and rinsing with a stream of water.

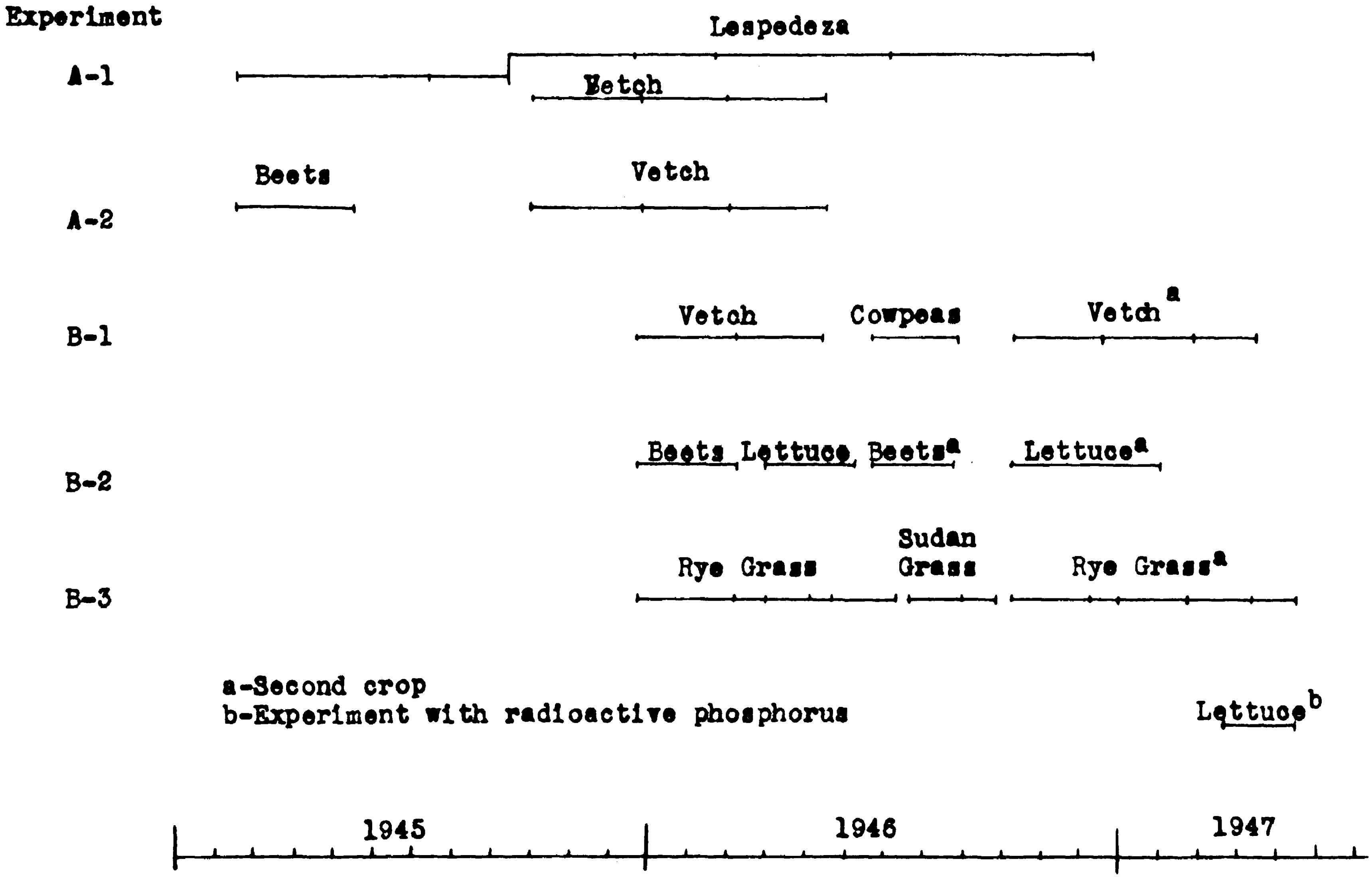

FIGURE 3. SEEDING AND HARVEST SCHEDULE OF GREENHOUSE CROPS.

Chemical Methods

Preparation of Soil Samples for the Laboratory. Representative samples were taken of all soils before fertilization and seeding. In experiment B, soil samples were taken following the harvest of each crop. The air-dry soil of replicate cans was mixed together and the sample taken with a sampling tube. These samples were weighed, passed through a 2-mm. sieve, and the quantity that passed was reweighed.

Moisture Determinations. A 25 or 50-gm. portion of 2-mm. air-dry soil was placed on a tared evaporating dish and dried to constant weight at 105° C.

Reaction. The pH of a 1:1 soil-water suspension which had been allowed to stand for one hour with occasional stirring was measured with a Beckman pH meter and glass electrode.

Exchangeable Hydrogen, Exchangeable Bases, and Cation Exchange Capacity. The rapid method of Brown (6) was used.

Mechanical Analysis. Determinations were performed by the pipette method through the courtesy of the mechanical analysis section of the Division of Soils, Fertilizers, and Irrigation, Bureau of Plant Industry, Soils, and Agricultural Engineering, United States Department of Agriculture, Beltsville, Maryland.

Conductivity. Fifty gm. of soil were shaken with 250-ml. of water and allowed to stand overnight. The conductivity of the supernatant liquid was measured with a conductivity bridge.

Total Phosphorus in Soil. A 1-gm. sample of 60-mesh oven-dry soil was digested with 20 ml. of 72 per cent perchloric acid in a 70-ml. Kjeldahl flask until colorless or nearly so. The contents were transferred to a 250-ml. volumetric flask, made to volume, mixed, and allowed to settle. An aliquot (containing less than 0.05 mgm. phosphorus) was transferred to a 50-ml. volumetric flask and the reaction adjusted with five per cent sodium carbonate and 1 N sulfuric acid to colorless with quinaldine red indicator. The volume was then made to 35 ml. and the molybdenum blue color developed by the method of Peech et. al. (51). The transmittency was measured using a 660 mμ filter with an Evelyn photoelectric colorimeter.

Readily Soluble Phosphorus (Modified Truog Method). Four gm. of 2-mm. soil were shaken for 30 minutes with 400 ml. of 0.002 N sulfuric acid containing three gm. of ammonium sulfate per liter. The suspension was filtered through 11-cm. number 42 Whatman filter paper discarding the first portion of filtrate. Phosphorus was determined in a portion of the clear filtrate by the molybedenum blue method described above.

Alkali-extractable Phosphorus. A 5-gm. portion of soil was placed in a 100-ml. centrifuge tube. A 50-ml. portion of 0.5 N sodium acetate (adjusted to pH 5.7) was added and stirred with the soil. The tube was centrifuged and the solution discarded. This procedure was repeated three times. A 50-ml. portion of 0.1 N sodium hydroxide was added and the tube immersed in a boiling water bath with occasional stirring for

30 minutes. At the end of this period, a 5-ml. portion of 1 N sodium chloride was added and the tube centrifuged. The clear extract was poured into a 250-ml. volumetric flask. This process was repeated once with heating and then twice more, omitting the heating. The combined extracts in the flask were made to volume and mixed. A 10-ml. aliquot of this extract was evaporated to dryness with dilute sulfuric acid containing magnesium nitrate (8.75 gm. $MgNO_3.6H_2O$ per 100 ml. 1N H_2SO_4). When dry, the residue was gently ignited, cooled, digested with 1 N sulfuric acid, made to volume in a 50-ml. volumetric flask, mixed, and allowed to settle overnight. Phosphorus was determined in an aliquot of this solution by the molybedenum blue method.

Exchangeable Phosphorus. A 75-ml. aliquot of the alkali extract was pipetted into a 100-ml. volumetric flask and made to volume with 1.2 N sulfuric acid. This mixture was treated with a small amount of decolorizing carbon (Darco G60) and filtered through 11 cm. Whatman number 42 filter paper, discarding the first portion of the filtrate.. Phosphorus in the clear extract was determined after evaporation and ignition as for total alkali-extractable phosphorus.

Apatitic Phosphorus. The soil remaining after the sodium hydroxide treatment was transferred to an Erlenmeyer flask with a 250-ml. portion of 0.5 N sulfuric acid and shaken for one hour. Phosphorus was determined in an aliquot of the filtered extract.

Exchangeable Phosphorus by the Arsenate Method. The procedure of Rubins and Dean (55) was followed.

Exchangeable Phosphorus by the Ammonium Fluoride Method. The procedure of Rubins and Dean (55) was followed.

Anion Exchange Capacity. A 5-gm. portion of soil was pre-treated with 0.5 M sodium acetate as given in the method for alkali-extractable phosphorus. The soil was saturated with phosphorus by treating with four 50-ml. portions of 0.5 M sodium phosphate adjusted to pH 5.7, the soil being heated at 100° C with the first two portions for 30-minute periods. The excess saturating solution was washed out as follows: the soil was stirred with 25 ml. of water and then 25 ml. of 95 per cent ethyl alcohol was added. After centrifuging and discarding this wash mixture, the process was repeated three times with 50 ml. portions of 95 per cent alcohol. The adsorbed phosphorus was then displaced with 0.1 N sodium hydroxide as for exchangeable phosphorus. Phosphorus was determined in the extract by the procedure given for exchangeable phosphorus.

Dry Weight of Plant Tissue. Plant harvests were placed in beakers and dried to constant weight at 60-70° C.

Phosphorus in Plant Tissue. In experiments A and B the dried plant material was ground, using a Wiley mill with a 20-mesh screen or a hammer mill. An oven-dry ground sample of 0.1 to 0.5 gm. was moistened with a 2-ml. portion of alcoholic magnesium nitrate (40 gm. of salt to 100 ml. of

95 per cent ethyl alcohol). This was placed on a triangle and ignited with a taper. The burning was assisted with a very low Bunsen flame which was gradually increased until ignition was complete. A platinum wire was used to break up lumps of partially burned sample. After cooling, 10 ml. of 1 N sulfuric acid was added and the covered crucible digested on a hot plate. The contents were then transferred to a volumetric flask using a stream of distilled water from a wash bottle and a policeman. The contents were made to the mark, mixed and allowed to stand overnight. Phosphorus was determined in a clear aliquot of the supernatant liquid by either the molybdenum-blue method or the vanado-molybdate method (36), using an Evelyn photoelectric colorimeter.

Radioactivity of Plant Tissue. Total phosphorus and P^{32} in the dried material was determined by the method of Mackenzie and Dean[1]. In brief, this method involved the digestion with nitric and perchloric acids of a sample of plant material containing from five to 35 milligrams of phosphorus. After filtering off the silica, the phosphate was precipitated as the molybdate and reprecipitated as magnesium ammonium phosphate. This was collected on a tared filter disk consisting of filter paper fastened by trim cement to an aluminum ring. The filter disk with precipitate was dried to constant weight at a relative humidity of 50 per cent, the net weight being recorded as magnesium ammonium phosphate hexahydrate. Total phosphorus having

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[1]L. A. Dean, private communication.

thus been determined, the radioactivity (P^{32}) of the precipitate was measured with a Geiger-Müller counter. For comparison standards, a weighed sample of the original fertilizer was dissolved in dilute nitric acid and made to volume. Suitable aliquots were carried through the analysis for total phosphorus and radioactivity.

Radioactivity for this work was expressed as the number of disintegrations per second per mgm. of total phosphorus (at an arbitrarily chosen reference time). This is known as 'specific activity'. The ratio of the specific activity of the phosphorus in a given plant sample to the specific activity of the phosphorus in the radioactive superphosphate which was applied is the proportion of phosphorus in the plant sample derived from the fertilizer. For convenience this ratio is converted to per cent.

RESULTS

Sampling and Chemical Information Obtained on the Soils Used in the Various Experiments

The soil type and phosphorus content of the five soils used for experiment A-1 in which lespedeza and vetch were grown and for experiment A-2 in which beets and vetch were grown are given in table 1. The soils were surface soils and represented a variety of textures. The Davidson clay loam contained very little readily soluble phosphorus and was at a very low degree of saturation with respect to phosphorus. The other soils contained more phosphorus in the readily soluble and exchangeable forms and were at a higher degree of phosphorus saturation. One of the Sassafras loamy sands (E1171) gave the highest value for readily soluble phosphorus and also was highest with respect to phosphate saturation. The other Sassafras loamy sand possessed a considerably lower phosphate level. This is indicated by lower values for exchangeable phosphorus, degree of phosphorus saturation and readily soluble phosphorus. The Caribou loam contained the greatest quantity of exchangeable phosphorus but had a lower value for phosphorus saturation and readily soluble phosphorus than some of the sandier soils.

The six soils used for the remainder of the experiments were acid surface soils from sites in the Eastern seaboard states that had been used for commercial white potato

TABLE 1. The total phosphorus, exchangeable phosphorus, degree of phosphorus saturation, and readily soluble phosphorus in soils used for greenhouse experiments with lespedeza, beets, and vetch.

Nine hundred grams of air-dry 2-mm. soil per replicate.

Soil Type and Number	Total Phosphorus per Replicate	Exchangeable Phosphorus per Replicate*	Degree of Phosphorus Saturation*	Readily Soluble Phosphorus per Replicate
	mgm.	mgm.	per cent	mgm.
Davidson clay loam E787	696	155	5	8
Caribou loam E1124		530	13	56
Sassafras loam E1141´	1015	475	41	113
Sassafras loamy sand E1171	603	391	110	140
Sassafras loamy sand E1173		182	50	47

*Determined by the arsenate method.

production for a number of years and had received large applications of commercial fertilizers. Sampling data and results of chemical and mechanical analyses for these soils are given in tables 2 and 3. As mentioned earlier, field tests with white potatoes had shown many of these soils to be giving little or no response to phosphate fertilization (table 2, columns 5 and 6).

TABLE 2. The number, type, location, phosphorus treatment, and field experiment yield of potatoes of soils from commercial potato-producing areas used in greenhouse tests.

Soil Number and Type	Description of Soil Series	Geographic Location	Cropping History and Reference	P_2O_5 Treatment lb./acre	Potato Yield bu./acre
1 Sassafras sandy loam (451585)*	Well-drained, medium acid Coastal Plain podzolic soil developed on unconsolidated outwash from the Piedmont.	Onley, Va. (Va. Truck Exp. Substation)	Dr. Carolus' white potato experiment; 160 lbs. P_2O_5 per acre for 4 years. (11)	80	90
				160	105
				240	120
2 Moyock loamy fine sand (451586)*	Fair to well drained Coastal Plain soil; poorly developed profile; derived from beds of fine sands, sandy clays.	Driver, Va. Farm of M. P. Harrell			
3 Caribou loam (451587)*	Well-drained podzol developed on glacial till derived from calcareous shales and limestone.	Aroostook Co., Me. (Farm of A. McKenny)	Area surrounding the site of phosphorus field exp. no. 3 (1945) (30)	0	366
				40	373
				80	380
				120	368
				160	374
4 Caribou loam (451488)*	See above	Aroostook Co., Me., (Farm of A. McKenny)	Area surrounding the site of phosphorus field exp. no. 4 (1945) (30)	0	339
				40	359
				80	372
				120	376
				160	367
5 Caribou loam (451589)*	See above	Aroostook Co., Me., Aroostook Farm, Me. Exp. Sta.	Area surrounding the site of phosphorus field exp. no. 5 (1945) (30)	40	304
				80	316
				120	324
				160	322
				200	322
6 Collington loam (451590)*	Well-drained, medium acid Coastal Plain, podzolic soil, developed from greensand marl.	Freehold, N.J. (Farm M. Story)	Site of phosphorus response study (1946) (10)	0	372
				80	354
				160	306
				240	342

*Bureau of Plant Industry number.

TABLE 3. The phosphorus content, pH value, exchangeable ions, mechanical analysis, and organic content of soils from commercial potato-producing areas used in greenhouse tests.

	Soil Number					
	1	2	3	4	5	6
Phosphorus content						
Total %	0.044	0.122	0.196	0.198	0.134	0.189
Readily soluble p.p.m.	86	236	181	176	71	189
Exchangeable (by NaOH) mmol. per 100 gms.	1.13	2.[illegible]5	4.37	4.45	2.83	3.25
Anion exchange capacity mmol. per 100 gm.	3.42	8.38	20.00	30.49	32.19	19.26
Saturation of anion exchange capacity %	33	35	15	15	9	17
pH Value	5.48	5.01	5.11	5.34	5.04	4.40
Exchangeable bases meq. per 100 gm.	2.2	3.9	7.2	8.7	7.9	5.0
Exchangeable hydrogen meq. per 100 gm.	1.4	3.0	6.4	6.4	7.5	5.5
Exchange capacity meq. per 100 gm.	3.6	6.9	13.6	15.1	15.4	10.5
Mechanical analysis						
Gravel, fine %	0.9	0.1	6.7	6.2	5.9	0.7
Sand, coarse %	15.8	0.4	7.2	6.9	6.7	4.7
Sand, medium %	29.5	3.6	4.5	4.9	4.1	10.2
Sand, fine %	26.8	64.8	9.8	11.3	10.0	11.4
Sand, very fine %	0.9	5.9	8.7	5.9	9.7	5.7
Silt %	20.9	19.0	49.4	47.8	49.5	50.3
Clay %	5.2	6.2	13.7	14.0	14.1	17.0
Organic matter %	0.7	1.6	4.0	4.2	4.7	2.2

The data of table 3 for phosphorus content is graphed in figures 4, 5, and 6. In table 3 the data is expressed in units in common use for the determination of the particular phosphorus fraction. In figures 4, 5, and 6, however, all quantitative data are expressed in units common to all for comparative purposes.

It may be seen from figure 4 that all these soils contained considerable but varying quantities of phosphorus in exchangeable form. One millimol of phosphorus per 100 gm. is equal to 1420 pounds P_2O_5 per acre. Soil 1 contained the least amount of exchangeable phosphorus while soils 3 and 4 contained almost four times as much. A high proportion of the total phosphorus of all of these acid soils was exchangeable, however. Readily soluble phosphorus was considerably lower in amount than exchangeable phosphorus in all cases. The greatest amount of readily soluble phosphorus was found in soil 2, while the least was found in soils 1 and 5.

The data of table 3 for exchangeable phosphorus, anion exchange capacity, saturation of anion exchange capacity, and readily soluble phosphorus is graphed for the various soils in figure 5. Anion exchange capacity varied greatly, being high on the fine-textured Caribou soils (3,4, and 5) and low on the sandy soils 1 and 2. The degree of saturation with phosphorus varied from 33 and 35 per cent in the sandy soils to nine per cent in soil 5. This indicates that all soils were potentially capable of absorbing much more

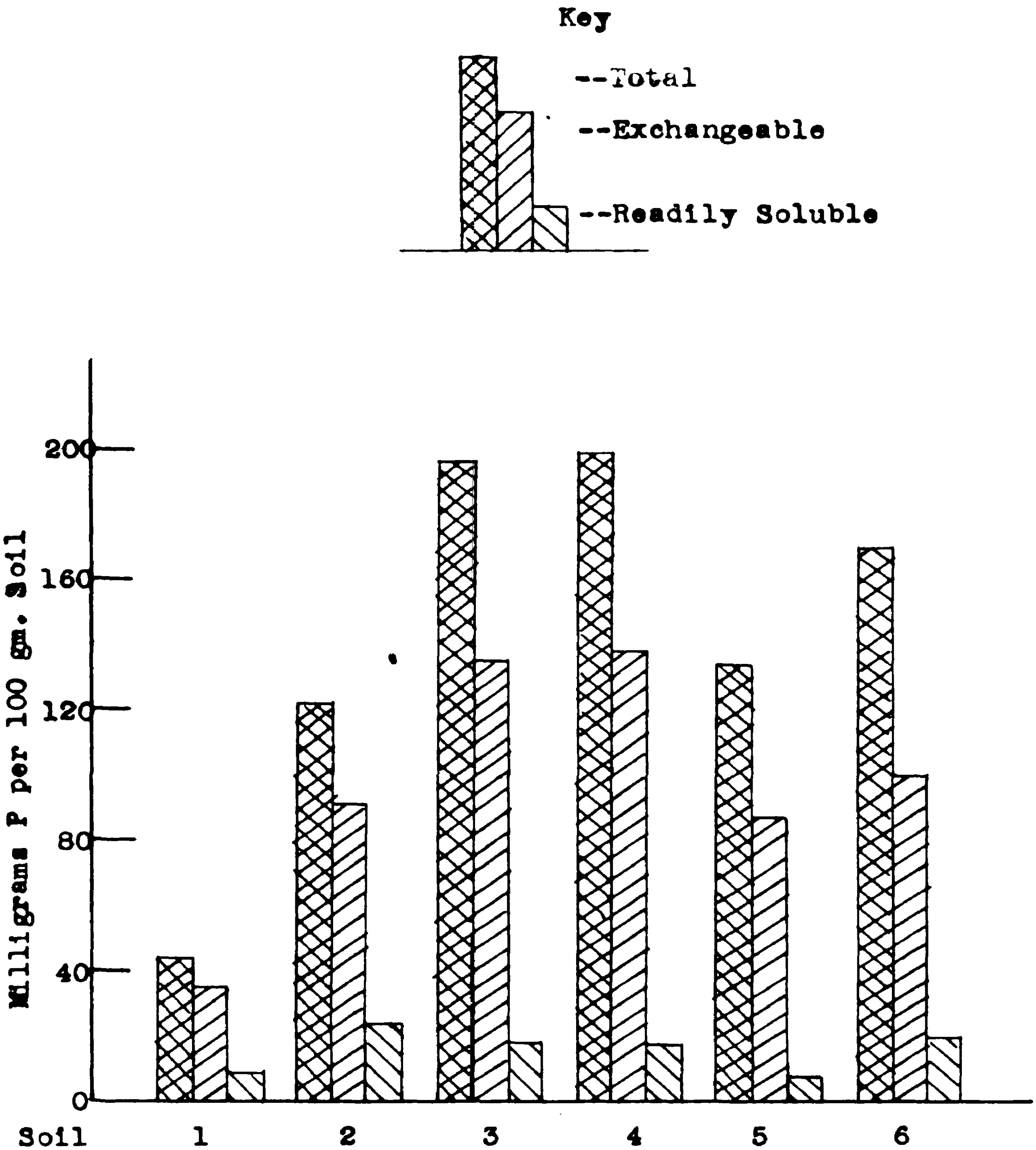


FIGURE 4. TOTAL, EXCHANGEABLE, AND READILY SOLUBLE PHOSPHORUS OF HEAVILY FERTILIZED COMMERCIAL POTATO SOILS.

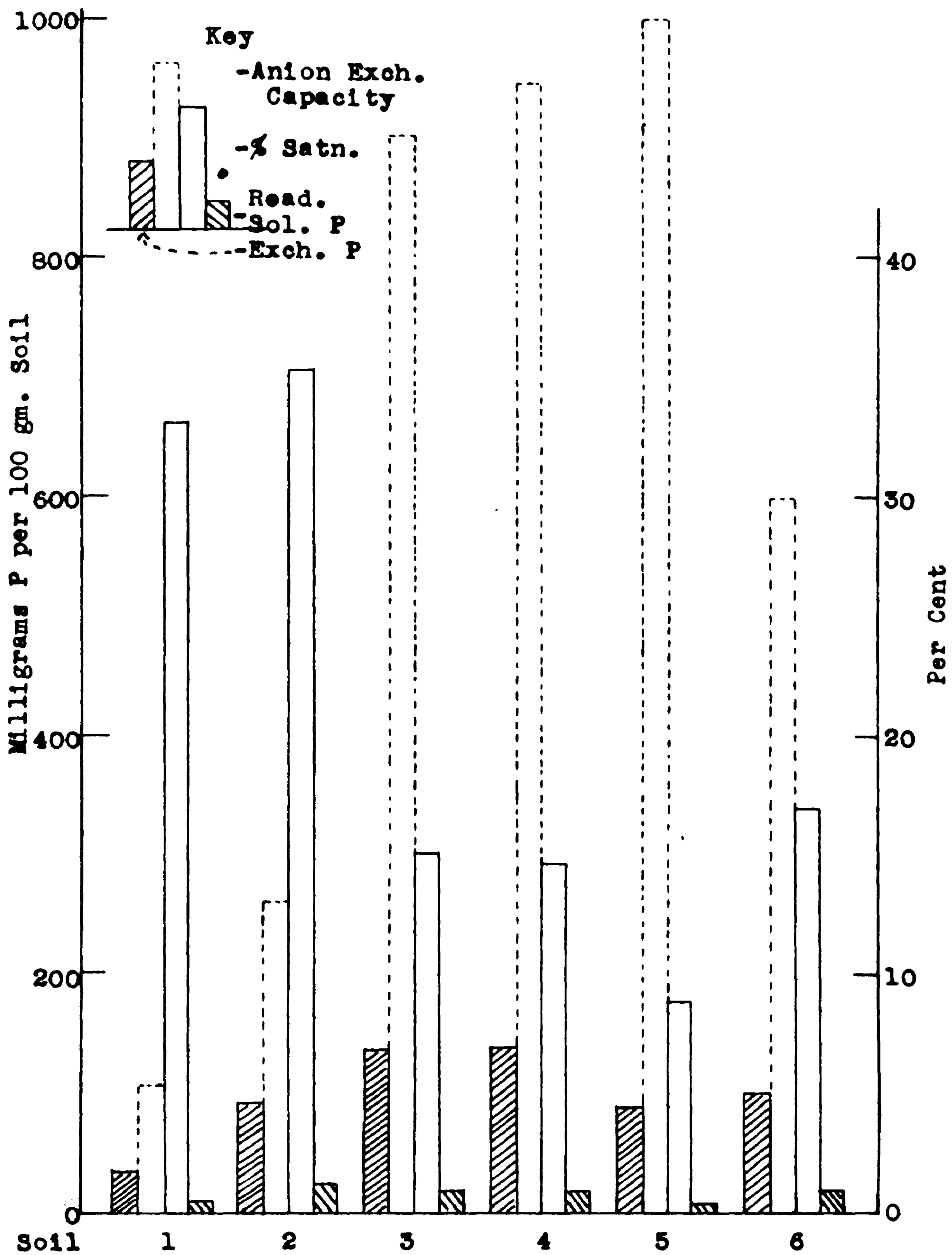


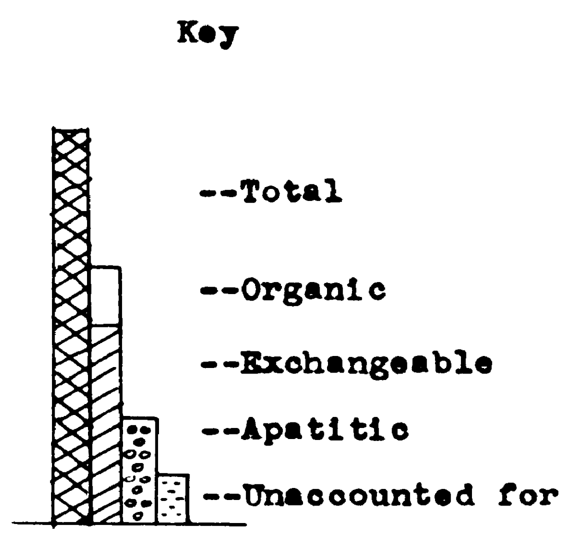
FIGURE 5. EXCHANGEABLE AND READILY SOLUBLE PHOSPHORUS, ANION EXCHANGE CAPACITY AND PHOSPHORUS SATURATION OF HEAVILY FERTILIZED COMMERCIAL POTATO SOILS.

phosphorus. Note that readily soluble phosphorus of soil 2 with high percentage saturation is greater than that of similarly saturated soil apparently because of the difference in absolute amount of exchangeable phosphorus. Soil 5 with a relatively large amount of exchangeable phosphorus has a low readily soluble value apparently because of a low percentage saturation.

The data of figure 6 show that most of the alkali-extractable phosphorus was made up of exchangeable phosphorus while considerably lesser amounts were found as organic phosphorus. Apatitic (alkali-insoluble and acid-soluble) phosphorus and phosphorus of unknown composition (by difference) also made up a minor portion of the total phosphorus.

Phosphorus Removed and Dry Weight Produced by Cropping

Experiment A: The Removal of Residual Phosphorus from Soils by Different Crops. In this experiment the ability of certain crops to grow on soils of different textures and their ability to remove residual phosphorus from these soils was studied. The phosphorus removed by the lespedeza and vetch used in experiment A-1 is summarized in table 4. Lespedeza did not become well established on the Sassafras loam and the Sassafras loamy sands in this experiment. It grew well on such fine-textured soils as Davidson clay loam and Caribou loam, however, and removed considerable phosphorus from these soils. Vetch was substituted for lespedeza on the three Sassafras soils following the second cutting of lespedeza.



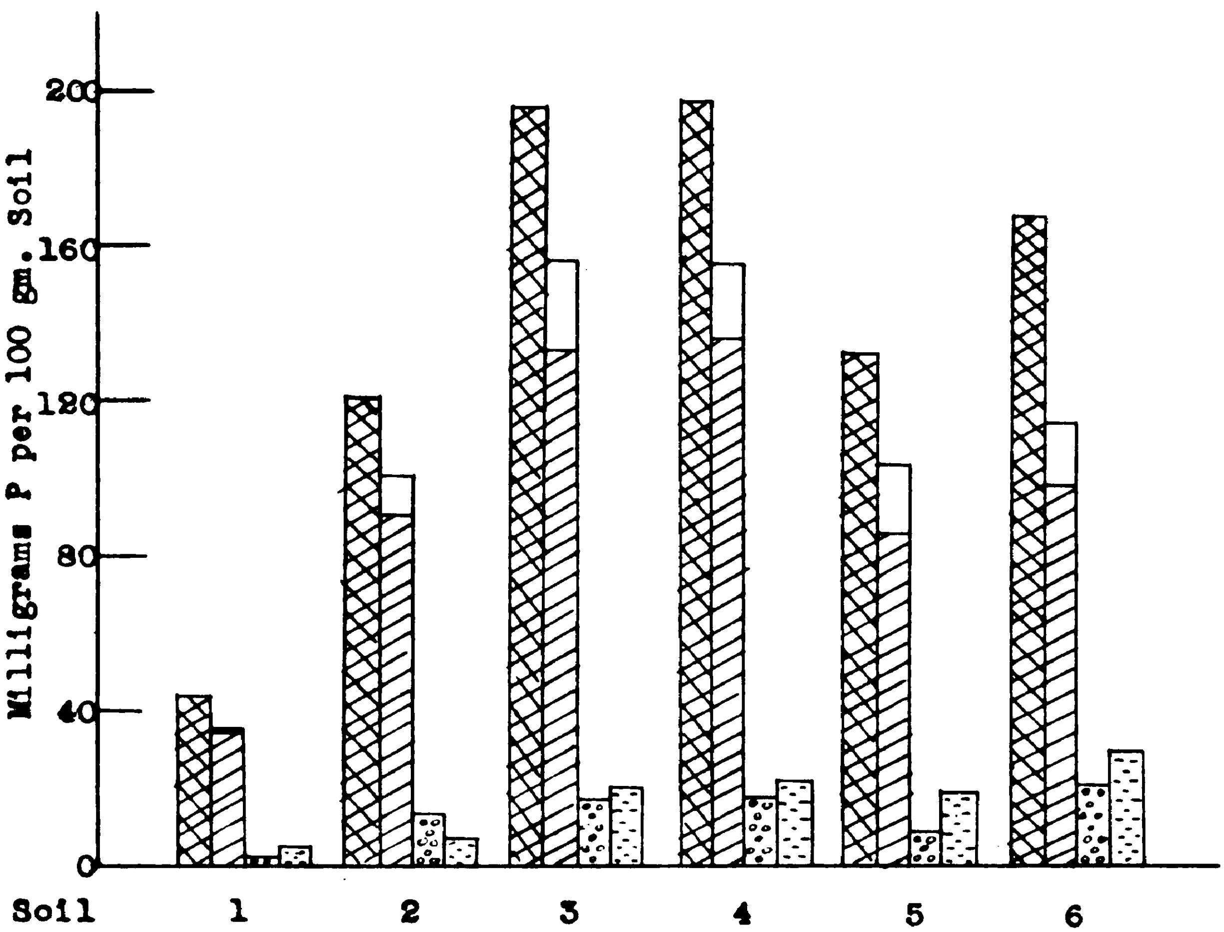


FIGURE 6. FRACTIONATION OF THE PHOSPHORUS OF HEAVILY FERTILIZED SOILS FROM COMMERCIAL POTATO-PRODUCING AREAS.

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TABLE 4. Phosphorus removed by lespedeza and vetch in greenhouse experiment.

Results expressed as milligrams per replicate.

Crop Grown	Harvest	Davidson Clay Loam	Caribou Loam	Sassafras Loam	Sassafras Loamy Sand	Sassafras Loamy Sand
Lespedeza	1st	4.39	11.58	8.64	8.01	2.07
	2nd	2.99	14.87	4.77	6.99	3.82
	3rd	2.76	12.13			
	4th	3.85	15.06			
	5th	4.15	19.04			
	6th	5.25	15.19			
	7th	8.98	33.35			
Lespedeza total		32.37	121.22	13.41	15.00	5.89
Vetch	1st			12.37	23.80	6.31
	2nd			16.94	25.48	7.26
	3rd			10.01	9.02	7.22
Vetch total				39.32	58.30	20.79
Experiment total		32.37	121.22	52.73	73.30	26.68

In experiment A-2, the cropping plan was beets followed by vetch on all soils. The phosphorus removed by these crops did not appear to be influenced by texture (table 5), being relatively high on one of the Sassafras loamy sands, the Caribou loam, and the Sassafras loam and low on the other Sassafras loamy sand and the Davidson clay loam. Although the total amount of phosphorus removed by lespedeza on the Davidson clay loam was relatively low, the ratio of such removal to the removal by beets and vetch on this soil was relatively great as compared with that on the other soils.

Experiments A-3 and A-4 were carried out in an artificial light chamber. The adaptability of Crotalaria retusa and

TABLE 5. Phosphorus removed by beets and vetch in greenhouse experiment.

Results expressed as milligrams per replicate.

Crop	Harvest	Davidson Clay Loam	Caribou Loam	Sassafras Loam	Sassafras Loamy Sand	Sassafras Loamy Sand
Beets		2.26	20.19	30.48	54.31	10.93
Vetch	1st	2.54	11.48	10.86	14.18	7.15
	2nd	2.93	7.27	12.91	13.91	8.16
	3rd	3.81	16.07	10.73	12.17	6.19
Vetch total		9.28	34.82	34.50	40.26	21.50
Expt. total		11.54	55.01	64.98	94.57	32.43

Slobolt lettuce for removing residual phosphorus from heavily fertilized commercial potato-producing soils of varied textures was studied. It may be seen from the data in table 6 that *C. retusa* grew poorly on the sandy soils 1 and 2 and on soil 6 and was therefore unsuited for this work. The lettuce appeared to be more adaptable to various textural conditions and made good growth on the first four soils but failed on soil 6.

Experiment B: The Removal of Residual Phosphorus from Heavily Fertilized Commercial Potato-producing Soils by Different Cropping Systems. In this experiment the ability of crops to utilize residual phosphorus was studied by means of rotations of different types of crops. Changes in level of various phosphorus fractions were measured during the course of these rotations. Lime and fertilizer, with the exception of phosphorus, were added as needed and the amounts

TABLE 6. The dry weight and phosphorus content of Crotalaria and lettuce grown in artificial light chamber on soils from commercial potato-producing areas.

Soil No.	Soil per Replicate*	Dry Weight of Tops per Replicate	Phosphorus Content of Tops per Replicate
	gm.	gm.	mgm.
		Crotalaria retusa	
1	2000	0.15	0.66
2	2000	0.11	0.51
3	1950	2.32	6.19
4	1900	5.71	15.30
5	1900	2.71	5.16
6	2000	0.27	0.83
		Slobolt lettuce	
1	2000	7.24	34.48
2	2000	3.50	15.36
3	1950	4.91	22.14
4	1900	7.08	28.49
5	1900	1.45	4.47
6	2000	Failed	-----

*Air-dry quarter-mesh soil.

used are given in tables 7 through 12 along with pH value and other data. The quantity of soil used (tables 7, 9, and 11) was adjusted to approximate equal volumes, being greatest for the sandy soils.

The legume rotation (experiment B-1) consisted of two crops of hairy vetch with an intermediate crop of cowpeas. Two cuttings were secured with the first vetch crop and three with the second. Figure 7 is a photograph of the second vetch crop just prior to the first cutting. The data for dry weight and phosphorus content of the plant material are given in table 13 for the various crops. The

TABLE 7. The pH value and amount less than 2-mm. particle size of soils used in greenhouse tests with vetch and cowpeas; the nitrogen and potassium added in nutrients, and the phosphorus added in seeds to the soils.

Soil No.	Crop Grown	pH Value	Oven-dry Soil less than 2-mm. Particle Size[a]	Total Nutrients Added to Soil[a]: Nitrogen	Total Nutrients Added to Soil[a]: Potassium	Phosphorus Added in Seeds[a]
			kgm.	gm.	gm.	mgm.
1	Vetch	5.48	11.856		4.81	10.98
	Cowpeas	4.80	11.512	0.18	1.00	46.75
	Vetch[b]	5.48	11.192		1.98	8.12
	(Final soil)	4.54				
2	Vetch	5.01	11.616		4.81	10.61
	Cowpeas	4.70	11.261	0.18	1.00	48.50
	Vetch[b]	5.22	10.920		1.98	8.41
	(Final soil)	4.90				
3	Vetch	5.11	9.415		3.06	11.11
	Cowpeas	4.93	9.046	0.18	1.00	46.41
	Vetch[b]	5.14	8.739		1.98	8.49
	(Final soil)	4.96				
4	Vetch	5.34	9.650		3.06	11.00
	Cowpeas	4.95	9.305	0.18	1.00	48.60
	Vetch[b]	5.20	8.950		1.98	8.56
	(Final soil)	5.01				
5	Vetch	5.04	9.625		4.56	10.66
	Cowpeas	4.77	9.178	0.18	1.00	49.13
	Vetch[b]	5.10	8.862		1.98	8.78
	(Final soil)	4.98				
6	Vetch	4.40	11.376		3.31	9.84
	Cowpeas	4.50	11.084	0.18	1.00	47.53
	Vetch[b]	4.96	10.717		1.98	9.07
	(Final soil)	4.69				

a - Total for six replicates.
b - Second crop.

TABLE 8. Detailed statement of nutrients added to grow vetch and cowpeas.

Amounts are expressed as grams per total of six replicates.

Soil No.	Crop Grown	Nutrients Added Before Seeding: $CaCO_3$	$MgCO_3$	K_2SO_4	Nutrients Added During Growth Period: KNO_3	K_2SO_4	K_2CO_3	Mg.	Mn	H_3BO_3
1	Vetch	1.50	0.25	3.33		6.82	0.44	0.12	0.06	0.12
	Cowpeas	3.00	0.50		1.29	1.10				
	Vetch*					4.42		0.12		
2	Vetch	3.00	0.50	3.33		6.82	0.44	0.12	0.06	0.12
	Cowpeas	4.50	0.76		1.29	1.10				
	Vetch*	3.00	0.50			4.42		0.12		
3	Vetch	6.00	1.00			6.82		0.12	0.06	0.12
	Cowpeas	6.00	1.00		1.29	1.10				
	Vetch*	6.00	1.00			4.42		0.12		
4	Vetch	6.00	1.00			6.82		0.12	0.06	0.12
	Cowpeas	6.00	1.00		1.29	1.10				
	Vetch*	6.00	1.00			4.42		0.12		
5	Vetch	6.00	1.00	3.33		6.82		0.12	0.06	0.12
	Cowpeas	9.00	1.50		1.29	1.10				
	Vetch*	6.00	1.00			4.42		0.12		
6	Vetch	4.50	0.75			6.82	0.44	0.12	0.06	0.12
	Cowpeas	9.00	1.50		1.29	1.10				
	Vetch*	6.00	1.00			4.42		0.12		

*Second crop.

TABLE 9. The pH value and amount less than 2-mm. particle size of soils used in greenhouse tests with beets and lettuce; the nitrogen and potassium added in nutrients, and the phosphorus added in seeds to the soils.

Soil No.	Crop Grown	pH Value	Oven-dry Soil less than 2-mm. Particle Size[a]	Total Nutrients Added to Soil[a]		Phosphorus Added in Seeds[a]
				Nitrogen	Potassium	
			kgm.	gm.	gm.	mgm.
1	Beets	5.48	11.856	1.20	1.50	5.70
	Lettuce	5.20	11.652	1.62	1.37	0.94
	Beets[b]	5.09	11.202	1.20	1.00	6.35
	Lettuce[b]	5.53	10.989	1.50	0.75	0.94
	(Final soil)	4.52				
2	Beets	5.01	11.616	1.20	1.50	5.76
	Lettuce	4.93	11.400	1.62	1.37	0.94
	Beets[b]	4.88	11.027	1.20	1.00	6.16
	Lettuce[b]	5.45	10.806	1.80	1.00	0.94
	(Final soil)	5.35				
3	Beets	5.11	9.405	1.20		5.72
	Lettuce	5.34	9.220	1.62	1.37	0.94
	Beets[b]	5.02	8.994	1.20	1.00	6.21
	Lettuce[b]	5.30	8.784	1.80	1.00	0.94
	(Final soil)	5.17				
4	Beets	5.34	9.544	1.20		6.04
	Lettuce	5.50	9.334	1.62	1.37	0.94
	Beets[b]	5.16	9.054	1.20	1.00	5.93
	Lettuce[b]	5.40	8.822	1.80	1.00	0.94
	(Final soil)	5.34				
5	Beets	5.04	9.543	0.60	1.50	5.53
	Lettuce	4.93	9.394	1.62	1.37	0.94
	Beets[b]	5.07	9.110	1.20	1.00	5.98
	Lettuce[b]	5.30	8.904	1.80	1.00	0.94
	(Final soil)	5.20				
6	Beets	4.40	11.376	0.60		5.12
	Lettuce	4.27	11.214	0.90	0.75	0.94
	Beets[b]	4.90	10.872	1.20	1.00	5.93
	Lettuce[b]	5.00	10.586	1.80	1.00	0.94
	(Final soil)	5.18				

a - Total for six replicates.
b - Second crop.

TABLE 10. Detailed statement of nutrients added to grow beets and lettuce.

Amounts are expressed as grams per total of six replicates

Soil No.	Crop Grown	Nutrients Added Before Seeding			Nutrients Added During Growth Period					
		$CaCO_3$	$MgCO_3$	K_2SO_4	NH_4NO_3	$NaNO_3$	KNO_3	Mg	Mn	H_3BO_3
1	Beets	1.50	0.25	3.33	0.86	5.47		0.12	0.06	0.12
	Lettuce	1.50			3.19		3.55	0.12		
	Beets*	3.00	0.50		2.40		2.58			
	Lettuce*				2.66	1.82	1.94	0.12		
2	Beets	3.00	0.50	3.33	0.86	5.47		0.12	0.06	0.12
	Lettuce	3.00			3.19		3.55	0.12		
	Beets*	6.00	1.00		2.40		2.58			
	Lettuce*				3.26	1.82	2.59	0.12		
3	Beets	6.00	1.00		0.86	5.47		0.12	0.06	0.12
	Lettuce				3.19		3.55	0.12		
	Beets*	6.00	1.00		2.40		2.58			
	Lettuce*				3.26	1.82	2.59	0.12		
4	Beets	6.00	1.00		0.86	5.47		0.12	0.06	0.12
	Lettuce				3.19		3.55	0.12		
	Beets*	6.00	1.00		2.40		2.58			
	Lettuce*				3.26	1.82	2.59	0.12		
5	Beets	6.00	1.00	3.33	0.86	1.82		0.12	0.06	0.12
	Lettuce	6.00			3.19		3.55	0.12		
	Beets*	6.00	1.00		2.40		2.58			
	Lettuce*				3.26	1.82	2.59	0.12		
6	Beets	4.50	0.75		0.86	1.82		0.12	0.06	0.12
	Lettuce	12.00			1.80		1.94	0.12		
	Beets*	6.00	1.00		2.40		2.58			
	Lettuce*	6.00	1.00		3.26	1.82	2.59	0.12		

*Second crop.

TABLE 11. The pH value and amount less than 2-mm. particle size of soils used in greenhouse tests with rye grass and Sudan grass; the nitrogen and potassium added in nutrients and the phosphorus added in seeds to the soils.

Soil No.	Crop Grown	pH Value	Oven-dry Soil less than 2-mm. Particle Size[a]	Total Nutrients Added to Soil[a]		Phosphorus Added in Seeds[a]
				Nitrogen	Potassium	
			Kgm.	gm.	gm.	mgm.
1	Rye grass	5.48	11.856	3.45	4.33	0.37
	Sudan grass	5.92	11.442	1.80	1.50	1.51
	Rye grass[b]	4.55	11.099	3.00	1.76	0.37
	(Final soil)	4.38				
2	Rye grass	5.01	11.616	3.45	4.33	0.37
	Sudan grass	5.55	11.236	1.80	1.50	1.63
	Rye grass[b]	4.58	10.904	3.00	1.76	0.37
	(Final soil)	4.85				
3	Rye grass	5.11	9.451	3.45	2.83	0.37
	Sudan grass	5.46	8.951	1.80	1.50	1.63
	Rye grass[b]	4.98	8.591	3.00	1.76	0.37
	(Final soil)	5.12				
4	Rye grass	5.34	9.583	3.45	2.83	0.37
	Sudan grass	5.63	9.090	1.80	1.50	1.58
	Rye grass[b]	5.07	8.727	3.00	1.76	0.37
	(Final soil)	5.30				
5	Rye grass	5.04	9.422	3.45	4.33	0.37
	Sudan grass	5.27	8.942	1.80	1.50	1.58
	Rye grass[b]	5.00	8.559	3.00	1.76	0.37
	(Final soil)	5.15				
6	Rye grass	4.40	11.376	2.15	2.00	0.37
	Sudan grass	4.84	10.903	1.80	1.50	1.58
	Rye grass[b]	4.71	10.509	3.00	1.76	0.37
	(Final soil)	4.85				

a - Total for six replicates.
b - Second crop.

TABLE 12. Detailed statement of nutrients added to grow rye grass and Sudan grass. Amounts are expressed as grams per total of six replicates.

Soil No.	Crop Grown	Nutrients Added Before Seeding			Nutrients Added During Growth Period						
		$CaCO_3$	$MgCO_3$	K_2SO_4	$(NH_4)_2SO_4$	NH_4NO_3	$NaNO_3$	KNO_3	Mg	Mn	H_3BO_3
1	Rye grass	1.50	0.25	3.33		5.66	2.74	7.32	0.24	0.06	0.12
	Sudan grass				6.00			3.87			
	Rye grass*	3.00	0.50			5.48	2.72	4.54	0.12		
2	Rye grass	3.00	0.50	3.33		5.66	2.74	7.32	0.24	0.06	0.12
	Sudan grass				6.00			3.87			
	Rye grass*	3.00	0.50			5.48	2.72	4.54	0.12		
3	Rye grass	6.00	1.00			5.66	2.74	7.32	0.24	0.06	0.12
	Sudan grass				6.00			3.87			
	Rye grass*	6.00	1.00			5.48	2.72	4.54	0.12		
4	Rye grass	6.00	1.00			5.66	2.74	7.32	0.24	0.06	0.12
	Sudan grass				6.00			3.87			
	Rye grass*	6.00	1.00			5.48	2.72	4.54	0.12		
5	Rye grass	6.00	1.00	3.33		5.66	2.74	7.32	0.24	0.06	0.12
	Sudan grass	3.00	.50		6.00			3.87			
	Rye grass*	6.00	1.00			5.48	2.72	4.54	0.12		
6	Rye grass	4.50	0.75			5.66	2.74	5.16	0.24	0.06	0.12
	Sudan grass	6.00	1.00		6.00			3.87			
	Rye grass*	6.00	1.00			5.48	2.72	4.54	0.12		

*Second crop.

FIGURE 7. SECOND VETCH CROP[a] GROWN ON HEAVILY FERTILIZED COMMERCIAL POTATO SOILS.

a - Prior to first cutting.

FIGURE 8. SECOND RYE GRASS CROP[c] GROWN ON HEAVILY FERTILIZED COMMERCIAL POTATO SOILS.

b - Prior to second cutting.

TABLE 13. Dry weight and phosphorus content of vetch and cowpeas grown on six soils from commercial potato-producing areas.

Results expressed as total of six replicates

Soil	Crop Grown	Tops: Dry Weight	Tops: Phosphorus Content	Roots: Dry Weight	Roots: Phosphorus Content	Total: Phosphorus Content
		gm.	mgm.	gm.	mgm.	mgm.
1	Vetch[a]	95.45	290.8	12.69	30.8	321.6
	Cowpeas	51.34	161.4	12.77	25.6	187.0
	Vetch[b]	110.70	350.9	47.44	105.7	456.6
2	Vetch[a]	111.84	410.8	19.01	65.6	476.4
	Cowpeas	79.78	281.5	17.32	55.1	336.6
	Vetch[b]	114.92	548.8	42.33	141.0	689.8
3	Vetch[a]	176.30	666.6	39.28	134.8	801.4
	Cowpeas	179.70	551.5	23.42	61.3	612.8
	Vetch[b]	101.53	402.0	46.69	111.9	513.9
4	Vetch[a]	212.15	807.4	34.17	114.1	921.5
	Cowpeas	186.46	573.5	25.71	69.4	642.9
	Vetch[b]	161.91	724.3	65.52	198.7	923.0
5	Vetch[a]	164.95	365.3	51.83	103.7	469.0
	Cowpeas	188.57	439.9	27.02	58.5	498.4
	Vetch[b]	126.82	435.0	65.62	206.7	63[illegible].7
6	Vetch[a]	71.44	237.3	12.54	36.3	273.6
	Cowpeas	128.26	488.5	16.80	49.7	538.2
	Vetch[b]	192.39	737.1	60.82	165.1	902.2

a - Two cuttings.
b - Second crop, three cuttings.

data for the various cuttings of the two vetch crops are broken down in table 14.

In figure 9 the total dry weight of tops for the various crops is expressed graphically. The greatest quantity of dry matter was produced on soil 4 for the first vetch crop. The next highest amounts were produced on soils 3 and 5, in that order. A considerably smaller quantity of dry matter was produced on the remaining soils, the order being 2, then 1 with 6 the least. With the following crop of cowpeas, the greatest quantity of dry matter was obtained on the three Caribou loams (soils 3, 4, and 5), there being little difference among them. Soil 6 was intermediate in rank with soils 2 and 1 the lowest. On the final vetch crop, the greatest amount of dry matter was produced by the Collington loam, soil 6. Soil 4 was next followed by soil 5, while the least amounts were produced on soils 2, 1, and 3, in that order.

The phosphorus content of tops and roots for the various crops in the legume rotation is expressed graphically in figure 10. The rank of the soils was the same as for the production of dry matter (figure 9) for the first vetch crop. The relative amounts of dry matter production and phosphorus content were quite similar except for soil 5, where the phosphorus content was much lower with respect to the other soils than was the dry matter, indicating a lower percentage of phosphorus for the crop on this soil. With the cowpea crop, most phosphorus was removed on the Caribou

TABLE 14. Dry weight and phosphorus content of tops from separate cuttings of two vetch crops grown on six soils from commercial potato-producing areas.

Results expressed as total of six replicates

Soil	Crop	1st Cutting		2nd Cutting		3rd Cutting	
		Dry Weight	Phosphorus Content	Dry Weight	Phosphorus Content	Dry Weight	Phosphorus Content
		gm.	mgm.	gm.	mgm.	gm.	mgm.
1	First	39.80	136.9	55.65	153.9		
	Second	34.97	142.9	30.62	95.5	45.11	112.5
2	First	39.57	169.2	72.27	241.6		
	Second	40.61	207.2	38.77	192.5	35.54	149.1
3	First	54.05	225.9	122.25	440.7		
	Second	48.61	220.7	15.74	52.2	37.18	129.1
4	First	62.43	231.5	149.72	575.9		
	Second	54.76	231.5	41.24	193.4	65.91	274.4
5	First	41.78	135.6	123.17	249.7		
	Second	42.30	151.7	31.70	134.5	52.82	146.8
6	First	30.53	104.5	40.91	132.8		
	Second	61.74	243.6	53.74	225.4	76.01	263.1

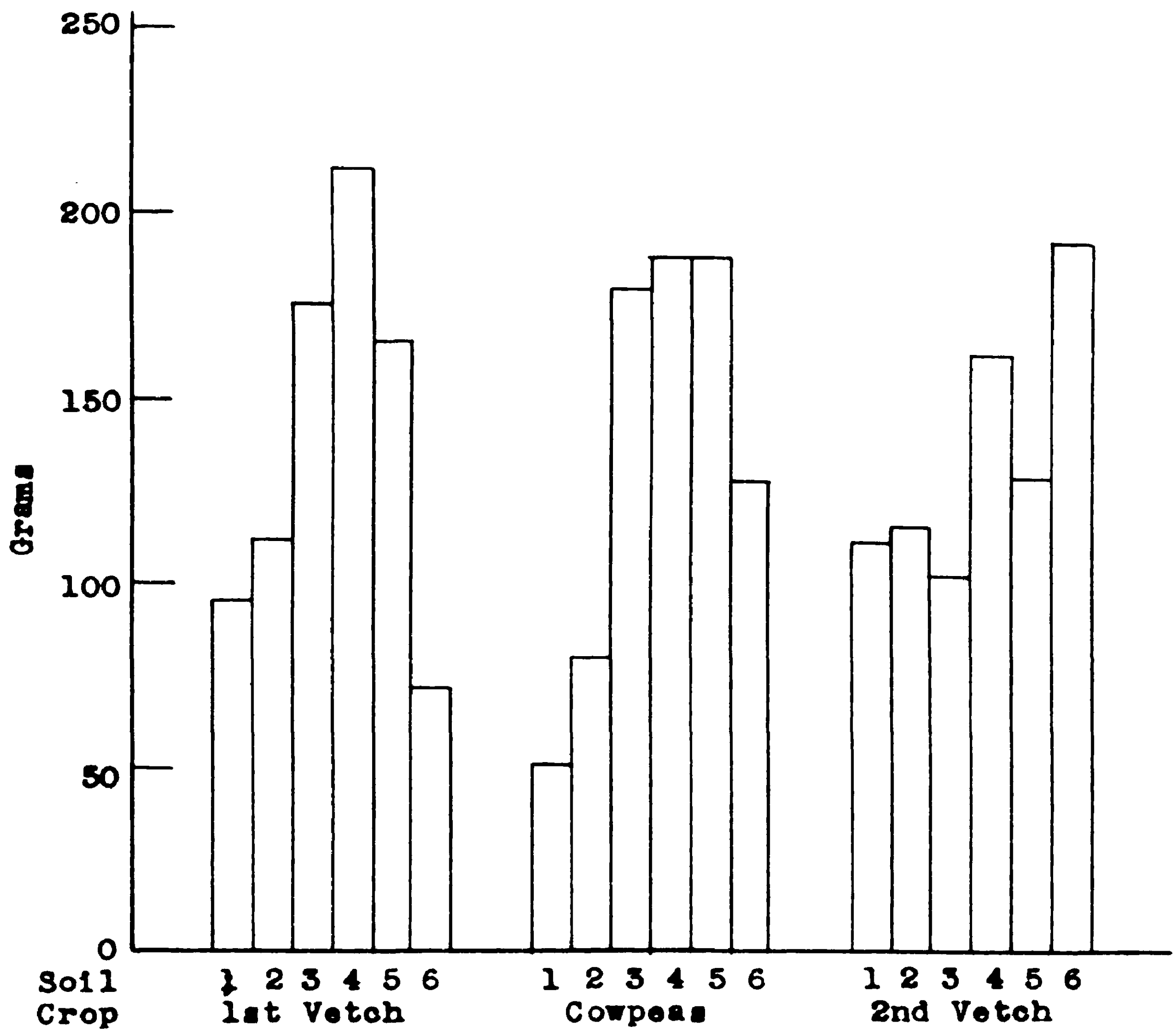

FIGURE 9. LEGUME ROTATION: DRY WEIGHT OF TOPS

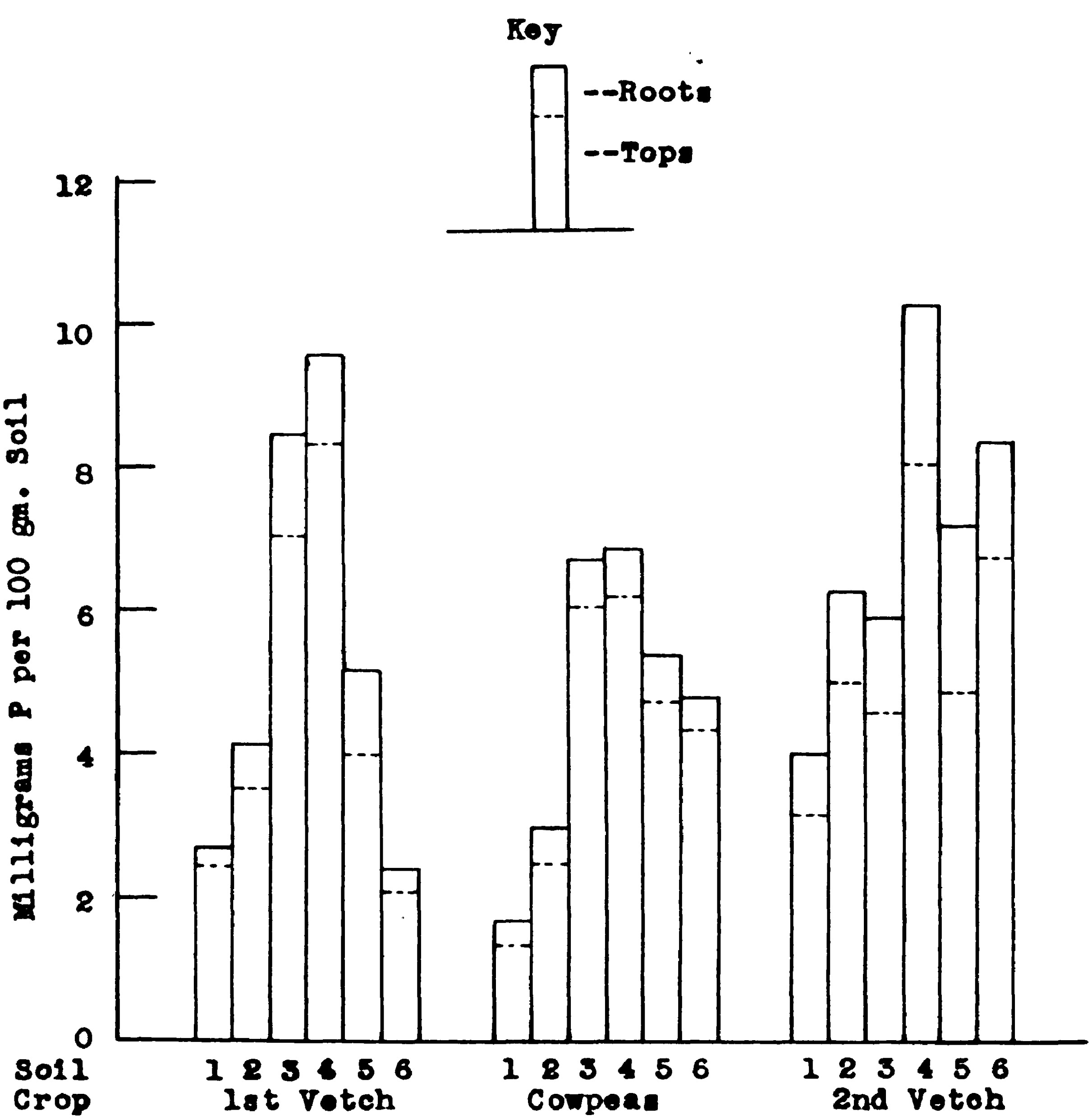

FIGURE 10. LEGUME ROTATION: PHOSPHORUS CONTENT OF TOPS AND ROOTS.

soils, although among these the phosphorus removal on soil 5 was relatively low. Soil 6 advanced to an intermediate position in this regard, while phosphorus removal on soil 1 was lowest and on soil 2 next lowest. The greatest phosphorus removal occurred on soil 4 with the second vetch crop, although it ranked second in dry matter production. Soil 6 advanced greatly in relation to all soils but soil 4 and ranked second in phosphorus removal followed by soils 5, 2, 3, and 1, in that order.

Values for cumulative phosphorus removal are expressed graphically in figure 11. The greatest cumulative phosphorus removal was on soil 4 throughout, with soils 3 and 5 ranking second and third, respectively. The cumulative phosphorus removal on soil 6 increased from the lowest ranking with the first vetch crop to fourth position at the end of the second vetch crop. Soil 2 ranked fifth, while the least phosphorus was removed on soil 1.

The vegetable rotation (experiment B-2) consisted of two crops of beets, each of which was followed by a crop of lettuce. The summary of data for dry weight and phosphorus content of the plant material is given in table 15. Figures 12 and 13 are photographs of the first and second lettuce crops.

The dry weights of tops in the vegetable rotation are shown graphically in figure 14. The dry weights obtained on the first four soils with the first beet crop were almost identical in amount, while a considerably smaller quantity

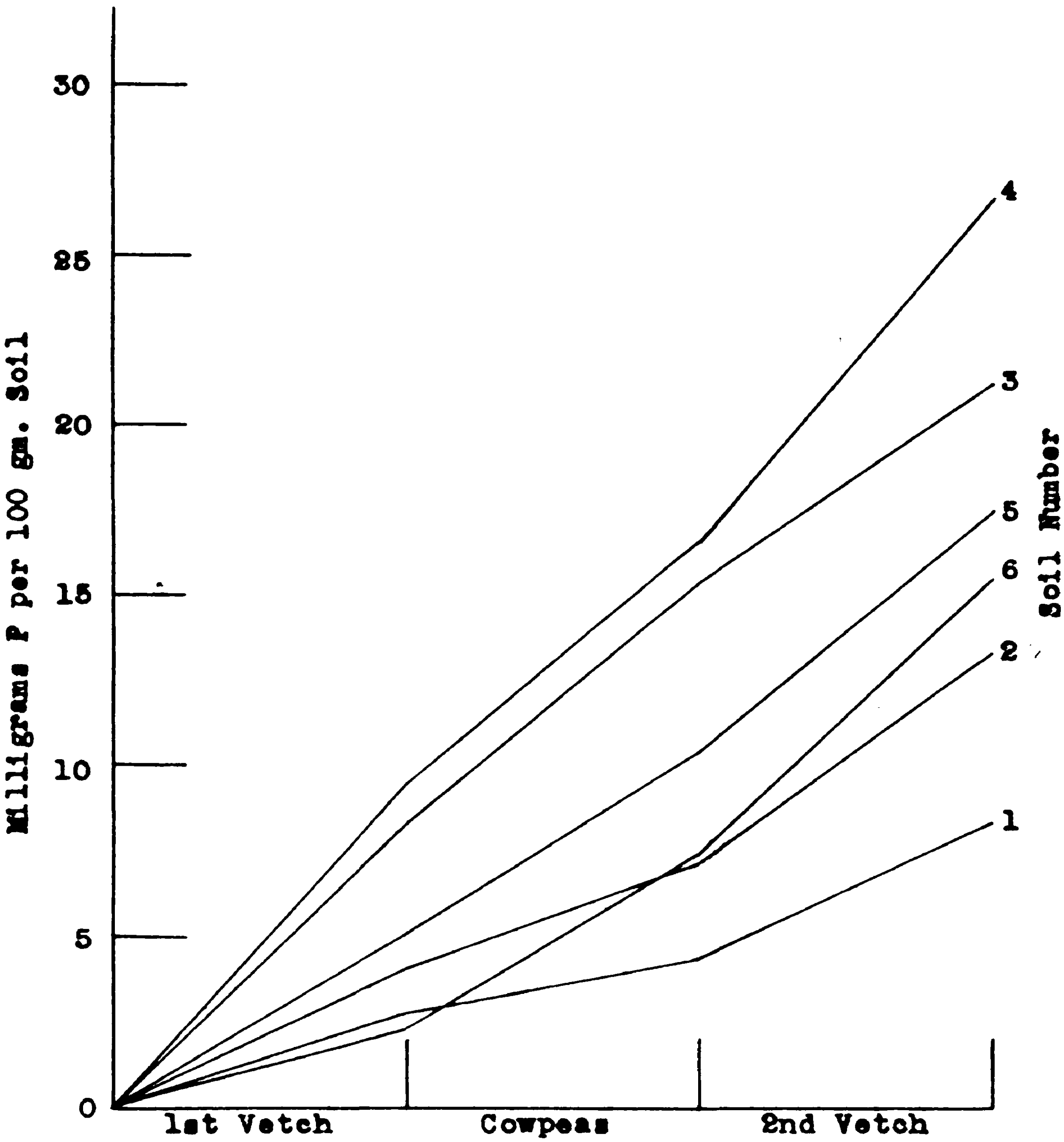

FIGURE 11. LEGUME ROTATION: CUMULATIVE REMOVAL OF PHOSPHORUS IN THE CROPS.

TABLE 15. Dry weight and phosphorus content of beets and lettuce grown on six soils from commercial potato-producing areas.

Results expressed as total of six replicates

Soil	Crop Grown	Tops		Roots		Total
		Dry Weight	Phosphorus Content	Dry Weight	Phosphorus Content	Phosphorus Content
		gm.	mgm.	gm.	mgm.	mgm.
1	Beets	23.81	162.2	25.77	140.6	302.8
	Lettuce	70.91	146.6			146.6
	Beets*	16.80	73.5	17.00	56.4	129.9
	Lettuce*	4.56	6.4			6.4
2	Beets	22.21	166.9	22.32	136.2	303.1
	Lettuce	92.55	330.4			330.4
	Beets*	19.68	240.9	26.04	105.2	346.1
	Lettuce*	76.16	233.7	13.08	37.0	270.7
3	Beets	26.48	144.6	21.62	137.1	281.7
	Lettuce	71.14	241.2			241.2
	Beets*	23.89	157.1	22.92	104.9	262.0
	Lettuce*	62.04	176.8	12.67	26.8	203.6
4	Beets	28.04	185.7	25.99	163.4	369.1
	Lettuce	114.80	304.1			304.1
	Beets*	24.47	180.5	22.84	107.8	288.3
	Lettuce*	93.11	296.9	21.06	47.1	346.0
5	Beets	9.00	26.2	2.88	12.1	38.3
	Lettuce	62.84	190.4			190.4
	Beets*	24.91	79.6	24.17	83.6	163.2
	Lettuce*	59.83	147.3	7.87	14.9	162.2
6	Beets	10.95	37.2	2.60	10.2	47.4
	Lettuce	83.08	254.9			254.9
	Beets*	16.34	81.1	2.89	23.1	104.2
	Lettuce*	114.99	404.2	16.74	36.2	440.4

*Second crop.

FIGURE 12. FIRST CROP OF LETTUCE GROWN ON HEAVILY FERTILIZED COMMERCIAL POTATO SOILS.

FIGURE 13. SECOND CROP OF LETTUCE GROWN ON HEAVILY FERTILIZED COMMERCIAL POTATO SOILS.

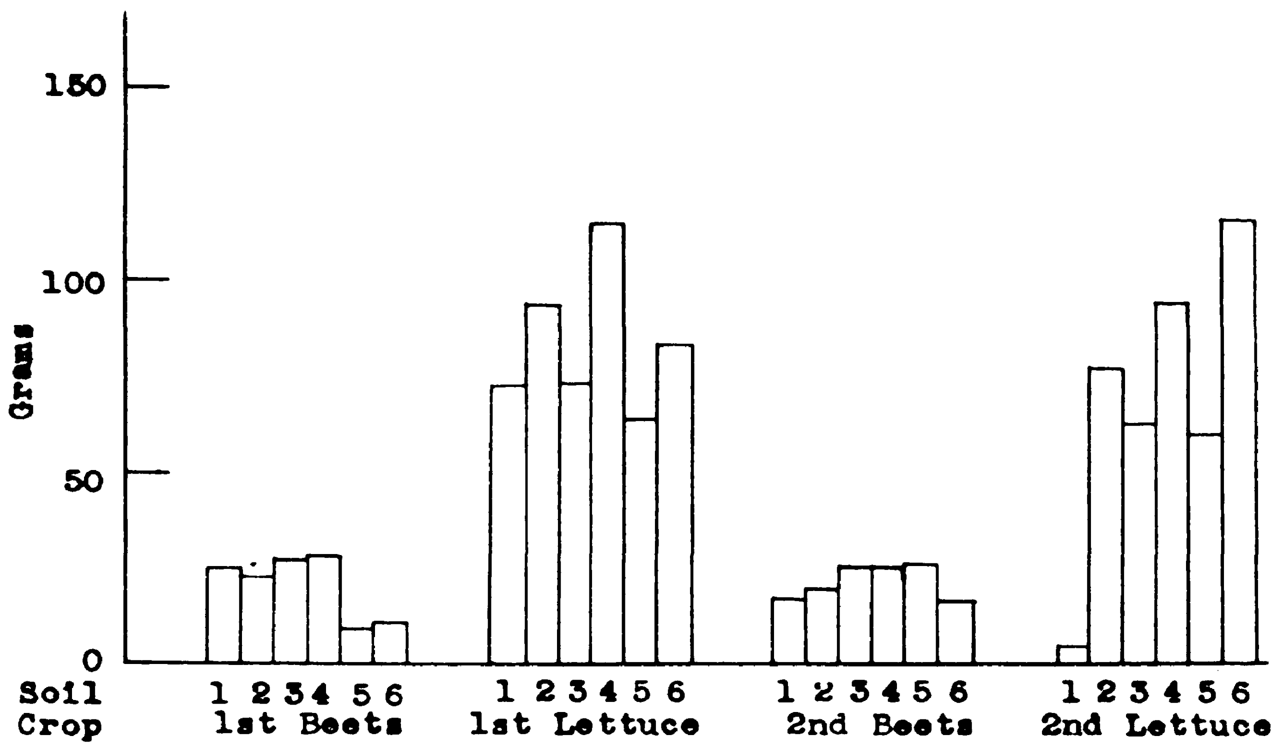

FIGURE 14. VEGETABLE ROTATION: DRY WEIGHT OF TOPS.

was obtained on soils 5 and 6. With the second beet crop the greatest dry weight was obtained on the Caribou soils with somewhat less on soils 2, 1, and 6, in that order. Much more dry weight of tops was obtained with the alternate lettuce crops. With the first lettuce crop, the greatest dry weight was obtained on soil 4, followed in order by soils 2, 6, 3, 1, and 5. In the case of the second lettuce crop, soil 4 ranked second with soil 6 first. Lesser amounts were obtained on soils 2, 3, and 5, in that order, while the crop on soil 1 virtually failed. Figures 12 and 13 illustrate this.

The data for phosphorus removed are expressed graphically in Figure 15. It is noted that there is much less difference between lettuce and beets with respect to phosphorus removed than is the case with similar comparisons involving dry weights. The phosphorus content of the beet roots constituted a considerable portion of the total phosphorus, since the fleshy axis was included with the roots. No roots were harvested in the case of the first lettuce crop and it will be seen from the graph for the second crop that the portion of the total phosphorus contributed by the harvested roots was rather small.

Figure 15 shows that the most phosphorus was removed by the first beet crop on soil 4, with soils 3, 2, and 1 following, in that order. Very little phosphorus was removed on soil 5 and 6. The second beet crop also had the highest phosphorus removed on soil 4, followed closely by

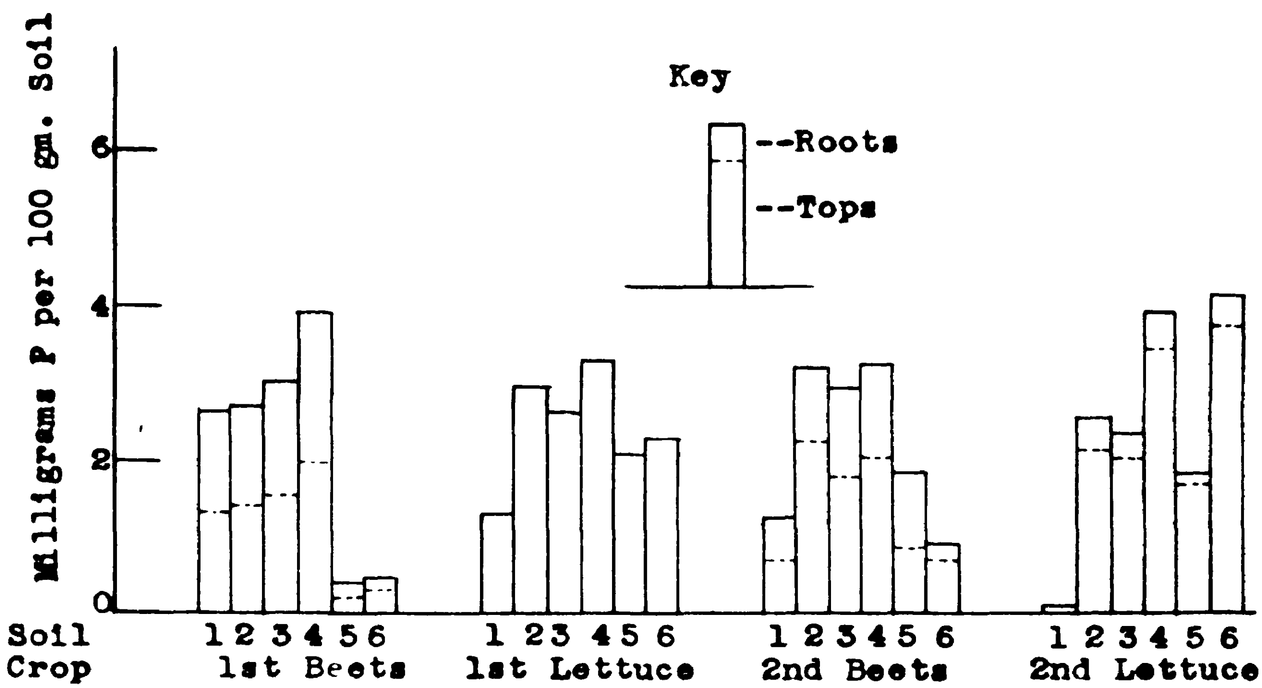

FIGURE 15. VEGETABLE ROTATION: PHOSPHORUS CONTENT OF TOPS AND ROOTS.

soils 2 and 3. Much less phosphorus was removed on soil 1 than was the case for the first beet crop. Much more phosphorus was removed by soils 5 and 6 than in the case of the first beet crop. Soil 6 still ranked last, however, with the former soil ranking fourth.

In the case of the first lettuce crop, the most phosphorus was removed on soil 4 with soils 2 and 3 ranking second and third respectively. Relatively much more phosphorus was removed on soils 5 and 6 by the lettuce than by the first beet crop. The least phosphorus was removed on soil 1. With the second lettuce crop, soil 6 ranked first in removal of phosphorus, followed closely by soil 4. Considerably less phosphorus was removed on soils 2, 3, and 5, while there was almost no removal on soil 1.

The cumulative removal of phosphorus (figure 16) shows that, as with the legume series, the greatest removal was on soil 4. Soil 2 ranked second just ahead of soil 3. Soil 6, with the vegetables as with the legumes, improved its position with cropping to rank fourth at the conclusion of the second lettuce crop. Soil 1 again was last and soil 5 was next to last.

The fact that lettuce failed to grow on soil 6 in experiment A-4, yet made satisfactory growth on this soil following the beet crop in experiment B-2, indicated that some factor other than phosphorus was involved and was inhibiting growth. The opinion that some inhibiting factor was present and was being removed by cropping, was confirmed

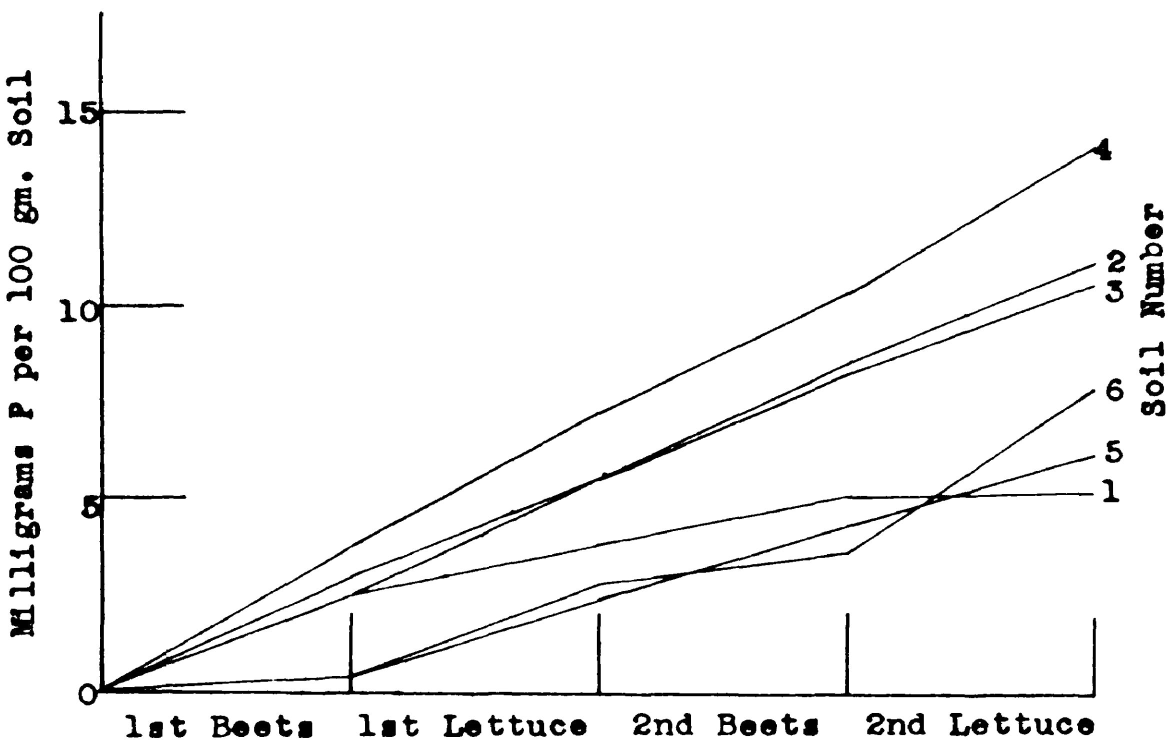

FIGURE 16. VEGETABLE ROTATION: CUMULATIVE REMOVAL OF PHOSPHORUS IN THE CROPS.

by the observation that ensuing crops of vetch and lettuce on this soil made better growth than preceding ones. Conductivity measurements were made on soil extracts from the six original soils. The data are given in table 16. These

TABLE 16. Conductivity of soils used in greenhouse experiments.

Soil Number	Conductivity (relative units)
1	25
2	37
3	86
4	88
5	68
6	222

show that soil 6 contained a much higher concentration of soluble salts than the other soils and that this probably was inhibiting growth until the high concentration was reduced by cropping.

The grass rotation (experiment B-3) consisted of two crops of rye grass with an intermediate crop of Sudan grass. Several cuttings were obtained with each of these crops. Figure 8 is a photograph of the second rye grass crop taken between the first and second cuttings. Data summarizing dry weight and phosphorus content of the plant material are given in table 17 for the various crops. The data for the various cuttings of the individual crops are broken down in table 18.

The total dry weight of tops for the various crops is expressed graphically in figure 17. The data for both the first and second rye grass crops show relatively small

TABLE 17. Dry weight and phosphorus content of rye grass and Sudan grass grown on six soils from commercial potato-producing areas.

Results expressed as total of six replicates

Soil	Crop Grown	Tops		Roots		Total
		Dry Weight	Phosphorus Content	Dry Weight	Phosphorus Content	Phosphorus Content
		gm.	mgm.	gm.	mgm.	mgm.
1	Rye grass[a]	107.11	444.3	87.73	138.7	583.0
	Sudan grass[b]	130.48	203.4	44.31	55.7	259.1
	Rye grass[c]	100.75	279.3	154.64	124.8	404.1
2	Rye grass[a]	117.35	530.1	72.03	147.3	677.4
	Sudan grass[b]	115.11	292.0	56.78	101.7	393.7
	Rye grass[c]	104.66	461.9	147.17	210.3	672.2
3	Rye grass[a]	114.07	480.7	127.38	247.3	728.0
	Sudan grass[b]	205.67	439.3	72.85	129.8	569.1
	Rye grass[c]	95.44	329.0	98.53	181.2	510.2
4	Rye grass[a]	128.96	532.8	98.38	183.3	716.1
	Sudan grass[b]	204.66	459.7	77.93	137.4	597.1
	Rye grass[c]	108.65	419.9	110.16	185.8	605.7
5	Rye grass[a]	110.29	320.5	84.30	127.4	447.9
	Sudan grass[b]	170.45	235.1	63.11	78.7	313.8
	Rye grass[c]	89.93	215.0	109.67	142.5	357.5
6	Rye grass[a]	135.58	566.5	55.57	114.7	681.2
	Sudan grass[b]	182.84	470.9	53.54	101.5	572.4
	Rye grass[c]	113.07	444.2	118.92	208.5	652.7

a - Five cuttings.
b - Two cuttings.
c - Second crop, five cuttings.

TABLE 18. Dry weight and phosphorus content of tops from separate cuttings of rye grass and Sudan grass grown on six soils from commercial potato-producing areas. Results expressed as total of six replicates.

Soil	Crop Grown	1st Cutting		2nd Cutting		3rd Cutting		4th Cutting		5th Cutting	
		Dry Weight	Phosphorus Content	Dry Weight	Phosphorus Content	Dry Weight	Phosphorus Content	Dry Weight	Phosphorus Content	Dry Weight	Phosphorus Content
		gm.	mgm.	gm.	mgm.	gm.	mgm.	gm.	mgm.	gm.	
1	Rye grass	13.66	71.3	10.63	43.5	17.05	88.1	13.31	75.7	52.41	160.7
	Sudan grass	76.14	114.3	54.34	89.1						
	Rye grass*	15.01	40.3	13.65	53.6	15.33	51.3	15.24	42.0	41.52	86.9
2	Rye grass	15.09	93.9	12.03	71.1	17.59	98.2	12.87	73.9	59.75	193.0
	Sudan grass	59.63	126.6	55.48	135.4						
	Rye grass*	14.60	86.1	13.75	34.3	14.07	64.5	14.76	72.9	48.42	144.1
3	Rye grass	16.63	95.5	12.13	52.5	17.46	89.1	13.69	73.6	54.16	166.8
	Sudan grass	120.70	235.7	84.97	203.6						
	Rye grass*	16.66	68.3	13.32	70.0	13.91	46.9	14.73	45.6	36.82	97.7
4	Rye grass	17.63	96.4	13.65	56.6	15.50	84.9	13.65	62.6	63.63	202.3
	Sudan grass	116.66	230.2	92.09	228.5						
	Rye grass*	20.38	87.6	15.44	39.9	15.43	60.0	15.79	57.1	41.61	125.1
5	Rye grass	12.57	44.3	11.67	39.6	16.42	61.5	12.94	50.6	56.59	123.6
	Sudan grass	92.75	115.7	77.70	113.4						
	Rye grass*	6.44	26.4	12.10	42.9	17.64	42.7	14.71	[illegible]	37.04	69.2
6	Rye grass	22.10	93.3	16.34	58.2	20.10	100.1	14.48	66.3	62.56	227.1
	Sudan grass	98.37	244.4	84.27	226.5						
	Rye grass*	19.95	96.4	14.92	93.3	15.96	56.6	16.91	62.4	45.33	133.0

*Second crop.

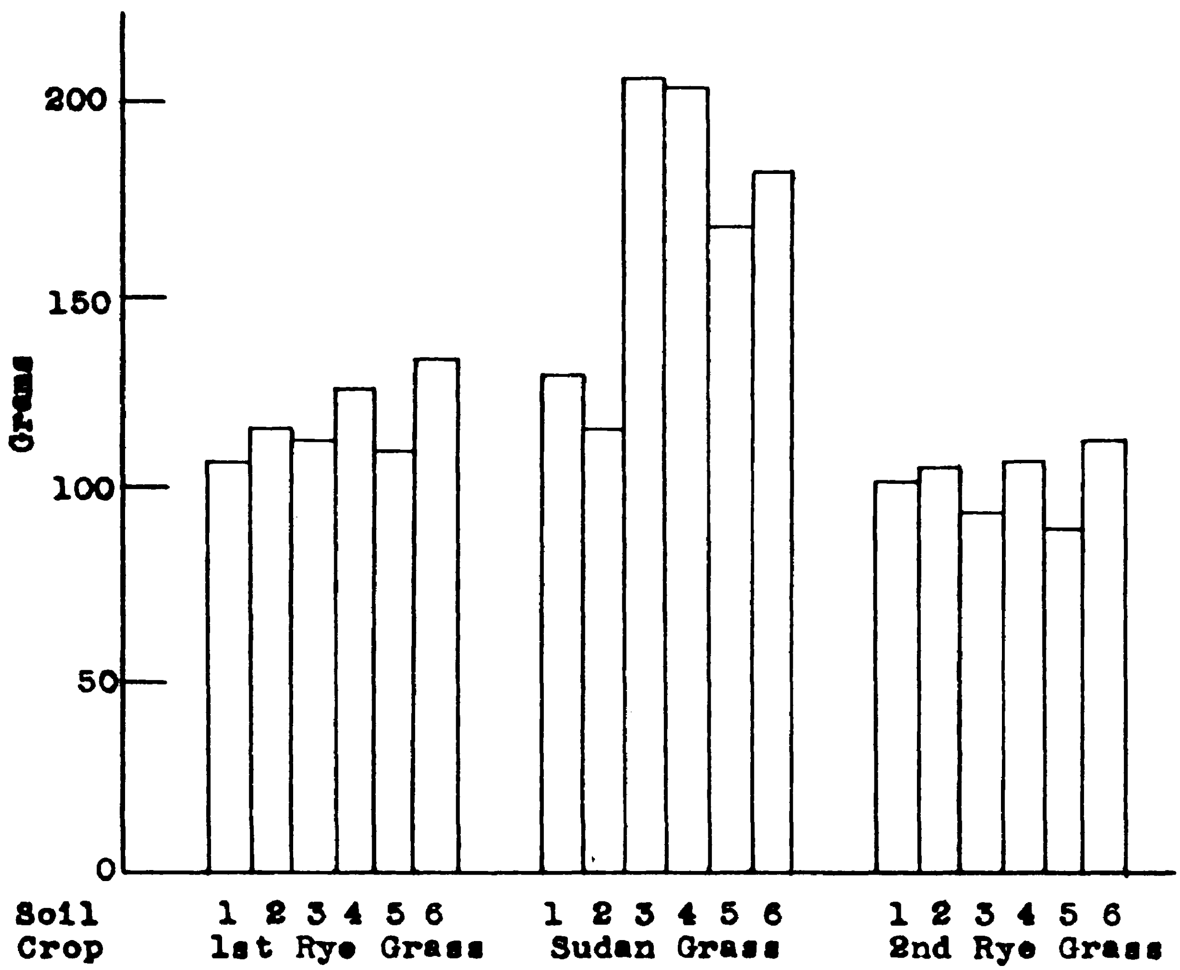

FIGURE 17. GRASS ROTATION: DRY WEIGHT OF TOPS.

differences between soils. The greatest growth occurred on soil 6 in both cases, with soil 4 ranking second and soil 2 ranking third. In the case of the intermediate Sudan grass, the greatest dry matter production was on soil 3, with soil 4 a close second. Soil 6 was third and soil 5 was fourth. The sandy soils 1 and 2 produced much less dry matter, soil 2 giving the least amount.

In the case of phosphorus removal (figure 18) the greatest amount occurred on soil 3 with soil 4 next with the first rye grass crop. Considerably less was obtained on soil 6, the third ranking soil. Soils 2, 1, and 5 ranked fourth, fifth, and sixth, respectively. In the case of the Sudan grass the greatest removal took place on soil 4 followed closely by soil 3. A somewhat smaller amount was removed on soil 6 while much less was removed on soils 2, 5, and 1. With the second rye grass crop, removal on soil 4 was greatest, with somewhat less removed on soils 2, 3, and 6. The removal of phosphorus on soils 1 and 5 was much lower.

The cumulative phosphorus removal data (figure 19) show that the greatest phosphorus uptake occurred on soil 4 and the least on soil 1, as with the other two cropping systems. Between these extremes, the soils ranked 3, 6, 2, and 5, in descending order. The improvement of soil 6 with respect to the other soils noted in the case of the legume and vegetable rotations with succeeding crops was not noted in the grass series. This is attributed to the fact that the grass crops were relatively salt tolerant, and the high soluble salt

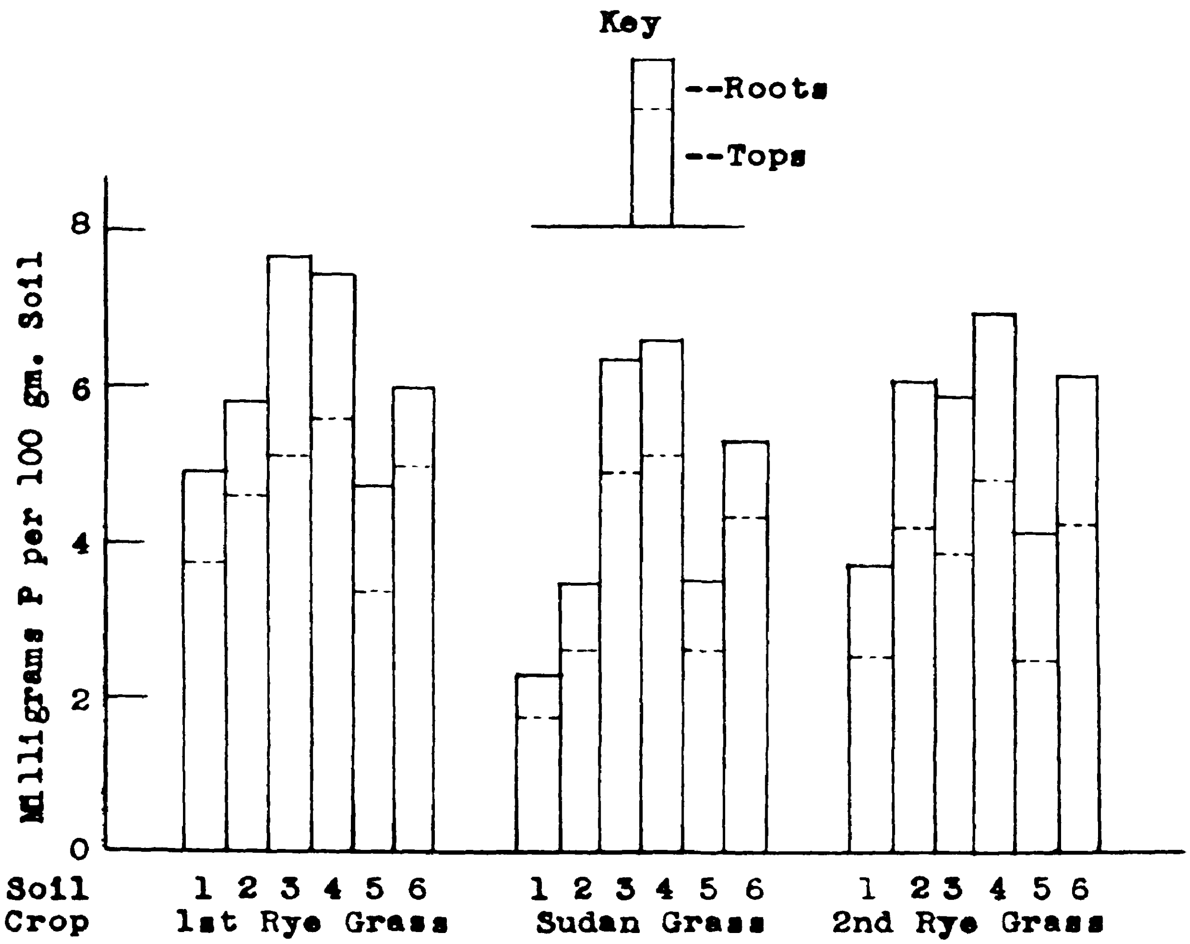

FIGURE 18. GRASS ROTATION: PHOSPHORUS CONTENT OF TOPS AND ROOTS.

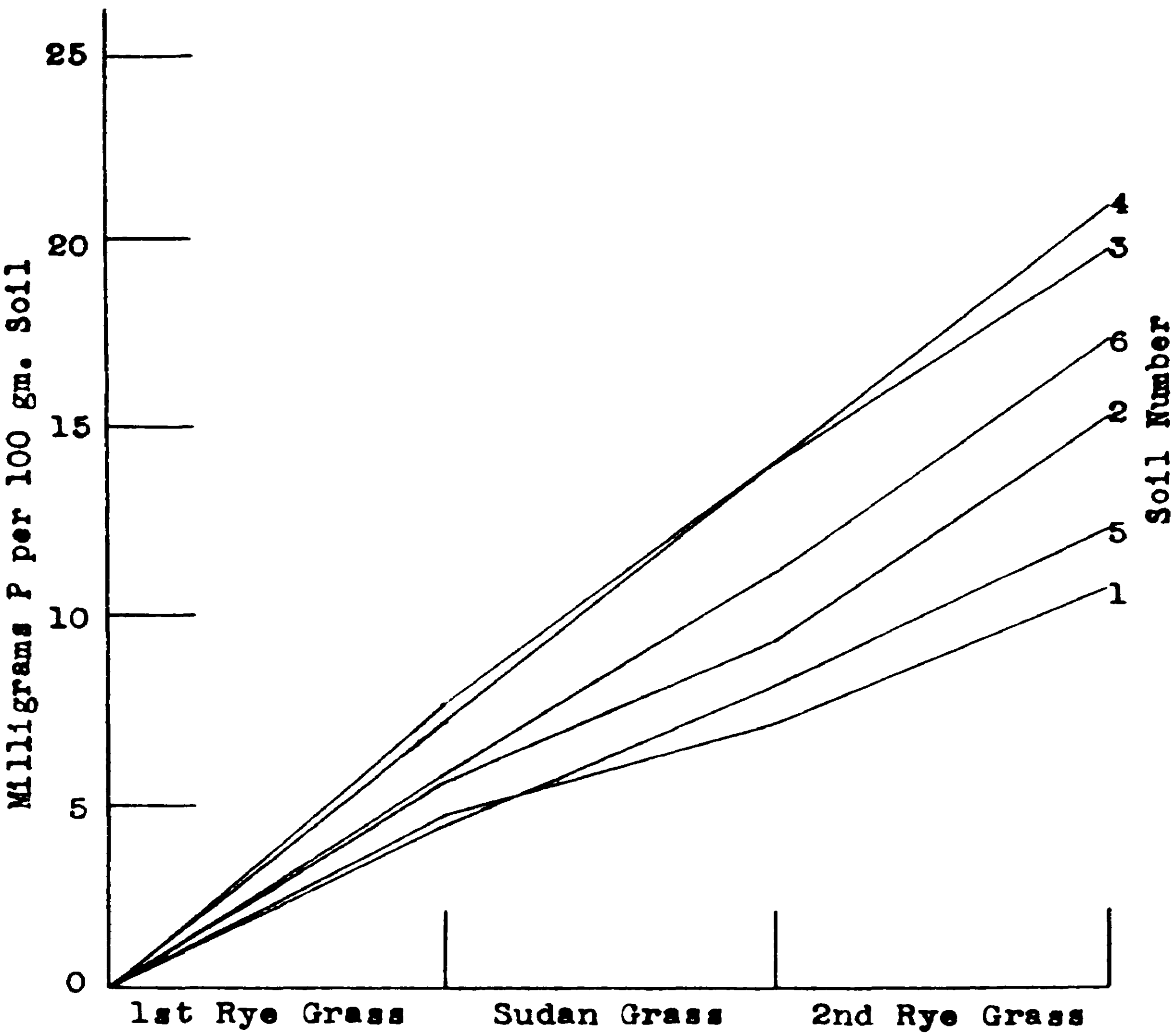

FIGURE 19. GRASS ROTATION: CUMULATIVE REMOVAL OF PHOSPHORUS IN THE CROPS.

level on soil 6 did not inhibit growth of the grasses as it did that of the legumes and vegetables. In all rotations, the earlier crop reduced the initial high soluble salt concentration in this soil to a point where its inhibiting effect was no longer felt.

Changes in Level of Soil Phosphorus Fractions Associated with Cropping

In experiment B, in which rotations of various types of crops were grown, representative soil samples were taken following each crop and various phosphorus fractions in these samples quantitatively determined. These results are presented in tables 19, 20, and 21 for the legume, vegetable, and grass rotations, respectively. The values include determinations of alkali-extractable, exchangeable, organic, apatitic, and readily soluble phosphorus. Some determinations of exchangeable phosphorus by the ammonium flouride method are included.

Alkali-extractable Phosphorus. The relative change in level of alkali-extractable phosphorus with cropping is plotted for the various roations in figures 20, 21, and 22. The quantity of this fraction in each of the original soils is arbitrarily set at 100 per cent. These figures illustrate the decline in alkali-extractable phosphorus with cropping. In all rotations the greatest decline occurred in soil 1, the Sassafras sandy loam, followed by soil 2, the Moyock loamy fine sand. The finer-textured Caribou and Collington soils all showed a lower relative decline

TABLE 19. The alkali-extractable, exchangeable, organic, apatitic, and readily soluble phosphorus of soils before and after growing vetch and cowpeas.

Results in milligrams per 100 gm. oven-dry 2-mm. soil.

Soil No.	Original Soil and Preceding Crop	Phosphorus Fraction					
		Alkali-extractable	Exchangeable	Organic	Apatitic	Readily Soluble	Exchangeable (by NH_4F)
1	(Original)	35.65	35.10	0.55	2.72	8.59	42.3
	Vetch	33.76	32.38	1.38	3.20	5.37	35.0
	Cowpeas	30.85	29.97	0.88	2.43	4.76	
	Vetch*	27.13	34.58	(-7.45)	2.58	4.41	
2	(Original)	100.81	91.37	9.44	13.68	23.55	99.1
	Vetch	97.90	83.42	14.48	11.95	17.13	88.4
	Cowpeas	92.21	79.10	13.11	12.18	13.98	
	Vetch*	80.77	72.21	8.56	11.31	17.11	
3	(Original)	157.87	135.47	22.40	18.98	18.14	81.7
	Vetch	150.70	126.74	23.96	16.34	12.39	70.1
	Cowpeas	143.44	122.20	21.24	14.75	9.93	
	Vetch*	134.08	110.75	23.33	18.18	10.99	
4	(Original)	156.47	137.90	18.57	18.20	17.55	84.1
	Vetch	145.95	126.92	19.03	16.77	12.89	73.9
	Cowpeas	141.17	122.06	19.11	15.46	9.84	
	Vetch*	130.57	114.97	15.60	16.81	10.21	
5	(Original)	104.59	87.65	16.94	9.60	7.10	45.0
	Vetch	99.82	81.82	18.00	8.30	4.99	39.9
	Cowpeas	92.64	77.24	15.40	8.44	3.39	
	Vetch*	86.99	71.01	15.98	9.34	3.14	
6	(Original)	115.54	100.56	14.98	22.02	18.94	89.5
	Vetch	113.84	98.46	15.38	23.87	15.13	78.9
	Cowpeas	110.08	94.59	15.49	24.90	11.77	
	Vetch*	100.77	87.03	13.74	26.02	12.04	

*Second crop.

TABLE 20. The alkali-extractable, exchangeable, organic, apatitic, and readily soluble phosphorus of soils before and after growing beets and lettuce.

Results in milligrams per 100 gm. oven-dry 2-mm. soil.

Soil No.	Original Soil and Preceding Crop	Phosphorus Fraction: Alkali-extractable	Exchangeable	Organic	Apatitic	Readily Soluble	Exchangeable (by NH_4F)
1	(Original)	35.65	35.10	0.55	2.72	8.59	42.3
	Lettuce	30.12			2.56	6.06	31.1
	Beets*	29.91	28.86	1.05	2.37	4.76	
	Lettuce*	28.60	33.77	(-5.17)	2.44	4.96	
2	(Original)	100.81	91.37	9.44	13.68	23.55	91.1
	Lettuce	92.70	80.78	11.92	11.77	19.12	87.5
	Beets*	88.86	80.61	8.25	13.46	14.10	
	Lettuce*	86.35	78.17	8.18	12.22	16.93	
3	(Original)	157.87	135.47	22.40	16.98	18.14	81.7
	Lettuce	150.94	129.93	21.01	15.25	12.88	72.0
	Beets*	146.02	125.70	20.32	16.91	10.83	
	Lettuce*	152.19	131.00	21.19	15.75	11.55	
4	(Original)	156.47	137.90	18.57	18.20	17.55	84.1
	Lettuce	149.90	130.36	19.54	16.17	13.00	75.9
	Beets*	143.00	125.00	18.00	18.40	10.67	
	Lettuce*	146.16	126.27	19.89	17.52	11.57	
5	(Original)	104.59	87.65	16.94	9.60	7.10	45.0
	Lettuce	97.64	84.12	13.52	9.72	5.30	40.6
	Beets*	96.40	81.35	15.05	10.51	4.04	
	Lettuce*	98.59	80.23	18.36	10.11	4.34	
6	(Original)	115.84	100.86	14.98	22.02	18.94	89.5
	Lettuce	110.87	96.09	14.78	23.88	15.85	75.0
	Beets*	111.55	95.56	15.99	25.47	13.52	
	Lettuce*	105.20	90.23	14.97	23.66	13.75	

*Second crop.

TABLE 21. The alkali-extractable, exchangeable, organic, apatitic, and readily soluble phosphorus of soils before and after growing rye grass and Sudan grass.

Results in milligrams per 100 gm. oven-dry 2-mm. soil.

Soil No.	Original Soil and Preceding Crop	Phosphorus Fraction: Alkali-extractable	Exchangeable	Organic	Apatitic	Readily Soluble	Exchangeable (by NH_4F)
1	(Original)	35.65	35.10	0.55	2.72	8.59	42.3
	Rye grass	29.81	32.38	(-2.57)	2.44	6.65	29.7
	Sudan grass	28.30	28.28	0.02	2.71	4.22	
	Rye grass*	24.93	29.27	(-4.34)	2.47	3.55	
2	(Original)	100.81	91.37	9.44	13.68	23.55	99.1
	Rye grass	90.53	81.28	9.25	12.51	19.57	87.5
	Sudan grass	89.50	81.10	8.40	11.44	14.19	
	Rye grass*	83.88	77.48	6.40	11.45	16.26	
3	(Original)	157.87	135.47	22.40	16.98	18.14	81.7
	Rye grass	147.00	128.19	18.81	15.47	13.98	71.2
	Sudan grass	141.88	121.08	20.80	16.62	10.41	
	Rye grass*	138.32	116.50	21.82	15.56	10.69	
4	(Original)	156.47	137.90	18.57	18.20	17.55	84.1
	Rye grass	143.91	128.69	15.22	17.79	14.33	74.4
	Sudan grass	141.11	123.74	17.37	17.14	10.98	
	Rye grass*	134.74	116.43	18.31	17.36	10.66	
5	(Original)	104.59	87.65	16.94	9.60	7.10	45.0
	Rye grass	98.73	83.93	14.80	8.32	5.27	39.4
	Sudan grass	90.22	75.42	14.80	8.89	3.97	
	Rye grass*	90.42	75.88	14.54	8.88	3.67	
6	(Original)	115.84	100.86	14.98	22.02	18.94	89.5
	Rye grass	108.88	93.[illegible]1	15.07	24.10	15.12	73.9
	Sudan grass	102.40	88.99	13.41	22.23	11.65	
	Rye grass*	98.11	85.61	12.50	23.34	11.33	

*Second crop.

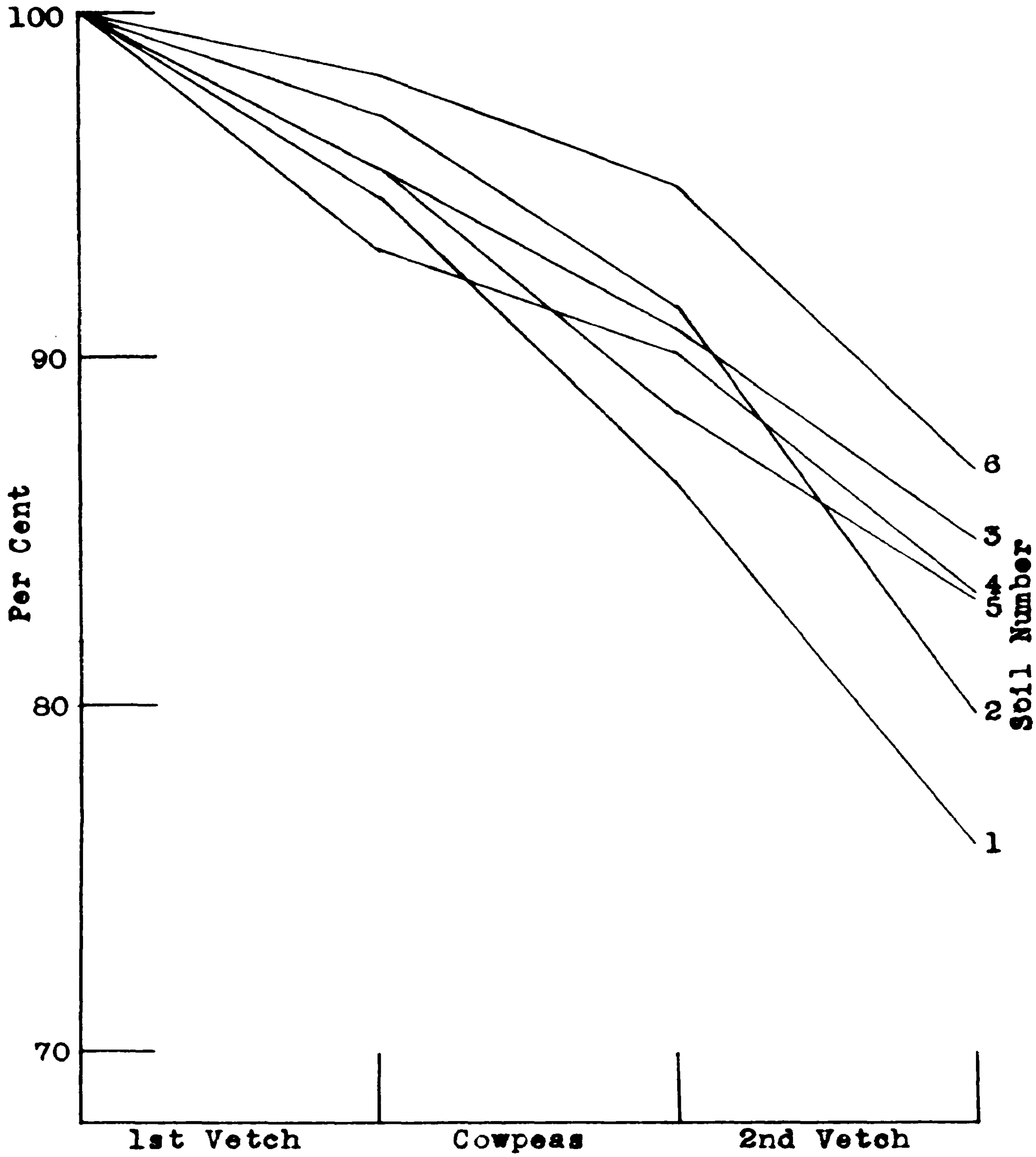

FIGURE.20. LEGUME ROTATION: RELATIVE CHANGE IN ALKALI-EXTRACTABLE PHOSPHORUS WITH CROPPING.

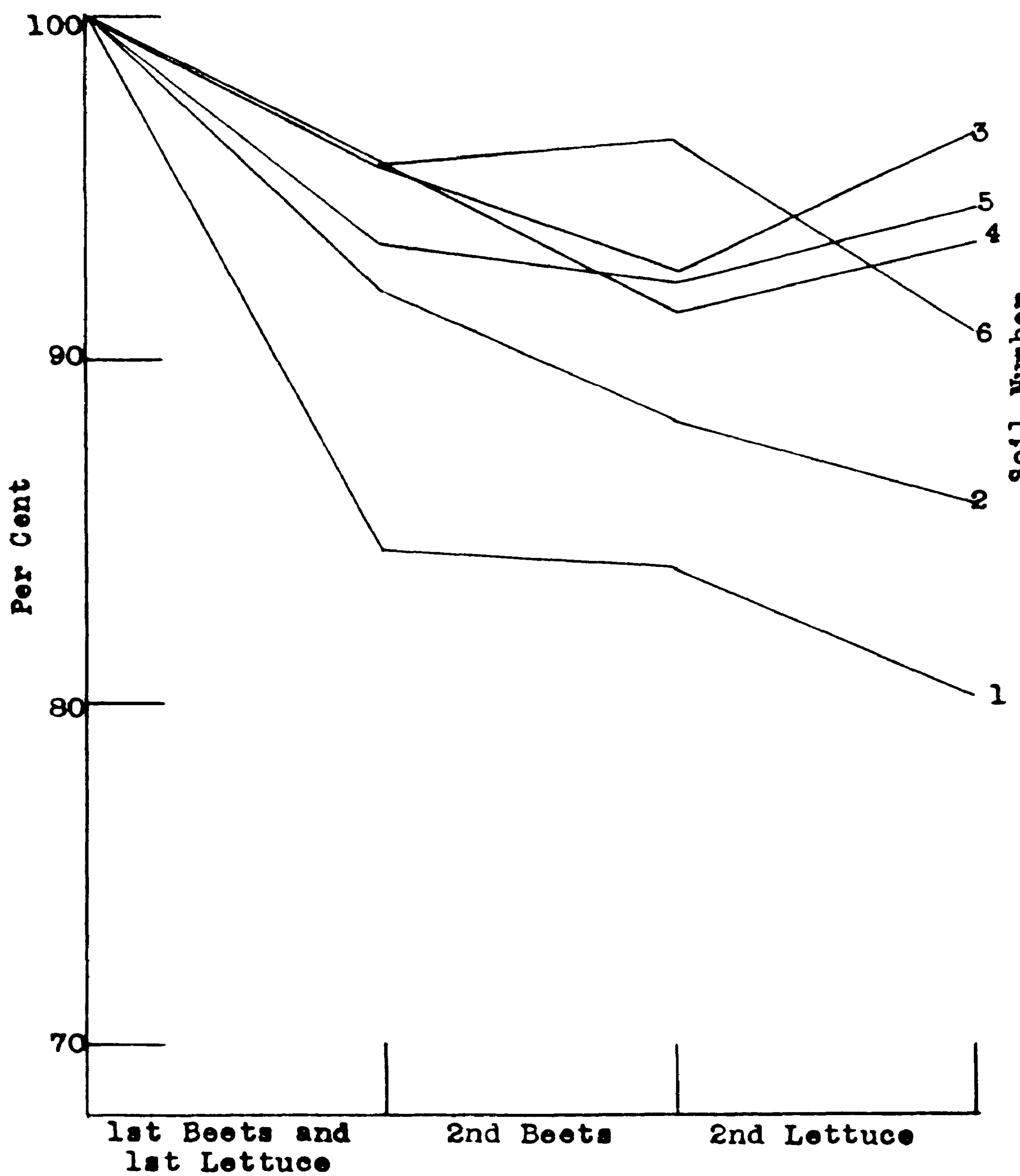

FIGURE 21. VEGETABLE ROTATION: RELATIVE CHANGE IN ALKALI-EXTRACTABLE PHOSPHORUS WITH CROPPING.

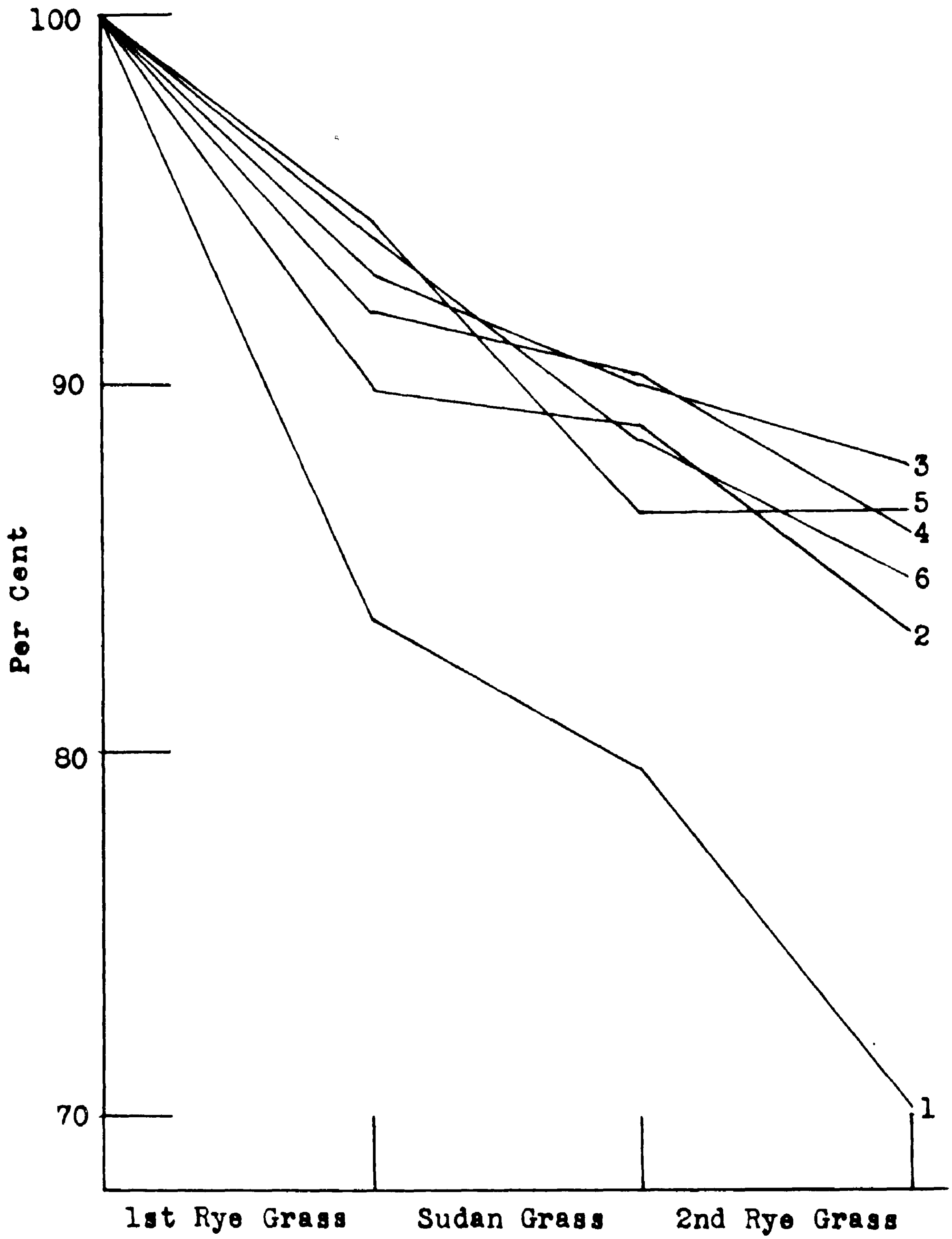

FIGURE 22. GRASS ROTATION: RELATIVE CHANGE IN ALKALI-EXTRACTABLE PHOSPHORUS WITH CROPPING.

in alkali-extractable phosphorus. The least decline was shown by soil 6, followed by soils 3, 4, and 5 in the legume rotation and by soil 3 followed by soils 5, 4, and 6 on both the vegetable and grass rotation.

Exchangeable Phosphorus and Organic Phosphorus. The exchangeable phosphorus, determined by the hydroxyl method and by the ammonium flouride method, declined with cropping in all rotations. The magnitude of the decrease in exchangeable phosphorus determined by the hydroxyl method agreed closely with that found for the alkali-extractable phosphorus. The difference between these two quantities, termed the organic phosphorus, made up a relatively small portion of the alkali-extractable phosphorus. It did not appear to vary in any consistent or regular way with cropping.

Apatitic Phosphorus. The phosphorus extracted by 0.5 N sulfuric acid following the alkali-extraction, termed apatitic phosphorus, was of the same order of magnitude as the organic phosphorus for the various soils. It was very low on soil 1, considerably higher on soils 2 and 5, still higher on soil 3 and 4, and highest on soil 6. It did not appear to vary with cropping.

Readily Soluble Phosphorus. Changes in amounts of soluble phosphorus with cropping for the various rotations in experiment B are given in tables 19, 20, and 21. For ease in comparison with data for the other phosphorus fractions, these values are expressed as milligrams phosphorus per 100 gm. of oven-dry, 2-mm. soil. However, it is customary to express the readily soluble phosphorus as parts per million or as pounds per acre. The variation in absolute amounts of readily soluble phosphorus are expressed graphically in figures 23, 24, and 25 for the three rotations of experiment B. In all rotations a sharp decline in this fraction with cropping occurred until the final crops.

The relative change in the readily soluble phosphorus fraction with cropping is shown in figures 26, 27, and 28 for the three rotations. The least relative decline was shown with soil 2 in both the legume and grass rotations and with soils 2 and 6 in the vegetable rotations. In all these rotations the greatest relative declines were shown on soils 1 and 5. The rate of decline of readily soluble phosphorus with cropping levelled off at the final cropping in all rotations. In many cases there was an actual increase in readily soluble phosphorus between the next to last and final harvests.

Comparison between Crop Removal of Phosphorus and Changes in Soil Phosphorus Fractions

One of the important parts of experiment B, in which various rotations were used, was the study of the effect the removal of residual phosphorus by the crop had upon the value of different soil phosphorus fractions. The change in alkali-extractable, exchangeable, and readily

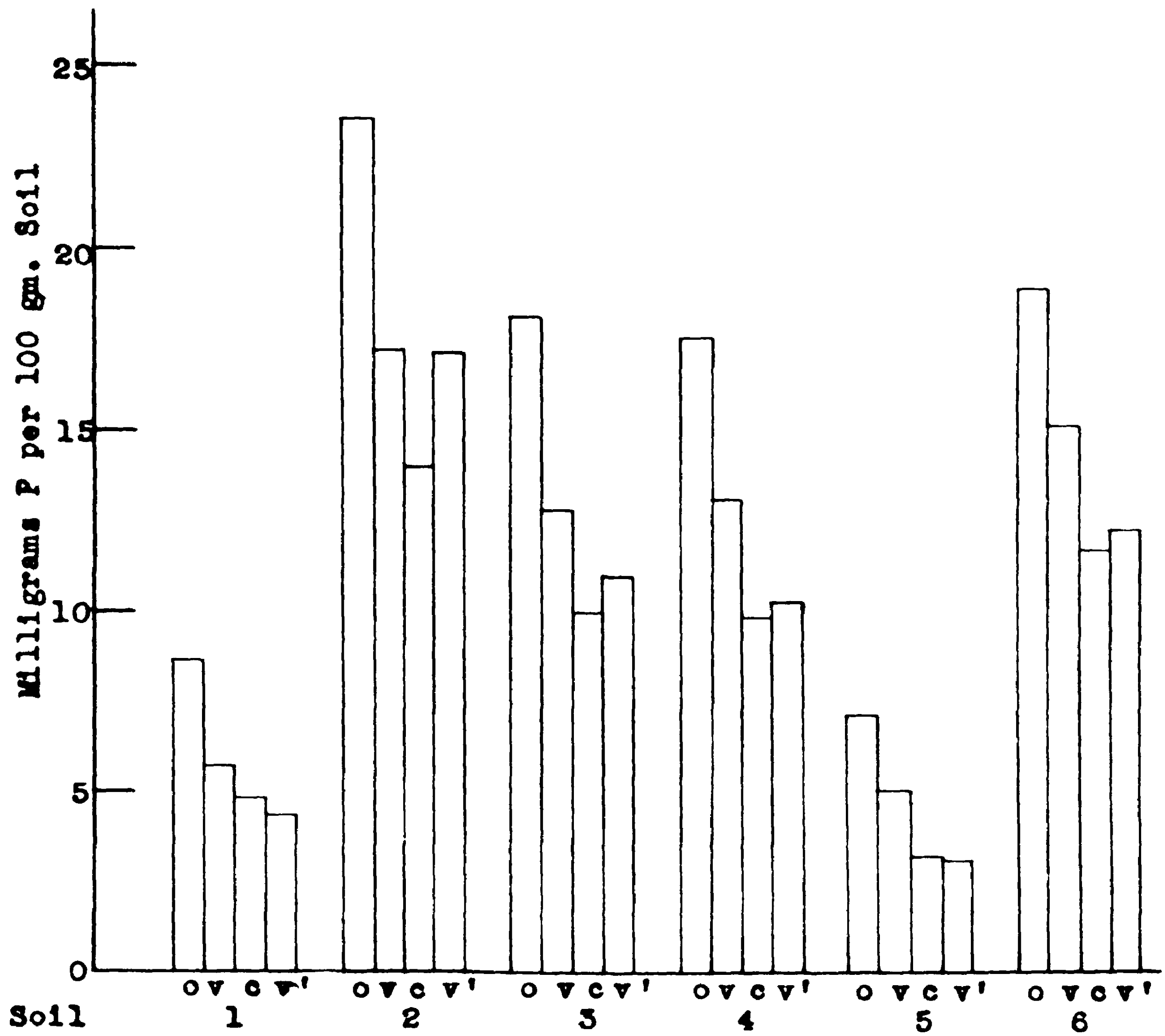

FIGURE 23. LEGUME ROTATION: CHANGE IN VALUE OF READILY SOLUBLE PHOSPHORUS WITH CROPPING.

Legend: o--uncropped soil; v--following 1st vetch; c--following cowpeas; v'--following 2nd vetch.

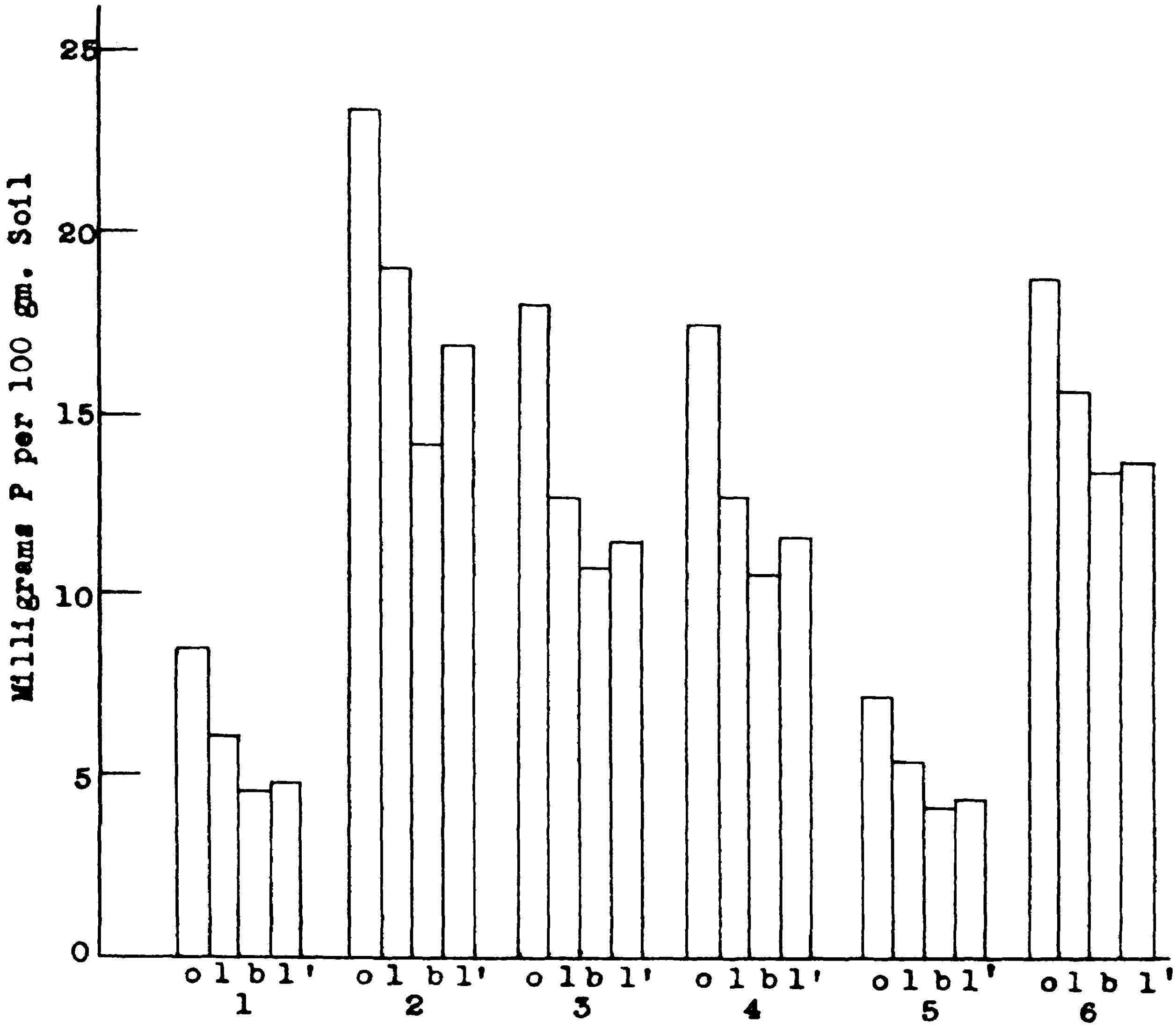

FIGURE 24. VEGETABLE ROTATION: CHANGE IN VALUE OF READILY SOLUBLE PHOSPHORUS WITH CROPPING.

Legend: o--uncropped soil; l--following 1st lettuce; b--following 2nd beets; l'--following 2nd lettuce.

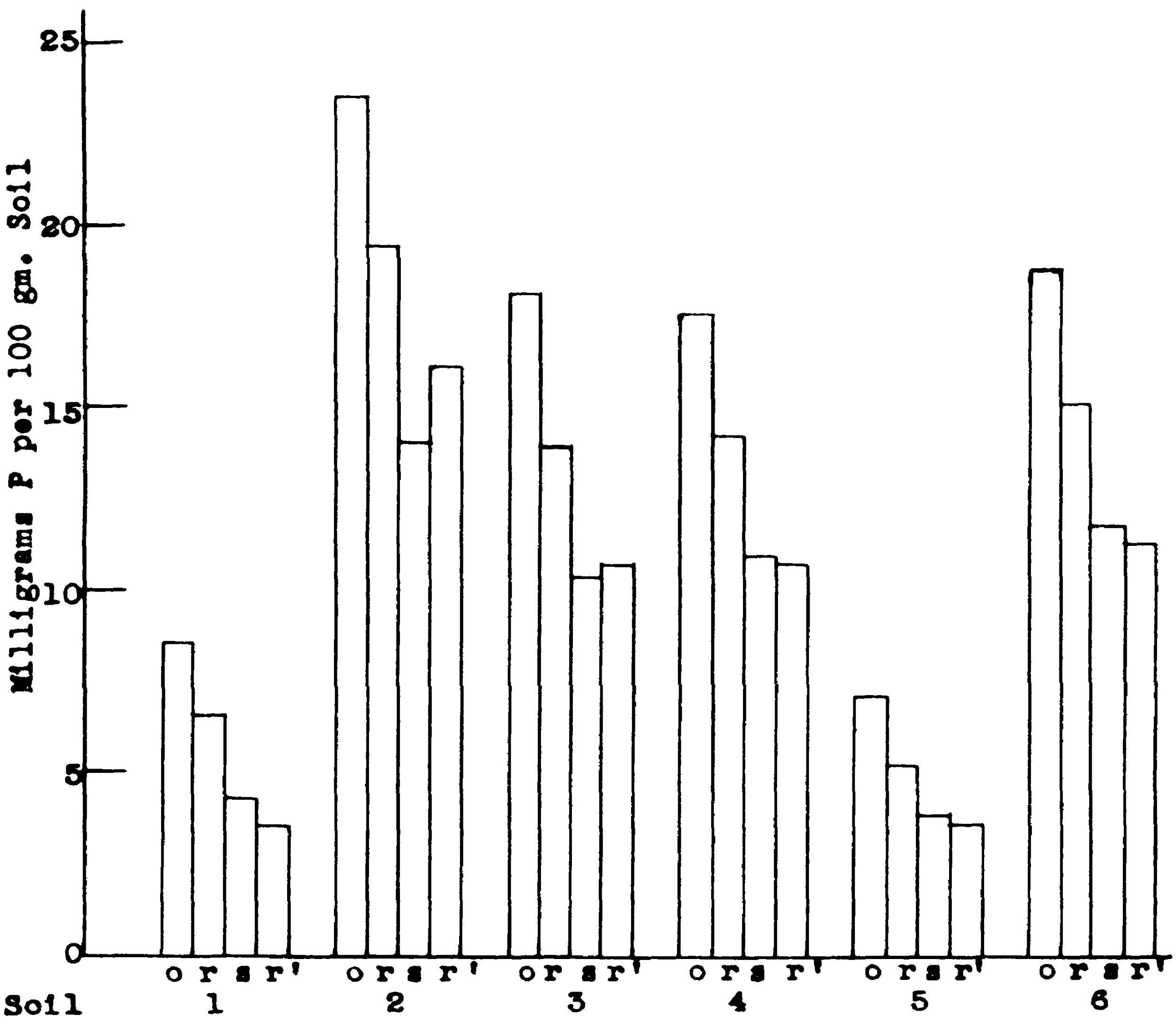

FIGURE 25. GRASS ROTATION: CHANGE IN VALUE OF READILY SOLUBLE PHOSPHORUS WITH CROPPING.

Legend: o--uncropped soil; r--following 1st rye grass; s--following Sudan grass; r'--following 2nd rye grass.

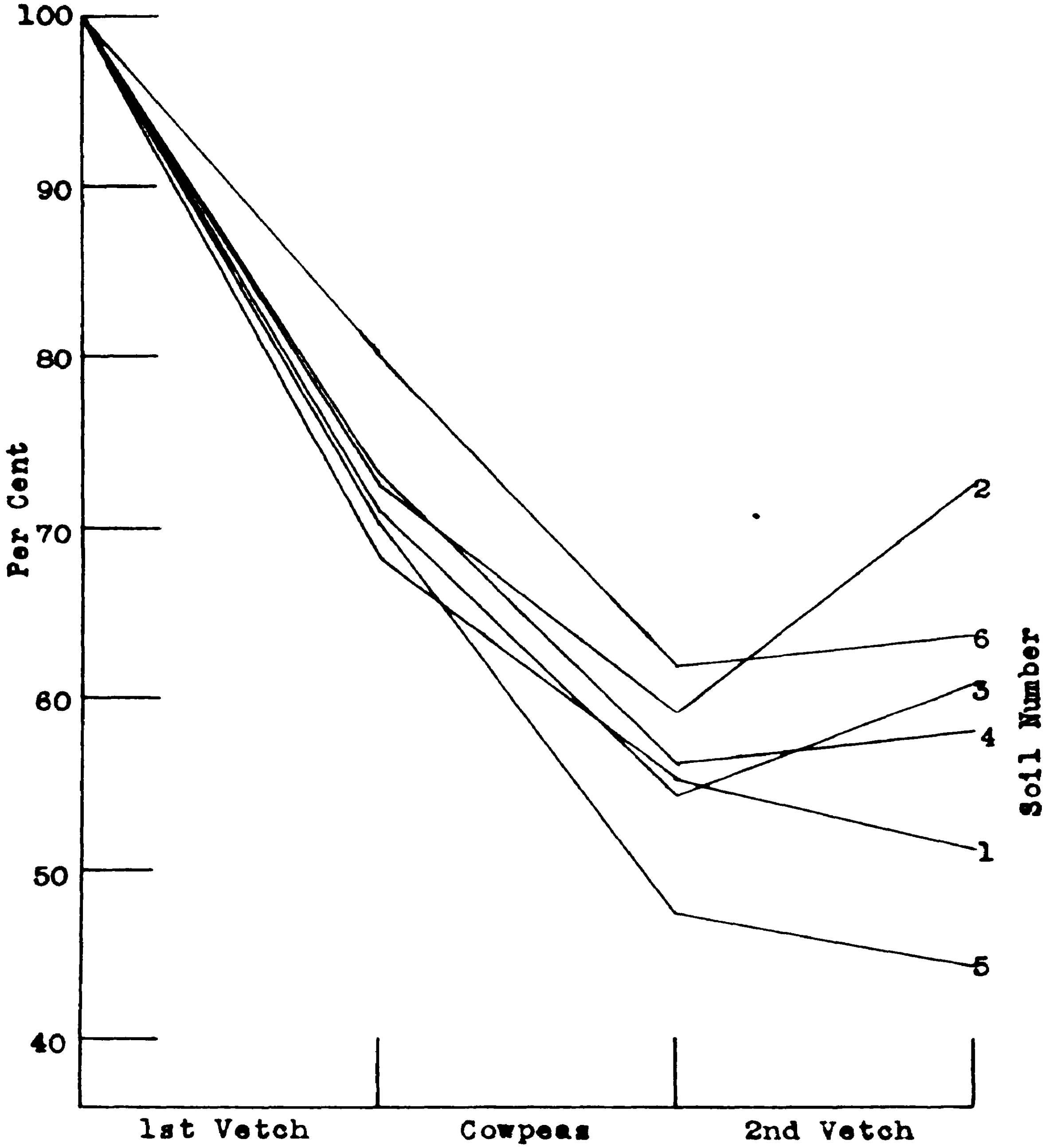

FIGURE 26. LEGUME ROTATION: RELATIVE CHANGE IN VALUE OF READILY SOLUBLE PHOSPHORUS WITH CROPPING.

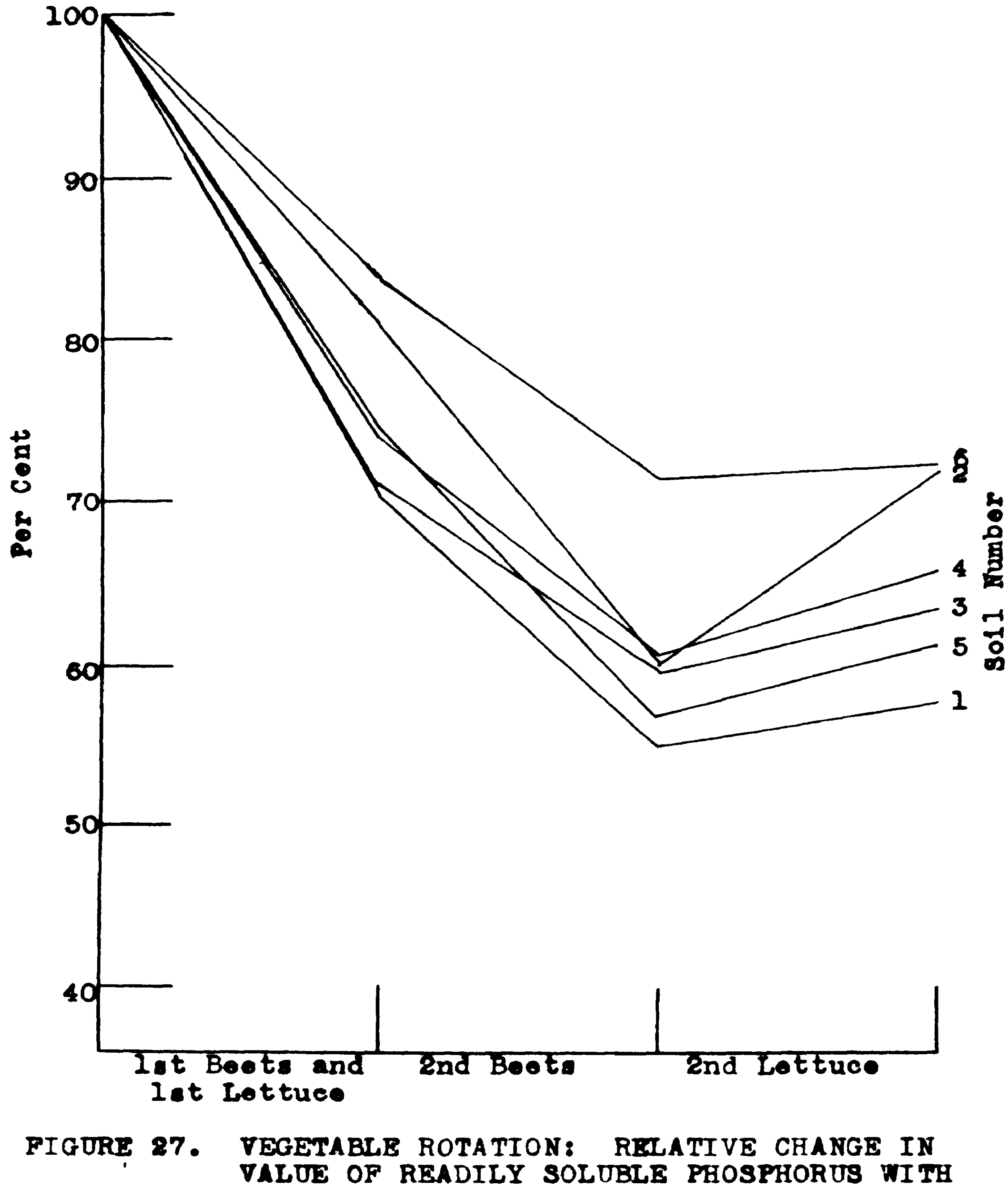

FIGURE 27. VEGETABLE ROTATION: RELATIVE CHANGE IN VALUE OF READILY SOLUBLE PHOSPHORUS WITH CROPPING.

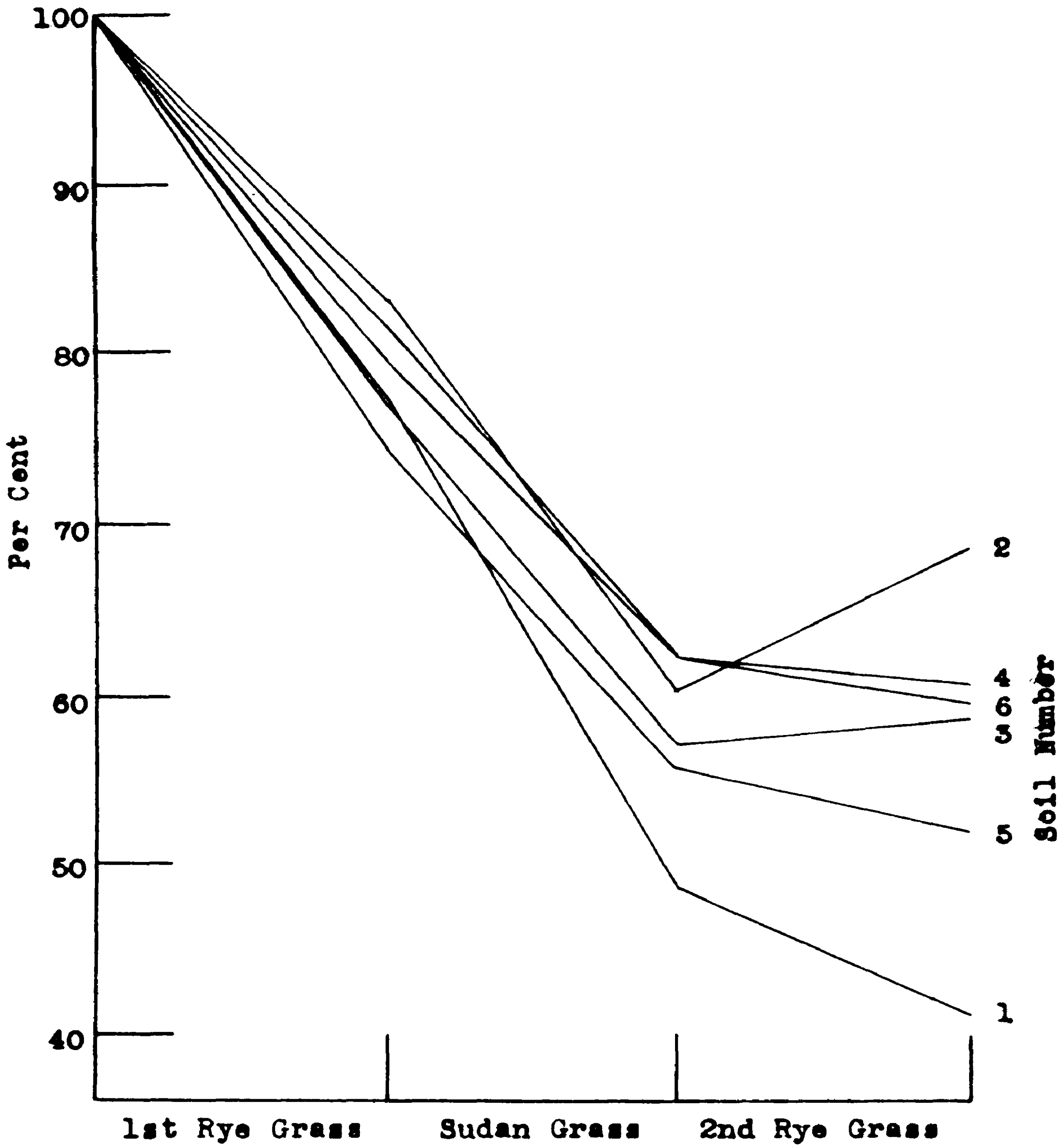

FIGURE 28. GRASS ROTATION: RELATIVE CHANGE IN VALUE OF READILY SOLUBLE PHOSPHORUS WITH CROPPING.

soluble phosphorus at various stages of cropping is compared, in tables 22, 23, and 24, with the amount of phosphorus removed from the soil by the various crops. All data in these tables are expressed in terms of mgm. of phosphorus per 100 gm. of oven-dry 2-mm. soil in order to facilitate direct comparison of crop and soil data. It will be seen that changes in alkali-extractable phosphorus and the exchangeable phosphorus (by the hydroxyl method) often agreed closely in magnitude with the phosphorus removed from the soil by cropping. Changes in the exchangeable phosphorus by the ammonium fluoride method did not agree well with that removed by the crop, being much too great in most cases.

The comparison between crop removed phosphorus and the decline in alkali-extractable and exchangeable phosphorus (NaOH method) is expressed graphically for the various rotations in figures 29, 30 and 31. In the legume rotation (figure 29) there is close agreement between the phosphorus removed in the crop and the decline in alkali-extractable phosphorus except in the case of soil 2. The agreement is close in the comparison with exchangeable phosphorus except on soil 2 and the final cropping on soil 1. In the case of the vegetable rotation (figure 30) the agreement between crop removed phosphorus and change in alkali-extractable and exchangeable phosphorus is not as close as with the legume rotation. The agreement between changes in these chemical fractions with the crop

TABLE 22. A comparison between crop removal of phosphorus and reduction in alkali-extractable phosphorus, exchangeable phosphorus, and readily soluble phosphorus in soils which grew vetch and cowpeas.

Results in milligrams per 100 gm. oven-dry 2-mm. soil.

Soil	Crop Grown	Phosphorus Removed in Crops: Tops	Roots	Crop Total	Expt. Total	Reduction in Soil Phosphorus Fractions: Alkali-extractable: Crop Total	Expt. Total	Exch. by NaOH: Crop Total	Expt. Total	Exch. by NH_4F: Crop Total	Readily soluble: Crop Total	Expt. Total
1	Vetch	2.45	0.26	2.71	2.71	1.89	1.89	2.72	2.72	7.3	2.72	2.72
	Cowpeas	1.40	0.22	1.62	4.33	2.91	4.80	2.41	5.13		1.11	3.83
	Vetch*	3.14	0.94	4.08	8.41	3.72	8.52	-4.61	0.52		0.35	4.18
2	Vetch	3.54	0.57	4.11	4.11	2.91	2.91	7.95	7.95	10.7	6.42	6.42
	Cowpeas	2.50	0.49	2.99	7.10	5.69	8.60	4.32	12.27		3.15	9.57
	Vetch*	5.03	1.29	6.32	13.42	11.44	20.04	6.89	19.16		-3.13	6.44
3	Vetch	7.08	1.43	8.51	8.51	7.17	7.17	8.73	8.73	11.6	5.25	5.25
	Cowpeas	6.10	0.68	6.78	15.29	7.26	14.43	4.54	13.27		2.96	8.21
	Vetch*	4.61	1.28	5.89	21.18	9.36	23.79	11.45	24.72		-1.06	7.15
4	Vetch	8.37	1.18	9.55	9.55	10.52	10.52	10.98	10.98	10.2	4.66	4.66
	Cowpeas	6.16	0.75	6.91	16.46	4.78	15.30	4.86	15.84		3.05	7.71
	Vetch*	8.10	2.22	10.32	26.78	10.60	25.90	7.09	22.93		-0.37	7.34
5	Vetch	4.00	1.08	5.08	5.08	4.77	4.77	5.83	5.83	5.1	2.11	2.11
	Cowpeas	4.79	0.64	5.43	10.51	7.18	11.95	4.58	10.41		1.60	3.71
	Vetch*	4.89	2.33	7.22	17.73	5.68	17.63	6.23	16.64		0.25	3.96
6	Vetch	2.09	0.32	2.41	2.41	2.00	2.00	2.40	2.40	10.6	3.81	3.81
	Cowpeas	4.41	0.45	4.86	7.27	3.76	5.76	3.87	6.27		3.36	7.17
	Vetch*	6.87	1.54	8.41	15.68	9.31	15.07	7.56	13.83		-0.27	6.90

*Second crop.

TABLE 23. A comparison between crop removal of phosphorus and reduction in alkali-extractable phosphorus, exchangeable phosphorus, and readily soluble phosphorus in soils which grow beets and lettuce.

Results in milligrams per 100 gm. oven-dry 2-mm. soil.

Soil	Crop Grown	Phosphorus Removed in Crops: Tops	Phosphorus Removed in Crops: Roots	Phosphorus Removed in Crops: Crop Total	Phosphorus Removed in Crops: Expt. Total	Reduction in Soil Phosphorus Fractions: Alkali-extractable: Crop Total	Alkali-extractable: Expt. Total	Exch. by NaOH: Crop Total	Exch. by NaOH: Expt. Total	Exch. by NH_4F: Crop Total	Readily soluble: Crop Total	Readily soluble: Expt. Total
1	Beets	1.37	1.19	2.56	2.56							
	Lettuce	1.28		1.28	3.84	5.53	5.53			11.2	2.53	2.53
	Beets*	0.66	0.50	1.16	5.00	0.21	5.74	6.24	6.24		1.30	3.83
	Lettuce*	0.06		0.06	5.06	1.31	7.05	-4.91	1.33		-0.20	3.63
2	Beets	1.44	1.17	2.61	2.61							
	Lettuce	2.90		2.90	5.51	8.11	8.11	10.59	10.59	11.6	4.43	4.43
	Beets*	2.15	0.98	3.13	8.64	3.84	11.95	0.17	10.76		5.02	9.45
	Lettuce*	2.16	0.34	2.50	11.14	2.51	14.46	2.44	13.20		-2.88	6.57
3	Beets	1.54	1.46	3.00	3.00							
	Lettuce	2.62		2.62	5.62	6.93	6.93	5.54	5.54	9.7	5.26	5.26
	Beets*	1.75	1.17	2.92	8.54	4.92	11.85	4.23	9.77		2.05	7.31
	Lettuce*	2.01	0.30	2.31	10.85	-5.17	6.68	-5.30	4.47		-0.72	6.59
4	Beets	1.95	1.92	3.87	3.87							
	Lettuce	3.26		3.26	7.13	6.57	6.57	7.54	7.54	8.2	4.55	4.55
	Beets*	1.99	1.19	3.18	10.31	6.90	13.47	5.36	12.90		2.33	6.88
	Lettuce*	3.39	0.53	3.92	14.23	-3.16	10.31	-1.27	11.63		-0.99	5.89
5	Beets	0.27	0.13	0.40	0.40							
	Lettuce	2.03		2.03	2.43	6.95	6.95	3.53	3.53	4.4	1.80	1.80
	Beets*	0.87	0.92	1.79	4.22	1.24	8.19	2.77	6.30		1.26	3.06
	Lettuce*	1.65	0.17	1.82	6.04	-2.19	6.00	1.12	7.42		-0.30	2.76
6	Beets	0.33	0.09	0.42	0.42							
	Lettuce	2.27		2.27	2.69	4.07	4.07	4.77	4.77	14.5	3.09	3.09
	Beets*	0.76	0.21	0.96	3.65	-0.[illegible]	4.2[illegible]	0.53	5.30		2.33	5.42
	Lettuce*	3.82	0.34	4.16	7.81	6.35	10.54	5.33	10.63		-0.23	5.19

*Second crop.

TABLE 24. A comparison between crop removal of phosphorus and reduction in alkali-extractable phosphorus, exchangeable phosphorus, and readily soluble phosphorus in soils which grew rye grass and Sudan grass.

Results in milligrams per 100 gm. oven-dry 2-mm. soil.

Soil	Crop Grown	Phosphorus Removed in Crops				Reduction in Soil Phosphorus Fraction						
						Alkali-extractable		Exch. by NaOH		Exch. by NH_4F	Readily soluble	
		Tops	Roots	Crop Total	Expt. Total	Crop Total	Expt. Total	Crop Total	Expt. Total	Crop Total	Crop Total	Expt. Total
1	Rye grass	3.75	1.17	4.92	4.92	5.84	5.84	2.72	2.72	12.6	1.94	1.94
	Sudan grass	1.78	0.49	2.27	7.19	1.51	7.35	4.10	6.82		2.43	4.37
	Rye grass*	2.51	1.12	3.63	10.82	3.37	10.72	-0.49	6.33		0.67	5.04
2	Rye grass	4.57	1.27	5.84	5.84	10.28	10.28	10.09	10.09	11.6	3.98	3.98
	Sudan grass	2.60	0.91	3.51	9.35	1.03	11.31	0.18	10.27		5.38	9.36
	Rye grass*	4.23	1.93	6.16	15.51	5.02	16.33	5.82	16.09		-2.07	7.29
3	Rye grass	5.08	2.62	7.70	7.70	10.87	10.87	7.28	7.28	10.5	4.16	4.16
	Sudan grass	4.90	1.45	6.35	14.05	5.12	15.99	7.11	14.39		3.57	7.73
	Rye grass*	3.83	2.11	5.94	19.99	3.56	19.55	4.58	18.97		-0.28	7.45
4	Rye grass	5.56	1.91	7.47	7.47	12.56	12.56	9.21	9.21	9.7	3.22	3.22
	Sudan grass	5.05	1.51	6.56	14.03	2.80	15.36	4.95	14.16		3.35	6.57
	Rye grass*	4.81	2.13	6.94	20.97	6.37	21.73	7.31	21.47		0.32	6.89
5	Rye grass	3.40	1.35	4.75	4.75	5.86	5.86	3.72	3.72	5.6	1.83	1.83
	Sudan grass	2.63	0.88	3.51	8.26	8.51	14.37	8.51	12.23		1.30	3.13
	Rye grass*	2.52	1.66	4.18	12.44	-0.20	14.17	-0.46	11.77		0.30	3.43
6	Rye grass	4.98	1.01	5.99	5.99	6.96	6.96	7.05	7.05	15.6	3.82	3.82
	Sudan grass	4.32	0.93	5.25	11.24	8.48	15.44	4.32	11.37		3.27	7.09
	Rye grass*	4.23	1.98	6.21	17.45	4.29	17.73	3.88	15.25		0.52	7.61

*Second crop.

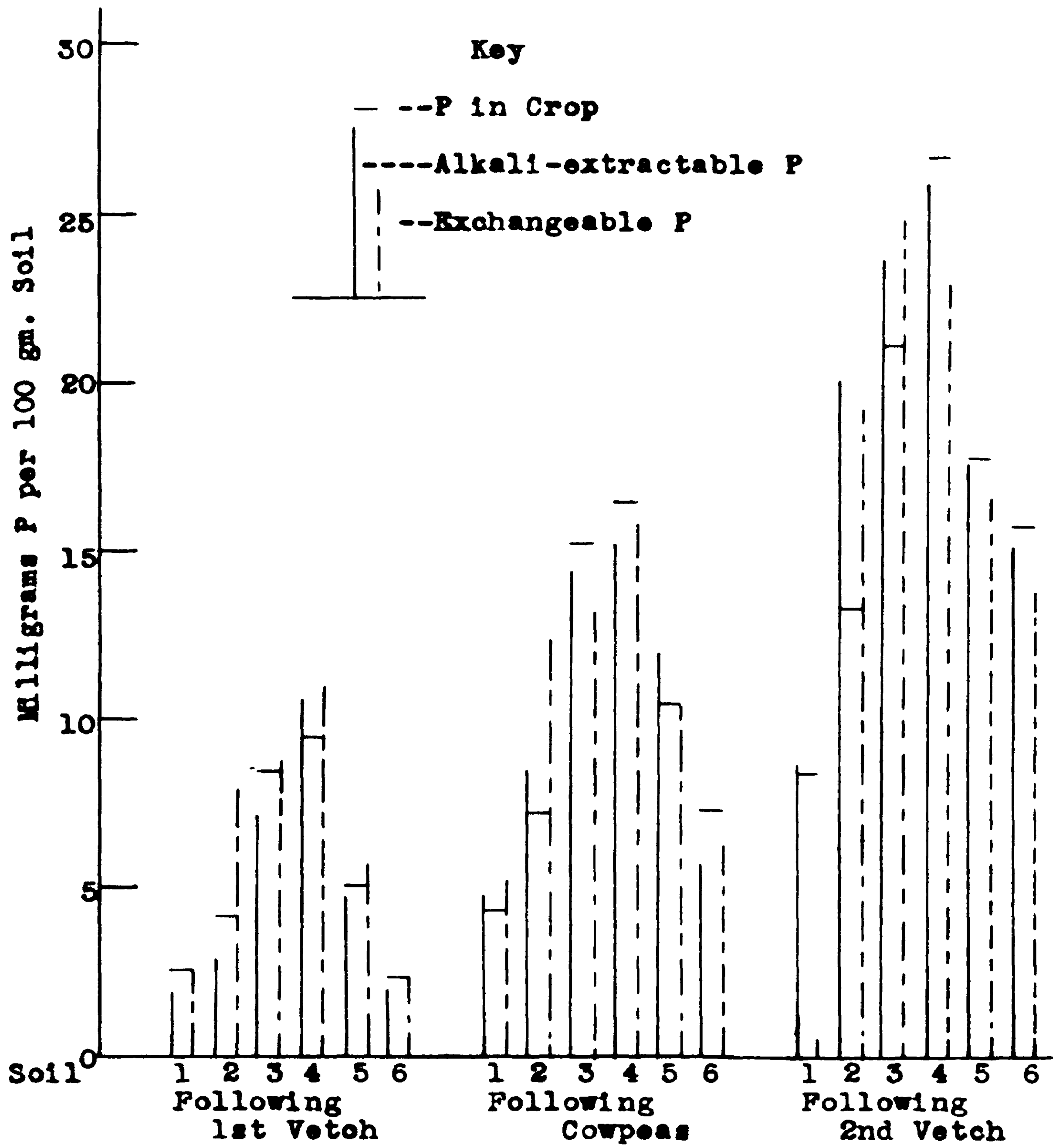

FIGURE 29. LEGUME ROTATION: COMPARISON OF CHANGE IN ALKALI-EXTRACTABLE AND EXCHANGEABLE PHOSPHORUS VALUES WITH CUMULATIVE REMOVAL OF PHOSPHORUS IN THE CROPS.

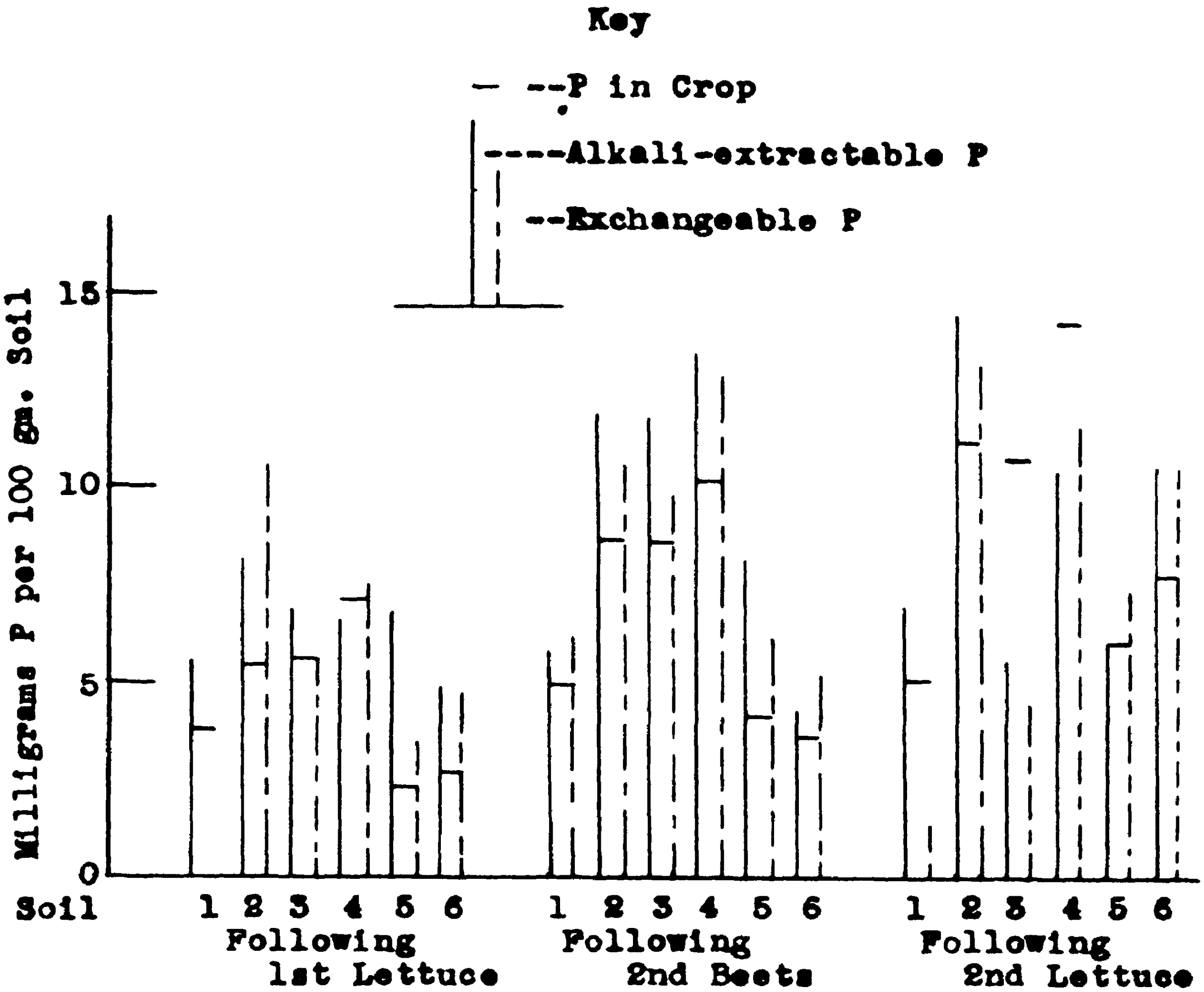

FIGURE 30. VEGETABLE ROTATION: COMPARISON OF CHANGE IN ALKALI-EXTRACTABLE AND EXCHANGEABLE PHOSPHORUS VALUES WITH CUMULATIVE REMOVAL OF PHOSPHORUS IN THE CROPS.

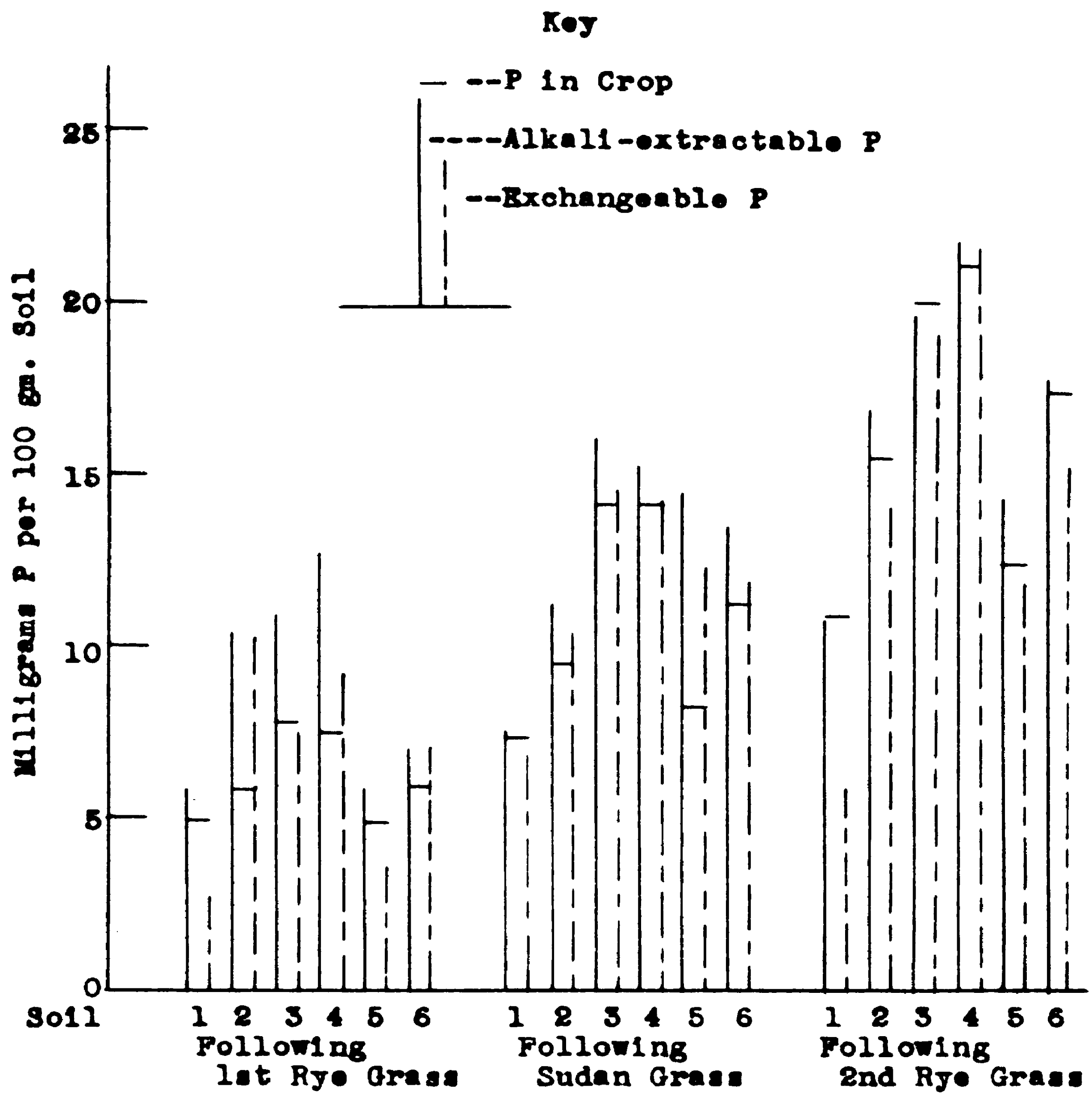

FIGURE 31. GRASS ROTATION: COMPARISON OF CHANGE IN ALKALI-EXTRACTABLE AND EXCHANGEABLE PHOSPHORUS VALUES WITH CUMULATIVE REMOVAL OF PHOSPHORUS IN THE CROPS.

removed phosphorus in the soils used for the grass rotation (figure 31) is quite close at the final harvest but somewhat less so at the intermediate harvests.

At the beginning of the legume and the vegetable rotations there was frequently rather good agreement in magnitude of decline in readily soluble phosphorus and crop removal of phosphorus (tables 22 and 23). As the rotations continued, however, the change shown in readily soluble phosphorus lagged far behind the phosphorus actually removed by the crop. In the case of the grass rotation (table 24) the change in readily soluble phosphorus was less than the phosphorus removed in the crop at all stages of the rotation.

The Measurement of Crop Utilization of Applied Phosphate Using Radioactive Superphosphate

According to the work of the Rothamsted Experimental Station, reviewed by Russell (57), the proportion of phosphorus which a crop takes up from an application of phosphate to soil or sand culture amounts to only about 20 to 30 per cent of the amount supplied. It would be expected that the proportion of applied phosphate taken up by the crop would depend, in part at least, upon the quantity and availability of residual phosphorus already present in the soil. The use of radioactive phosphorus simplifies the measurement of the proportion of crop uptake of this element derived from a given material. In order to study the utilization of applied phosphorus on soils that contained different amounts of residual phosphorus, a test, using radioactive superphosphate, was performed on soils from which some of the residual phosphorus had been cropped in the vegetable rotation (experiment B-2). These soils were treated with radioactive superphosphate and a crop of lettuce (Slobolt) was grown on them. The corresponding heavily-fertilized original soils, from which none of the residual phosphorus had been cropped, were treated and cropped in a like manner. The proportion of added phosphate utilized by the crops was determined by the method described in the experimental section.

It was found in experiment A-4 that lettuce did not grow on the uncropped Collington loam (soil 6). As conductivity tests showed that this soil contained a high quantity of soluble salts (table 16), 25 pounds of it was leached with 11 liters of deionized water. Conductivity measurements indicated the soluble-salt concentration was greatly reduced by this treatment. No change occurred in the alkali-extractable or exchangeable phosphorus in the leached soil over the unleached soil by virtue of this treatment, these values being 114.4 and 100.4 mgm. phosphorus per 100 grams air-dry soil, respectively, for the leached soil and 114.0 and 99.3 mgm. for the original soil.

The quantity of soil used, liming, and fertilization are recorded in tables 25 and 26. The weights of air-dry quarter-mesh soil varied from 2200 gm. per can in the case

TABLE 25. The reaction, amount of soil used, and fertilization at seeding of cropped and uncropped soils treated with radioactive superphosphate for growth of lettuce.

Soil No.	Treatment	pH Value	Amount of Soil[a]	Fertilization[b]				
				P_2O_5[c]	$CaCO_3$	$MgCO_3$	NH_4NO_3	KNO_3
			gm.	mgm.	mgm.	mgm.	mgm.	mgm.
1	Cropped	4.52	2200	200	750	126	50	54
	Uncropped	5.30	2200	200	500	84	100	108
2	Cropped	5.35	2000	200	250	42	100	108
	Uncropped	4.89	2000	200	1000	168	100	108
3	Cropped	5.17	1800	200	1000	168	100	108
	Uncropped	4.95	1800	200	1500	252	100	108
4	Cropped	5.34	1800	200	750	126	100	108
	Uncropped	5.15	1800	200	1000	168	100	108
5	Cropped	5.20	1800	200	1000	168	100	108
	Uncropped	4.94	1800	200	1500	250	100	108
6	Cropped	5.18	1900	200	1000	168	100	108
	Uncropped	5.15	1900	200	1000	168	100	108

a-Air-dry quarter-mesh soil per replicate.
b-Per replicate.
c-Added as superphosphate containing 22.3 per cent P_2O_5.

TABLE 26. Fertilization during growth of lettuce* on cropped and uncropped soils treated with radioactive superphosphate.

Data in milligrams per replicate.

Soil	Treatment	Date of Application						
		April 4		April 18		May 1		May 6
		NH_4NO_3	KNO_3	NH_4NO_3	KNO_3	NH_4NO_3	KNO_3	H_3BO_3
1	Cropped					50	54	
	Uncropped	50	54	50	54	100	108	10
2	Cropped	50	54	50	54	100	108	
	Uncropped	50	54	50	54	100	108	10
3	Cropped	50	54	50	54	100	108	
	Uncropped	50	54	50	54	100	108	10
4	Cropped	50	54	50	54	100	108	
	Uncropped	50	54	50	54	100	108	10
5	Cropped	50	54			50	54	
	Uncropped	50	54			50	54	10
6	Cropped	50	54	50	54	100	108	
	Uncropped	50	54	50	54	100	108	10

*Seeded March 25, 1947.

of soil 1 to 1800 gm. per can for the Caribou soils. A more nearly equal volume of soil was maintained per pot than had been the case in experiment B.

Two harvests of the lettuce were made. In the first, one month from planting, four of the eight plants in each can were removed. Exceptions occurred on the cropped soil 1 where no harvest was made because of the poor growth of lettuce. Also, in the few cases where less than eight plants survived, fewer than four were removed in order that four plants would remain for the final harvest. The final harvest was made three weeks after the first harvest. Four plants were taken from all cans except on cropped soil 1, where six plants were removed from each of two cans and four and three plants, respectively, from the other two. In table 27 the data for dry weight, phosphorus content, and percentage phosphorus in the lettuce tops for the first and final harvests are presented. The percentage phosphorus in the crop derived from the radioactive superphosphate applied to the various soils is also given in this table.

Values for dry weight of lettuce tops are illustrated graphically in figure 32. Greater dry weights were obtained on both the cropped and uncropped soil 3 than on any other soil. Uncropped soil 6, uncropped soil 2, cropped soil 4, and uncropped soil 1, followed in that order but there was little difference among them. The uncropped soil 1 produced a great deal more dry weight than its cropped

TABLE 27. Dry weight, phosphorus content, and phosphorus derived from the fertilizer in lettuce harvested from cropped and uncropped soils fertilized with radioactive superphosphate.

Results as average of four replicates.

Soil No.	Treatment	First Harvest April 21			Second Harvest May 13		
		Dry Weight	Phos-phorus Content	Phosphorus Derived from Fertilizer	Dry Weight	Phos-phorus Content	Phosphorus Derived from Fertilizer
		gm.	mgm.	%	gm.	mgm.	%
1	Cropped				2.74	8.16	28.9
	Uncropped	0.58	2.48	25.3	8.11	30.33	23.1
2	Cropped	0.47	1.62	20.8	7.25	24.22	15.3
	Uncropped	0.96	4.61	13.6	8.44	30.89	12.5
3	Cropped	0.74	2.45	16.1	9.88	26.90	13.0
	Uncropped	0.87	3.18	12.5	10.25	32.28	9.8
4	Cropped	0.70	2.31	15.1	8.23	26.48	12.5
	Uncropped	1.54	6.21	11.1	6.89	26.33	9.4
5	Cropped	0.27	0.81	26.5	6.30	14.84	23.6
	Uncropped	0.23	0.36	38.4	2.50	6.88	19.0
6	Cropped	0.65	3.71	14.2	7.53	22.27	13.0
	Uncropped	0.59	3.71	12.9	8.87	21.46	11.0

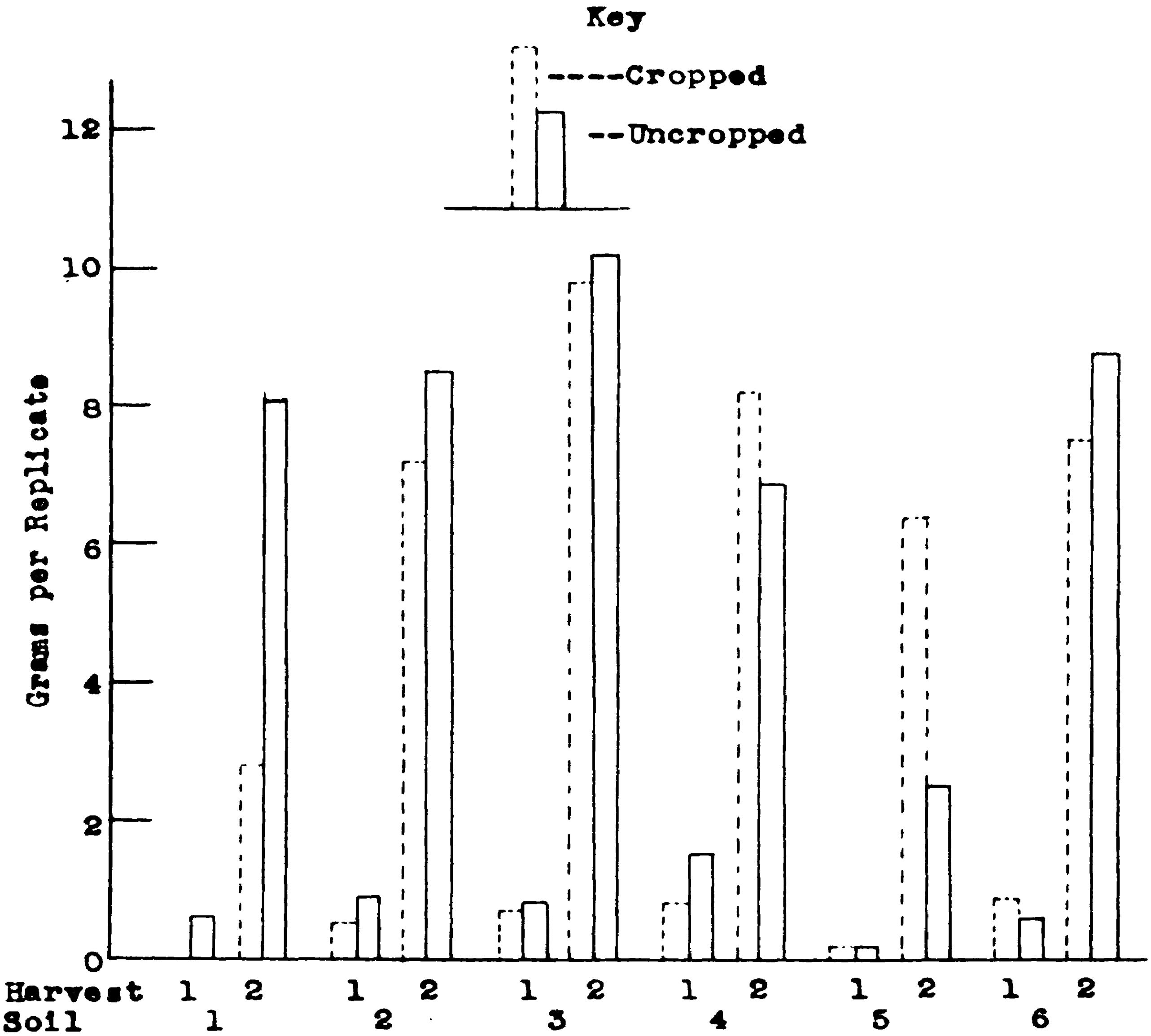

FIGURE 32. DRY WEIGHT OF LETTUCE FROM CROPPED AND UNCROPPED SOILS FERTILIZED WITH RADIO-ACTIVE SUPERPHOSPHATE.

counterpart. There was also distinctly more dry weight produced on the original soils than on the cropped soils in the case of soils 2 and 6. The situation was reversed in the case of soils 4 and 5, the difference in dry weight in favor of the cropped over original soil being especially marked in the case of soil 5.

Data for total phosphorus removed are expressed graphically in figure 33. The greatest removal occurred in the case of uncropped soils 3, 2, and 1 in that order. There were great differences in phosphorus removal in favor of uncropped soil 1 over its cropped counterpart. The reverse of this situation occurred with soil 5. The difference between cropped and uncropped soils was slight in the case of soils 4 and 6 in this regard. There were considerable differences in favor of the uncropped soils over cropped soils in the case of soils 2 and 3.

The data for phosphorus in the crop derived from the added fertilizer is graphed in figure 34. A higher percentage of phosphorus was derived from the added fertilizer at the first harvest than at the final harvest with all soils. Comparing cropped with uncropped soils, a greater proportion of phosphorus was derived from the fertilizer on cropped soils than on uncropped soils with one exception-- the first harvest on soil 5. The greatest proportion of phosphorus derived from the added phosphate occurred on soils 1 and 5. Considerably less came from the fertilizer on soils 2, 3, 4, and 6.

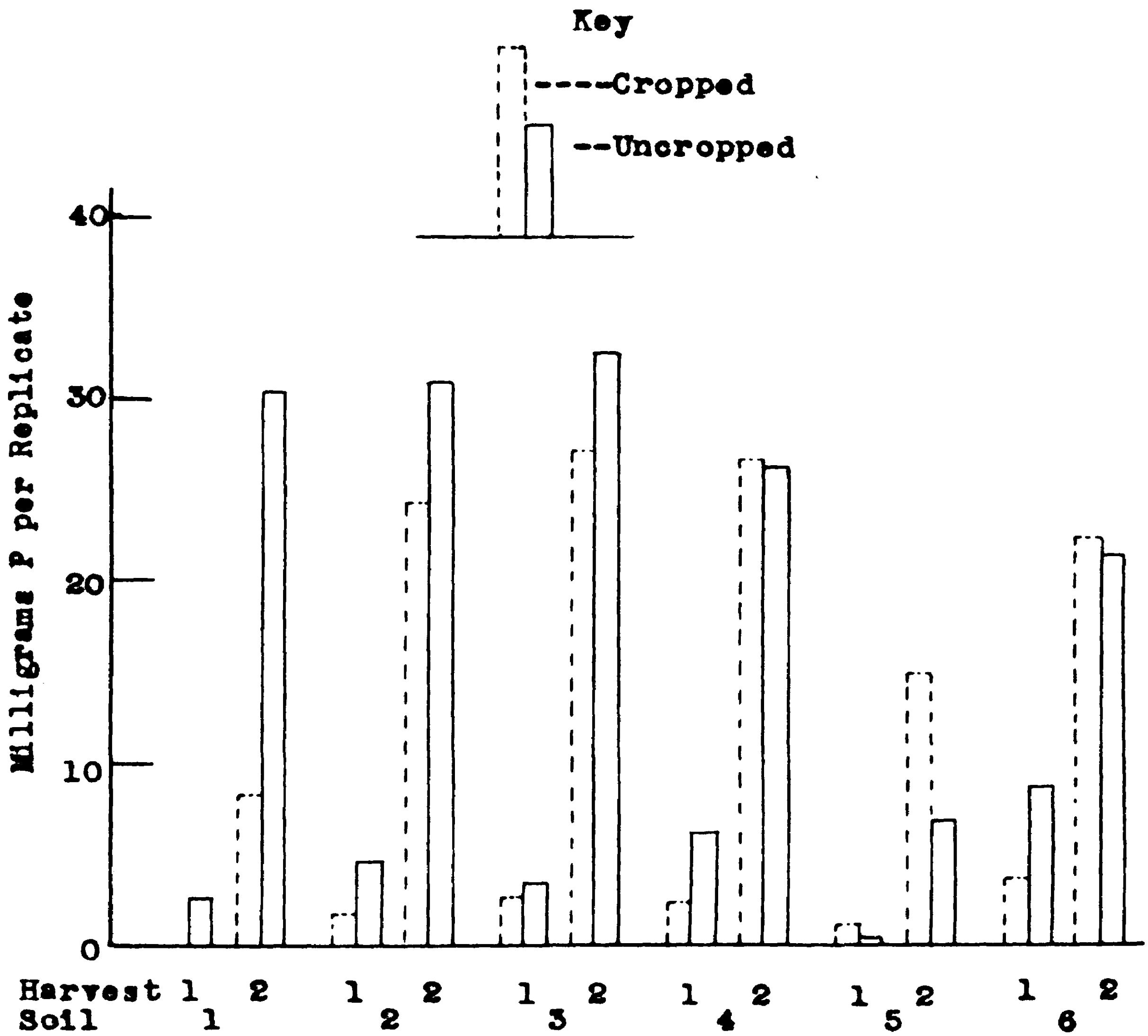

FIGURE 33. PHOSPHORUS CONTENT OF LETTUCE FROM CROPPED AND UNCROPPED SOILS FERTILIZED WITH RADIO-ACTIVE SUPERPHOSPHATE.

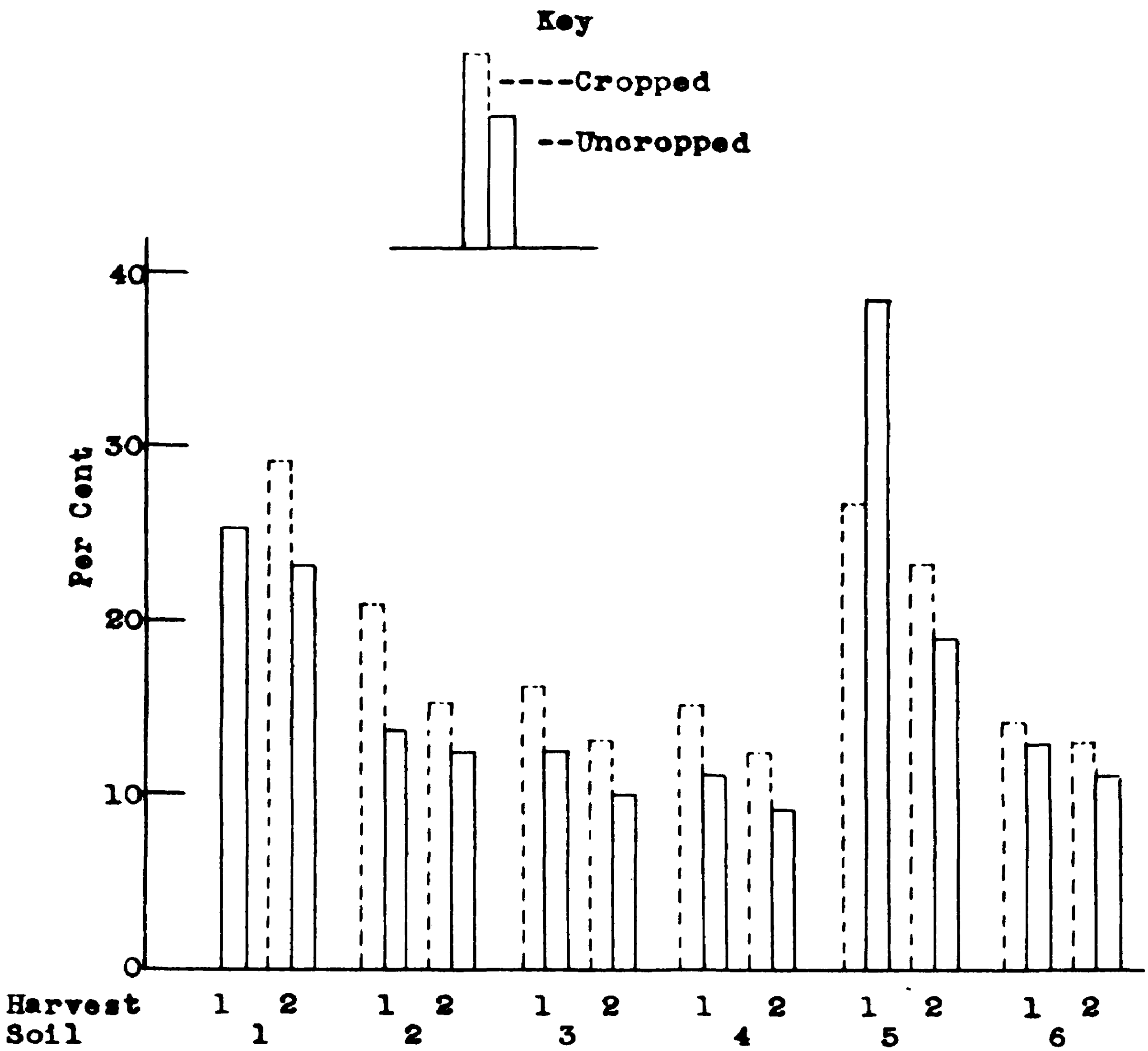

FIGURE 34. PHOSPHORUS DERIVED FROM THE FERTILIZER IN LETTUCE FERTILIZED WITH RADIOACTIVE SUPERPHOSPHATE.

DISCUSSION

Crop Growth

Cropping served two functions in this study. In the first place it enabled comparisons to be made between the abilities of different crops to make use of residual phosphorus under greenhouse conditions. In the second place, soil material divested of some of its original phosphorus was thereby prepared for laboratory tests.

Dry weight and phosphorus content were the criteria used for the measurement of crop ability to utilize residual phosphorus. However, the relation of such growth data to phosphorus fertility is frequently not simple nor direct. Complicating soil factors enter other than phosphorus level. Among these are differences in texture and moisture-holding capacity as well as excess or deficiency of elements other than phosphorus. The presence of any factor other than phosphorus which limits growth or retards maturity of a crop on one soil over that on another soil will seriously impair or completely rule out any comparisons drawn regarding soil phosphorus conditions. However, it is not always within the skill of the experimenter to recognize such a situation when it arises.

Lespedeza sericea and *Crotalaria retusa* seem to be unsuited to growth on sandy soils - at least under greenhouse conditions in small containers. Hairy vetch, beets, and lettuce are apparently much less affected by textural differences. From the results of experiment B it would appear that cowpeas and Sudan grass were also adversely affected on sandy soils. The dry weight and quantity of phosphorus removed by these crops on the sandy soils 1 and 2 were lower in relation to that of the other soils than was the case with the preceding and following crops in the rotation. However, the growth of the cowpeas and the Sudan grass took place in the summer when greenhouse temperatures were very high. With the small containers used there was difficulty in maintaining suitable moisture levels in soils 1 and 2 with their low water-holding capacity.

Liming the soils to a reaction not above pH 5.5 in the experiments with commercial potato soils was intended to maintain phosphorus in the forms found in the original acid soils used and avoid reverting it into forms which might be found at higher pH values. A pH of 5.5 or below may be less than the optimum pH for some of the crops used.

Supplementary fertilization was employed in this work to promote favorable conditions for growth and to prevent the development of deficiencies other than that of phosphorus. However, there is no certainty that optimum nutrient conditions for all elements save phosphorus were maintained except insofar as visual deficiency symptoms were absent.

There are factors other than those of soil conditions which must be considered when selecting greenhouse crops. One of these is that of the time of year at which the crops are grown. Some make better vegetative growth under long-day conditions, others under short-day conditions, while still others are indeterminant. Lespedeza sericea and Sudan grass flower under short-day conditions while vetch and rye grass flower under long-day conditions. Therefore, the former crops are adapted for spring and summer use and the latter for fall and winter growth, since vegetative growth rather than maturity is desirable in this type of work.

The results of experiment B indicate that legumes and grasses (figures 11 and 19) are more effective than vegetables, such as beets and lettuce, (figure 16) in removing residual phosphorus from soils. The most marked differences between the legumes and grasses on the one hand and the vegetables on the other appear on the soils of low phosphorus level. In experiment A it was found that the legume, lespedeza, is markedly efficient in removing residual phosphorus from the fine-textured soils to which it is adapted (table 4).

Matted, dense root systems were produced by rye grass and Sudan grass in experiment B. The ability of the grasses to utilize residual phosphorus shown in this study may find the explanation, in part at least, in the large root surface produced by this type of plant. The root system of both beets and lettuce, while more extensive than is often realized, was found to be less conspicuous and durable than those of the legumes, and especially the grasses, when the roots were harvested. To legumes has been attributed the ability to utilize phosphorus in forms relatively unavailable to some other types of plants (37). The ratio of phosphorus removed in roots to that in the tops is unusually great for beets (figure 15) because the former includes the fleshy axis. When beets are growing poorly, the root to top ratio lessens because the fleshy axis does not form well.

Relations of Crop Growth and Chemical Measures of Phosphorus Content

It has been pointed out that reduction in alkali-extractable and exchangeable phosphorus fractions agreed closely with crop removed phosphorus when both were expressed for the same unit of soil. Discrepancies to this may be noted in the data presented. Some of these may reflect sampling and analytical errors. The proportion of alkali-extractable (or exchangeable) phosphorus present in the soil which is removed by a single crop is relatively small. A small absolute error becomes relatively large when, as in this case, small differences are compared.

No significant trends or changes could be detected in the organic phosphorus or in the phosphorus soluble in 0.5 N sulfuric acid following alkali extraction (apatitic phosphorus) by the methods used in this work (tables 19, 20, and 21). However, it should be realized that the soils used were all acid, cropped soils. Changes in organic and apatitic phosphorus may or may not be of significance in other types of soils. With the acid, heavily-fertilized soils the exchangeable phosphorus as measured by the hydroxyl method, would appear to constitute the bulk of the residual phosphorus available for crop growth. Changes in this fraction apparently measure the crop removal of residual phosphorus. The exchangeable phosphorus determined by the fluoride method gives results seriously at variance with the crop removed phosphorus, being much too great especially on the sandy soils. Figures 20, 21, and 22 show that the greatest relative decline in alkali-extractable phosphorus occurred in the sandy soils with their lower anion exchange capacities.

Relations between exchangeable phosphorus, anion exchange capacity, and saturation of the anion exchange complex suggest that both the amount of exchangeable phosphorus and the degree of saturation of the anion exchange complex with phosphorus must be considered when determining phosphorus availability in acid soils (figure 5). For instance, among the three Caribou soils (3, 4, and 5) the anion exchange capacities were similar but soil 5 contained a lower amount of exchangeable phosphorus and was, therefore, at a lower saturation level than soils 3 and 4. The phosphorus removal data on these soils in experiment B (tables 12, 15 and 17, figures 10, 15, and 18) show that in almost every case soils 3 and 4 produced crops containing more phosphorus than did soil 5. An example of the opposite situation occured with soils 1 and 2. These were at the same degree of phosphorus saturation but soil 2 with its higher exchange capacity contained the greater amount of exchangeable phosphorus.

The data for phosphorus removal show that more phosphorus was removed by cropping on soil 2 than on soil 1.

The data of the experiment with radioactive superphosphate confirm these conclusions. The utilization of phosphorus from the added fertilizer (figure 34) was great in soil 1 with its relatively high percentage saturation but low amount of exchangeable phosphorus and in soil 5 with its relatively high amount of exchangeable phosphorus but low percentage saturation. The superiority of lettuce growth on the cropped soils 4 and 5 to that on the corresponding uncropped soils suggests that some other factor than phosphorus level was limiting growth in these cases (table 27).

It is evident from the radioactivity data that reduction of the phosphorus reserves by cropping reduces the ability of the plant to utilize that which remains. In all cases a greater proportion of the added phosphorus was utilized on the cropped soils. This occurred despite the fact that only a rather small proportion of the large amount of phosphorus originally present in alkali-extractable or exchangeable form had been removed by previous crops of beets and lettuce. This suggests that the exchangeable phosphorus is not equally available to the plant but that it is given up more and more reluctantly as its level is reduced. As plants mature they become better able to utilize residual phosphorus. This is seen by the fact that a higher proportion of radioactive phosphorus was taken up by the young lettuce plants at the first harvest than by the plants at the final harvest. Perhaps the development of a more extensive root system with the approach of maturity makes possible the better exploitation of residual soil phosphorus with less dependence on the recently added fertilizer.

It is of interest to study the relations of readily soluble phosphorus to percentage saturation, exchangeable phosphorus, and crop removal of phosphorus. If readily soluble phosphorus is the resultant both of degree of saturation to phosphorus and the absolute amount of exchangeable phosphorus as stated by Dean and Rubins (19), one would expect it to be relatively great on soils 2, 3, and 4 and low on soils 1 and 5. This is seen to be the case (figure 5). The readily soluble phosphorus on soil 6 is slightly greater than that of soils 3 and 4. The relative decline of readily soluble phosphorus with cropping (figures 26, 27, and 28) is greatest with soils 1 and 5 in all rotations. These soils gave the lowest readily soluble phosphorus values. In no case did the decline in readily soluble phosphorus equal in magnitude the phosphorus removed by the crop at the close of a rotation. The abrupt change in trend in readily soluble phosphorus values between the next to last and final crops in all rotations is unexplained. This change is greatest with soil 2, which gave the highest readily soluble phosphorus and least with soils 1 and 5, which gave the lowest readily soluble values. This phenomenon has been noted by Fraps and Fudge (24) for the phosphorus extracted by 0.2 N nitric acid. They state that it may be caused by soil phosphorus becoming more soluble in the extracting solution by virtue of the action of roots in the soil or that the soluble phosphoric acid fraction was being replenished from more insoluble compounds in the soil. The results of this work may mean that the readily soluble phosphorus of heavily fertilized soils must be reduced by cropping to below a certain critical level before the acid readily soluble fraction is replenished, thus accounting for the abrupt change in rate of decline. Possibly such replenishment takes place at the expense of exchangeable phosphorus rather than some still more insoluble form since this fraction continued to decline with cropping. The soils least able to replenish the readily soluble phosphorus from the exchangeable fraction were soils 1 and 5 by virtue, in the one case, of low absolute amount of exchangeable phosphorus and, in the other case, of low percentage saturation. These actually showed the least replenishment and the greatest tendency to continue the rate of decline of readily soluble phosphorus.

It appears from the work reported here that in heavily fertilized acid soils such as are used in commercial potato production, changes in the soil fraction determined by alkali extraction measure the phosphorus utilized by the crops. In such soils this portion constitutes a high proportion of the total phosphorus in the soil. This situation could not be expected to hold in soils possessing a greater amount of active calcium. In the latter soils it may be feasible to subdivide phosphorus into acid soluble (readily soluble) and exchangeable forms as do Burd and Murphy (8) and Bray and coworkers(3,4). However, in the soils studied here the alkali-extractable phosphorus appears to include the readily soluble phosphorus or at least that portion of the latter which is depleted by cropping. The justification of this statement is in the fact that changes in alkali-extractable phosphorus values accounted for crop uptake while changes in readily soluble phosphorus values did not especially at the latter stages of the rotations.

The determination of readily soluble phosphorus is a relatively simple matter and will doubtless continue to find wide usage. However, the limitations of data obtained for readily soluble phosphorus should be kept in mind when it is employed for estimating crop response and phosphate fertility levels. Some of the data reported in this study have shown this. When other environmental conditions were accounted for, the growth data for lespedeza, vetch, and beets in experiment A and for the crops in the rotations in experiment B followed quite well the readily soluble phosphorus values. The difficulty lies in determining the extent of influence of the "other environmental conditions" in the previous sentence.

It would appear that interpretation of readily soluble phosphorus data on acid soils may be refined by applying such information as exchangeable phosphorus, anion exchange capacity, and degree of phosphorus saturation, although the determination of these quantities is relatively tedious and time-consuming. A further consideration in favor of the determination of exchangeable phosphorus is the observation that, in this study, the phosphorus removed by the crops appeared to follow, in proportion, the absolute amount of exchangeable phosphorus quite closely.

SUMMARY AND CONCLUSIONS

Greenhouse experiments with various crops and crop rotations were carried out on soils from the Eastern seaboard. Many of these soils had received heavy past fertilization for commercial potato production and had accumulated considerable quantities of residual phosphorus. Chemical and physical conditions were made as favorable as practicable for crop growth except that no phosphorus was added and the utilization of the residual phosphorus by the various crops measured.

The varying response of different plant species to environmental factors other than phosphorus fertility is a complicating feature which must be considered when plant data is used as an index of phosphorus availability. Some of these factors are soil texture, moisture supply, excess or deficiency of different chemical elements, and length of day. *Lespedeza sericea* and *Crotalaria retusa* did not become well established on sandy soils under greenhouse conditions. Vetch, cowpeas, beets, lettuce, rye grass, and Sudan grass appear to be less sensitive to textural differences although all crops may be adversely affected on sandy soils during the summer because of the difficulty of maintaining suitable moisture levels in small containers. Rye grass is more tolerant of high salt concentrations than is vetch or lettuce. Vetch and rye grass make better vegetative growth under short-day than under long-day conditions. The opposite is true of

Lespedeza and Sudan grass.

Plant species present considerable variations in their ability to utilize the residual phosphorus of acid soils. Legumes and grasses appear to be better able to utilize residual phosphorus than are vegetables such as beets and lettuce and are less sensitive to lower levels of it. Lespedeza is markedly efficient in removing residual phosphorus from fine-textured soils. The well-developed root system of grasses may partly explain their superior foraging ability for residual phosphorus.

The soil phosphorus extracted by alkali declined with cropping. The greatest relative decline of this fraction took place on the sandy soils. The alkali-extractable phosphorus was divided into organic and inorganic or exchangeable portions. The exchangeable phosphorus also declined with cropping and the magnitude of decline agreed closely in amount with that removed in the crops. The exchangeable phosphorus made up the greater proportion of the total soil phosphorus of the acid soils studied. No significant trends or changes could be detected in the organic phosphorus as a result of cropping. This was also true of apatitic phosphorus which is that soluble in sulfuric acid following alkali extraction.

Readily soluble phosphorus, determined by the Truog method, also declined with cropping. The magnitude of the decline did not keep pace with crop removal of phosphorus but levelled off and actually increased in some cases as the soils were continuously cropped. In the soils studied, the exchangeable phosphorus may include at least that portion of the readily soluble phosphorus which declined with cropping since changes in the former appear to account for all phosphorus removed by cropping within sampling and analytical error.

The data obtained provide illustrations of the usefulness of a knowledge of anion exchange capacity and exchangeable phosphorus in applying the results of determinations of readily soluble phosphorus in measuring phosphorus availability. The contention is supported that readily soluble phosphorus is the resultant of both degree of phosphorus saturation of the anion exchange capacity and the absolute amount of exchangeable phosphorus on acid soils. Crop removal of residual phosphorus was better sustained on soils with higher readily soluble and exchangeable phosphorus values and higher degree of phosphorus saturation.

The experiment with radioactive superphosphate applied to lettuce indicated that reduction of the soil phosphorus reserves by cropping increased consumption of phosphorus from applied superphosphate. and that as plants mature they become better able to utilize residual phosphorus probably as a result of root system development. The greatest utilization of the applied fertilizer took place on the soils with the lowest phosphorus fertility as measured by the readily soluble and exchangeable phosphorus methods.

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