THE EFFECTS OF HEAVY APPLICATIONS OF PHOSPHORUS ON THE INTER-RELATION OF SOIL REACTION AND GROWTH METABOLISM OF LETTUCE, BEETS, CARROTS, AND SNAP BEANS

By

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INTRODUCTION

The results of studies concerning the inter-relation between soil reaction and growth of vegetable plants have attracted the attention of growers because of their economic importance. This is particularly pertinent to investigations conducted on the trucking soils of mineral origin in the Atlantic Coastal Plains area. These soils, because of their generally low organic and colloidal content, weak buffer action, low base exchange capacity, and natural deficiency in plant nutrients, present problems considerably more complicated than those usually encountered in the more fertile types. In the important trucking areas of the Atlantic Seaboard where potatoes is one of the principal crops the soils have usually been maintained in a strongly acid condition to prevent injury by the scab producing organism (Actinomyces scabies). The use of large amounts of physiologically acid fertilizers during the past few years has increased the soil acidity in many instances to the degree where even the growth of the potato plant has been retarded, and the more sensitive vegetables grown in rotation with them have frequently suffered severe injury. As a result, many growers have requested information regarding remedial treatment for the improvement of the growth of the more acid sensitive crops without exposing the potatoes to injury by the scab producing organisms. Definite information regarding the "critical" and the "optimum" reaction range for each of the more important vegetable crops is needed as a basis for practical recommendations.

During periods when profit from truck crop production is dependent largely on maintaining a low unit cost of production such information is of especial economic value. A further study of the practicability of substituting superphosphate for lime for reducing injury to sensitive plants on very acid soils without materially changing the reaction warrants attention. Since most of these soils are naturally deficient in phosphorus, the question has arisen also as to the economic value of heavy applications of superphosphate on even the less acid soils.

Although investigations have been made concerning the effect of acid soils on the content of certain mineral elements in plant tissues, a study of the carbohydrate and nitrogen composition has apparently been neglected. Phosphorus deficiency in tomato plants has been correlated with the nitrogen and carbohydrate content (44). It appeared possible that estimations of these constituents in plants grown at different soil reaction values might assist in explaining the role of phosphorus in stimulating growth of acid sensitive plants in strongly acid soils.

REVIEW OF LITERATURE

The older literature contains abundant references to the effect of lime on crop yields but investigations relating to the optimum soil reactions for plants are of more recent origin. One of the earlier reports of the latter type of research was published in 1920 by Joffe (40) who found the optimum reaction for alfalfa was near the neutral point. Arrhenius (5) who published reaction data for seventeen crop plants found double optima for many of these. The findings of Olsen (63) and later workers indicate single optima for most crops.

The first extensive studies in the United States concerning the acid tolerance of vegetable plants were made by Hartwell and Damon (33) who classified forty-five vegetables according to their relative response to lime. Part of these were reclassified by Burgess and Pember (17) according to their resistance to soil acidity and aluminum toxicity. Several investigators have published data relative to the optimum soil reaction range of the vegetables discussed in this paper. Burgess and Pember (17) found a reaction above pH 6.0 optimum for cos lettuce grown in mineral soil pot cultures. Hardenburg (30) working with pot cultures of muck soils found pH 5.0 to pH 6.5 to be the range for best growth. Crist (19) in studies regarding the effect of lime on the growth of lettuce in acid muck and sand mixtures, and with potting soil, concluded that the use of large amounts of lime is injurious. However, in one experiment he obtained best growth in neutral potting soil. His data cannot be interpreted in terms of optimum soil reaction range because the reaction values are not given.

Most investigators are now of the opinion that soil conditions associated with high H-ion concentrations, and not the acidity created by the hydrogen ions, are directly responsible for injury to most crop plants in very acid soils. Studies of plant growth in nutrient solutions by Van Alstine (89), Theron (84), Tarr and Noble (83), Duggar (21), and Zimmerley (92) (93) have shown that many plants will tolerate far higher concentrations of H-ions in water culture than in soils, without apparent injury.

The nature of the factors directly responsible for injury to plants grown in acid soils has been the subject of considerable contraversy among research workers in recent years. Abbott, Conner, and Smalley (1), Ruprecht (75), and Miyake (60) were among the earliest workers to publish regarding the toxic effect of aluminum on root growth. Hartwell and Pember (34) correlated soluble aluminum in very acid soils with retardation of plant growth and response to liming. Burgess and Pember (17) published later a tentative list of crops arranged according to their tolerance to soil acidity and aluminum toxicity. Mirasol (58), Arndt (4), Conner and Sears (18), McGeorge (56), Rothert (74), Blair and Price (8), Hardy (31), and others have recognized the toxic effect of aluminum on root development either in nutrient solutions or in soil media.

Burgess and Pember (17), the leading proponents of the "active aluminum" concept, found close correlation between the active aluminum content (Al soluble in .5 N acetic) of the soil and the severity of injury to plants which were intolerant of very strongly acid soils. They noted also that the addition of lime or of large amounts of superphosphate to the soil perceptibly lowered the "active aluminum" content. Opponents (47) of this theory claim that the so-called "active aluminum" is largely insoluble in soils above pH 4.5 and does not affect plant growth. Line (47) in precipitation experiments with aluminum compounds found that aluminum is precipitated as a hydroxide at pH 4.0 and as a phosphate between pH 3.0 and pH 4. A very small amount remains in solution as the colloidal hydroxide. He believes that the beneficial effect of large applications of phosphorus is principally in supplying nutrients and that the primary cause of marked depression in growth and of injury to root tissue is attributable to the actual acidity created by the H-ions. Olsen (64) in investigations with Danish soils concludes that in most cases the H-ion concentration is the probable cause of injury on the acid soils he studied. Magistrad (54) in a study of aluminum toxicity and its effect on crop plant growth found one to two p.p.m. of aluminum in solution at pH 5. and 6.5 p.p.m. at pH 4.5. At reactions less than pH 5. alfalfa, red clover, rye, and oats suffered little or no aluminum toxicity, while corn, barley, and soy beans were appreciably injured. Alfalfa and red clover were injured by H-ion toxicity. Pierre (69) in recent investigations of factors affecting growth concluded that H-ion concentration is neither the direct cause of poor growth nor the main factor governing plant distribution or response to liming. The data are taken to indicate that the percentage base saturation is a more important factor than soluble aluminum in determining plant growth on acid soils. He found that when the concentration of aluminum in the displaced soil solution is high, plant injury from soil acidity will occur at higher degrees of saturation than when the aluminum concentration is low. Because of this fact the old weathered soils of the Atlantic Coastal Plains area show more injury from the same concentration of aluminum than do soils with a higher percentage base saturation.

McLean and Gilbert (52) grew a number of crops alternately in a nutrient solution free of phosphorus and containing different concentrations of aluminum sulphate and in one containing phosphorus without aluminum. Concentrations of aluminum as low as 2 p.p.m. (the quantity Magistrad found soluble at pH 5.) resulted in injury to roots of lettuce, carrots, beets, and other sensitive crops. In their later experiments (53) different amounts of phosphorus were added to nutrient solutions containing aluminum sulphate. The phosphorus overcame the toxicity of the aluminum when the concentration of the phosphorus in the form of phosphate was equivalent to that of the aluminum. Burgess and Pember (17) found that very large amounts of superphosphate (8 to 20 tons per acre) added to strongly acid soils, greatly reduced the aluminum injury to sensitive plants. Analyses of lettuce and barley roots and tops showed that plants treated with heavy applications of phosphorus contained about as much aluminum as those untreated, but had absorbed three to ten times as much phosphorus. From these results they concluded that while heavy applications of phosphorus are of value in precipitating active aluminum in the soil, the chief function is in rendering the aluminum non-toxic within the plant.

Crist (19) working with a mixture of two-thirds acid muck soil deficient in phosphorus, and one-third coarse sand found that heavy applications of phosphorus were more effective than lime in the production of lettuce. Tissue analyses showed that the calcium, phosphorus, and iron content of the plants was considerably increased by heavy applications of phosphorus. He suggests the theory that phosphorus increased the permeability of the root membranes and the increased absorption of nutrients improved plant growth.

Fig. 1

View of Plats from West End, May 15, 1928.

View of Plats from East End, November 1928. Note area of poor growth (pH 4.9) marked by cross.

Part I

EXPERIMENTAL

Effects of Heavy Applications of Phosphorus on Growth

Arrangement and Treatment of Plats:

The experiments were conducted on the grounds of the Virginia Truck Experiment Station at Norfolk, Va. The soil in the field plats was classified by the Bureau of Soils of the United States Department of Agriculture as a Sassafras loam and that used in the cylinder experiments as Norfolk fine sandy loam. The field area used in the experiment was a fairly level, uniform soil containing twenty-eight 1/50 acre plats arranged in four replicate tiers of seven plats each. A general view of the area is shown in Fig. 1. The plats within each tier were separated lengthwise by permanently sodded alleys slightly elevated above the surface of the field to prevent lateral movement of the surface water to adjacent plats. The cross surface alleys were 6 feet in width with the exception of the middle one which was 16 feet wide. Each plat was divided crosswise by an alley two feet in width to separate the areas receiving different phosphate treatments.

The soil reactions before treatment varied between pH 5.2 and pH 5.4. Four plats in each tier were treated with commercial hydrated lime to procure reactions approximately pH 7.0; pH 6.5; pH 6.0; and pH 5.6; and two with aluminum sulphate to increase the acidity to pH 5.0 and pH 4.8. This provided four replications at each reaction. Considerable difficulty was encountered in adjusting and maintaining the soils in the various plats at the desired reactions. The first treatments were made in 1925 but satisfactory adjustments were not completed until the summer of 1927. Aluminum sulphate applied at the rate of 5,000 pounds per acre changed the reaction value of the upper six inches of soil from pH 5.3

to approximately pH 4.8 and 2,000 pounds per acre reduced it from pH 5.3 to pH 5.1 - 5.0. It was planned to maintain the most acid plats at pH 4.7 - pH 4.8 but the reaction changed to pH 4.9 - pH 5.0 in the autumn of 1927 and by occasional light applications of aluminum sulphate (500 to 1,000 pounds per acre) was maintained fairly constant thereafter. The initial quantities of hydrated lime (66% CaO) used per acre to effect the desired changes were as follows: pH 5.3 to pH 5.5, 800 pounds; pH 5.3 to pH 5.8, 1600 pounds; pH 5.3 to pH 6.0, 2,000 pounds; pH 5.3 to pH 6.5, 3,600 pounds; and pH 5.3 to pH 7.0, 6,000 pounds. Additional light applications were made when needed, to maintain the desired reaction.

Soil samples for pH determinations were taken in July and November, 1927; May, July, and November, 1928; and in July, 1929. Composite samples from ten separate samples taken at a depth of four to six inches were procured from each plat row. All reaction values were determined electrometrically with the quinhydrone electrode. More than two thousand pH determinations were made of the soils from the field plats during the course of the experiments. The average pH values are given in the tables showing the crop yields at the different reactions.

Fertilizer consisting of a mixture of 800 pounds nitrate of soda, 1,000 pounds superphosphate and 200 pounds muriate of potash was applied at the rate of one ton to the acre each season before the crops were planted. Nitrogen was applied in the nitrate form to eliminate nutritional differences which might have resulted if the ammonia or the organic forms had been used. The east half of each plat was given annually an application of superphosphate at the rate of two tons per acre, in addition to the other fertilizer treatment.

Crosby Egyptian beets, Chantenay carrots, and Bountiful snap beans were planted for both spring and fall crops. New York lettuce was used for spring planting and Big Boston for the fall crop.

Yield Records:

Weights were obtained, whenever possible, from large numbers of small crop units instead of total plat yields in order to provide a sufficient number of variates, at each reaction, for statistical examination.

For lettuce, the individual plants, minus roots, and for carrots and beets, bunches of five plants taken in consecutive order in the row, constituted the weight units. In several instances, where it was not feasible to obtain the small unit records, the plat row served as a unit and the yields are given without the probable errors.

The following two methods were used in the statistical analysis of the data:

(1) Where comparatively large numbers of measurements (40 to 80 at each reaction value) were available, the data was analyzed as follows:

$$\text{Standard Deviation} = \sqrt{\text{Mean of the Squares - Square of the Mean}}$$

$$\text{Probable Error of the Mean} = \pm \frac{.6745 \text{ S. D.}}{\sqrt{\text{Number of Variates}}}$$

$$\text{Probable Error of the Difference} = \pm \sqrt{(\text{P.E.M.}^1)^2 + (\text{P.E.M.}^2)^2}$$

$$\frac{\text{Difference}}{\text{P.E.D.}} = \text{Factor for Obtaining Odds}$$

Odds were obtained from table of odds (35)

Unless otherwise stated in the tables, odds were obtained by this method.

(2) Where small unit weights were not available or data obtained over a period of seasons was analyzed, the significance of differences

in the plat yields was calculated by Student's Method (5) of plat pair comparison. Odds less than 30 to 1 by either method are not given in the tables.

TABLE NO. 1

Average Weights of Individual Lettuce Plants
Grown on Soils of Different Reaction Values
(Averages from 80 Variates at Each pH)

November - 1927			May - 1928			November - 1928			May - 1929		
pH	Weight in Grams	Increase Over Wt. at Next Lower pH	pH	Weight in Grams	Increase Over Wt. at Next Lower pH	pH	Weight in Grams	Increase Over Wt. at Next Lower pH	pH	Weight in Grams	Increase Over Wt. at Next Lower pH
7.1	210.4±7.1	33.2 Odds 45:1	7.0	175.5±4.9	- 5.1	7.2	133.7±5.3	-121.1 Odds Infinite	7.1	233.2±4.0	-125.8 Odds Infinite
6.6	177.2±6.8	1.7	6.5	180.6±6.5	30.6 Odds 95:1	6.6	254.8±5.3	39.3 Odds 1500:1	6.5	359.0±6.5	21.8
6.0	175.5±5.1	24.1	5.9	150.0±4.5	1.5	6.0	215.5±5.1	4.5	6.0	337.2±8.3	21.8
5.8	151.4±6.7	60.8 Odds Infinite	5.7	148.5±5.1	-11.1	5.8	211.0±5.2	-22.0	5.7	309.6±6.4	26.6 Odds 44:1
5.4	90.6±7.2	3.1	5.5	159.6±6.7	2.5	5.5	233.0±6.5	79.3 Odds Infinite	5.4	261.8±4.5	96.8 Odds Infinite
5.2	87.5±5.5	56.3 Odds Infinite	5.2	157.1±5.5	91.6 Odds Infinite	5.3	153.7±5.3	122.1 Odds Infinite	5.1	165.0±5.4	55.0 Odds >10000:1
4.9	21.2±2.1		5.0	66.5±3.2		4.9	31.6±1.7		4.9	110.0±4.9	

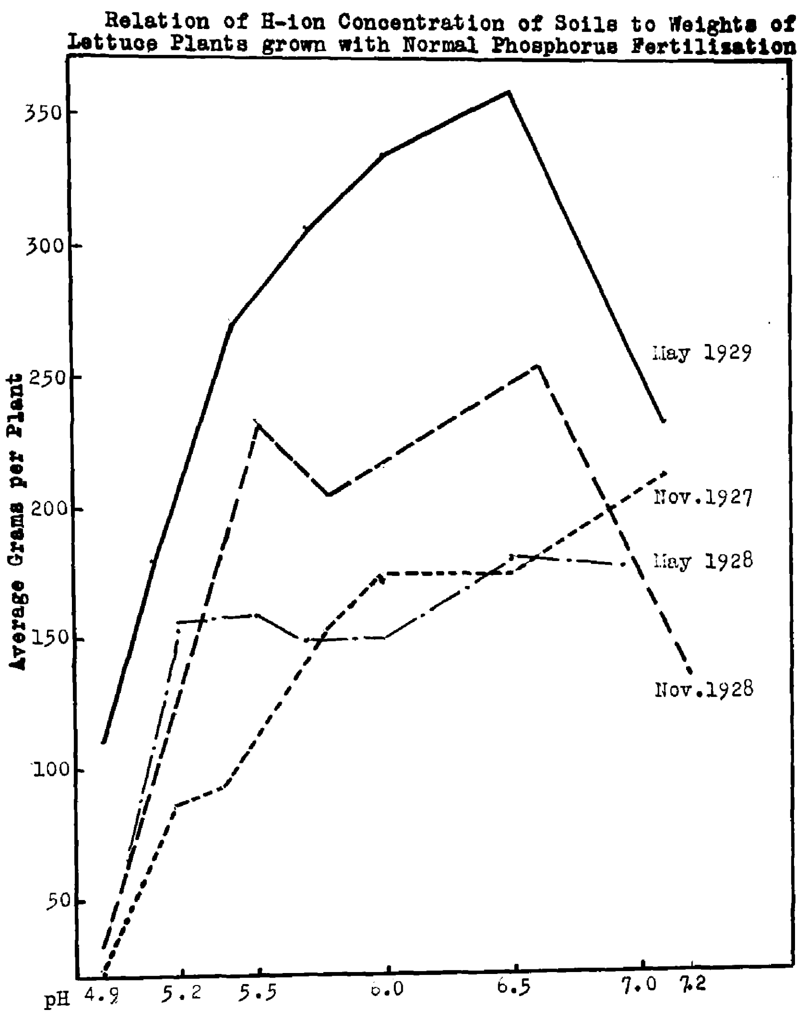

Relation of H-ion Concentration of Soils to Weights of Lettuce Plants grown with Normal Phosphorus Fertilisation
Average Grams per Plant
350
300
250
200
150
100
50
pH 4.9
5.2
5.5
6.0
6.5
7.0
7.2
May 1929
Nov.1927
May 1928
Nov.1928

Fig. 2

LETTUCE (*Lactuca sativa*)

Inter-relation Between Soil Reaction and Growth of Lettuce with Normal Phosphorus Treatment

To simplify the arrangement of data in tables and graphs, and to subject the records to statistical analysis it is expedient to discuss the results of yield data for each crop under two separate headings:

(1) The inter-relation between soil reactions and plant growth with normal fertilization.

(2) The relative effect of heavy and of normal applications of phosphorus at different soil reactions.

A summary of the average weights of 80 heads of lettuce with their P.E.M. at seven different reactions between pH 4.9 to pH 7.1 for each of four seasons is given in Table I and represented graphically in Fig. 2. The significance of differences between yields obtained at each successive increment decrease in acidity is stated in odds except when odds were less than 30 to 1.

The term "optimum reaction" in this paper indicates the pH at which best growth was obtained, provided the increase over the weight at the lower or higher reaction is significant. The optimum may extend over a range of reaction values in which there is no significant change in yield. The "critical" reaction represents the lowest degree of acidity (highest pH) at which severe injury or marked retardation of growth occurs. The "optimum" reaction ranges in the four seasons are as follows: pH 7.1 in the autumn of 1927; pH 6.5 to pH 7.0 in the spring of 1928; pH 6.6 in the autumn of 1928; and pH 5.7 to pH 6.5 in the spring of 1929.

All optima during the four seasons are included in the range of pH 5.7 to pH 7.1. The data indicates that pH 7.0 was beyond the optimum range in soils which had been maintained at that reaction for a number of years. The soils in the plats were limed in 1926 but additional liming was necessary in the spring of 1927 and 1928 to obtain the desired range. The yields given in Table I show that a neutral condition of the soil was not detrimental to growth in the fall crop of 1927 or the spring crop of 1928. In the fall of 1928 the lettuce on these plats appeared normal in color but made a slower growth than occurred at pH 6.5. This is shown in the weekly measurements given in Table 3 and in the average weight of heads at harvest. In the spring of 1929 the plants not only made relatively slow growth but also developed a chlorotic condition characterized by a yellowing of the foliage and the appearance of light brown dead areas on the more severely affected leaves.

The fact that injury did not occur on the neutral or slightly alkaline plats until 18 months after they had been heavily limed would indicate that it was due to a deficiency of some element which was gradually rendered insoluble at the neutral reaction. Sweet potatoes, snap beans, and soy beans in similarly treated soils did not develop "chlorosis" until one to two years after heavy liming.

Skinner (79) reported a similar condition on lettuce plants grown in alkaline Florida soils and attributed it to manganese deficiency. Applications of 50 pounds of manganese sulphate corrected the condition and increased the average weight of lettuce plants 2.5 pounds.

Crist (19) reported that large quantities of lime retarded the growth of lettuce and believed that the large amounts of calcium reduced the absorption of certain essential mineral elements.

Drought interfered with contemplated experiments with manganese on this crop in 1930, but further investigations are in progress at present.

The critical reaction points were 5.2 in 1927 and May, 1928; pH 5.3 in November, 1928; and pH 5.4 in May, 1929. At these reactions the roots were slightly discolored, thickened, and the ~~branches~~ laterals were fewer in number and much shorter than on the healthy plants (Fig. 19). The injury was most severe at pH 4.9 and pH 5.0. The type of injury was similar throughout the four seasons but was less noticeable in the spring crop which was produced from transplanted plants. In the fall where the plants were started directly from seed sown in the plats, the effect of acid soil conditions was apparent about two weeks after germination. The leaves of the seedlings were smaller and much darker green in color, and the petioles were generally tinged with red. Root injury was also noticeable at this time, and in many cases was so severe that a large per cent of the plants died. Weekly measurements of the average diameter of 40 plants at each reaction for a five week period are shown in Fig. 3. Earlier measurements were not feasible because so many plants died during the early stage of growth on the more acid plats that it was unsafe to thin them to a desirable stand until the first week in October. The average diameter of the plants grown at pH 4.9 was only 4.5 inches as compared with 11 inches at pH 5.2; 13.9 inches at pH 5.4; 14.4 inches at pH 5.8; 13.4 inches at pH 6.0; 13.8 inches at pH 6.5 and 10.6 inches at pH 7.0. The same relative size was maintained quite consistently throughout the five week period.

The results are in close agreement with the findings of Burgess and Pember (17) in pot culture studies with cos lettuce in mineral soils, but fail to substantiate those of Hardenburg (30) in muck soils. Hardenburg reported optimum yields of Grand Rapids lettuce at pH 4.9 to pH 6.5 with only a moderate retardation of growth on soils as acid as pH 4.0.

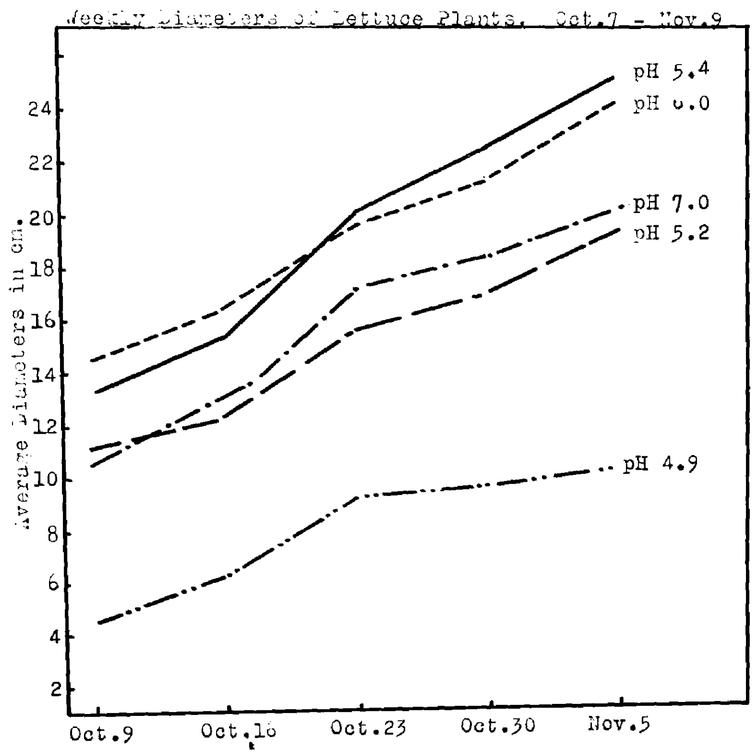

Weekly Diameters of Lettuce Plants. Oct.7 - Nov.9
Average Diameters in cm.
24
22
20
18
16
14
12
10
8
6
4
2
Oct.9
Oct.16
Oct.23
Oct.30
Nov.5
pH 5.4
pH 6.0
pH 7.0
pH 5.2
pH 4.9

Fig. 3

TABLE NO. 2

Effect of Heavy Applications of Phosphorus on Average Weight of

Lettuce Plants

Grown in Soils of Different Reactions.

Soil Reaction pH	Normal Phos. Treatment Av.Wt.5 Tops in Gms.	Heavy Phos. Treatment Av.Wt.5 Tops in Gms.	Increase of Heavy Phos. Over Normal Phos. Treatment		Significance of Increase or Decrease Stated in Odds
			Grams	Percent	
		November 1927			
4.9	31.24±2.10	54.55±3.77	23.31± 3.89	74.6	Infinite
5.2	49.1 ±5.48	98.3 ±7.61	49.2 ± 9.38	100.2	>1,000:1
5.4	90.6 ±7.24	112.18±7.44	22. ±10.7	24.3	
5.8	151.37±6.7	161.31±5.78	9.94± 8.7	6.5	
6.0	175.51±7.9	190.28±7.07	14.77±10.6	8.4	
6.6	177.22±6.9	172.67±6.08	-4.55± 9.2	- 2.7	
7.1	210.44±7.1	223.79±8.43	13.35±11.0	6.3	
		May 1928			
5.0	66.46±3.24	101.96±4.06	35.5 ± 5.2	53.4	Infinite
5.2	157.05±5.45	178.07±3.25	21.02± 6.4	13.4	35:1
5.5	159.61±6.67	194.26±3.8	34.65± 7.7	21.7	>100:1
5.7	148.53±5.06	229.76±5.56	81.23± 7.5	54.7	Infinite
5.9	149.95±4.49	197.56±6.48	17.61± 7.9	11.7	
6.5	180.62±6.45	202.49±7.87	21.87±10.2	12.1	
7.0	175.51±4.91	240.26±6.05	64.75± 7.8	36.9	Infinite
		November 1928			
4.9	31.60±1.69	96.9 ±5.41	65.3 ± 5.7	206.7	Infinite
5.3	153.70±5.29	247.0 ±6.49	93.3 ± 8.4	60.7	Infinite
5.5	233.00±6.66	278. ±7.24	45.0 ± 9.9	19.3	>400:1
5.8	205.10±4.24	262.0 ±5.49	56.9 ± 6.9	27.8	Infinite
6.0	215.50±5.07	252.6 ±6.29	37.1 ± 8.1	17.1	>400:1
6.6	254.80±5.3	275.7 ±6.13	20.9 ± 8.1	8.2	
7.2	133.7 ±5.3	210.8 ±4.39	77.1 ± 6.9	57.7	Infinite
		May 1929			
4.9	110.5 ±4.92	168.5 ±4.92	58. ± 7.0	52.5	Infinite
5.1	165.0 ±5.35	260. ±5.03	95. ± 7.3	57.5	Infinite
5.4	261.8 ±4.47	385.2 ±5.79	123.4 ± 7.4	47.1	Infinite
5.7	309.6 ±6.36	389.5 ±8.26	79.9 ±10.5	25.8	>1,000,000:1
6.0	337.2 ±8.34	408.2 ±8.94	71.0 ±12.2	21.1	>10,000:1
6.5	359. ±6.5	444.5 ±6.35	85.5 ± 9.1	23.8	Infinite
7.1	233.2 ±4.03	333.5 ±4.96	100.3 ± 6.4	43.0	Infinite

They are also at variance with conclusions drawn by Crist (9) from liming experiments for lettuce conducted in a medium composed of two-thirds acid muck and one-third coarse sand. He concluded that lettuce, at least under some conditions, is an acid tolerant plant. The lime requirement of his mixed soil was 14,760 pounds of calcium oxide as determined by the Jones method. Additions of lime sufficient to satisfy even 25% of the requirement resulted in a decrease in yield. Since his reactions are not stated as H-ion concentrations the results cannot be readily compared with those obtained by pH measurements. In his Table 2 (19) the final lime requirements of soil in plats 3 and 4 are indicated as zero, although only sufficient lime had been added to satisfy only 25% of the requirement. It may be that the reaction had been raised to the neutral point or even beyond.

Effect of Heavy Applications of Phosphorus on Growth of Lettuce at Different Reaction Values

The average weights of lettuce plants at each reaction in four season's tests are given in Table 2. All plats received similar treatment of nitrogen and potash. Those under the heading of "Normal Phosphorus Treatment" were fertilized with superphosphate at the rate of 1,000 pounds per acre and those under "Heavy Phosphorus Treatment" at the rate of 1,000 pounds per acre when the crop was planted and 4,000 pounds additional in February of each year. Significant increases ranging from 52.5 per cent to 206.6 per cent were obtained by the use of heavy applications of phosphorus on soils with reactions of pH 4.9 to pH 5.0. The benefits of this treatment were apparent by its effects in reducing injury to the roots and by increase in foliage growth even during the seedling

Effect of Normal and Heavy Applications of Phosphorus on Average Weights of Lettuce Plants.

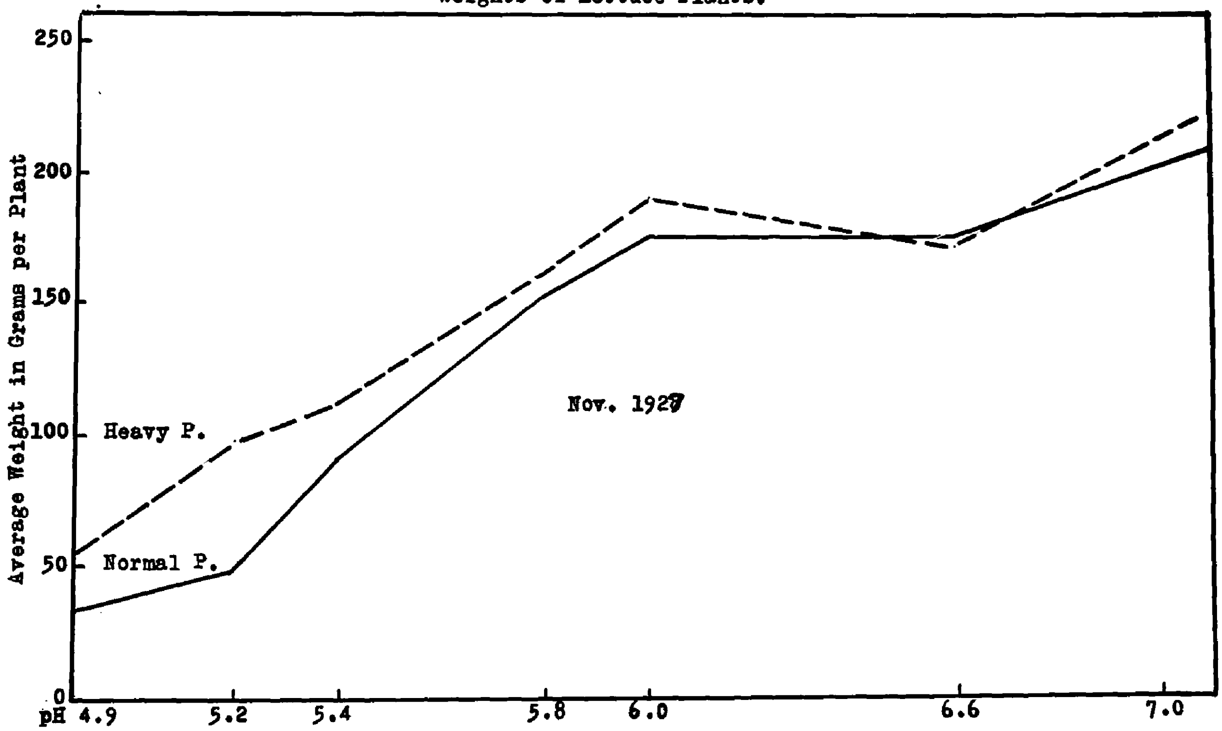


Fig. 4

Effect of Normal and Heavy Applications of Phosphorus on Average Weights of Lettuce Plants.

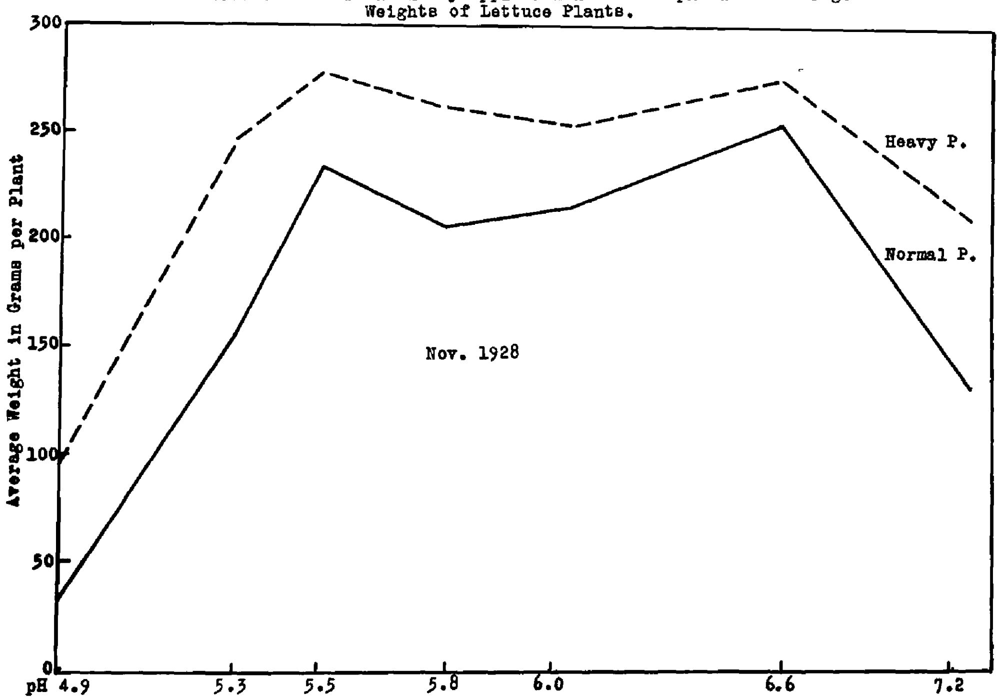


Fig. 5

Effect of Normal and Heavy Applications of Phosphorus on Average Weights of Lettuce Plants.

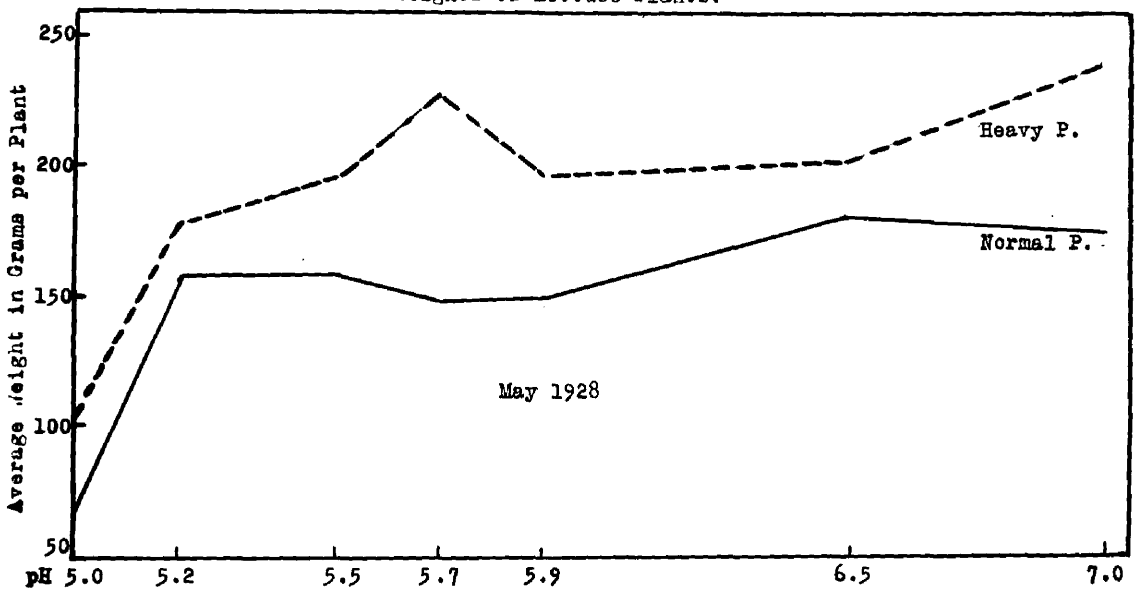


Fig. 6

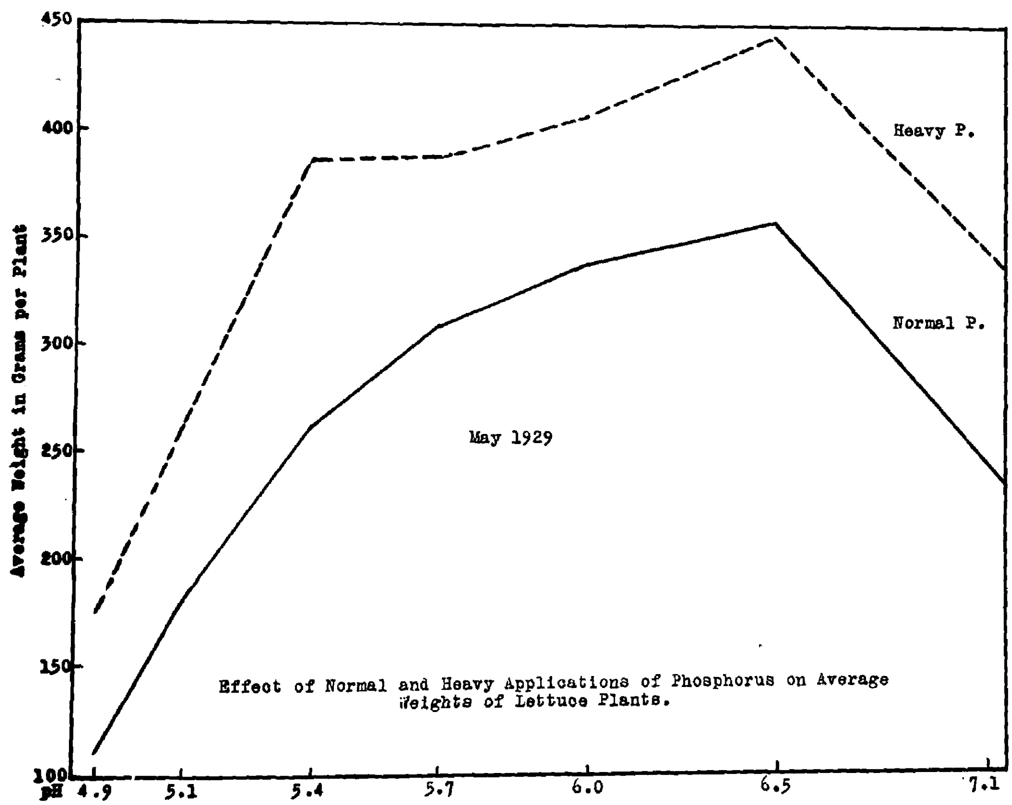


Fig. 7

stages of development. The effect of phosphorus was greater than the data indicate because it greatly reduced the loss of plants in the seedling stage. With normal fertilization , so large a number of the young plants died that it was difficult to obtain a final stand of plants spaced 12 inches apart, but with the heavy phosphorus treatment the stand usually averaged one to two plants per inch before thinning.

At reactions between pH 5.1 and pH 5.3 significant yield increases were also obtained from additional phosphorus throughout the four seasons test. Here again the improvement in growth and the relative freedom from root injury was readily apparent.

The increases, however, have a greater fundamental than economic significance and will be discussed later in connection with the effect of phosphorus on chemical composition. Since the heads of lettuce produced in soils more acid than pH 5.4 did not attain marketable size, the use of heavy phosphorus treatments without lime on these very acid soils could not be considered of commercial importance. The greatest benefits of phosphorus from the grower's viewpoint were obtained on soils within the reaction range of pH 5.4 to pH 6.5. The increases are more clearly shown in the graphic presentation in Figs. 4 to 7 inclusive. In November 1927 the large percentage increases were confined principally to the lower reaction range but in the following seasons they occurred at all reactions. With the exception of the first season, the shape of the curve was not greatly changed by the phosphorus treatment, but the values are consistently higher over the entire reaction range. This indicates a cumulative effect and plant response to a high phosphorus reserve in the soil. By referring to the column in Table I showing the

TABLE NO. 3

Average Diameter, at Weekly Intervals, of Lettuce Plants Grown in Soils of Different Reaction Values with Normal and with Heavy Applications of Phosphorus.

pH	Treatment	Average Diameter in Centimeters of 40 Plants				
		Oct. 9	Oct. 16	Oct. 23	Oct. 30	Nov. 5
4.9	Normal P.	4.5±.19	6.3	9.2	9.6	10.2± .32
	Heavy P.	7.2±.20	11.3	15.4	17.8	19.7± .32
5.2	Normal P.	11.0±.32	12.3	15.8	16.00	19.5± .40
	Heavy P.	12.0±.31	13.6	19.9	22.00	25.5± .30
5.4	Normal P.	13.9±.27	15.3	20.2	22.7	25.1± .39
	Heavy P	13.9±.27	15.8	20.4	23.1	26.2± .33
5.8	Normal P.	14.4±.25	16.0	19.1	20.8	24.0± .34
	Heavy P.	15.2±.34	17.7	19.2	21.7	24.9± .24
6.0	Normal P.	13.4±.36	16.6	19.7	21.2	24.3± .43
	Heavy P.	13.5±.35	16.6	19.7	22.6	25.8± .45
6.5	Normal P.	13.8±.27	16.6	19.8	22.9	26.7± .55
	Heavy P.	14.2±.28	17.0	20.5	24.2	27.6± .33
7.0	Normal P.	10.6±.31	13.7	17.2	18.7	20.5± .29
	Heavy P.	11.5±.30	15.4	19.3	22.1	24.7± .33

significance of the increases, the cumulative effect is even more apparent. In November 1927 only two increases were significant: In May, 1928, 5; in November, 1928, 6; and in May, 1929 all showed odds greater than 10,000 to 1. These data indicate that considerably larger amounts of superphosphate than are commonly applied could be used to advantage by the commercial growers.

Heavy applications would be particularly beneficial on soils with a reaction near pH 5.5 if potatoes were to be grown in rotation with lettuce, since liming might endanger the potato crop to severe scab infection. The inter-relation between diameter of plants and phosphorus treatment at the different reaction values is given in Table 3. These measurements are of interest principally in showing the relative growth rates of the heavily and normally phosphate treated plants at soil reactions of pH 4.9, pH 4.5, and pH 7.0. At the other reactions they do not evaluate the growth of the inner leaves which formed the head.

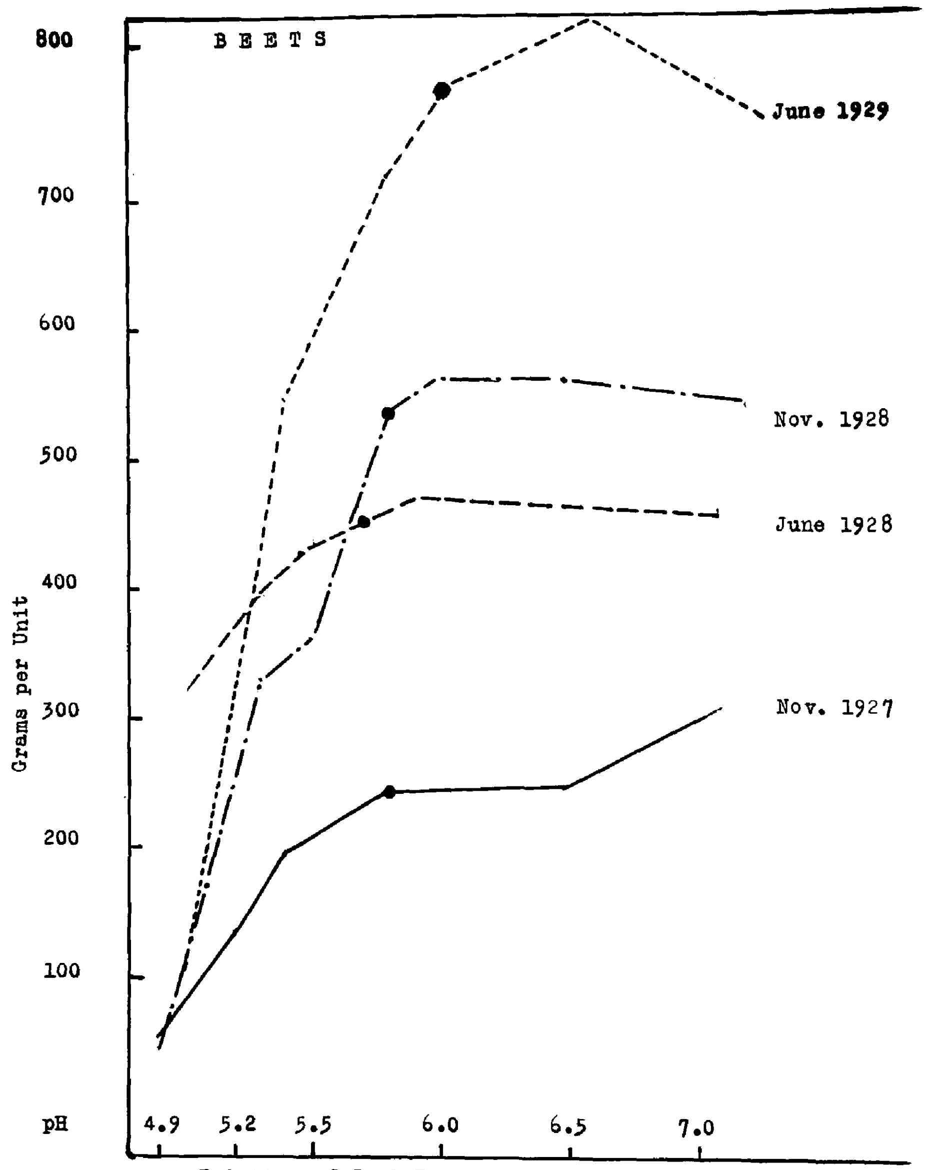
The results are in general agreement with those obtained by Burgess and Pember (17) with heavy applications of phosphorus to lettuce in pot cultures of strongly acid soil. These workers reported that the use of very large amounts of superphosphate (27 tons per acre) gave the greatest increases in growth.

TABLE NO. 4
AVERAGE GREEN WEIGHTS OF BEET ROOTS
From Plants Grown in Soils of Different Reaction Values.

November - 1927*			June - 1928**			November - 1928***			June - 1929***		
pH	Wt. in Grams	Increase Over Wt. at Next Lower pH	pH	Wt. in Grams	Increase Over Wt. at Next Lower pH	pH	Wt. in Grams	Increase Over Wt. at Next Lower pH	pH		Increase Over Wt. at Next Lower pH
7.1	303.03±9.3	64.7 Odds 1300:1	7.0	454.0	- 9.1	7.2	539.6±15.7	- 23.	7.1	731.2±12.3	- 77.6
6.6	238.3 ±8.6	- 2.8	6.5	463.1	- 8.1	6.6	562.6±17.3	- 2.3	6.5	808.8±21.7	42.3
6.0			5.9	471.2	17.2	6.0	564.9±13.7	30.6	6.0	766.5±14.	65.5 Odds 45:1
5.8	241.1 ±8.9	44.8 Odds 160:1	5.7	454.0	22.7	5.8	534.3±20.1	171.1 Odds >10000:1	5.8	701. ±13.04	157.8 Odds Infinite
5.4	196.3 ±6.7	60.0 Odds >10000:1	5.5	431.3	31.8	5.5	363.2±16.9	33.2	5.4	543.2±11.7	443.9 Odds Infinite
5.2	136.3 ±6.8	72.7 Odds >10000:1	5.3	399.5	101.7 Odds 131:1	5.3	330. ±11.89	284. Odds Infinite			
4.9	63.6 ±9.7		5.0	297.8		4.9	46. ±3.85		5.0	99.3±5.9	

* Average weights of individual roots (160 variates at each reaction).
** Averages from weights of quadruplicate plat yields.
*** Average weights of roots in groups of five (40 variates at each reaction).

Odds by Love's modification of Student's Method (   ).



Relation of Soil Reaction to Yield of Beet Roots.

Fig. 8

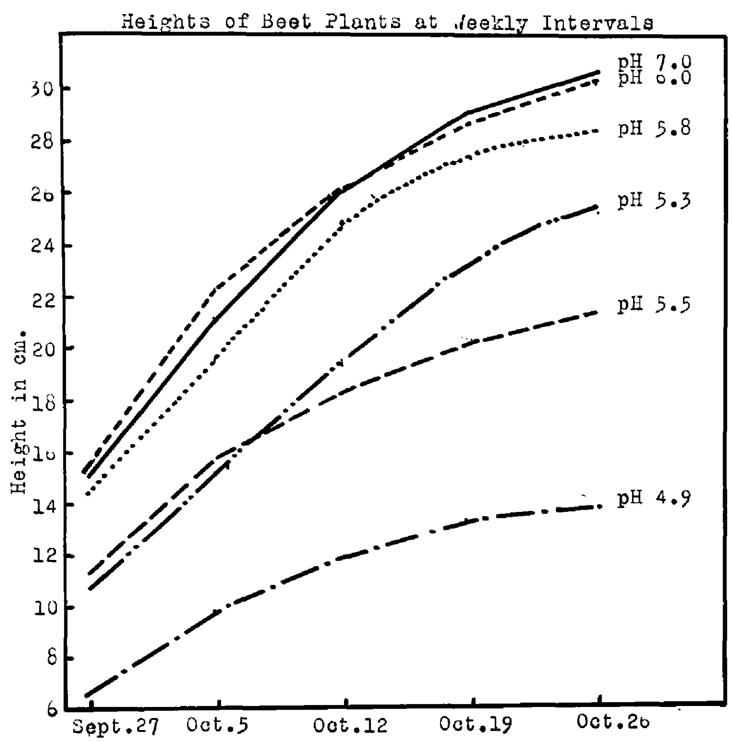
BEETS (Beta vulgaris)

Inter-relation Between Soil Reaction and Growth of Beets

Results in Field Plats:

The yield data given in Table 4 are average weights of beet roots in units of five taken consecutively along the plat row, with the exception of those of 1927 when weights of individual roots were recorded. Probable errors of the mean are not given for the data of June 1928 when yields were recorded by plats and the average weights of five beets calculated from these data. Odds were calculated by Love and Brunson's modification of Student's Method of plat pair comparisons. The results are presented graphically in Fig. 8. The optimum soil reaction was pH 7.1 in the autumn of 1927; pH 5.3 to pH 7.0 in the spring of 1928; pH 5.8 to pH 7.2 in the autumn of 1928; and pH 6.0 to pH 7.1 in the spring of 1929. Although the mean weights of roots grown in slightly alkaline soils in the autumn of 1928 and spring of 1929 were considerably less than those produced at slightly lower reactions, the differences are not statistically significant and reactions pH 7.1 and pH 7.2 are included in the optimum range.

The critical reactions were pH 5.2, pH 5.0, and pH 5.3, and pH 5.4 in the four respective seasons. Marked depression in yield occurred at pH 4.9 and pH 5.0. Severe root injury (Fig. 19), death of many plants in the seedling stage, slow growth of the remainder, and a dark red coloration of this foliage were characteristic growth conditions in these strongly acid soils. Injury was more severe in very dry, hot seasons. This was particularly noticeable during the drought in the summer of 1930. The precipitation during July was only 2.70 inches and temperatures were above normal throughout the month. A precipitation of



Heights of Beet Plants at Weekly Intervals
Height in cm.
30
28
26
24
22
20
18
16
14
12
10
8
6
Sept.27
Oct.5
Oct.12
Oct.19
Oct.26
pH 7.0
pH 6.0
pH 5.8
pH 5.3
pH 5.5
pH 4.9

Fig. 9

TABLE NO. 5

Yields of Beets Grown in Cylinders in Sassafras Sandy Loam Soil.
(All treatments in duplicate)
Soil Reaction of All Cylinders was pH 4.8 Before Treatment.

Lbs. $CaCO_3$ Added Per Acre	pH Reading in July	Av.Wt. 5 Roots in gms.	Av.Wt.Foliage in gms.	Increase In Wt. of Roots		Ratio Root Foliage
				Gms.	Percent	
-	4.8	46	66	-	-	.69
800	5.3	211	295	165	359	.72
1200	5.6	491	430	445	967	1.14
1600	5.8	446	395	400	870	1.13
2400	6.0	460	488	414	900	.94
3200	6.3	520	500	474	1030	1.04
4800	6.6	557	594.5	511	1111	.93
6400	7.0	514	651	468	1017	.79
8000	7.2	492	585	446	970	.84

1.25 inches on July 24th moistened the surface soil sufficiently to permit preparation of the seed bed. Beet seed was planted July 29th and the seedlings began to appear above ground on August 5th. A good germination was obtained on all plats. In a few days the plants grown in soils with reactions below pH 5.1 showed signs of injury. The cotyledons were very dark red, made very little growth and wilted badly during the warmer part of the day. The main roots were shrivelled and the few lateral roots which had emerged from them were blackened and dead. A light rain on August 11th failed to revive the injured seedlings and by August 16th all of the plants on the four more acid plats (pH 4.8 to pH 5.0) had succumbed. A large percentage of those grown in the less acid soils survived. The plats were replanted on August 19th and all the seedlings on the more acid plats died within two weeks after germination.

In the spring of 1927 preliminary experiments were conducted with a Sassafras sandy loam soil in terra cotta cylinders fifteen inches in diameter and 24 inches in depth. The treatments and results are given in Table 5. The optimum range was between pH 6.3 and pH 7.0 and the critical reaction point was pH 5.3. The relative retardation of growth and root injury at pH 4.8 was similar to that which occurred on the very strongly acid soils in the field experiment.

The close agreement of results at similar reactions obtained by different treatments is of special interest. The more acid reactions in the field plats were obtained by the use of aluminum sulphate. The soils used in the cylinder experiments were originally acid and changes in reaction were accomplished by the use of lime. The soils rendered acid by aluminum sulphate reacted similarly to those rendered slowly acid by natural means.

TABLE NO. 6

Effect of Heavy Applications of Phosphorus on Average Weights of

Beet Roots

Grown in Soils of Different Reactions.

Soil Reaction pH	Normal Phos. Treatment Av.Wt.5 Roots in Gms.	Heavy Phos. Treatment Av.Wt.5 Roots in Gms.	Increase of Heavy Phos. Over Normal Phos. Treatment		Significance of Increase or Decrease Stated in Odds
			Grams	Percent	
		November 1927			
4.9	63.6± 2.2	88.0± 5.9	24.4± 6.7	38.3	65:1
5.2	136.3± 6.8	173.2± 7.1	36.9± 9.8	37.0	78:1
5.4	196.2± 6.3	188. ± 6.5	- 8.2± 9.0	- 4.1	
5.8	241.1± 8.9	243.1± 9.6	2. ±13.1	.8	
6.0*					
6.6	238.3± 8.6	249.4± 8.4	11.1±12.0	4.6	
7.1	303. ± 9.3	293.9± 9.3	-9.1±13.2	-3.0	
		June 1928			
5.0	297.8	363.3	65.5	22.	
5.2	399.5	485.3	85.8	21.4	
5.5	431.3	478.2	46.9	10.9	
5.7	454.0	544.8	90.8	2.0	
5.9	472.0	504.6	32.6	6.9	
6.5	463.1	494.9	31.8	6.8	
7.0	454.0	485.0	31.0	6.8	
		November 1928			
4.9	46.1± 3.9	128.2± 6.04	82.1± 7.2	177.0	Infinite
5.3	330. ±11.9	384.2±13.2	54.2±10.7	16.0	>1,000:1
5.5	363.2±16.9	400. ±15.5	36.8±22.9	10.1	
5.8	534.3±20.1	511.3±16.5	-23.0±26.0	-4.3	
6.0	564.9±13.7	564.4±16.6	- .5±21.5	- .1	
6.6	562.6±17.3	499. ±14.3	-63.6±22.5	-11.3	
7.2	539.6±15.7	473.8±16.0	-65.8±22.4	-12.2	
		July 1929			
5.0	99.3± 5.9	326.5±15.2	227.2±16.4	227.1	Infinite
5.4	543.2±11.7	642.8±11.9	99.6±16.7	18.3	>10,000:1
5.8	701. ±13.0	744.5±13.	43.0±18.4	6.1	
6.0	766.5±14.	742.8±12.4	-23.7±18.7	- 3.1	
6.5	808.8±21.6	860.1±16.4	51.3±27.1	6.3	
7.1	731.2±12.3	842.1±11.3	110 .9±16.7	15.2	>100,000:1

TABLE NO. 7

Effect of Heavy Applications of Phosphorus on Average Weight of Beet Foliage from Plants Grown in Soils of Different Reactions.

Soil Reaction pH	Normal Phos. Treatment Av.Wt.5 Tops in Gms.	Heavy Phos. Treatment Av.Wt.5 Tops in Gms.	Increase of Heavy Phos. Over Normal Phos. Treatment Gms.	Increase of Heavy Phos. Over Normal Phos. Treatment Percent	Significance of Increase or Decrease Stated in Odds.
			June 1928		
5.0	404.1	517.6	113.5	28.1	
5.2	494.9	573.4	78.5	15.9	
5.5	517.6	493.6	- 24.0	- 4.6	
5.7	513.	567.5	54.5	10.7	
5.9	582.4	567.5	- 14.5	2.5	
6.5	471.3	553.9	82.6	17.5	
7.0	533.5	528.0	- 5.5	-1.0	
		November 1928			
4.9	69.5±5.1	162.2 ± 8.3	92.7 ± 9.7	133.4	Infinite
5.3	344. ± 12.9	361. ± 13.61	17. ± 18.7	4.9	
5.5	365.4± 15.	316. ± 18.9	-39.4 ± 24.1	- 10.8	
5.8	408.6± 8.7	315.4 ± 11.7	-93.2 ± 14.6	- 22.8	>10,000:1
6.0	402.8± 11.9	362. ± 13.1	-40.8 ± 17.7	- 10.1	
6.6	422.4± 14.7	417.1 ± 11.5	- 5.3 ± 18.7	- 1.2	
7.2	447. ± 12.3	403.4 ± 19.	-43.6 ± 22.6	- 9.7	
			July 1929		
4.9	186.6± 8.8	331.4 ± 10.15	150.8 ± 13.3	80.8	Infinite
5.1	562.8± 9.8	576.7 ± 10.7	13.9 ± 14.5	2.4	
5.7	654.5± 11.9	633.2 ± 10.8	-21.3 ± 16.	- 2.1	
6.0	670.7± 14.4	654.4 ± 11.7	-16.3 ± 18.6	- 2.4	
6.5	658.8± 20.3	647.7 ± 15.2	-11.1 ± 22.9	- 1.6	
7.1	609.3± 12.4	597.3 ± 10.8	-12. ± 16.5	- 1.9	

Foliage Growth on Field Plats:

Measurements were made of the heights of 40 plants at each reaction at weekly intervals from September 27th to November 26th, 1929. These averages are shown graphically in Fig. 9 and indicate the relation of the different soil reactions to the foliage growth rate. The progressive loss of plants by death in the most acid plats, until the latter part of September, prevented earlier measurements. There is a close relation between height of plants and average weights of foliage at harvest (Tables 5 and 8) with the exception of those grown at pH 5.7. The most rapid foliage growth occurred at the optimum reactions (pH 5.8 to pH 7.0) for root development.

These results agree closely with those of Blair and Prince (7) who obtained the highest yields of beets within the soil reaction range of pH 6.0 to pH 7.7 in two season's tests in field plats of Sassafras loam.

Effect of Heavy and Normal Applications of Phosphorus

The benefits derived from heavy applications of superphosphate were greatest on the more acid soils. Increases (Table 6) of 38.3%, 22%, 177%, and 227.1% were recorded in November 1927, June 1928, and July 1929 on soils with reactions of pH 4.9 and pH 5.0. The larger increases in November 1928 and July 1929 indicate the cumulative effect of the heavy phosphorus treatments. Within the reaction range of pH 5.2 to pH 5.4 the differences between yields resulting from heavy applications and normal treatments of phosphorus were significant but smaller than those obtained in the more acid soils. The heavy applications of phosphorus, with one exception, failed to produce significant increases in weight of roots at reaction values above pH 5.4.

TABLE NO. 8

Average Heights, at Weekly Intervals, of Beet Plants
Grown in Soils of Different Reaction Values
with Normal and with Heavy Applications of Phosphorus. Fall 1928.

pH	Treatment	Average Height in Centimeters of 40 Plants				
		Sept. 27	Oct. 5	Oct. 12	Oct. 19	Oct. 26
4.9	Normal P.	6.5$\pm$.48	9.9	11.6	13.4	13.8$\pm$ .5
	Heavy P.	7.7$\pm$.38	12.4	14.0	16.2	17.9$\pm$ .61
5.3	Normal P.	11.2$\pm$.37	15.1	19.2	23.9	25.2$\pm$ .45
	Heavy P.	11.9$\pm$.34	16.5	19.8	24.4	25.9$\pm$ .44
5.5	Normal P.	11.0$\pm$.37	15.7	18.7	20.5	21.8$\pm$ .42
	Heavy P.	12.5$\pm$.26	15.7	18.3	20.3	21.5$\pm$ .52
5.8	Normal P.	14.0$\pm$.40	19.4	24.8	27.4	28.4$\pm$ .64
	Heavy P.	16.3$\pm$.48	20.6	25.0	26.5	27.4$\pm$ .30
6.0	Normal P.	15.1$\pm$.41	22.0	26.1	28.5	30.5$\pm$ .58
	Heavy P.	17.3$\pm$.36	22.8	25.5	28.4	20.0$\pm$ .49
6.5	Normal P.	14.4$\pm$.30	20.1	25.5	27.4	28.3$\pm$ .411
	Heavy P.	13.7$\pm$.39	19.4	25.1	26.9	27.7$\pm$ .535
7.0	Normal P.	14.4$\pm$.34	21.0	26.1	29.3	30.8$\pm$ .37
	Heavy P.	15.2$\pm$.50	20.1	24.6	28.3	29.8$\pm$ .29

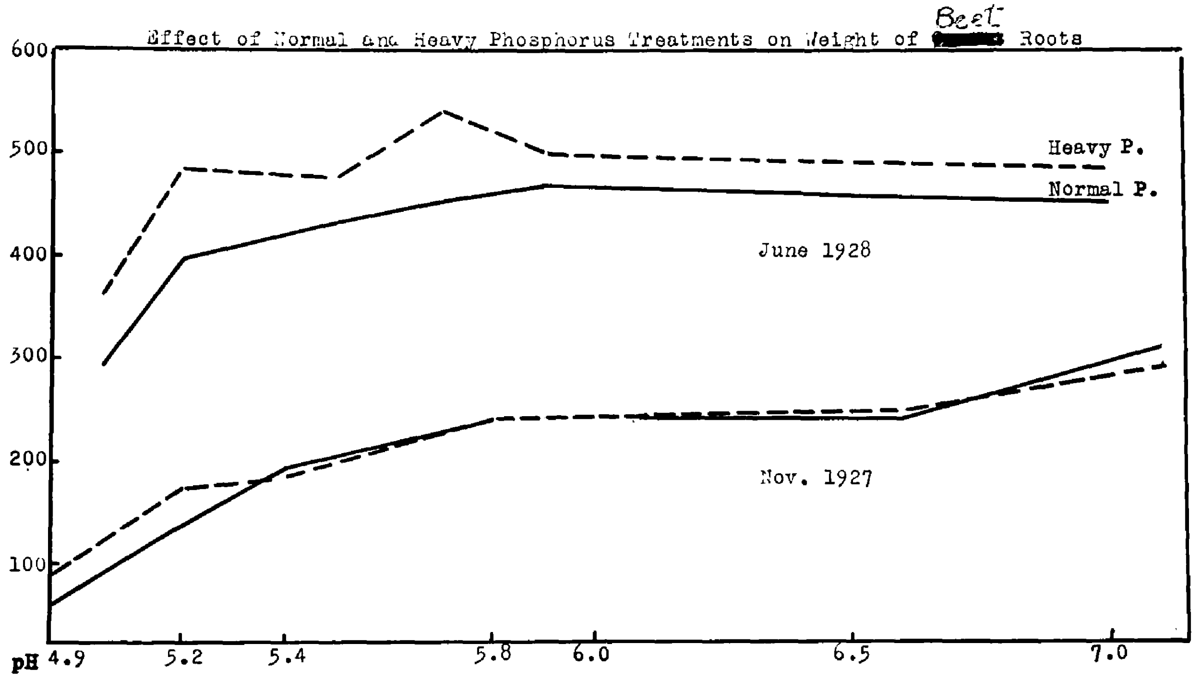

Effect of Normal and Heavy Phosphorus Treatments on Weight of Beet [redacted] Roots
600
500
400
300
200
100
Heavy P.
Normal P.
June 1928
Nov. 1927
pH 4.9
5.2
5.4
5.8
6.0
6.5
7.0

Fig. 10

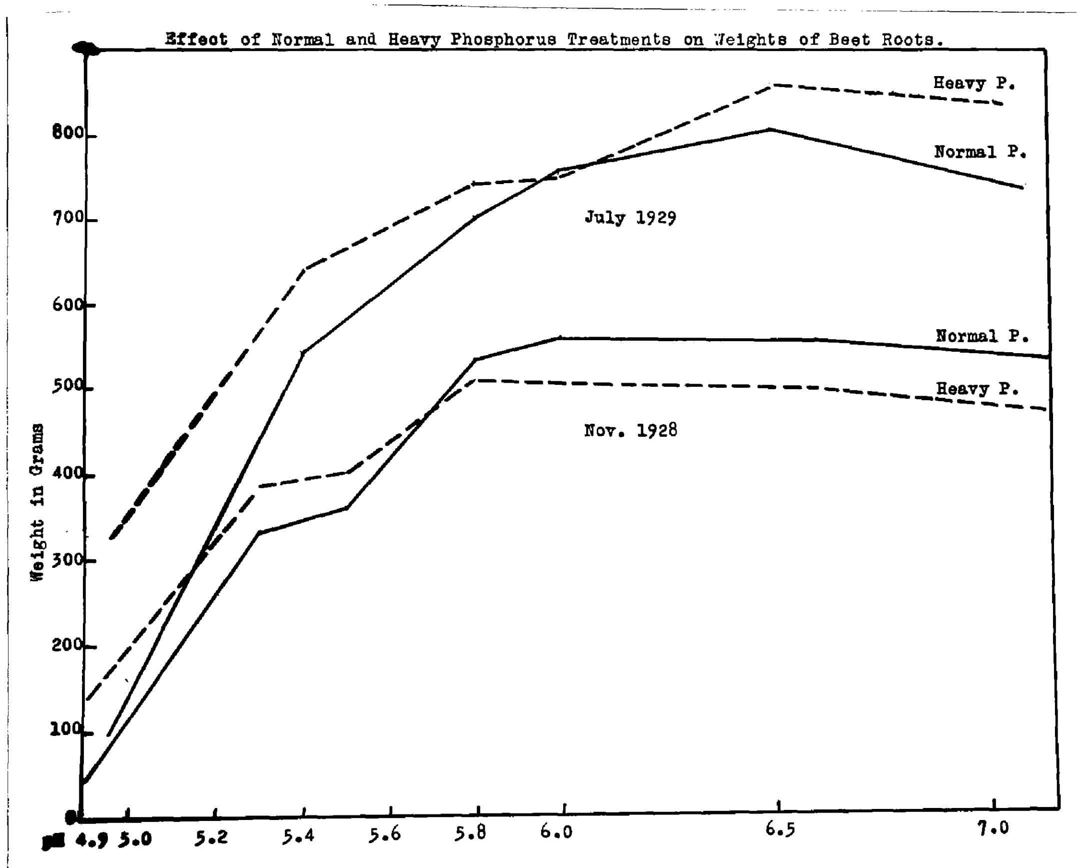

Effect of Normal and Heavy Phosphorus Treatments on Weights of Beet Roots.
Weight in Grams
800
700
600
500
400
300
200
100
0
Heavy P.
Normal P.
July 1929
Normal P.
Heavy P.
Nov. 1928
pH 4.9 5.0
5.2
5.4
5.6
5.8
6.0
6.5
7.0

Fig. 11

TABLE NO. 9

Ratio of Root/Top Growth of Beets
with Normal and with Heavy Phosphorus Treatments
At Different Reaction Values.

pH	June 1928		Nov. 1928		July 1929	
	Normal P.	Heavy P.	Normal P.	Heavy P.	Normal P.	Heavy P.
4.9-5.0	.74	.69	.66	.78	.53	.99
5.1-5.3	.81	.84	.96	1.06	.96	1.11
5.5	.83	.97	.99	1.26		
5.7-5.8	.88	.89	1.31	1.62	1.07	1.17
5.9-6.0	.98	.89	1.40	1.55	1.14	1.13
6.5-6.6	.98	.89	1.33	1.19	1.23	1.32
7.0-7.2	.85	.92	1.21	1.18	1.20	1.41

The response of foliage growth was less than that of roots. Significant increases were obtained only at the lower reactions. Increasing the phosphorus applications resulted in slight decreases in foliage growth at reactions within the optimum range, particularly in November 1928 and July 1929. These, however, were not significant.

Effect on Height of Beet Plants Measured at Weekly Intervals

In Table 8 is shown a comparison of the heights of beet plants at weekly intervals for a five-week period. The only significant increases which resulted from the use of heavy applications of phosphorus occurred on the most acid soil (pH 4.9). At pH 5.2 slight increases resulted throughout the five-week period. At reactions of pH 5.4, pH 5.8, pH 6.0, and pH 7.0 the plants treated with large amounts of phosphorus were slightly taller on September 17th and shorter on October 28th than those grown with normal fertilization.

Effect of Soil Reaction and Phosphorus Treatments on Root/Top Ratio

The data given in Table 9 shows the relative weight of roots and tops at the different soil reactions with heavy and with normal phosphorus treatments. The root/top ratio of beets generally reflects the stage of the maturity of the plant. During the early stages of growth the ratio is usually small and increases with the development of the fleshy root. The low ratio for beet plants grown at pH 4.9 to pH 5.0 shows a condition of retarded development.

Heavy phosphorus treatment increased the root/top ratio on soils within the reaction range of pH 4.9 to pH 5.3 in the fall of 1928

TABLE NO. 10

AVERAGE WEIGHTS OF 5 CARROT ROOTS
From Plants Grown on Soils of Different Reaction Values.

December - 1927*			June - 1928*			November - 1928**			June - 1929***		
pH	Wt. in Grams	Increase Over Wt. at Next Lower pH	pH	Wt. in Grams	Increase Over Wt. at Next Lower pH	pH	Wt. in Grams	Lower pH	pH	Wt. in Grams	Increase Over Wt. at Next Lower pH
7.1	615.	-318. Odds 41:1	7.0	236.1	- 60.4	7.2	224. ±6.1	- 30.5	7.1	237.9±7.0	- 43.8 Odds 65:1
6.6	933.	259. Odds 131:1	6.5	296.5	21.4	6.6	254.5±7.9	- 44.5 Odds 45:1	6.5	281.7±8.9	- 21.3
6.0	674.	5.	5.9	275.1	- 42.7	6.0	299. ±9.6	24.9	6.0	303. ±5.45	8.1
5.8	669.	146.9 Odds 144:1	5.7	317.8	81.3	5.8	274.1±6.5	18.1	5.7	294.9±5.6	14.4
5.4	522.1	591.	5.5	236.5	- 95.4	5.5	256. ±10.5	38.	5.4	280.5±5.4	36. Odds 50:1
5.2	463.1	249.7 Odds 87:1	5.3	331.9	278.8 Odds 151:1	5.3	218. ±8.02	132.5 Odds Infinite	5.1	244.5±8.5	89.7 Odds Infinite
4.9	213.4		5.0	53.1		4.9	85.5±4.8		4.9	154.8±8.1	

* Averages from quadruplicate plats.

** Average of 40 variates at each pH.

Odds: Love's Modification of Students Method.

*** Average of 80 variates at each pH.

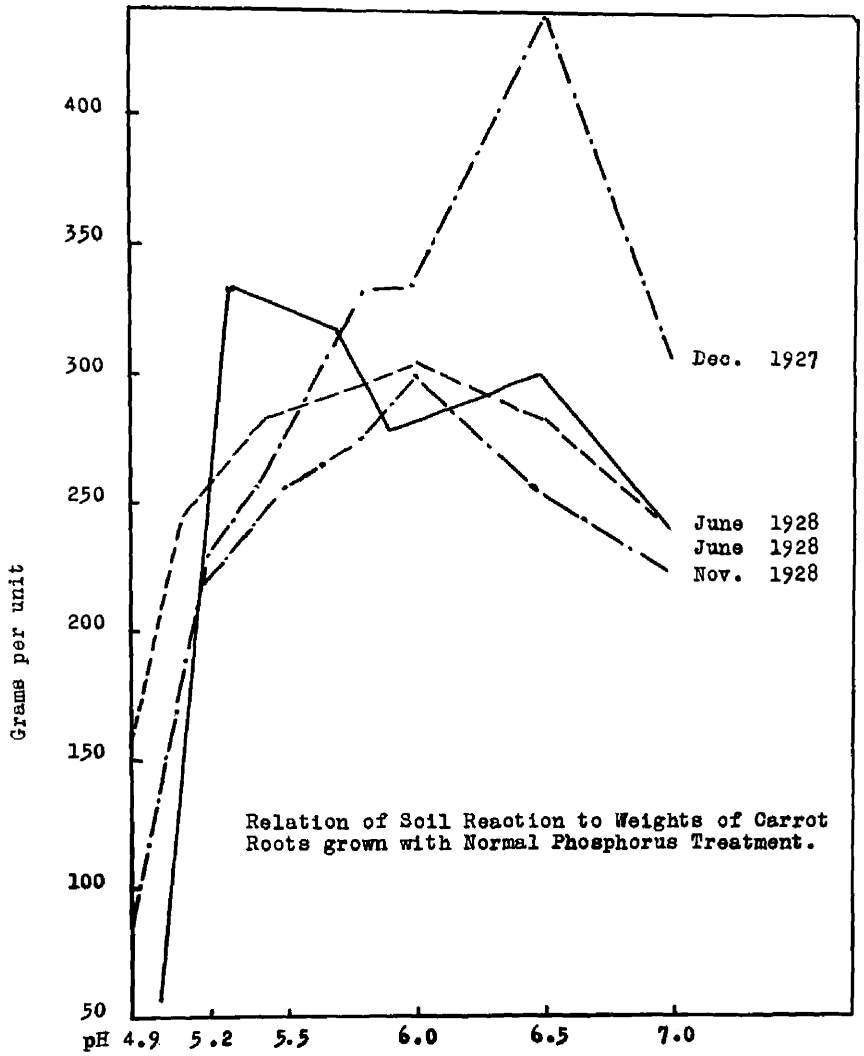

Grams per unit
400
350
300
250
200
150
100
50
pH 4.9
5.2
5.5
6.0
6.5
7.0
Dec. 1927
June 1928
June 1928
Nov. 1928
Relation of Soil Reaction to Weights of Carrot Roots grown with Normal Phosphorus Treatment.

Fig. 12

and the spring of 1929. The highest ratio for both heavy and normal treatments generally occurred in the soils within the optimum reaction range for root development.

CARROTS (Daucus carota)

Inter-Relation Between the Yield of Carrots and Soil Reaction

The average weights of carrot roots, in units of five, grown on soils covering a reaction range of pH 4.9 to pH 7.2 are given in Table 10, and represented graphically in Fig. 12. In December 1927 and June 1928 the plat was considered a unit in recording data and the significance of the differences in weights obtained were calculated from quadruplicate plat pair comparisons by Love's Modification of Students Method (51). Five plants in consecutive order in the plat row were taken as units for recording yield data in November 1928 and June 1929. Probable errors of the mean were calculated by the standard method on 40 variates at each reaction in November 1928 and from 80 variates in June 1929.

The optimum reaction for the fall crop in 1927 was pH 6.6; for the spring crop of 1928, pH 5.3 to pH 7.0; for the fall crop in 1928, pH 5.3 to pH 6.6; and for the spring crop of 1929, pH 5.4 to pH 6.5. The critical reaction value was within the range of pH 5.1 to pH 5.3 during the four seasons. The yields were consistently low at soil reactions of pH 4.9 and pH 5.0 and in 1928 the plants failed to produce marketable roots on these strongly acid soils. That the critical reaction is sharply defined and consistent is shown in Fig. 12. It will be noted that the slope from pH 5.2 to pH 4.9 is much steeper for carrots than for beets or lettuce. This indicates that carrots is rather tolerant of acid soil conditions above pH 5.2 and has a low optimum reaction range. The depression in yield near the neutral point is also quite consistent. These

TABLE NO. 11

Average Heights of 40 Carrot Plants
At Each Soil Reaction
At Weekly Intervals

pH	Average Height in Centimeters					Av.Wt.5 Tops at Harvest (gms)
	Oct. 8	Oct.15	Oct.22	Oct.30	Nov. 5	
4.9	8.9±.28	11.3	13.90	14.7	15. ±.33	69.5± 5.1
5.3	12.9±.31	17.0	19.9	21.4	23.1±.51	344.±12.9
5.5	12.4±.39	15.7	18.5	19.2	21.9±.39	365.4±15.
5.8	12.9±.28	17.7	21.1	22.7	24.7±.44	408.6± 8.7
6.0	14.9±.49	20.3	24.2	26.6	27.5±.37	402.8±11.9
6.6	14.5±.27	20.2	25.9	25.7	27.9±.42	422.4±14.7
7.2	10.9±.21	15.2	18.8	20.6	22.1±.43	447. ±12.3

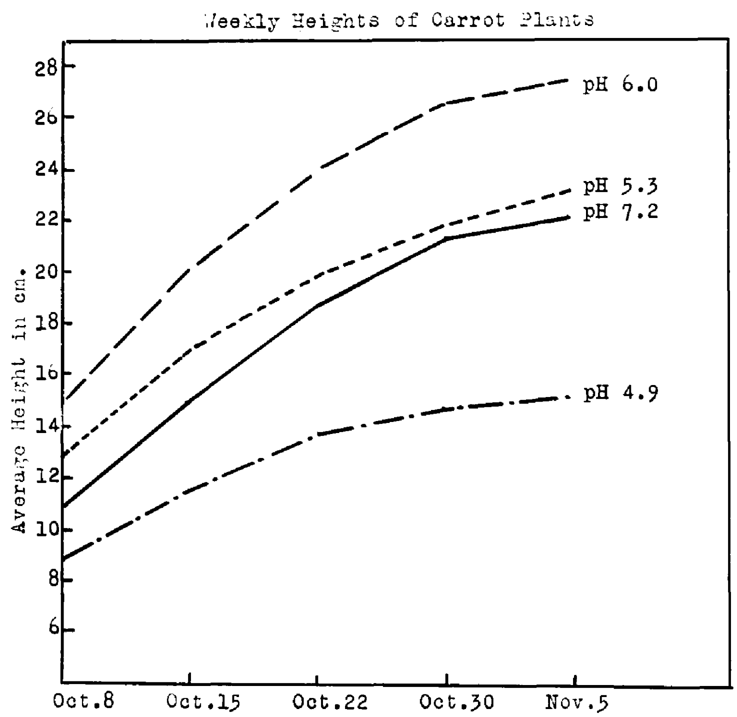

Weekly Heights of Carrot Plants
Average Height in cm.
28
26
24
22
20
18
16
14
12
10
8
6
pH 6.0
pH 5.3
pH 7.2
pH 4.9
Oct.8
Oct.15
Oct.22
Oct.30
Nov.5

Fig. 13

decreases, however, were significant statistically only in 1927 and 1929. The variability of the roots in all plats throughout the four seasons was quite large and particularly so in the spring of 1928. This accounts for the fact that rather large differences are not significant in many instances.

The carrot roots showed severe injury only at soil reaction values of pH 4.9 to pH 5.0. Many of the seedlings died in soils of these reactions. The percentage loss, however, was less than for beet and lettuce.

The foliage growth relations at the different soil reactions at weekly intervals from October 8th to November 5th, 1928 and the average weights at harvest are shown in Table 11. On October 18th the average foliage heights of the plants grown on the most acid soil (pH 4.9) was only 8.8 cm. compared with 12.9 cm. at pH 5.3; 12.9 cm. at pH 5.8; 14.9 cm. at pH 6.0; 14.4 cm. at pH 6.5; and 10.9 cm. at pH 7.0. During the five weeks period the average increases in height at pH 4.9 was only 6.2 cm. as compared with 11.2 cm. at pH 5.3; 11.8 cm. at pH 5.8; 12.6 cm. at pH 6.0; and 13.5 cm. at pH 6.5. This shows the slowest top growth occurred on the plats with a soil reaction of pH 4.9 and the most rapid on the areas at pH 6.5. The average weight of tops shows the same relationship to soil reaction as is indicated by height of plants with the exception that those grown at pH 6.0 were slightly heavier than those produced at pH 6.5. A clearer conception of the relative growth rates at pH 4.9, pH 5.3, pH 6.0, pH 6.5, and pH (7.0) may be had by examination of Fig. 13 which represents graphically the growth for the five weekly periods. The largest average foliage weights were obtained at pH 6.5 to pH 6.6 in November 1927 and June 1929, at pH 6.0 in November 1928, and at pH 5.7 in June 1928.

These results agree with those of Blair and Prince (7) who

TABLE NO. 12

Effect of Heavy Applications of Phosphorus on Average Weight of Carrot Roots

From Plants Grown in Soils of Different Reactions.

Soil Reaction pH	Normal Phos. Treatment Av.Wt.5 Roots in Gms.	Heavy Phos. Treatment Av.Wt.5 Roots in Gms.	Increase of Heavy Phos. Over Normal Phos. Treatment		Significance* of Increase Stated in Odds
			Gms.	Percent	
			December 1927		
4.9	213.4	227	13.6	6.3	
5.2	463.1	624.3	161.2	34.8	38:1
5.4	522.1	694.6	172.5	33.0	32:1
5.8	669.	771.8	102.8	15.3	
6.0	674.2	715.	40.8	6.1	
6.6	887.5	938.	45.5	5.2	
7.1	615.0	772.	157.0	25.5	
			June 1928		
5.0	53.1	151.6	98.5	185.5	144:1
5.2	333.0	351.9	20.9	6.3	
5.5	236.5	303.8	67.3	24.2	
5.7	317.8	374.6	56.8	17.8	
5.9	275.1	331.9	56.8	20.6	
6.5	296.5	335.1	38.6	13.0	
7.0	236.1	349.1	113.1	48.0	158:1
			November 1928		
4.9	85.5 ±4.8	126. ±5.1	40.5 ±7.	47.3	>10,000:1
5.3	218. ±8.0	289.2 ±8.5	71.2 ±11.7	32.6	>10,000:1
5.5	256. ±10.5	202. ±7.6	-54. ±13.3	-21.1	>100:1
5.8	274. ±6.5	264. ±6.6	-10 ±9.2	- 3.7	
6.0	299.7 ±7.9	297.3 ±9.6	- 2.4 ±12.5	- .8	
6.6	254.5 ±7.9	290. ±9.6	35.5 ±12.6	13.9	
7.2	224. ±6.1	257. ±7.3	33. ± 9.5	14.7	30:1
			June 1929		
4.9	154.8 ±8.1	199.9 ±9.5	45.1 ±12.5	29.1	65:1
5.1	280.5 ±5.4	306.5 ±5.4	26. ± 7.6	9.3	45:1
5.4	294.9 ±5.6	288.4 ±6.8	- 6.5 ± 8.8	- 2.2	
5.7	287.8 ±6.7	293.3 ±7.7	5.5 ±10.2	1.9	
6.0	303. ±5.5	356.7 ±7.	53.7 ±11.8	17.7	>100:1
6.5	281.7 ±8.9	340. ±9.7	58.3 ±13.2	20.7	>100:1
7.1	237.9 ±6.7	315.2 ±6.7	72.3 ± 9.5	32.5	Infinite

* December 1927 and June 1928 calculated by Love's Modification of Student Method.

November 1928 and June 1929 calculated by Standard Method.

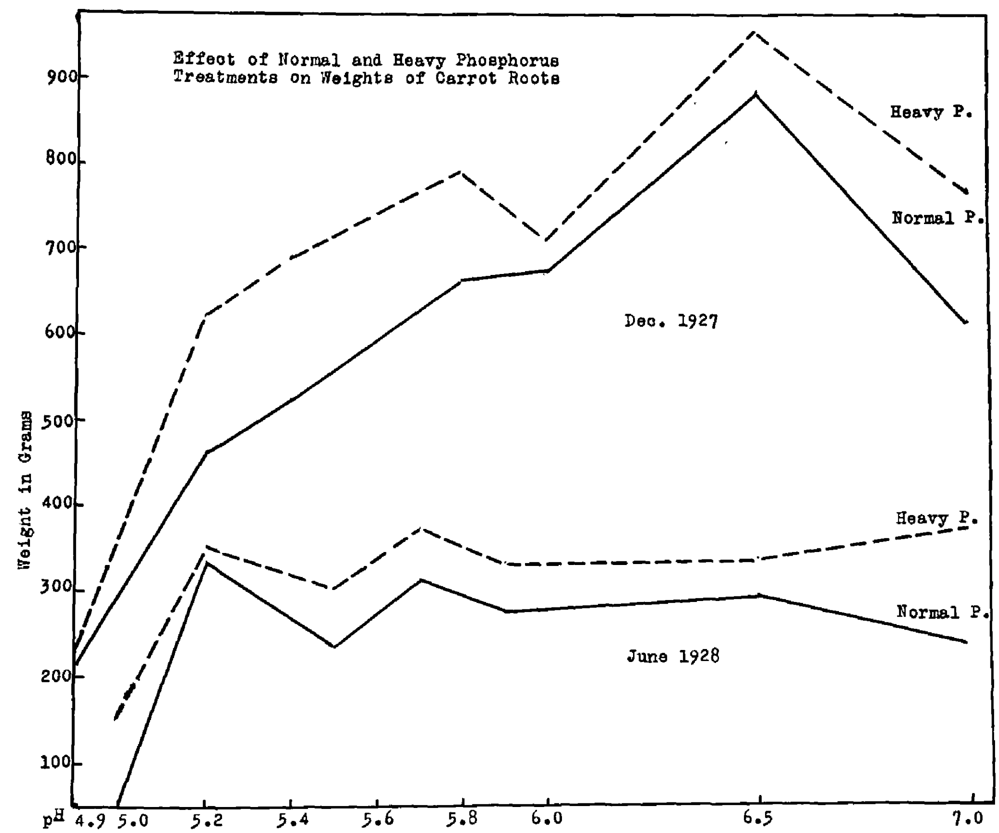
TABLE NO. 13

Effect of Heavy Applications of Phosphorus on Average Weight of Carrot Foliage from Plants Grown in Soils of Different Reactions.

Soil Reaction pH	Normal Phos. Treatment Av.Wt.5 Tops in Gms.	Heavy Phos. Treatment Av.Wt.5 Tops in Gms.	Increase of Heavy Phos. Over Normal Phos. Treatment		Significance* of Increase Stated in Odds
			Gms.	Percent	
			November 1927		
4.9	88.5	97.6	9.1	10.3	
5.2	147.6	174.8	27.2	18.4	
5.4	170.3	227.0	56.7	33.3	45:1
5.8	188.4	211.1	22.7	12.0	
6.0	195.2	202.0	6.8	3.4	
6.6	229.2	242.9	13.7	5.9	
7.1	177.0	227.	50.0	28.2	
			June 1928		
5.0	49.0	134.4	85.4	174.3	124:1
5.2	184.3	198.9	14.6	7.8	
5.5	143.5	160.6	17.0	11.8	
5.7	201.6	221.6	20.0	9.9	
5.9	178.9	198.9	20.0	11.2	
6.5	176.6	184.3	7.7	4.3	
7.0	142.1	190.2	48.1	33.8	77:1
			November 1928		
4.9	33.8 ±1.7	51.7 ±2.	17.9 ±2.6	52.9	>100,000:1
5.3	80.5 ±2.9	108.1 ±3.2	27.6 ±4.3	34.3	>100,000:1
5.5	104.7 ±4.6	95.4 ±2.6	-9.3 ±5.3	-8.9	
5.8	111.8 ±3.3	107. ±2.9	-4.8 ±5.5	-4.3	
6.0	118. ±3.3	119.8 ±4.4	1.8 ±5.3	1.5	
6.6	111. ±3.1	133. ±3.10	22. ±4.4	20.0	
7.2	107. ±2.43	115. ±2.6	8. ±3.6	7.5	
			June 1929		
4.9	112. ± 6.3	139.5 ±6.	27.5 ±8.7	14.5	
5.1	184.5± 3.7	200.2 ±4.4	15.7 ±5.8	8.5	
5.4	204.1 ±4.1	200.7 ±4.3	- 3.4 ±5.9	- 1.6	
5.7	185.9 ±4.13	240. ±5.3	54.1 ±7.7	29.1	>100,000:1
6.0	200.3± 4.24	236. ±5.2	35.7 ±6.7	17.8	>1,000:1
6.5	220.7 ±6.6	235.9 ±6.1	15.2 ±8.9	6.9	
7.1	157.4 ±5.4	184.7 ±4.8	27.3 ±7.3	17.7	54:1

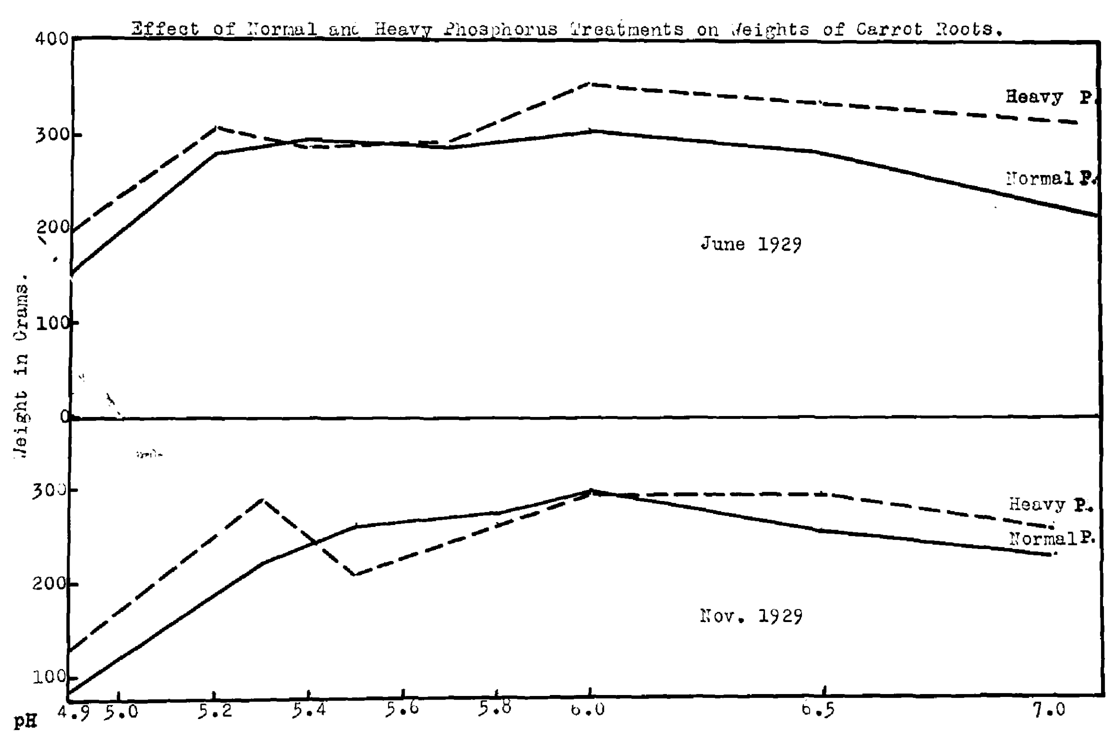
* November 1927 and June 1928 calculated by Love's Modification of Student Method.

November 1928 and June 1929 calculated by Standard Method.



Effect of Normal and Heavy Phosphorus
Treatments on Weights of Carrot Roots
Heavy P.
Normal P.
Dec. 1927
Heavy P.
Normal P.
June 1928
Weight in Grams
900
800
700
600
500
400
300
200
100
pH 4.9 5.0 5.2 5.4 5.6 5.8 6.0 6.5 7.0

Fig. 14



Effect of Normal and Heavy Phosphorus Treatments on Weights of Carrot Roots.
Heavy P.
Normal P.
June 1929
Heavy P.
Normal P.
Nov. 1929
Weight in Grams.
400
300
200
100
0
300
200
100
pH 4.9 5.0 5.2 5.4 5.6 5.8 6.0 6.5 7.0

Fig. 15

reported crop failures with carrots on soil with reactions of pH 4.95. Their optimum yields were obtained near the neutral point. Burgess and Pember (17) obtained good yields of carrots on soils as acid as pH 5.0. McLean and Gilbert (53) found that carrots were severely injured by the presence of very small quantities of soluble aluminum in water cultures and were unable to explain why this crop was not injured in strongly acid soils.

Effects of Heavy Applications of Phosphorus on Growth of Carrots

The use of heavy applications of phosphorus(Table 12) (Figs. 14 and 15) resulted in significant increases in yield of roots within the reaction range of pH 4.9 to pH 5.3, with one exception. In this instance the yield obtained by normal phosphorus treatment was comparatively large and a marked increase could hardly be expected. Significant increases were also obtained in June 1928, November 1928, and June 1929 in soils near the neutral point.

Heavy phosphorus applications gave significant increases in average weight of roots in only three instances within the reaction range of pH 5.4 to pH 6.5. There was a much closer relation between increases in root growth and top growth than occurred with beets. A comparison of the contents of Tables 12 and 13 shows that with few exceptions the percentages increases or decreases are relatively consistent for tops and roots. Three of the four decreases in average weight of roots are accompanied by similar decreases in foliage weights. The greatest discrepancies in root/foliage relations occurred in June 1929 at pH 5.7.

The ratio of Root/Foliage weights is given in Table 14. The

TABLE NO. 14

Ratio of Root/Foliage Weights of Carrots
with Normal and with Heavy Phosphorus Treatments.

pH	Nov. 1927		June 1928		Nov. 1928		July 1929	
	Normal P.	Heavy P.	Normal P.	Heavy P.	Normal P.	Heavy P.	Normal P.	Heavy P.
4.9-5.0	2.41	2.33	1.08	1.13	2.53	2.42	1.38	1.42
5.1-5.3	3.14	3.51	1.80	1.77	2.70	2.67	1.52	1.53
5.5	3.06	3.04	1.63	1.89	2.45	2.11	1.44	1.43
5.7-5.8	3.54	3.66	1.57	1.70	2.44	2.46	1.54	1.63
5.9-6.0	3.40	3.53	1.53	1.66	2.54	2.48	1.52	1.51
6.5-6.6	3.83	3.84	1.67	1.82	2.29	2.18	1.37	1.44
7.0-7.2	3.47	3.40	1.66	1.83	2.09	2.23	1.51	1.60

ratio was consistently lower throughout the four seasons for the plants grown on soils with reactions of pH 4.9 to pH 5.0. Heavy phosphorus treatments increased the ratios at these lower reactions in the fall and decreased them in the spring, but these differences are too small to be considered significant. There is apparently no correlation between the phosphorus treatments and root/top ratios.

The effects of seasonal conditions on the ratios were quite apparent, as they are considerably larger for the autumn than for the spring crops.

The results obtained by the use of large amounts of superphosphate for carrots are of fundamental rather than of practical interest. The use of lime would be more economical on the very strongly acid soils even if potatoes are to be grown in rotation. The lower limits (pH 5.2 to pH 5.4) of the reaction ranges for satisfactory growth are below the danger points for severe scab infection.

TABLE No. 15

Yields of Snap Beans in Grams Per Plat Row.
Averages from Quadruplicate Plats,
With Normal Phosphorus Treatment.

pH	July 1927	July 1928	July 1929	June 1930	Oct. 1930
5.0	1192.	1351.5	1553.	934.	686.3
5.3	1873.5	1820.5	1115.	1211.3	1056.3
5.6	1930.	2196.	996.7	1371.5	1155.
5.8	1759.5	1700.5	865.	1229.5	1010.
6.0	1816.5	1614.	643.8	1188.8	1312.5
6.5	1589.5	1481.8	246.3	1257.5	1103.8
7.1	1362.5	1246.0	16.3	523.5	470.0
	With Heavy Phosphorus Treatment				
5.0	1589.5	1728.5	1672.5	1099.	898.8
5.3	1986.8	2336.	1660.	1480.8	1211.3
5.6	1589.	1936.2	1653.3	1461.8	1273.8
5.8	1816.5	2172.5	1542.5	1517.5	1214.5
6.0	1532.8	1959.5	1211.3	1472.5	1476.3
6.5	2157.0	2069.5	988.8	1404.3	1126.3
7.1	1674.5	1778.8	1015.0	608.8	827.5

TABLE NO. 16

Yields of Snap Beans on Soils of Different H. ion Concentrations.
Averages of Five Seasons Results,
with Quadruplicated Plats at Each Soil Reaction.

pH	Av. Yield in Gms. From 25 ft. Row	Increases Over Yield at Next Lower pH		Decreases Under Yield at Next Lower pH		Significance* of Increase or Decrease
		Gms.	Percent	Gms	Percent	
5.0	1143.3					
5.3	1415.2	271.9	23.7			Odds 86:1
5.6	1522.4	107.2	7.6			9:1
5.8	1328.9			193.5	12.7	25:1
6.0	1315.1			13.8	1.0	2:1
6.5	1135.8			179.2	13.7	302:1
7.1	724.7			411.1	36.2	9999:1

* Plat pair comparisons by Student Method.

Healthy bean plants.
July 19, 1929.

Fig. 16

Bean plants badly affected by
chlorosis. July 19, 1929.

BEANS

Inter-Relation Between Soil Reactions and Yield of Beans Grown with Normal Phosphorus Treatment

Snap beans (Phaseolus vulgaris) variety Bountiful were grown in field plats as a spring crop from 1927 to 1930 and as a fall crop in 1928 and 1930. The records of the 1928 crop are not included because of severe injury to the roots by Fusarium Martii.

Average yield records for each season are given in Table 15 and averages for the five seasons are shown in Table 16 and presented graphically in Figure 16.

The plants grown at a soil reaction of pH 5.6 gave the highest relative yields throughout the five seasons with the exception of the fall crop of 1930, when reaction pH 6.0 proved optimum. The differences, however, between the average yields within the reaction range of pH 5.3 to pH 6.0 (Table 16) were not statistically significant. Although yields were significantly reduced at pH 5.0, no serious injury to roots or foliage was apparent. Snap beans are apparently more resistant to acid soil conditions than are lettuce, beets, or carrots.

The lowest yields were obtained on the slightly alkaline soils. The plants grown in soils within the reaction range of pH 7.0 to pH 7.2 were affected with "Chlorosis" during the last three seasons of the experiment. The severity of the chlorosis varied in the different seasons. Mild cases were characterized by a slight yellowing of the foliage and a moderate retardation in growth; and severe injury was accompanied by the appearance of dead areas in the leaf tissue, marked dwarfing of plants, and on one occasion, by premature defoliation (Fig. 16). In the spring of 1929 the crop on the neutral and slightly alkaline plats was a total failure. The plants grown in soils with a reaction of pH 6.5 also were affected with a mild case of chlorosis and produced a very low yield of beans.

Experiments with manganese, magnesium, and iron treatments on neutral and alkaline soils are now being conducted to determine the effect of those materials in reducing chlorosis.

Giles and Carrero (28) in a study of the cause of lime induced chlorosis in rice plants attributed the injury to a depression in the availability of iron under alkaline conditions. These workers have cited a comprehensive bibliography on chlorosis. Their summary of the evidence from ash analysis in regard to the cause of lime induced chlorosis is as follows:

> "In five cases, with seven different species of plants, it appeared that an excessive absorption of calcium was the causal factor; in two cases it was not responsible. Potash was determined in six of the different plants and only in three cases did it appear that chlorosis was associated with potash deficiency. Iron was determined in five kinds of plants and in all cases it appeared that chlorosis was due to a deficiency of this element."

Gilbert, McLean and Hardin (27) and Skinner (79) found that chlorosis in snap beans on alkaline soils was due to manganese deficiency. Willis (91) found that chlorosis in soybeans in North Carolina was frequently due to lack of available manganese in heavily limed soils. Garner, McMurtrey, Bacon, Moss (25) attributed the trouble in tobacco to magnesium deficiency.

The yields of July 1929 were rather unusual. Table 15 shows that the largest pickings were obtained at pH 5.0, with a somewhat regular reduction in yield with each increment of decrease in acidity.

Relation of Soil Reaction to Nodule Formation

Bryan (13) found that high concentrations of H-ions were toxic to nodule forming bacteria in soils and in culture media. In his experiments alfalfa bacteria were killed at pH 5.0; red clover bacteria at pH 4.5 to pH 4.7; and soybean bacteria at pH 3.5 to pH 3.9.

Snap bean roots growing in soils of different reaction values in the field plats were examined in July 1930 and observations recorded. Counts of nodules on the roots could not have been made accurately without removing and screening immense quantities of soil. The nodules were most abundant on the roots of the plants grown at pH 5.8 to pH 6.5; less numerous at pH 5.5; present in small numbers at pH 5.3; and absent at pH 5.0. Nodules were more abundant on the portions of the plats treated with large amounts of superphosphate at soil reaction values pH 5.3 to pH 7.0. At pH 5.0 neither normal nor heavy phosphorus treatments were conducive to nodule formation. Since the bean crop was fertilized with 800 pounds of nitrate of soda per acre, it is not likely that the nodule formation greatly influenced yield. It, however, would be an important factor on soils deficient in nitrogen where absence of nodules might result in reduced yields in soils of low reaction values.

Effect of Phosphorus on Growth and Yield of Beans

Highly significant increases in yield were obtained by the heavy phosphorus treatments on soils throughout the entire reaction range, with the exception of those at pH 5.6 (Table 17). It is interesting to note that this exception occurred at the reaction which gave optimum yields

TABLE NO. 18

Average Height of Bean Plants
Grown in Soils of Different Reactions
with Normal and with Heavy Applications of Phosphorus.
(Av. of 40 plants at each pH)

pH	Treatment	Average Height in cm.		
		Aug. 28	Sept. 7	Sept. 14
4.9	Normal P.	8.72	15.73	22.87
	Heavy P.	8.88	18.14	27.08
5.2	Normal P.	8.95	18.32	27.16
	Heavy P.	9.61	20.32	27.51
5.4	Normal P.	9.31	14.08	22.48
		8.85	18.25	22.81
5.8	Normal P.	9.82	21.76	26.79
	Heavy P.	9.84	22.76	28.49
6.0	Normal P.	9.87	17.47	23.62
	Heavy P.	9.82	18.56	26.46
6.5	Normal P.	9.91	17.28	20.91
	Heavy P.	10.03	20.23	24.69
7.0	Normal P.	9.98	14.30	17.11
	Heavy P.	10.34	16.71	22.47

TABLE NO. 17

Effect of Heavy Applications of Phosphorus on Yield of Snap Beans Grown at Different Soil Reactions.
Av. of Five Seasons' Results with Four Replications Each Season.

pH	Average Yield in Grams Per 25 ft. Row		Increase by Heavy Phosphorus Applications	Significance of Increase in Odds
	Normal P. Applications	Heavy P. Applications		
5.0	1143.3	1396.7	253.4	>3332:1
5.3	1415.2	1734.9	319.7	>10000:1
5.6	1522.4	1561.4	38.9	2:1
5.8	1328.9	1676.1	347.2	>3332:1
6.0	1315.1	1530.4	215.3	168:1
6.5	1135.8	1549.2	413.4	>9999:1
7.1	724.7	1248.6	523.4	>9999:1

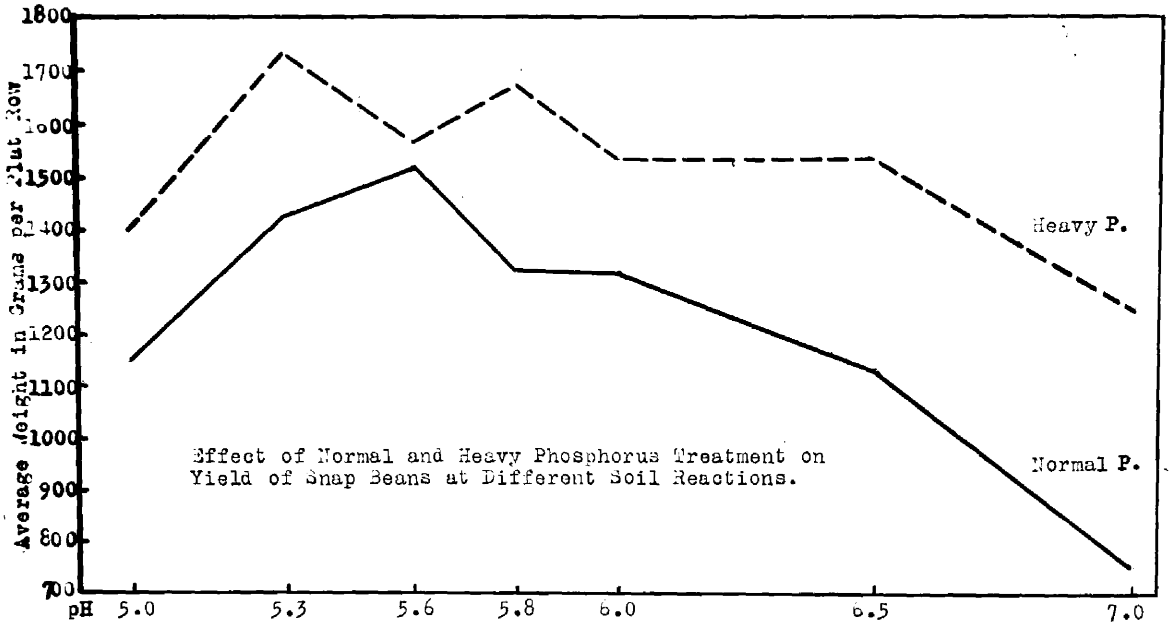

1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
Average Weight in Grams per Plot Row
pH
5.0
5.3
5.6
5.8
6.0
6.5
7.0
Heavy P.
Normal P.
Effect of Normal and Heavy Phosphorus Treatment on
Yield of Snap Beans at Different Soil Reactions.

Fig. 16a.

with normal fertilization. It appears that phosphorus may have been more readily available at this reaction since large amounts failed to give significant increases.

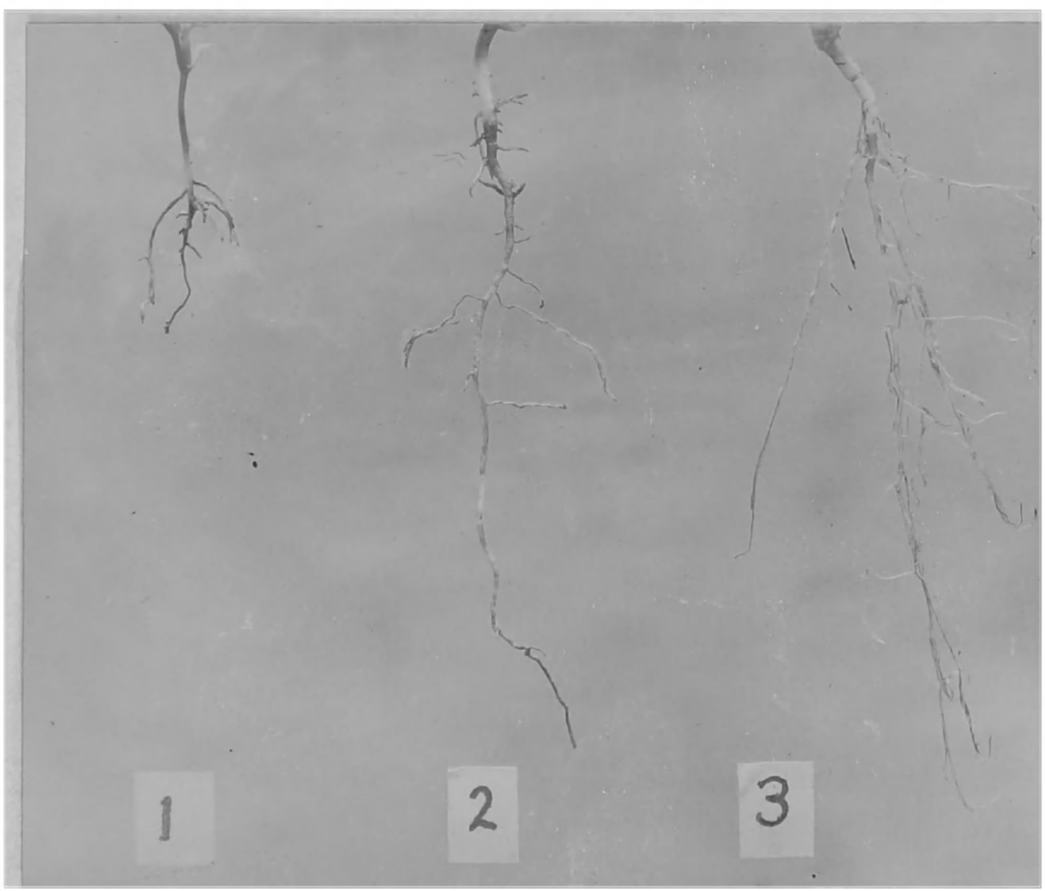
Another point worthy of special attention in its effect on yield near the neutral point: The use of large amounts of phosphorus greatly reduced the injury from chlorosis within the range of pH 6.5 to pH 6.9. This is reflected in the yield of beans and also in the height of plants recorded at three weekly intervals in the fall of 1928 (Table 18). It will be noted that on August 28th the plants grown at pH 6.5 and pH 6.9 with normal and with heavy phosphorus treatments were slightly larger than those on the more acid plats. This lead in height was not maintained. Chlorosis made its appearance on the neutral plats before the second measurement was made, and retarded growth. The relative sizes of the plants indicate that heavy phosphorus treatments reduced the growth retarding effect of chlorosis to a marked degree. Unfortunately, measurements of growth were not made in the June 1929 experiment when the protecting effects of phosphorus were even more apparent. Willis (91) reported that oats were more severely affected by chlorosis on plats fertilized heavily with phosphorus. The difference in response of these two crops is interesting and warrants further investigation.

There is a possibility that the chlorotic condition of the bean plants was not caused by manganese deficiency. Applications of manganous sulphate in solution at the rate of 50 pounds and 100 pounds per acre on badly affected plants in October 1930 had no apparent effect. As the plants were already severely injured it is possible that treatment was made too late for possible effect.

The effect of heavy applications of phosphorus in relation to its physiological effects will be discussed later in this paper. The fact that large amounts of superphosphate resulted in such marked increases in yield throughout most of the reaction range opens up a new field of fertilization research with this crop. It should be noted that lettuce and snap beans responded markedly to heavy phosphorus treatments over a wide soil reaction range, while beets and carrots showed little response at reactions less acid than pH 5.4.

Fig. 17

Fig. 18



Roots of lettuce plants grown in soil with:
1. Reaction pH 4.8 with normal phosphorus treatment.
2. Reaction pH 4.8 with heavy phosphorus treatment.
3. Reaction pH 6.0 with normal phosphorus treatment.

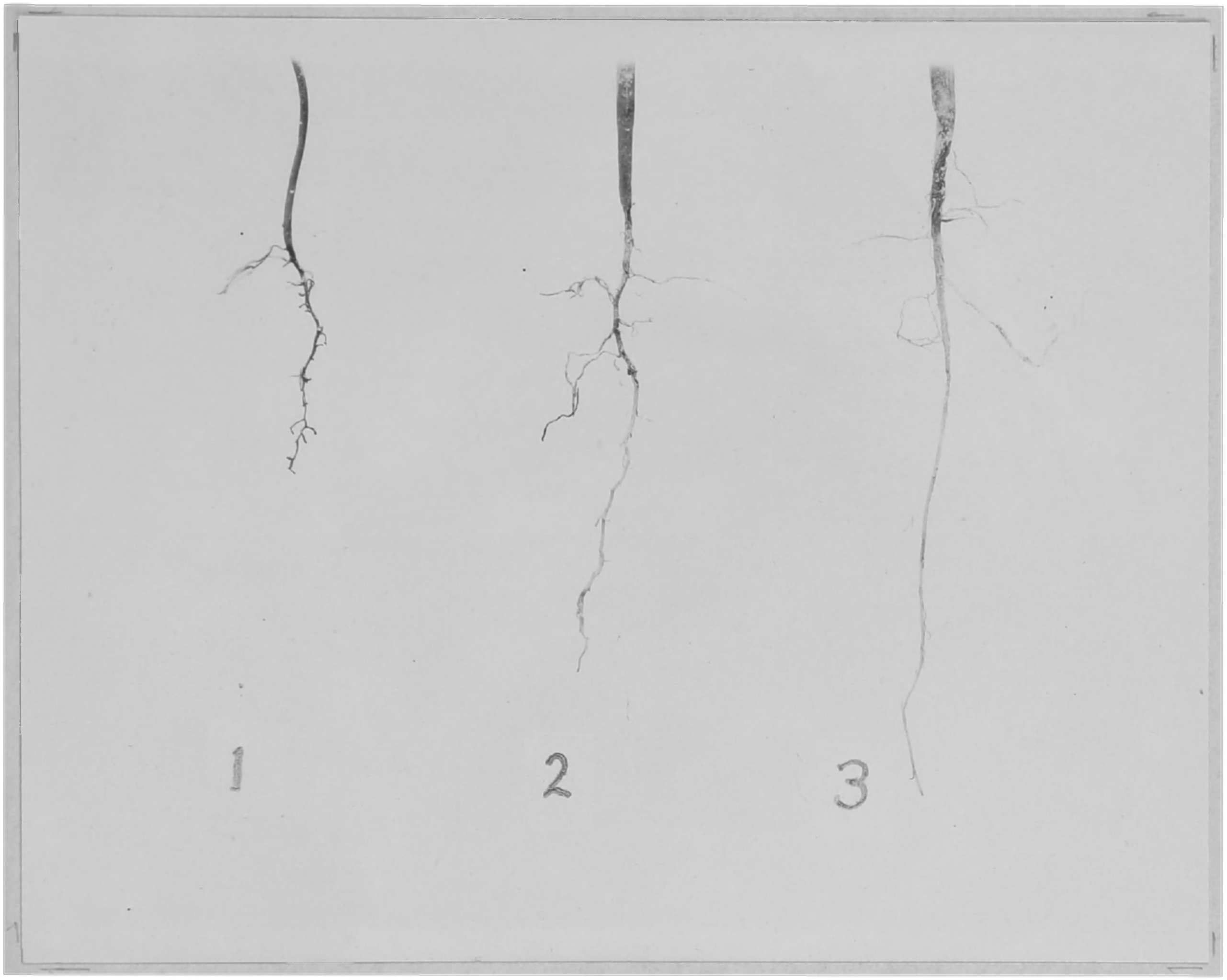


Fig. 19

Roots of beets grown in soil with:
1. Reaction 4.8 and normal phosphorus treatment.
2. Reaction 4.8 and heavy phosphorus treatment.
3. Reaction 6.0 and normal phosphorus treatment.

ROOT INJURY

Observations throughout the course of the experiment showed a consistent relation between foliage growth and root development of the crops studied. Marked retardation in growth was always associated with severe root injury. In soils treated with only normal amounts of superphosphate the injury to beets, lettuce, and carrot roots was particularly severe at reaction values below pH 5.0. Only slight injury was apparent on beet and lettuce roots at pH 5.1 to pH 5.3. Carrot roots proved more resistant and developed normally in soils less acid than pH 5.0.

Severely affected roots of lettuce were discolored, thickened, dwarfed, poorly branched (Fig. 18), and frequently killed. The lower ends of the main roots were killed and growth was continued by laterals near the surface of the soil (Fig. 18, No. 1). Where injury was less severe laterals emerged at intervals along the main root. These, however, were soon discolored, thickened and showed little evidence of rebranching. Beet roots usually presented a blackened, shrivelled appearance with a marked constriction a short distance below the proximal end (Fig. 19).

An examination of cross sections of the injured portions showed that the injury was confined largely to epidermal and cortical cells. The conducting tissues were in most cases uninjured. Laterals originating in the xylem region emerged through the injured cortical tissues. They, however, were soon discolored and made a short, crooked growth. Frequently the tap root was so badly damaged that the plant died in the seedling stage.

Carrot roots were damaged only in the very strongly acid soils (below pH 5.1). The most severe injury occurred in the seedling stage, when many of the plants died. They showed greater recuperative ability than beet or lettuce roots. The main roots which were not completely killed soon developed numerous laterals which generally made fair growth.

Heavy applications of superphosphate greatly reduced the severity of the injury to lettuce, beet and carrot roots. The beneficial effect of this treatment was evidenced by a marked increase in growth, lesser discoloration, and better branching, but injury was not entirely eliminated.

In Figs. 17, 18, 19 are shown typical roots of beet and lettuce grown in soils with a reaction of pH 4.9 with normal phosphorus treatment (No. 1); pH 4.9 with 4 tons superphosphate per acre (No. 2); and at pH 6.0 with normal phosphorus treatment (No. 3).

Burgess and Pember (17) and Blair and Prince (8) attributed the injury to roots in very acid soils to the effects of toxic aluminum. They found that large quantities of superphosphate greatly reduced the amount of "active aluminum" in the soil. Magistrad (54) found that certain plants were injured by small quantities of soluble aluminum but did not include beet, lettuce or carrots in his experiments. Hoffer and Carr (39) by means of microchemical tests showed that aluminum and iron were present in large quantities in injured corn roots. McLean and Gilbert (53) reported injury to roots of beets and lettuce by two parts per million of aluminum in water cultures. Haematoxylin was used to detect the accumulation of aluminum in the injured roots grown in solution containing aluminum sulphate. The cortical cells of roots of the aluminum treated corn and cabbage plants were strongly stained.

Roots of lettuce plants grown in the Virginia Truck Experiment Station greenhouse in soils with reactions of pH 4.8 and pH 6.0 were sectioned and treated overnight in Haidenhain's haematoxylin stain B, diluted 1 to 20. The use of stain A which serves as a mordant was omitted so that only dead tissues would be stained. Microscopic examinations after washing the sections showed that the epidermal and most of the cortical cells of the injured roots were stained a dark brown, while those tissues in the healthy roots were not affected appreciably by the stain. The lignified walls of the tracheae were stained in both healthy and injured tissue. This test, however, merely proves that the epidermal and much of the cortical tissues of the roots of lettuce grown in very acid soils had been killed. It does not prove that aluminum was the causal agent.

Pierre (68) in an extensive study of the factors affecting plant growth in many types of acid soils found evidence that aluminum may be a secondary causal factor. A low percentage base saturation and high K/Ca ratio was correlated with injury to plants grown in acid soils. In a study of Table 5 of Pierre's (69) paper it will be found that there is good negative correlation between the amount of aluminum present in the displaced solution of 13 different soils and the yield of sorghum. In all cases a concentration of aluminum greater than 1 p.p.m. resulted in a decrease in yield. High concentrations of aluminum were particularly injurious in two samples of Norfolk sandy loam in which the percentage base saturation was low.

These data indicate that aluminum toxicity may be the important causal factor of injury to roots of sensitive plants grown in the mineral types of coastal plains soils with a low percentage base saturation (70) and high concentration of H-ions. This will be discussed further in connection with chemical composition, in the second part of this paper.

PART II

CHEMICAL COMPOSITION

Literature relating to investigations concerning plant composition and nutrient deficiencies is voluminous. The more important early papers have been comprehensively reviewed by Duley and Miller (22) and the later references by Salter and Ames (76). A number of investigators (22, 26, 27, 32, 37, 39, 43, 46, 55, 62, 76, 78) have found that the concentration of available nutrients in water or soil cultures affected the percentage nitrogen and mineral elements in the plant composition. There apparently exists a general relation between the intake of a given element and its supply under field conditions. Since the effect of nutrient concentrations on plant composition is usually more marked during the early periods of growth (15, 22, 26, 78), the stage at which material is sampled for analysis is highly important. Other factors, as temperature (26) and moisture (22) are apparently important in influencing the relation of nutrient supply and composition.

Literature showing the effect of soil reactions on the chemical composition of plants is rather limited. Gunter (29) showed that the absorption of potassium and phosphorus by rye seedlings in the Neubauer test is practically unaffected by changing the reaction value of the soil from pH 5.0 to pH 6.5. Rye, however, is not as sensitive to soil acidity as beets, lettuce or carrots. Burgess and Pember (17) found that the percentage composition of phosphorus in lettuce was markedly affected by H-ion concentration of the soil. Crist (19) found that heavy applications of lime greatly reduced the intake of calcium, phosphorus, iron and aluminum; and Hardenburg (30) reported that there is some indication that the iron, aluminum, and calcium content in lettuce tissue decreased with increasing pH values of the soil.

Studies of the effect of the composition of the soil or the nutrient media on the carbohydrate content of the plant have to a large extent been neglected except with reference to the effect of nitrogen. Kraybill and Smith (44) found that phosphorus affected the carbohydrate and nitrogen content. Tomato plants grown in a nutrient medium without phosphorus were relatively high in soluble nitrogen, total nitrogen, free reducing sugars and total carbohydrates, and lower in insoluble nitrogen.

Loehwing (50) in a rather extensive study of the effect of calcium, potassium and iron balance on growth and composition of wheat, corn, and clover on four types of muck soils concluded that a study of the chemical composition of the plant was more valuable than soil analysis. Crop responses to lime and to potash were fairly well correlated with organic products in the plants investigated. Injury by lime or potash was in general associated with increase in nitrates and reduction in organic nitrogen and carbohydrates. Lime applications diminished the potash content to a point of starvation, which interfered with normal carbohydrate metabolism. If potassium is essential for synthesis of carbohydrates and inorganic nitrogen into proteins, its deficiency in lime-injured plants may be responsible for a low organic nitrogen content.

METHODS

Samples for Analysis:

Lettuce, beet, and carrot samples were obtained from plants grown with normal and with heavy applications of phosphorus in the more acid soils (pH 4.9 to pH 5.0) and from those near the optimum reaction (pH 5.9 to pH 6.0).

Bean samples were procured from the chlorotic plants grown at pH 6.9 to pH 7.2 and from the healthy ones grown at pH 5.4. Each sample comprised aliquot portions of twenty to fifty plants. The larger numbers were taken from the more acid plats because the plants were relatively small compared with those grown under optimum conditions.

For lettuce samples, only the outer leaves were used because the plants at pH 4.9 failed to "head". Both blades and petioles were included in the foliage samples of beets and carrots. In July 1929 the blades and petioles from the bean plants were sampled together but in September 1930 they were taken separately.

Plant tissues were finely cut and thoroughly mixed before sampling. Duplicate samples of 50 grams each were removed for carbohydrate and nitrogen determinations, and of 100 grams each for phosphorus and ash analysis.

Preservation of Samples:

Finely cut 50 gram samples were quickly transferred to one pint milk bottles containing .2 grams of calcium carbonate. Sufficient boiling 95% alcohol was added to bring the final concentration of alcohol to 75-80 per cent. The bottles were immediately placed in a boiling water bath and the contents boiled for approximately five minutes to inactivate enzymes. then stoppered, cooled, and sealed with paraffin. Weighed samples for phosphorus and ash analysis were dried at 70°- 75°C. in a ventilated oven.

Grinding and Extracting:

The alcoholic solution from the stored samples, together with the rinsings, was transferred to a 500 cc volumetric flask. The residue was transferred to an evaporating dish, dried to constant weight at 70° - 75° C, cooled in a dessicator, weighed, ground to pass through a 60 mesh sieve, and stored in a stoppered sample bottle. Suitable aliquots of the residue were extracted for three hours in a Soxhlett apparatus and combined with aliquots of the alcohol from the stored samples. Estimations of starch, acid hydrolyzable substances, and insoluble nitrogen were made upon the residue. Sugars and soluble nitrogen were estimated in the extract. The residue for starch estimations were ground to pass through a 100 mesh sieve. Material for phosphorus and for ash analyses was ground to pass through a 20 mesh sieve.

Carbohydrate and Nitrogen Analysis:

The methods of determining the percentage of the various carbohydrate constituents were essentially the same as those described by Boswell (9, 10). The starch estimations were made by a modification of the method of Walton and Coe (88). Alcohol insoluble nitrogen was determined in the residue, and total nitrogen in the residue plus alcohol extract by the Gunning Kjeldahl method modified to include nitrates ~~(87)~~ ~~and~~ (72).

Total phosphorus in plant tissue was determined by the magnesium nitrate fusion method furnished by Dr. R. P. Thomas of the Department of Agronomy of the University of Maryland.

Phosphorus Determination of Plant Tissue

Fusion: To 1 g. of dried ground material add 10 ml. of the alcohol solution of magnesium nitrate (see p. 38). Add this carefully from a pipette so as not to lose any of the sample. Ignite the alcohol from the top and allow the alcohol to burn off without applying any other heat. Then apply a small flame and heat the crucible slowly until all the moisture has been driven off, then heat over a full flame of a Meekker burner until the ash is white throughout. This process is hastened considerably if the material is stirred occasionally by a glass stirring rod. Dissolve the sample in distilled water and add just enough concentrated Hcl acid to insure a complete solution of the ash. 1 or 2 ml. of acid should be sufficient. Make up to 100 ml. volume.

Phosphorus Determination: Place a 25 ml. aliquot of the above solution in a 200 ml. Erlenmeyer flask, add 1 drop of 5% solution of ferric chloride. (This ferric chloride is to indicate whether the contents of the Erlenmeyer flask is alkaline or acid. Add slowly 1 to 1 ammonium hydroxide until a precipitate begins to appear. Clear up the solution and dissolve the precipitate by adding 1 or 2 drops of concentrated nitric acid. Then add 4 ml. of concentrated nitric acid and 10 ml. of 75% strength ammonium nitrate solution. The solution is now ready for precipitation of the phosphorus.

Place the flask in a 60° C water bath. When the contents of the flask has reached 60° C add slowly from a pipette 10 ml. of ammonium molybdate solution which should also be at a temperature of 60° C. While adding the molybdate solution, gently rotate the flask so as to thoroughly mix the solutions. Allow the flask to remain in the 60° water bath for 10 minutes after adding the molybdate solution. Then either transfer to a

40° water bath or lower the temperature of the bath in which the flask is contained to 40° C. Let stand at 40° for 20 to 30 minutes. Then filter immediately, using a 9 cm # 40 Whatman filter paper and a small funnel. Do not shake the flask containing the precipitate but decant off as much as possible before transferring any precipitate onto the filter. This hastens filtering. Now rinse the flask with 5 ml. portions of cold distilled water and pour upon the filter. Each flask should be rinsed 5 or 6 times with the 5 ml. portions of distilled water. The filter paper and precipitate in the funnel are now washed with cold distilled water, by directing a stream of water from a wash bottle, slightly below the top of the filter paper and rotating the funnel. After the washings are free of acid loosen the filter paper from the funnel by means of a spatula, fold over the filter paper and use it to wipe out the inside of the funnel. This is necessary because usually some of the ammonium phospho-molybdate precipitate creeps over the edge of the filter paper. Place the filter paper in the flask in which it was precipitated and stopper immediately. Then add from 10 to 15 ml. of a .1485 N sodium hydroxide solution and shake until the filter paper is thoroughly disintegrated, then wash the stopper and the sides of the flask with distilled water. Add 3 drops of phenolphthalein and titrate with nitric acid having approximately the same normality as the sodium hydroxide. In washing the stopper and inside of the flask with distilled water it is best not to use much over 25 ml.of water (care must be taken to exclude CO_2 from the flask). Also, it is best to use CO_2 free distilled water. 1 ml. of .1485 N sodium hydroxide is equivalent to .2 milligram of phosphorus.

The magnesium nitrate solution used in the fusion is prepared by dissolving 320 g. $Mg(NO_3)_2$ $6H_2O$ in enough 95% alcohol to make one liter.

Molybdic Solution:

To a solution consisting of 155 ml. of concentrated NH_4OH diluted to 417 cc giving a solution of sp. gr. 0.96 add slowly with shaking 100 g. of McO_3. Filter to remove insoluble matter. Dilute 490 cc of HNO_3 sp. gr. 143 to 1250 cc giving a solution of sp. gr. 1.20. Cool both solutions and add the ammonium molybdate solution to the HNO_3 solution in portions of about 25 to 50 ml. at a time, shaking well after each addition. Transfer the solution to a clean stoppered bottle and add a few drops of 10 per cent $NaHPO_4$. Shake and then let stand till the precipitate settles when the solution is ready for use. This reagent now consists of ammonium molybdate dissolved in a solution strongly acid with nitric acid.

Estimations of ash, silica, and ferric and aluminum oxides were made according to official methods (6). Calcium was determined by the tentative method (6).

Determinations of readily available phosphorus in soil samples were made according to the method of Truog (85). Estimations of the water soluble phosphorus were obtained by shaking the soil in distilled water instead of .002 normal sulphuric acid, and following the Truog method in all other respects.

TABLE NO. 19

Carbohydrate Composition of Bean Plants

Soil Reaction pH	Phos. Treat-ment	Part of Plant	Condition of Leaves	% Dry Matter	% Reducing Substances Based On		% Sucrose By Difference Based On		% Total Sugars Based On		% Acid Hydro-lyzable Substances Based On		% Starch Based On		% Total Carbohydrates Based On		% Sol. N Based On		% Insol.N Based On		% Total N Based On	
					Fresh Wt.	Dry Wt.	Fresh Wt.	Dry Wt.	Fresh Wt.	Dry Wt.	Fresh Wt.	Dry Wt.	Fresh Wt.	Dry Wt.	Fresh Wt.	Dry Wt.	Fresh Wt.	Dry Wt.	Fresh Wt.	Dry Wt.	Fresh Wt.	Dry Wt.
							July 1929															
7.1	Normal	Blades and Petioles	Chlorotic	15.76	.133	.81	.25	1.61	.383	2.42	1.91	12.10	.312	2.36	2.29	14.52	.205	1.27	.388	.245	.593	3.72
6.9	Heavy	Same	Slightly Chlorotic	15.13	.202	1.33	.27	1.81	.470	3.14	1.87	12.35	.482	3.18	2.34	15.49	.137	.82	.448	2.95	.585	3.77
5.4	Normal	Same	Green	16.38	.305	1.85	.33	2.01	.633	3.86	2.36	14.41	.629	3.83	2.99	18.27	.0851	.52	.5012	3.05	.586	3.58
5.4	Heavy	Same	Green	16.51	.398	2.41	.32	1.93	.727	4.34	2.30	13.94	.553	3.34	3.03	18.28	.0587	.35	.5123	3.09	.571	3.45
							September 1930															
7.2	Normal	Petioles	Chlorotic	12.19	.088	.71	.255	2.08	.343	2.80	1.97	16.12			2.31	18.92	.240	1.97	.225	1.80	.465	3.77
7.0	Heavy	same	Slightly Chlorotic	13.77	.622	4.51	.405	2.94	1.03	7.45	2.81	20.41			3.84	27.86	.133	.97	.212	1.54	.346	2.51
7.2	Normal	Blades	Chlorotic	14.16	.035	.24	.265	1.87	.300	2.11	2.076	14.65			2.38	16.76	.284	2.00	.456	3.42	.740	5.21
7.0	Heavy	same	Slightly Chlorotic	16.07	.217	1.34	.357	2.22	.573	3.56	2.59	16.09			3.16	19.65	.158	.98	.561	3.49	.719	4.47
5.4	Normal	Petioles	Green	16.62	.930	5.59	.623	3.65	1.55	9.24	3.52	21.16			5.07	30.40	.116	.70	.267	1.60	.383	2.3
5.4	Heavy	same	Green	15.88	1.07	6.69	.673	4.21	1.74	10.9	3.38	21.12			5.12	32.02	.093	.58	.219	1.37	.312	1.95
5.4	Normal	Blades	Green	18.16	.363	1.99	.513	2.83	.877	4.82	3.60	19.83			4.48	24.65	.081	.44	.615	3.38	.696	3.83
5.4	Heavy	Blades	Green	18.32	.430	2.34	.480	2.62	.910	4.96	3.74	20.41			4.65	25.37	.048	.26	.662	3.60	.710	3.87

TABLE NO. 20

Effect of Chlorosis on Sugar Content of Bean Plants

Part of Plant	% Reducing Substances		% Sucrose		% Total Sugars	
	Based on Dry Wt.	Ratio of Normal to Chlorotic	Based on Dry Wt.	Ratio of Normal to Chlorotic	Based on Dry Wt.	Ratio of Normal to Chlorotic
			July 1929			
Chlorotic Leaves	.81		1.61		2.42	
Normal Leaves	1.85	2.3:1	2.01	1.2:1	3.86	1.6:1
		September 1930				
Chlorotic Leaf Blades	.24		1.87		2.11	
Normal Leaf Blades	1.99	8.3:1	2.83	1.5:1	4.82	2.3:1
Chlorotic Petioles	.71		2.08		2.80	
Normal Petioles	5.59	7.9:1	3.65	1.8:1	9.24	3.3:1

DISCUSSION OF RESULTS

SNAP BEANS

Effect of Soil Reaction on Carbohydrate and Nitrate Composition of Plants Grown with Normal Phosphorus Treatment

The results of the carbohydrate and nitrogen analysis for plants grown with normal and with heavy phosphorus at pH 6.9 to pH 7.2 and at pH 5.4 are given in Table 19, and the effects of chlorosis on the sugar content is summarized in Table 20. Blades and petioles were sampled compositely in 1929 and separately in 1930. All samples were taken between 1:00 and 2:00 P.M. on clear days in order to permit an accumulation of sugars in the leaves and provide optimum conditions for a comparison of the effect of chlorosis in the process of sugar metabolism. References to composition will be on the dry weight basis unless otherwise stated.

The effect of chlorosis, which occurred on all plants grown at pH 7.1 to pH 7.2, was most pronounced on their reducing sugar content. In 1929 the chlorotic leaf tissues from plants grown in nearly neutral soil contained only .81% reducing substances as compared with 1.85% in the healthy foliage from the plats with a reaction value of pH 5.4. In 1930 when the chlorotic condition was ~~even~~ more severe than in 1929 the results are even more striking. The chlorotic blades contained only .24% reducing sugars while the normal ones from plants grown at pH 5.4 analyzed 1.99%, or 8.3 times the amount found in the yellowed tissues. The comparatively low content of the simple sugars in the yellowed leaves indicates that chlorosis greatly reduced photosynthetic action. The accumulative effect is best shown by the composition of the petioles which apparently serve as storage organs.

Petioles from healthy plants grown at pH 5.4 contained 5.59% as compared with only .71% reducing substances in those of the badly yellowed plants grown at pH 7.2. The sucrose content was affected less than that of the reducing sugars. In 1929 the sucrose content of the chlorotic plants was 1.61 per cent and of the healthy ones 2.01 per cent. In 1930, however, the differences were somewhat greater for both blades and petioles. The normal blades and petioles contained 2.83 per cent and 3.65 per cent respectively, while the chlorotic ones analyzed only 1.87 per cent and 2.08 per cent. The total sugar content of the healthy leaves was 1.6 times as great as that of the diseased tissues in 1929. In 1930 the total sugar contents of blades and petioles of the normal plants were 2.3 and 3.3 times as large as found in the chlorotic tissues.

The percentages of hydrolyzable materials were slightly higher in 1929 and considerably greater in 1930 in the healthy tissues. The comparative starch content of the chlorotic and normal leaves showed greater differences than in case of the total hydrolyzable content. The total carbohydrate content of the leaves of the chlorotic plants grown under slightly alkaline conditions was in all cases considerably lower than that of the foliage of normal plants grown at pH 5.4.

Chlorosis was in all cases associated with a relatively high soluble nitrogen content. The soluble nitrogen content of the yellow leaves in 1929 was 1.27% as compared with .52% in the green leaves. The blades and petioles of the yellowed plants analyzed 2.00 per cent and 1.97 per cent respectively, while those from the healthy plants contained only .44 per cent and .70 per cent. The insoluble nitrogen composition of the chlorotic leaves was slightly lower than that of the green ones in 1929 and generally higher in 1930. The total nitrogen content of the yellowed leaves was only slightly higher than that of the normal tissues in 1929, but in 1930 when chlorosis was more severe the difference was very pronounced. The chlorotic blades contained 5.21 per cent and the petioles 3.77 per cent total nitrogen as compared with 3.83 per cent and 2.3 per cent found in the respective parts of the green plants.

The effect of chlorosis on the content of dry matter is striking and unusual. Retarded growth is usually associated with relatively high percentage of dry matter but in this case the reverse occurred. In both seasons the chlorotic plants contained lower percentages of dry matter than the normal tissues. The results in 1930 were particularly interesting, especially with respect to the petioles. Those of the chlorotic plants contained only 12.19% dry matter as compared with 16.62% in those of the normal specimens. This was apparently due to the fact that the chlorotic plants made rapid growth during the early part of the season (Table 18). After chlorosis developed, the plants apparently continued growth as long as an abundant supply of carbohydrates was available. This resulted in a marked depletion of storage reserve of this material and a reduction in the percentage of dry matter. Because of the high moisture content of the chlorotic tissues, the relative percentages of carbohydrates and of insoluble nitrogen computed on the weight of fresh material present even more striking differences than when compared on the dry weight basis.

Loehwing (50) found that grain crops on acid muck soils low in potash are often injured by additions of calcium carbonate which may have caused potash deficiency and consequent interference with carbohydrate storage, or induced chlorosis by making sap too alkaline to hold iron in solution. Injury by lime was in general marked not only by increase in soluble nitrogen but also by reductions in organic nitrogen and carbohydrates. His findings in regard to nitrogen and carbohydrate content were similar to those found in the composition of the chlorotic bean tissues at pH 7.2.

The results of investigations by Gile and Carrero (28) and Milad (59) and Lipman (48) have shown that lime and the concomitant reduction in acidity has reduced iron solubility and reduced plant growth. Gilbert and McLean and Hardin (27), Skinner (79), and Willis (91) found that a deficiency of manganese was the cause of lime induced chlorosis. Garner, McMurtrey and Bacon (25) found chlorosis in tobacco was caused by manganese deficiency.

Manganese and magnesium determinations in chlorotic and healthy bean tissue indicated a lower percentage of each of these elements in the chlorotic leaves. Because of failure to obtain close checks between duplicate samples and lack of time and material for repeating the determinations, the results will not be published until more comprehensive data have been obtained.

Effect of Heavy Applications of Superphosphate on Nitrogen and Carbohydrate Composition of Bean Leaves

Heavy applications of phosphorus had considerable effect on photosynthetic activity and sugar metabolism. In all cases the percentages of reducing sugars were considerably higher where large amounts of superphosphate had been applied. The most marked effect occurred in the plants grown near the neutral point. The amount of chlorosis was considerably reduced and the reducing sugar content increased from .81% to 1.33% in 1929. In 1930 it was increased from .24 per cent to 1.34 per cent in the blades and from .71 per cent to 4.51 per cent in the petioles. Unfortunately the soil reaction of the areas treated with large amounts of superphosphate was slightly less than that given normal phosphorus treatment and may have been responsible to some extent for the reduction in the degree of chlorosis. It was noted, however, that the foliage of the plants at pH 6.5 with normal phosphorus treatment was more seriously injured by chlorosis than the heavily phosphated plants at pH 6.9 to pH 7.0.

The percentage of total sugars in the leaves of plants grown on nearly neutral soils was considerably increased by heavy phosphorus applications. The more outstanding differences occurred in the samples obtained in 1930. The total sugar content of the petioles of the normally phosphated plants was only 2.8 per cent as compared with 7.45 per cent in the petioles of those which received additional phosphorus. The total sugar content of the blades was 2.11 per cent and 3.56 per cent for these respective treatments.

Heavy phosphorus treatments had little effect on the total acid hydrolyzable content but considerably increased the percentage of starch.

The consistent decrease in the percentage of soluble nitrogen in all leaf tissues from plants grown with heavy phosphorus treatments indicates its effect on protein synthesis.

Loehwing (50) partially attributed a high soluble nitrogen content in chlorotic corn plants to lack of potassium which has been found important in protein synthesis. There is a possibility that the presence of a high phosphorus concentration in the soil solution may have increased the permeability of the protoplasmic membranes to potassium, manganese, magnesium, all of which appear to be important either in carbohydrate metabolism or protein synthesis. The antagonistic effect of different ions in establishing a physiological balance in nutrient solutions have been shown by Loeb (49), Osterhout (66), Waynick (89), and many other workers. Breazeale (11) working with wheat seedlings found that the absorption of potassium was increased by the presence of other plant nutrients. Crist (19) found that the use of large amounts of superphosphate increased the absorption of iron, aluminum, and calcium in lettuce plants grown in heavily limed soils.

There is also a possibility that the absorption of large amounts of phosphorus buffered the plant sap sufficiently to prevent the precipitation of iron. Loehwing (50) noted that sap acidity favored iron solubility and absorption.

Phosphorus may also have had a direct action on photosynthesis. Stoklasa (81) found that phosphorus together with magnesium and potassium takes a very important part in the process of photosynthesis.

Relation of Soil Reaction and Phosphorus Treatments to Carbohydrate and Nitrogen Composition of Lettuce, Beets, and Carrots

The results of the carbohydrate and nitrogen estimations upon lettuce, beets, and carrots are given in Tables 21 to 26. These determinations were made with the expectation that phosphorus deficiency would be reflected in the carbohydrate and nitrogen composition of the plants. Kraybill and Smith (44) found that phosphorus deficiency in the tomato plant was correlated with a high total nitrogen, a high soluble nitrogen, a low insoluble nitrogen, and a high carbohydrate content. A careful scrutiny of the tables shows that no such relationship exists in the composition of the beet, lettuce and carrot tissues. It would be expected that the marked differences in the rapidity of growth of plants at the different reaction values would have resulted in consistent differences

TABLE NO. 21

Carbohydrate Composition of Lettuce Leaves.

Soil Reaction pH	Phos. Treat-ment	% Dry Matter	% Reducing Substances Based on		% Sucrose By Difference Based on		% Total Sugars Based on		% Acid Hydro-lyzable Substances Based on		% Starch Based on		% Total Carbohydrates Based on	
			Fresh Wt.	Dry Wt.	Fresh Wt.	Dry Wt.	Fresh Wt.	Dry Wt.	Fresh Wt.	Dry Wt.	Fresh Wt.	Dry Wt.	Fresh Wt.	Dry Wt.
May 1928														
4.9	Normal	10.45	.763	7.30	1.33	12.55	2.09	19.85	1.30	12.44	.388	3.71	3.39	32.29
4.9	Heavy	9.73	.773	7.94	1.27	13.00	2.04	20.94	1.31	13.41	.353	3.63	3.35	34.35
6.0	Normal	9.23	.628	6.81	1.37	14.86	2.00	21.67	1.20	13.02	.328	3.56	3.20	34.69
6.0	Heavy	9.40	.650	6.86	1.45	15.53	2.10	22.39	1.23	13.08	.340	3.62	3.23	35.47
November 1928														
4.9	Normal	12.99	.814	6.05	2.76	21.50	3.57	27.55	1.04	7.97	.24	1.80	4.61	35.52
4.9	Heavy	10.49	.935	8.92	1.52	14.43	2.45	23.35	1.32	12.23	.25	2.39	3.77	35.58
6.0	Normal	9.76	.562	5.77	1.27	13.01	1.83	18.78	1.08	11.07	.22	2.26	2.91	29.85
6.0	Heavy	8.49	.823	9.69	1.05	12.22	1.87	21.91	1.10	12.87	.18	2.13	2.97	34.78
May 1929														
4.9	Normal	8.97	.690	7.70	.82	9.13	1.51	16.83	1.14	12.7	.341	3.80	2.65	29.54
4.9	Heavy	8.43	.790	9.37	.83	9.84	1.62	19.21	1.14	13.47	.291	3.45	2.76	32.68
6.0	Normal	7.95	.450	5.67	.88	11.00	1.33	16.67	.98	12.22	.269	3.38	2.31	28.89
6.0	Heavy	7.58	.569	7.51	.64	8.53	1.21	16.04	.90	11.88	.269	3.55	2.11	27.92

TABLE NO. 22

Nitrogen, Phosphorus, Calcium, Aluminum, and Iron Content of Lettuce Leaves.

Soil Reaction pH	Treat-ment	Av.Grm. Gr. Wt. Per Plant	% Sol. N Based on		% Insol.N Based on		% Total N Based on		% CaO Based on		% Phos. Based on		% Fe & Al Oxides Based on		% Ash Based on	
			Fresh Wt.	Dry Wt.	Fresh Wt.	Dry Wt.	Fresh Wt.	Dry Wt.	Fresh Wt.	Dry Wt.	Fresh Wt.	Dry Wt.	Fresh Wt.	Dry Wt.	Fresh Wt.	Dry Wt.
							May 1928									
4.9	Normal	66.46	.076	.727	.280	2.68	.356	3.41	.138	1.32	.015	.142	.037	.354	1.272	12.17
4.9	Heavy	101.96	.100	1.10	.253	2.60	.353	3.76	.146	1.59	.023	.239	.040	.411	1.248	12.82
6.0	Normal	149.95	.109	1.13	.228	2.47	.337	3.59	.165	1.79	.019	.203	.030	.323	1.401	15.17
6.0	Heavy	197.56	.117	1.21	.223	2.37	.340	3.58	.172	1.87	.021	.225	.022	.234	1.405	14.95
							November 1928									
4.9	Normal	31.6	.059	.45	.316	2.43	.375	2.88	*		.031	.239	*		*	
4.9	Heavy	96.9	.026	.26	.262	2.49	.288	2.75			.032	.303				
6.0	Normal	215.5	.035	.36	.273	2.80	.308	3.16			.023	.231				
6.0	Heavy	252.6	.044	.51	.222	2.62	.266	3.13			.036	.423				
							May 1929									
4.9	Normal	110.5	.033	.37	.207	2.31	.240	2.68	.116	1.51	.018	.204	*		.822	9.39
4.9	Heavy	168.5	.010	.11	.231	2.75	.241	2.86	.107	1.66	.031	.364			.801	9.50
6.0	Normal	337.2	.041	.51	.195	2.46	.236	2.97	.114	1.80	.022	.273			.873	10.81
6.0	Heavy	408.2	.051	.66	.191	2.53	.241	3.19	.120	1.90	.030	.392			.933	12.31

* Not estimated.

TABLE NO. 23

Carbohydrate Composition of Beets.

Soil Reaction pH	Phos. Treat- ment	Part of Plant	% Dry Matter	% Reducing Substances Based On		% Sucrose By Difference Based On		% Total Sugars Based On		% Acid Hydro- lyzable Substances Based On		% Starch Based On		% Total Carbohydrates Based On	
				Fresh Wt.	Dry Wt.	Fresh Wt.	Dry Wt.	Fresh Wt.	Dry Wt.	Fresh Wt.	Dry Wt.	Fresh	Dry	Fresh Wt.	Dry Wt.
							November 1928								
4.9	Normal	Tops	11.06	.207	1.87	.558	5.05	.765	6.92	1.45	13.11	.209	1.88	2.22	20.03
4.9	Heavy	Tops	10.26	.250	2.44	.580	5.65	.830	8.09	1.05	10.19	.170	1.66	1.88	18.28
6.0	Normal	Tops	9.47	.207	2.18	.503	5.43	.71	7.61	1.07	11.25	.142	1.50	1.78	18.86
6.0	Heavy	Tops	8.88	.255	2.88	.455	5.12	.71	8.00	1.21	13.63	.141	1.58	1.92	21.63
4.9	Normal	Roots	17.5	.147	.87	4.79	27.25	4.94	28.12	2.36	13.49	.295	1.68	7.30	41.61
4.9	Heavy	Roots	13.8	.209	1.52	5.94	43.02	6.15	44.54	1.90	13.74	.203	1.48	8.05	58.28
6.0	Normal	Roots	12.4	.140	1.13	4.25	42.06	5.38	43.39	1.49	12.02	.140	1.12	6.87	55.41
6.0	Heavy	Roots	13.43	.118	.88	5.51	42.01	6.39	47.52	1.72	12.81	.147	1.13	8.11	60.33
							June 1929								
4.9	Normal	Tops	9.54	.195	2.04	.110	1.15	.305	3.19	.775	8.12			1.08	11.31
4.9	Heavy	Tops	9.53	.175	1.84	.105	1.10	.280	2.95	.740	7.76			1.02	10.71
6.0	Normal	Tops	8.85	.136	1.53	.064	.72	.200	2.25	.685	7.74			.89	9.99
6.0	Heavy	Tops	8.93	.177	1.96	.098	1.09	.275	3.25	.695	7.77			.97	11.02
4.9	Normal	Roots	13.28	.103	.77	5.15	38.84	5.25	39.61	1.46	10.92			6.71	51.53
4.9	Heavy	Roots	10.99	.103	.93	4.51	41.02	4.61	41.95	1.19	10.81			5.80	52.76
6.0	Normal	Roots	10.07	.143	1.42	4.26	42.27	4.40	43.69	1.05	10.36			5.45	54.05
6.0	Heavy	Roots	10.24	.105	1.03	4.50	44.06	4.60	45.09	.93	9.06			5.53	54.15

TABLE NO. 24

Nitrogen, Phosphorus, Calcium, and Ash Content of Beet Plants.

Soil Reaction pH	Phos. Treat-ment	Part of Plant	Av.Gm. Gr.Wt. Per Plant	% Sol. N Based On		% Insol.N Based On		% Total N Based On		% Phos. Based On		% CaO Based On		% Ash Based On	
				Fresh Wt.	Dry Wt.	Fresh Wt.	Dry Wt.	Fresh Wt.	Dry Wt.	Fresh Wt.	Dry Wt.	Fresh Wt.	Dry Wt.	Fresh Wt.	Dry Wt.
					November 1928										
4.9	Normal	Tops	13.9	.093	.84	.349	3.15	.442	3.99	.0355	.33			2.367	22.12
4.9	Heavy	Tops	32.4	.082	.79	.299	2.92	.381	3.71	.0371	.35			2.214	21.57
6.0	Normal	Tops	80.6	.088	.93	.294	3.10	.382	4.03	.0296	.33			2.003	22.44
6.0	Heavy	Tops	72.4	.074	.84	.237	2.67	.311	3.51	.0289	.31			2.049	22.56
4.9	Normal	Roots	9.2	.164	.95	.272	1.55	.436	2.50	.0513	.31				
4.9	Heavy	Roots	25.6	.198	1.43	.113	.82	.311	2.25	.0417	.31				
6.0	Normal	Roots	112.9	.211	1.70	.108	.87	.319	2.57	.0411	.31				
6.0	Heavy	Roots	112.9	.171	1.27	.107	.80	.278	2.07	.0415	.30				
					July 1929										
4.9	Normal	Tops	37.3	.096	1.01	.338	3.54	.434	4.55	.036	.39	.170	1.86	2.34	25.64
4.9	Heavy	Tops	66.3	.057	.70	.342	3.50	.399	4.20	.033	.36	.211	2.34	2.24	24.63
6.0	Normal	Tops	174.1	.050	.54	.315	3.58	.365	4.12	.051	.57	.214	2.41	2.04	23.05
6.0	Heavy	Tops	130.9	.040	.45	.31	3.47	.50	3.92	.044	.54	.228	2.74	2.04	24.46
4.9	Normal	Roots	19.8	.189	1.40	.157	1.19	.346	2.59	.052	.41				
4.9	Heavy	Roots	65.3	.149	1.35	.111	1.01	.259	2.35	.049	.43				
6.0	Normal	Roots	153.5	.128	1.27	.092	.915	.220	2.19	.050	.50				
6.0	Heavy	Roots	148.5	.151	1.48	.074	.715	.224	2.19	.065	.65				

TABLE NO. 25

Carbohydrate Composition of Carrots.

Soil Reaction pH	Treat-ment	Part of Plant	% Dry Matter	% Reducing Substances Based On		% Sucrose By Difference Based On		% Total Sugars Based On		% Acid Hydro-lyzable Substances Based On		% Total Carbohydrates Based On	
				Fresh Wt.	Dry Wt.	Fresh Wt.	Dry Wt.	Fresh Wt.	Dry Wt.	Fresh Wt.	Dry Wt.	Fresh Wt.	Dry Wt.
Spring Crop 1928													
4.9	Normal	Tops	16.15	.25	1.52	.63	4.51	.98	6.03	2.27	14.07	3.35	20.10
4.9	Heavy	Tops	17.39	.27	1.54	.88	5.02	1.15	6.56	2.38	13.66	3.53	20.22
6.0	Normal	Tops	17.10	.53	3.07	1.03	6.01	1.56	9.08	2.48	14.50	4.04	23.58
6.0	Heavy	Tops	17.02	.41	2.38	.87	5.11	1.28	7.49	2.45	14.39	3.73	21.88
4.9	Normal	Roots	11.21	2.16	19.26	2.65	22.75	4.71	42.01	1.28	11.38	5.99	53.39
4.9	Heavy	Roots	12.19	2.12	16.60	2.77	22.66	4.79	39.26	1.45	11.90	6.24	51.16
6.0	Normal	Roots	11.06	2.00	18.00	2.94	26.67	4.94	44.67	1.45	13.00	6.39	57.67
6.0	Heavy	Roots	11.62	1.97	16.93	2.97	25.06	4.94	41.99	1.57	13.48	6.51	55.47
Fall Crop 1928													
5.0	Normal	Tops	18.73	.33	1.78	1.45	7.63	1.78	9.41	2.70	14.12	4.48	23.53
5.0	Heavy	Tops	18.12	.37	2.08	1.33	7.28	1.70	9.36	2.66	14.66	4.36	24.02
6.0	Normal	Tops	17.78	.57	3.23	1.49	8.38	2.06	11.62	2.72	15.26	4.78	26.88
6.0	Heavy	Tops	17.32	.40	2.31	1.57	9.21	1.99	11.52	2.30	13.30	4.29	24.82
5.0	Normal	Roots	13.00	2.25	17.36	3.43	26.35	5.68	43.71	1.84	14.16	7.52	57.87
5.0	Heavy	Roots	11.55	2.28	19.78	3.18	27.56	5.46	47.34	1.71	14.79	7.17	62.13
6.0	Normal	Roots	12.01	1.76	14.65	4.08	33.98	5.84	48.63	1.95	16.71	7.79	65.34
6.0	Heavy	Roots	12.61	2.05	16.31	3.00	23.79	5.06	40.10	1.61	12.80	6.67	52.90

TABLE NO. 26

Nitrogen, Phosphorus, Calcium, and Ash Content of Carrot Plants.

Soil Reaction pH	Phos. Treat-ment	Part of Plant	Av.Gm. Gr.Wt. Per Plant	% Sol. N Based On		% Insol.N Based On		% Total N Based On		% Phos. Based On		% CaO Based On		% Ash Based On	
				Fresh Wt.	Dry Wt.	Fresh Wt.	Dry Wt.	Fresh Wt.	Dry Wt.	Fresh Wt.	Dry Wt.	Fresh Wt.	Dry Wt.	Fresh Wt.	Dry Wt.
						June	1928								
5.0	Normal	Tops	9.8	.09	.52	.47	2.93	.56	3.45	.041	.261	.421	2.62	2.49	15.17
5.0	Heavy	Tops	26.9	.07	.33	.51	2.93	.58	3.26	.040	.225	.501	2.98	2.50	14.88
6.0	Normal	Tops	35.8	.10	.59	.43	2.52	.53	3.11	.038	.215	.553	3.23	2.78	16.26
6.0	Heavy	Tops	39.7	.06	.34	.46	2.69	.52	3.03	.046	.226	.564	3.44	2.57	15.55
5.0	Normal	Roots	10.6	.06	.54	.17	1.52	.23	2.06	.041	.365				
5.0	Heavy	Roots	30.3	.06	.60	.17	1.39	.24	1.99	.049	.403				
6.0	Normal	Roots	55.0	.06	.57	.16	1.40	.22	1.97	.050	.448				
6.0	Heavy	Roots	66.4	.06	.47	.18	1.51	.24	1.98	.053	.455				
						November	1928								
5.0	Normal	Tops	6.7	.061	.75	.495	2.64	.553	3.39	.045	.225	.406	2.14	2.63	13.98
5.0	Heavy	Tops	10.3	.058	.35	.492	2.68	.550	3.03	.050	.265	.439	2.33	2.69	14.24
6.0	Normal	Tops	23.6	.045	.25	.493	2.80	.543	3.05	.039	.215	.451	2.42	2.62	14.08
6.0	Heavy	Tops	23.9	.047	.30	.504	2.88	.551	3.18	.063	.335	.446	2.37	2.71	14.44
5.0	Normal	Roots	17.1	.062	.445	.099	.785	.161	1.23	.029	.225				
5.0	Heavy	Roots	25.2	.044	.382	.090	.778	.134	1.16	.030	.255				
6.0	Normal	Roots	59.9	.058	.482	.108	.902	.166	1.38	.036	.305				
6.0	Heavy	Roots	59.5	.073	.568	.103	.812	.176	1.38	.035	.320				

in carbohydrate and nitrogen composition but they were not evident in the plants as sampled.

The failure of the slow growing plants in the strongly acid soils to show a relatively large accumulation of soluble nitrogen may have been due to interference with nitrogen absorption by the injured condition of the roots. This, however, does not account for the relatively small differences in the carbohydrate content. A relatively greater accumulation of sugars would be expected in the leaf tissues of the slow growing plants, since they are utilized more slowly in protein synthesis than by the more rapidly growing specimens.

The only consistent effect of soil reaction on carbohydrate composition was found in the lettuce tissues. Leaves of lettuce plants grown in the more acid soils (pH 4.9) contained a higher percentage of reducing substances, starch, and total carbohydrates than those produced at a reaction of pH 6.0. It is possible that more consistent differences would have been apparent in beet and carrot tissues if samples had been obtained during earlier periods of growth.

Slow growth was generally correlated with a high percentage of dry matter in the beet, lettuce and carrot tissues.

Relation of Soil Reaction and Phosphorus Treatments to Phosphorus Content of Lettuce, Beet, and Carrot Plants

The results of phosphorus determinations on mature lettuce, beet, and carrot plants grown at pH 4.9 to pH 5.0 and pH 6.0 in field plats are given in Tables 22, 24, and 26. The phosphorus content of younger plants grown in pots in the greenhouse are shown in Tables 27 and 28.

TABLE NO. 27

Effect of Soil Reaction and of Phosphorus Deficiency on Phosphorus Content of Plants Grown in Pots in Greenhouse.

Soil Reaction pH	Soil	Fertilizer Treatment N. P. K.	Crop	Age of Plants (Days)	Av. Wt. of Plant Based on Fresh Wt.	Av. Wt. of Plant Based on Dry Wt.	% Phosphorus In Leaf Tissue Based on Fresh Wt.	% Phosphorus In Leaf Tissue Based on Dry Wt.	Percentage Difference in P Content of Pairs Dry Weight Basis
6.0	No.1*	7-0-5	Lettuce	42	1.32	.099	.0157	.2084	
6.0	1	7-8-5	"	42	2.44	.142	.0225	.3864	85.4
4.8	2**	7-8-5	"	42	.90	.080	.0221	.2516	
6.0	2	7-8-5	"	42	1.80	.124	.0268	.3896	54.7
6.0	1	7-0-5	"	60	5.5	.333	.0153	.2119	
6.0	1	7-8-5	"	60	10.32	.649	.0264	.3271	54.4
4.8	2	7-8-5	"	60	.62	.057	.0294	.3172	
6.0	2	7-8-5	"	60	9.82	.647	.0291	.4392	38.4
6.0	1	7-0-5	Beets	42	3.38	.245	.0153	.2119	
6.0	1	7-8-5	"	42	7.38	.588	.0264	.3271	54.4
4.8	2	7-8-5	"	42	.74	.068	.0212	.2732	
6.0	2	7-8-5	"	42	3.07	.228	.0318	.4298	57.3
6.0	1	7-0-5	"	60	9.03	.631	.0216	.3064	
6.0	1	7-8-5	"	60	11.11	.777	.0320	.4548	48.4
4.8	2	7-8-5	"	60	3.3	.264	.0213	.2732	
6.0	2	7-8-5	"	60	8.75	.665	.0318	.4298	57.3
6.0	1	7-0-5	Carrots	60	1.71	.155	.0342	.377	
6.0	1	7-8-5	"	60	2.37	.246	.0373	.359	4.7
4.8	2	7-8-5	"	60	1.63	.191	.0353	.300	
[illegible]	[illegible]	[illegible]	[illegible]	60	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

LETTUCE

The results of the phosphorus estimations of lettuce leaves was quite consistent in the samples collected during the three seasons of the field experiments. In most cases the plants from the more acid soils where growth was relatively slow, gave the lowest percentages of phosphorus. Heavy applications of superphosphate increased the phosphorus content not only in the plants grown at pH 4.9 to pH 5.0 but also in those produced under optimum conditions. The use of large amounts of phosphorus increased the phosphorus content of the plants grown at pH 4.9 to pH 5.0 to exceed that found in the tissues produced at pH 6.0 with normal phosphorus treatment. Increases in phosphorus content were correlated in all cases with an increase in plant yield (Table 22).

A new series of experiments were conducted in the greenhouse during the fall and winter of 1930-1931 to compare the effects of phosphorus deficiency on the phosphorus contents of plants grown in phosphorus deficient soils and in strongly acid soils treated with one ton of 7-8-5 fertilizer per acre. The phosphorus deficient Sassafras loam soil contained less than 25 pounds of available phosphorus per acre according to the Truog test (85). Treatments were made with 7-8-5 and 7-0-5 NH_3-P_2O_5-K_2O fertilizer. The results of the phosphorus estimations on plants 42 days and 60 days after germination are given in Table 27. In all cases the plants grown in soil No. 1 without additional phosphorus treatment, and those with phosphorus applications in soils at pH 4.8, gave a relatively poor yield and had a low phosphorus content. The composition of the plants in soil No. 1 with a 7-0-5 fertilizer was similar to that of the plants in the strongly acid soils treated with normal amounts of phosphorus. The content in the younger plants grown at pH 6.0 is higher than that of the older plants at the same reaction in the field plats (Table 22). Other workers

TABLE NO. 28

Relative Effects of Phosphorus Applications on Phosphorus Content of Plants During Early Period of Growth. Plants Grown in Pots in Greenhouse.

Soil Reaction pH	Lbs. Super-phosphate per Acre	Crop	Age of Plants (Days)	Av. Wt. of Plant Based on		% Phosphorus In Leaf Tissue Dry Wt. Basis	Percentage Increase By Heavy Appl. Phosphorus
				Fresh Wt.	Dry Wt.		
4.8	1,000	Lettuce	60	.62	.06	.317	
4.8	9,000	"	"	6.08	.42	.531	67.3
5.1	1,000	"	"	6.04	.44	.290	
5.1	9,000	"	"	8.75	.53	.664	121.7
6.0	1,000	"	"	9.83	.65	.439	
4.8	1,000	Beets	"	3.30	.26	.418	
4.8	9,000	"	"	8.53	.68	.988	136.3
5.1	1,000	"	"	6.70	.55	.542	
5.1	9,000	"	"	6.10	.53	1.353	148.3
6.0	1,000	"	"	8.75	.67	.676	
4.8	1,000	Carrots	"	1.63	.19	.300	
4.8	9,000	"	"	3.43	.34	.469	56.8
5.1	1,000	"	"	3.04	.35	.295	
5.1	9,000	"	"	4.31	.50	.422	43.0

TABLE NO. 29

Phosphorus Content of Soil Extracts.

Soil Reaction pH	Normal Phos. Treatment: No. of Estimations Made	Normal Phos. Treatment: P.P.M.Phos. in 1-200 Water Extract	Heavy Phos. Treatment: No. of Estimations Made	Heavy Phos. Treatment: P.P.M.Phos. in 1-200 Water Extract	Increase by Heavy Appl. Phos.: P.P.M.Phos. in 1-200 Water Extract	Increase by Heavy Appl. Phos.: Lbs. Per Acre
4.9-5.0	20	.126	4	.209	.083	33.2
5.5-5.7	4	.199	4	.336	.137	54.8
5.9-6.0	21	.207	4	.275	.068	27.2
6.5-6.6	21	.255	4	.380	.125	50.
7.0	17	.220	4	.351	.131	52.4
		P.P.M.Phos. in 1-200 .002 N.Sulphuric Acid Extract		P.P.M.Phos. in 1-200 .002 N.Sulphuric Acid Extract	P.P.M.Phos. in 1-200 .002 N.Sulphuric Acid Extract	Lbs. Per Acre
4.8-5.0	2	.60	2	.86	.20	80.
5.1-5.3	2	.65	2	.88	.23	92.
5.9-6.0	2	.86	2	1.49	.63	252.
6.5-6.6	2	.96	2	2.03	1.07	428.
7.0	2	.96	2	1.63	.67	268.

(22) and (26) have shown that phosphorus content of plants is usually highest during the early periods of growth.

The relative effects of heavy and of normal applications of superphosphate on the phosphorus composition of lettuce plants grown in the greenhouse is shown in Table 28. The increases were 67.3 per cent at pH 4.8 and 121.7 per cent at pH 5.1. The yields of the heavily treated plants on the very acid soils compared favorably with those grown at pH 6.0.

BEETS

The results of analyses of mature beet foliage and roots (Table 24) show that in 1929 the phosphorus content was higher in the plants grown at pH 6.0, and in 1928 the soil reaction had no effect on the phosphorus composition. These conflicting results were probably due to the age of the plants. In the greenhouse experiments with plants 42 and 60 days old the results were similar to those obtained with lettuce (Table 27). The plants grown in soils at pH 4.8 with 7-8-5 fertilizer treatment showed a phosphorus content about equal to that of the plants in the phosphorus deficient soils without additional phosphorus fertilization. Phosphorus treatment on soil No. 1, and liming the acid soil No. 2 produced similar increases in the phosphorus content of the plants. The additions of very large amounts of superphosphate (Table 28) resulted in greatly increased growth, a reduction of root injury, and a higher phosphorus content of the foliage.

CARROTS

The phosphorus content was lowest in the roots of the mature plants grown in the strongly acid soils of the field plats (Table 26). Analysis of the foliage failed to give consistent results. The data in

Table 27 indicate that an analysis of carrot tissue does not indicate phosphorus deficiency as well as analysis of lettuce and beets. Phosphorus treatment in soil No. 1 greatly increased the yield but had little effect on percentage composition. The same is true of the effect of differences in soil reaction. Very heavy applications of phosphorus (9000 pounds per acre), however, resulted in increases of 56 per cent at pH 4.8 and 43 per cent at pH 5.1.

The results of the analysis of tissues of beets and lettuce particularly from plants during the earlier periods of growth, indicate that phosphorus deficiency may have been partly responsible for retardation of growth in the more acid soils. The fact that the phosphorus content of the plants grown in the soils at pH 4.8 to pH 4.9 fertilized with normal amounts of phosphorus was similar to that of the tissues produced in soils known to be deficient in available phosphorus, furnishes additional evidence in the support of this theory. The decreased absorption of this material by normally phosphated plants grown in very acid soils may have been due both to injury to the absorptive surface of the roots and to a deficiency of available phosphorus in the soil.

Soil samples obtained from the plats of different reaction values in the autumn of 1930 were analyzed for water soluble and for available phosphorus by the Truog (85) method.

Estimations of phosphorus in soil extracts with distilled water and also with .002 normal sulphuric acid (Table 29) indicate that there was less soluble phosphorus in the more acid soils. In all cases the addition of large amounts of superphosphate to the soils resulted in a considerable increase in the soluble phosphorus content of the extract. The heavily phosphated soils at reactions of pH 4.9 to pH 5.0 contained practically the same amounts as the normally treated soils at pH 6.0.

There appears to be a lack of agreement among investigators (3) regarding the effect of soil acidity on the availability of phosphorus, but in general it has been found (67) that liming increases the phosphorus content of the soil solution. Although the data present in Table 29 may not show the absolute amounts available for absorption by the plants they at least indicate the relative amounts present in solution. An increase in the water soluble or the "available" phosphorus content was in all cases associated with a reduction in the amount of root injury and an increase in root and top growth.

It is probable that the high concentration of phosphorus ions reduced aluminum toxicity by precipitating the soluble aluminum compounds as phosphates (53) and thereby increased the absorbing area of the roots.

Relation of Soil Reaction and Phosphorus Treatments to Calcium Content

The effect of soil reaction and phosphorus treatment on the calcium oxide content of beets, carrots and lettuce is shown in Tables 22, 24 and 26. In all cases the percentage of calcium oxide on the dry weight basis was lowest in the plants grown in the more acid soils. The percentage in lettuce leaves from plants grown at pH 4.9 in May 1928 was 1.32 as compared with 1.79 at pH 6.0, or an increase of 35.7% at the higher reaction. In May 1929 the percentages were 1.51 and 1.80 for the leaves of the plants grown at pH 4.9 and pH 6.0 respectively. Heavy applications of phosphorus resulted in an increase of the calcium content at both reactions.

The calcium content of beet tissues was determined only in the samples of foliage collected in July 1929. The effect of the soil reaction on the calcium content was similar to that found in the lettuce leaves. The foliage grown at pH 4.9 contained 1.86% compared with 2.41% at pH 6.0.

The effect of heavy applications of phosphorus on the calcium content at pH 4.9 was more pronounced than with the lettuce tissue at a similar reaction. It was increased from 1.86% to 2.34% which was very nearly equal to that of the leaves grown at pH 6.0 (2.41%). Heavy applications of superphosphate also resulted in a considerable increase at pH 6.0.

Estimations on carrots showed a consistently lower calcium content in the foliage of the plants grown in the more acid soils as compared with that at pH 6.0 but the differences were less than in the lettuce and the beet tissues. Heavy applications of phosphorus resulted in an increase from 2.62% to 2.98% at pH 4.9 in June 1928, and from 2.14% to 2.33% in November 1928. At pH 6.0 the phosphorus treatment had practically no effect on the calcium content.

The consistently lower calcium content of the leaves of beets, lettuce, and carrots grown in the more acid soils indicates that interference with calcium metabolism may have been one of the factors responsible for slow growth. The calcium content of the plant was apparently not due to a deficiency of calcium in the soil but to the inability of the roots to absorb that already present. Previous to the beginning of the experiment this area had been used for general truck crop production and was fertilized with at least 1000 pounds of superphosphate annually. During the experimental period the normally fertilized plats received this amount semi-annually. It is apparent that the soil had been abundantly supplied with calcium since superphosphate contains 50% calcium sulphate. Pierre (68) working with several types of acid soils found no correlation between the calcium content of the soil solution and retardation in growth of acid sensitive crops.

Additions of large amounts of superphosphate reduced root injury and increased the calcium metabolism. This indicates that interference with calcium absorption in the very acid soils was partly due to the injured condition of the root tissues. Since heavy phosphorus treatments increased the calcium content of plants grown at an optimum reaction, it is apparent that phosphorus affected also the absorption of calcium. Crist (19) found that phosphorus increased the absorption of calcium by lettuce plants. Other workers (11) and (36) have also noted that the effect of one ion on the absorption of another.

There is also a possibility that the H-ion concentration of soil may have affected the ability of the plant to absorb calcium as reported by Bryan (14). Greatly retarded calcium metabolism may also have been one of the causes of retarded root growth. Sorokin and Sommer (80) found that absence of calcium in the meristematic cells adversely affected mitotic division.

GENERAL DISCUSSION AND CONCLUSIONS

The data obtained in investigations extending over four seasons indicate that there is a close inter-relation between soil reaction and growth of lettuce, beets, carrots, and snap beans. The "critical" reaction at which definite root injury occurred and growth was markedly affected was fairly definite for each of the crops studied. Variations which occurred in the reaction values for optimum growth in the different seasons are generally attributable to the effects of normal meteorlogical fluctuations.

Of the four crops studied, beets and lettuce were the more sensitive to acid soil conditions. Foliage growth was considerably retarded in soils more acid than pH 5.4 and the roots were slightly discolored and thickened. In soils as acid as pH 5.0, top growth was badly stunted and the roots were so severely injured that many plants died in the seedling stage. Carrots proved tolerant of acid soil conditions above pH 5.2 but suffered severe root injury and marked retardation in growth at lower reactions. Snap beans were only slightly affected by strongly acid soil conditions. No root injury was noted even in soils as acid as pH 4.9 and yields were not markedly reduced. This crop, however, proved to be the least tolerant of conditions existing in soils which had been maintained in a neutral or alkaline condition for a considerable time. The plants were slightly yellowed by chlorosis at pH 6.5 and pH 7.0 to pH 7.2 reactions gave particularly severe injury. The chlorotic plants generally produced only a relatively small yield of beans, and in some cases the crop was a total failure. Nearly neutral soils were also unfavorable for the optimum development of lettuce and carrots. Lettuce plants became chlorotic at pH 6.9 to pH 7.1 and carrot roots made relatively slow growth.

Heavy applications of superphosphate greatly reduced root injury and markedly stimulated foliage growth of beets, lettuce, and carrots in the more acid soils, and increased the yield of lettuce and snap beans throughout the entire reaction range.

The results of these studies indicate that the soil conditions associated with the various reactions and not the H-ion concentration itself were to a large extent the direct cause of the different growth relations. Marked retardation in the growth of beets, lettuce, and carrots in the more acid soils was always associated with severe root injury which is attributable to the presence of toxic materials. A number of investigators (8) (17) and (53) working with acid soils of the Atlantic Coastal Plains area have furnished rather convincing evidence that soluble aluminum is the direct cause of severe root injury to these crops. They attribute the beneficial effect of heavy applications of superphosphate to the precipitation of the soluble aluminum salts as phosphates.

Chemical analysis of beet and lettuce tissues indicate that phosphorus and calcium deficiencies may also have been contributing factors in the retarded development of these crops in strongly acid soils. Increases in growth resulting from a reduction in acidity or from heavy applications of superphosphate were associated with marked increases in the calcium and the phosphorus content of the leaf tissues.

It is probable that the higher concentrations of soluble phosphorus in the heavily phosphate treated soils reduced aluminum toxicity by precipitating the soluble aluminum compounds, and also increased the permeability of the absorbing membranes to phosphorus and calcium. The H-ion concentrations of the soil solution may also have influenced the absorption of these nutrients. Other investigators (14) (37) and (65) have noted that the absorption of essential ions is affected by the

the reaction of the nutrient medium.

It is improbable, however, that the effect of H-ion concentration on the absorption of nutrients was responsible for the chlorotic condition of the bean and the lettuce plants grown in neutral or slightly alkaline soils. The fact that chlorosis did not appear on lettuce and bean plants grown at reactions of pH 7.0 to pH 7.2 until 18 months after the soil had been brought to this reaction by heavy liming, indicates that it was due to a deficiency of some element which was gradually rendered insoluble under alkaline conditions. Other workers (25) (26) (27) (28) (79) (91) have attributed chlorosis to a deficiency of iron, manganese, or magnesium. Chemical analysis of chlorotic bean plants indicated a possible deficiency of both manganese and magnesium. A chlorotic condition in beans was associated with a marked interference with photosynthetic activity and carbohydrate metabolism. The yellowed tissues were characterized by a very low content of reducing sugars, sucrose, starch, total carbohydrates, and dry matter, and a high percentage of soluble nitrogen as compared with that of normal foliage. Gilbert, McLean and Adams (26) reported a relatively high soluble nitrogen content in chlorotic beet and spinach tissues.

Estimations of the carbohydrate and nitrogen content of the beet, lettuce, and carrot plants failed to show relationships which are indicative of phosphorus deficiency. Interference with nitrogen metabolism because of the injured condition of the absorbing surfaces of the roots may have been partly responsible for this lack of correlation.

Numerous observations of these crops grown commercially in soils of various degrees of acidity, indicate that the optimum ranges reported in this paper are applicable to most of the mineral soils of the Atlantic

Coastal Plains Province of Virginia. These are also in general agreement with the results of investigations reported by New Jersey (7) and Rhode Island (17) workers. They, however, may not be applicable to soils of high organic content (19) (30) or mineral soils of a distinctly different geological origin.

PRACTICAL RECOMMENDATIONS

The yield data given in the tables in the first part of this paper indicate the practical importance of maintaining the soil reaction within the ranges of optimum growth. Both the yield and the quality of the product were greatly reduced by too acid or too alkaline soil conditions. High quality was directly correlated with rapid growth and high yield in the crops studied. The crops produced in the soils beyond the limits of the optimum reaction range were usually unmarketable. The range of optimum growth for beets was pH 5.8 to pH 7.1; for lettuce pH 5.7 to pH 6.5; for carrots pH 5.3 to pH 6.0; and for beans pH 5.3 to pH 6.0. A soil reaction of approximately pH 6.0 should prove satisfactory for these and many other vegetable plants (94).

Potatoes, however, should be grown at reactions lower than pH 5.5 to avoid severe injury by scab. These data indicate that beans and carrots may be grown economically in rotation with potatoes in soils maintained at pH 5.3 to pH 5.4 . Beets and lettuce may also be grown successfully at these reactions if large amounts of superphosphate ($2\frac{1}{2}$ to 3 tons per acre) are applied annually, but this practice may not prove economical because of the increased cost of production. Superphosphate is not recommended as a substitute for lime in the culture of beets, lettuce, and carrots in soils more acid than pH 5.2 because its effect on yield and quality were insufficient to be of practical importance. The fact that the use of large amounts of this material generally resulted in marked increases in the yield of lettuce and snap beans over the entire optimum reaction range, indicates its importance as a plant nutrient and the need of further investigations for determining the optimum amount for use in commercial practice.

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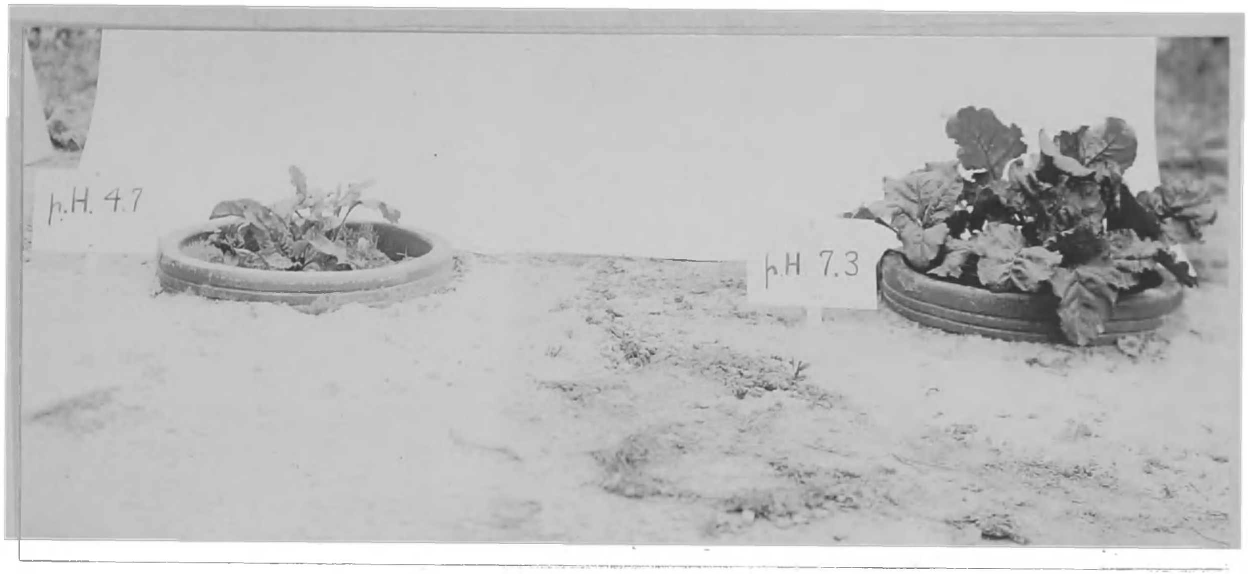
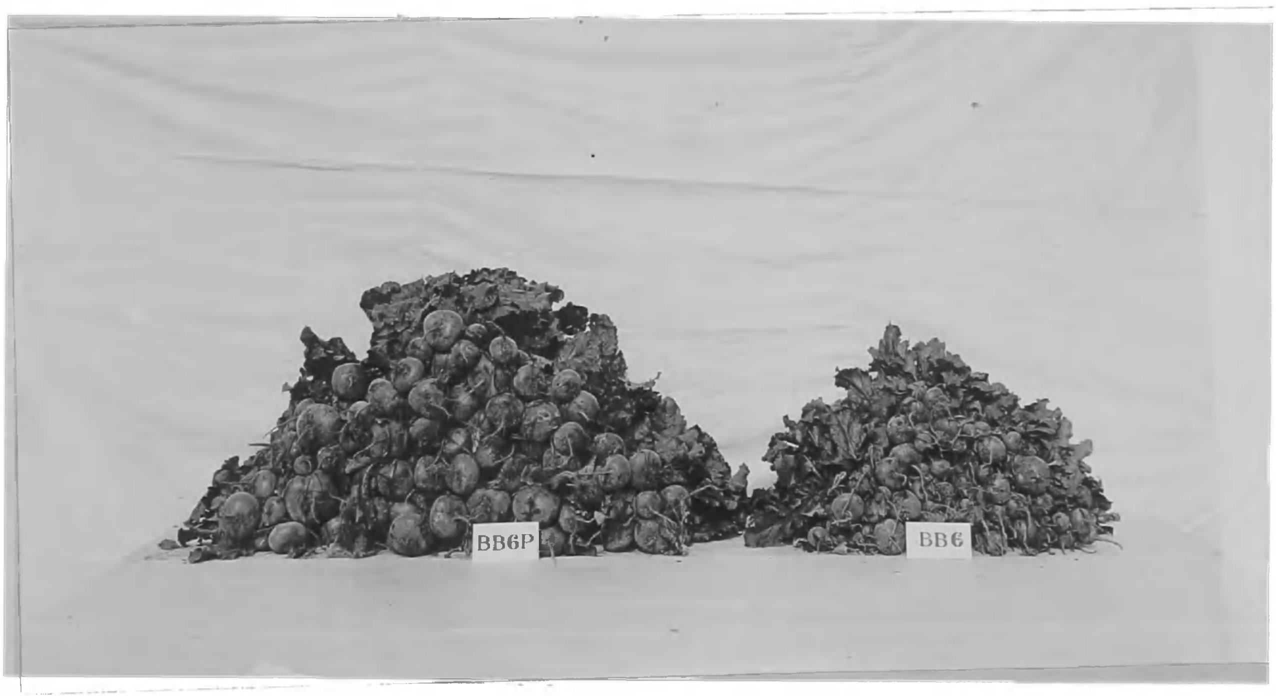


Effect of soil reaction on growth of beets in cylinders.
June 6, 1927.

Effect of soil reaction and phosphorus treatment on yield of beets.
P denotes heavy phosphorus treatment.

Effect of soil reaction on yield of beets.
Plat BB2 - pH 6.0
" B6 - pH 4.9



Effect of phosphorus treatment on beets grown at pH 4.9
BB6P - Heavy phosphorus treatment.
BB6 - Normal phosphorus treatment.

Comparative yields of lettuce at pH 6. (BB2) and pH 5. (B6)
Spring crop 1929.

Effect of soil reaction and phosphorus treatment on yield of lettuce. Fall crop 1928.

BB7 - pH 6.5
BB6 - pH 4.9
P indicates heavy phosphorus treatment.

Effect of phosphorus on growth of lettuce at pH 5.3
Heavy phosphorus treatment on left.
Normal phosphorus treatment on right.

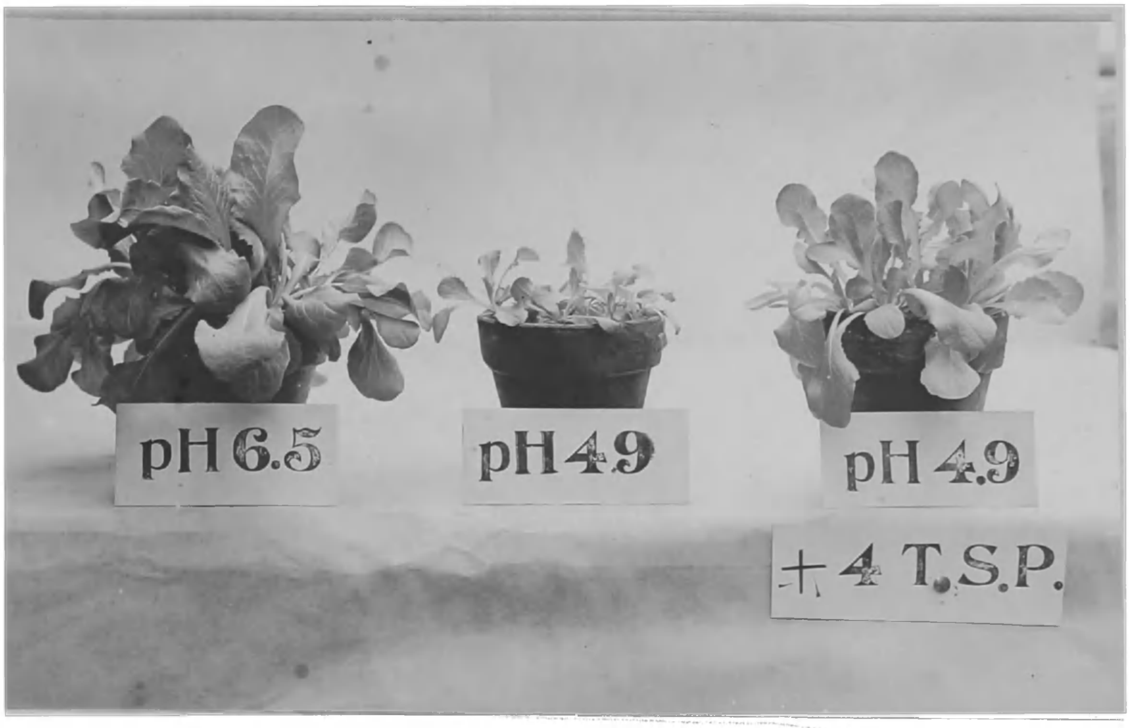
Effect of phosphorus in growth of lettuce at pH 5.1
Heavy phosphorus on left.
Normal phosphorus on right.

Effect of soil reaction and phosphorus treatment on yield of carrots.
A6, B6 - pH 4.9
A2 - pH 6.0
P denotes heavy phosphorus treatment.

Lettuce plants grown at pH 4.9 and 6.0.

Poor growth of beets, lettuce and carrots on left (pH 5.) and good growth on right (pH 6.).

Good growth of beets in left foreground (pH 6.0) and poor growth on right (pH 5.0).



Lettuce

Beets

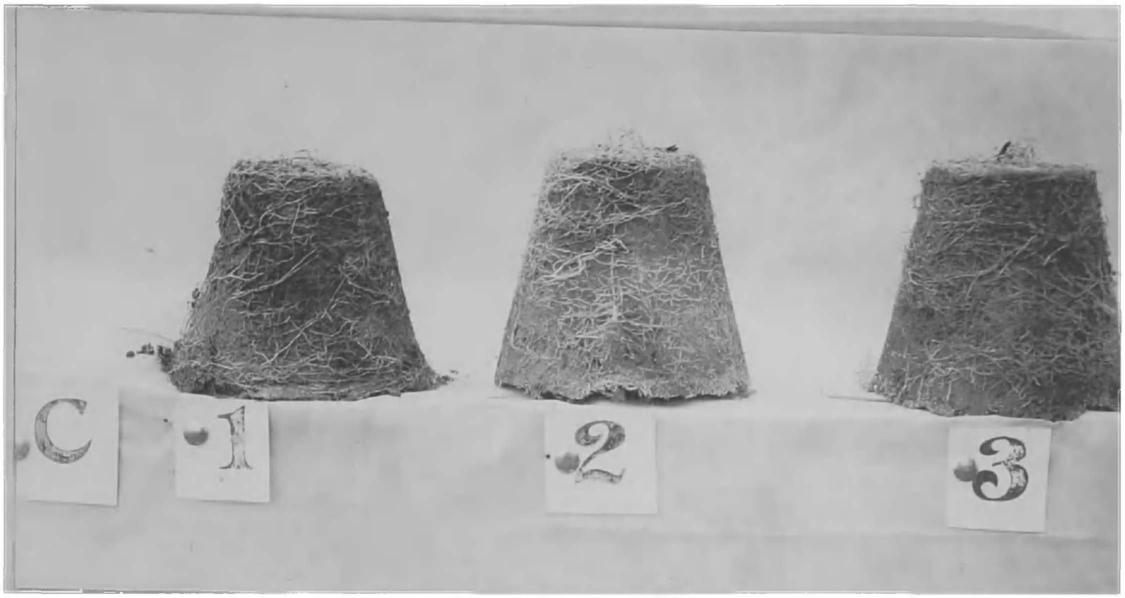
Plants 60 days old used for phosphorus analyses (Table 28).
Left to right:
pH 6.5 with normal phosphorus fertilization.
pH 4.9 with normal phosphorus fertilization.
pH 4.9 with 4 tons superphosphate per acre.

Beets

Lettuce

Plants 42 days old grown in greenhouse, used for phosphorus analyses (Table 27).

(1) pH 4.9 with normal phosphorus treatment.
(2) pH 6.0 " " "
(3) Phosphorus deficient soil at pH 6.0 without phosphorus treatment.
(4) Phosphorus deficient soil at pH 6.0 with normal phosphorus treatment.



Effect of soil reaction and phosphorus on growth of roots of plants 60 days old grown in pots. C - carrots. L - lettuce.

(1) pH 4.8 with normal phosphorus treatment.
(2) pH 4.8 with heavy phosphorus treatment.
(3) pH 6.5 with normal phosphorus treatment.