BULLETIN No. 268 JUNE 1949

PHOSPHORUS STUDIES with VEGETABLE CROPS on DIFFERENT SOILS

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First Printing, 3M

PHOSPHORUS STUDIES with VEGETABLE CROPS on DIFFERENT SOILS

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RESULTS of phosphorus studies reported in this bulletin are a part of a larger study dealing with the requirements of important vegetable crops for nitrogen, phosphorus, and potash on representative soils of the State. In its broader aspects, the purpose of the experiment was to obtain data by which vegetables might be classified according to their requirements for and responses to these three major elements. An earlier but brief report has been made on the needs and response of vegetable crops to nitrogen *(45)*.

Experiments were designed to permit classification of important vegetable crops according to their requirements and feeding capacity for and response to phosphorus on soils differing in physical and chemical properties.

REVIEW OF LITERATURE

While the volume of literature on the general subject of phosphorus is large, the literature on the more restricted subject of phosphorus as applied to vegetable crops is less extensive. Review of literature does not reveal any investigation directed primarily at a classification of vegetable crops according to their requirements and feeding capacity for, response to, and general behavior toward phosphorus.

LITERATURE RELATING TO PHOSPHORUS FOR VEGETABLE CROPS

Much work has been done in the several states and by the United States Department of Agriculture on fertilizers for vegetable crops. Most of the investigations were concerned with a limited number of crops, usually grown on one soil type. Results of these studies could not be used to classify vegetables according to their phosphorus requirements and needs. Where systematic studies of phosphorus were made, only a limited number of crops were used.

Lloyd and Strubinger *(22)* working with 25 vegetable crops found only a few crops that gave much response to phosphorus.

Mack *(23)* in his studies on applications of phosphorus, nitrogen, potash, and organic materials obtained greatest response from phosphorus applied to cabbage, tomatoes, and potatoes.

Cooper and Watts *(10)* in a study of fertilizer needs of five crops reported that phosphorus gave largest increases on one soil and increases on a second soil equal to nitrogen.

Zimmerley *(46)* at the Virginia Truck Crop Experiment Station made rather detailed studies of the effect of artificially regulated soil acidity on plant growth and composition of vegetable crops when fertilized with medium and high rates of phosphorus. Greatest response resulted from use of the larger amount of phosphorus with lettuce and beans at all soil reactions and with beets and carrots at reaction below 5.4 pH.

Comin and Bushnell *(9)* in Ohio found that phosphorus gave increases in yields of cabbage, cucumbers, and tomatoes, either when applied alone or used as a supplement to other fertilizers.

Parker *(28)*, working with tomatoes at the Virginia Truck Experiment Station, found that 40 and 80 pounds of P_2O_5 per acre gave significant increases in yields while 100 pounds gave a slight increase in yield over that produced with 80 pounds of P_2O_5. Zimmerley and Brown *(47)* found that potatoes did not give an increase in yield with more than 96 pounds of P_2O_5.

LITERATURE RELATING TO SOIL PHOSPHORUS

It has been pointed out by many investigators that phosphorus constitutes one of the most important elements in soil fertility. Some investigators have stated that conservation of phosphates is the most crucial, most important, and most far-reaching with respect to the Nation's future of any of the conservation problems.

The work of Truog *(40, 41)*, Gile *(16)*, Ford *(15)*, Spurway *(38, 39)*, Scarseth and Tidmore *(35, 36, 37)*, Davis *(11, 12)*, and others has shown the nature of phosphorus retention in soil and the chemical basis for differences in availability of phosphorus on different soils. Ford *(15)* and Plummer *(32)* found that lime reduces the rate of phosphorus fixation into relatively insoluble phosphates, and that the application of lime increased the efficiency of phosphatic fertilizers. Ensminger and Cope *(13)* found that there was some movement of phosphorus into the subsoil on sodium nitrate plots that had been limed. Gile *(16)* reported that the efficiency of superphosphate had a tendency to be highest at a pH 4.5 to 5.0 and lowest in the neighborhood of neutrality with soils that had a depressing effect on phosphorus. Scarseth and Tidmore *(35)* found that the efficiency of phosphorus decreased with the time of contact with the soil. They *(36)* also found that the phosphorus-fixing capacity of soil colloids varied inversely with the silica-sesquioxide ratio of the colloid.

A number of workers have shown that the application of phosphorus to the soil builds up a reserve of this element, which is available to crops in later years. This has been shown by the work of Anderson and others *(3)* with tobacco in Connecticut, by Bryant *(5)* with citrus in Florida, by Hester *(20)* with tomatoes in Virginia and New Jersey, by Chapman *(8)* with citrus fruits in California, by Ware, Brown, and Yates *(44)* with potatoes in Alabama, and by Volk *(43)* with cotton in Alabama.

Literature Dealing with Principles Underlying Phosphorus Absorption, Retention, and Availability

Many investigators *(25, 34, 35, 36, 37)* have shown that phosphorus is retained largely by the clay fraction of the soil, and that the chemical composition and characters of the colloids present determined the amount and nature of fixation and availability of phosphorus. Mattson *(24)* has offered a basic explanation for fixation of phosphorus and other materials in the soil. According to this explanation, phosphorus combines with base materials in the soil, consisting of iron, aluminum, calcium, magnesium, and to a less extent of sodium and potassium. On the other hand, phosphates will replace or be replaced by humates, silicates, and similar acidoid soil constituents.

Several workers *(13, 27, 29, 32, 33, 38)* have shown that the amount and nature of phosphorus fixation in soil is influenced by acidity of the soil and the proportion of bases, consisting of the iron or aluminum on the one hand or of calcium on the other. They also showed that, as acidity of the soil is reduced by liming, the proportion of calcium in the exchange complex is increased. The result is an increase in amount of calcium phosphates formed.

Pierre *(31)*, and Albrecht and Schroeder *(1)* pointed out the higher ratio of iron and aluminum to silica in the colloids of the red and yellow soils of the Southeastern States. This fact is used to explain the relatively low availability of phosphorus in these soils.

GENERAL METHODS AND PROCEDURES

The investigation included laboratory, greenhouse, and field studies, which were started in 1933. Soil properties were studied and plant analyses were made in the laboratory, and limited experiments were carried on in the greenhouse. The principal studies were conducted in field bins.

METHODS USED IN PREPARING AND FILLING FIELD BINS WITH SOIL

The soils were selected to represent wide differences as possible in physical and chemical properties, and to represent the several agricultural regions of the State. Norfolk, Eutaw, and Cecil soils were the three used in the more extensive field-bin studies. The Norfolk was a sandy loam soil of the Coastal Plain Region, the Eutaw a heavy clay soil of the Black Belt Region, and the Cecil a sandy clay soil of the Piedmont Region. Less extensive studies were conducted on a Decatur clay soil of the Tennessee Valley Region, a Hartsells sandy loam soil of the Appalachian Region, an Oktibbeha clay soil of the Black Belt Region, and a Chesterfield sandy loam of the Coastal Plain-Piedmont transition.

The field bins were small field plots separated by concrete walls. The soils in the bins representing the series and types were selected by soil technicians. The soils were brought in and placed in the concrete bins to a depth of 8 inches on a clay subsoil of the Coastal Plain-Piedmont transition. The soils were equally distributed and composited in each bin throughout each complete series.

METHODS OF HANDLING CROPS

In the more extensive field bins composed of the Norfolk, Eutaw, and Cecil soils, there were five sets of bins. The number permitted five vegetable crops each season (spring, summer, and fall) to be grown in succession each year on each soil. Each crop was grown for a period of 2 to 4 years. The crops were rotated from one set of bins to another.

RATES AND METHODS OF APPLYING FERTILIZERS

Rates of phosphorus applications on the Norfolk sandy loam soil consisted of 0, 40, 80, 120, and 160 pounds per acre per year of P_2O_5, whereas the rates used on the Cecil and Eutaw soils were double those applied to the Norfolk soil. One-third of the annual application was added to each of the three successive crops grown. During the first year, two-thirds of an annual application was added during the summer prior to the first crop grown in the fall and one-third added at planting time. The fertilizer was drilled in the rows, and the position of the rows remained approximately the same throughout the experiment. Lime was added as one treatment in conjunction with the high rate of phosphorus.

Phosphorus application rates used on the Decatur soil were the same as those on the Cecil and Eutaw soils, whereas the rates used on the Hartsells soil were the same as those used on the Norfolk sandy loam.

Nitrogen and potash at the rate of 90 pounds of N and 45 pounds of K_2O per acre, were applied to each crop for each rate of phosphorus applied.

RESIDUAL PHOSPHORUS STUDIES

At the end of 9 years, four sets of bins for each of the soils were used in a phosphorus residual study. One-half of the bins received a phosphorus-maintenance application and one-half received no further application of phosphorus. Rates used in the phosphorus-maintenance application during the period of the residual study consisted of one-half of the rates used in the preceding 9-year period. The residual studies extended over a 5-year period.

YIELD RECORDS

Crop yields were taken by harvest periods. Both tops and roots of those crops having enlarged roots or tubers were weighed. In the case of such crops as beans, the weights of both pods and vines were taken. However, the fibrous roots were not weighed.

LABORATORY PROCEDURES

Laboratory studies consisted of physical and chemical determinations of soil properties, of dilute acid-soluble phosphorus in the soil, and of total phosphorus in plant tissue.

Soil texture was studied by the Bouyoucos hydrometer method *(4)*. Some of the data on chemical properties of the soils were supplied by the soils laboratory of the Alabama Agricultural Experiment Station and by the laboratory of the Bureau of Plant Industry, Soils, and Agricultural Engineering, United States Department of Agriculture.

Phosphorus-fixing properties of the principal soils used were determined in the laboratory by measuring the amount of phosphorus fixed by the three soils over a period of 4 weeks. Samples were taken from the zero phosphorus plots. Different amounts of superphosphate at the rates of P_2O_5 used in the principal studies were added and mixed with the soil. Soil moisture was then brought up to levels similar to those of field conditions and maintained. The amounts of dilute acid-soluble phosphorus were determined at the end of 1, 7, and 28 days.

Dilute acid-soluble phosphorus in the soil was determined by Truog's modified method *(42)*. These determinations were made annually.

Total phosphorus in crops was determined by the method of Fiske and Subbarow *(14)* modified to include organic phosphorus.

METHODS OF STATISTICAL ANALYSIS

Analysis of variance, least significant difference between phosphorus rates, coefficient of variation of the experiment and an equation for second degree polynomials were computed for each set of yield data. In a number of comparisons Student's paring method was used in obtaining odds for significance.

In making the analysis of variance on crop yields, the zero rate of phosphorus in all instances has been omitted. Therefore, values for "F", high enough for significance means that differences exist between the several rates of phosphorus applications above the zero rate.

PRESENTATION OF DATA

CHARACTERISTICS OF THE SOILS USED

The textural and chemical nature of the soils used in the principal studies, and their phosphorus-absorbing capacities and phosphorus-fixing properties are given in Tables 1, 2, and 3.

PHYSICAL PROPERTIES. The physical properties of the three

TABLE 1. PHYSICAL PROPERTIES OF PRINCIPAL SOILS USED

Soil Class	Percentages in several textural separates					
	Sand	Silt	Clay: Coarser texture	Clay: Finer texture	Clay: Total	Colloids
	Pct.	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*
Norfolk sandy loam	75.8	13.8	3.6	6.8	10.4	13.2
Eutaw clay	25.2	22.0	3.6	49.2	52.8	58.8
Cecil sandy clay	53.2	15.8	1.4	29.6	31.0	38.8

principal soils used in this study, as determined by the hydrometer method of Bouyoucos *(4)*, are given in Table 1.

The soils are very different from each other in their physical make-up, as shown by their wide differences in percentages of sand, silt, and colloids.

CHEMICAL PROPERTIES OF THE SOILS. The total anion-exchange capacity in terms of P_2O_5, amount of exchangeable phosphorus present, and percentage of phosphorus saturation of the three untreated soils are given in Table 2. The Eutaw soil had a total anion-exchange capacity of about 2.4 times that of the Cecil soil and about 6 times that of the Norfolk soil. While the Eutaw soil had about 50 per cent more exchangeable phosphorus in the untreated soil than the other two soils, this larger amount represented only 4.5 per cent of the anion-exchange capacity of the Eutaw, as compared to 5.8 per cent of the Cecil and 19 per cent of the Norfolk.

TABLE 2. PHOSPHORUS-EXCHANGE CAPACITY OF THE SOIL USED[1]

Soil class	Amount per acre: Anion-exchange-capacity P_2O_5	Amount per acre: Exchangeable P_2O_5	Phosphorus saturation
	Pounds	*Pounds*	*Per Cent*
Norfolk sandy loam	3,477	675	19.0
Eutaw clay	21,514	971	4.5
Cecil sandy clay	9,045	522	5.8

[1] Data from analysis by Bureau of Plant Industry, Soils, and Agricultural Engineering, cooperating with Alabama Agricultural Experiment Station.

PHOSPHORUS FIXATION. A detailed study was made of the apparent fixation of phosphorus by periods for each soil at each rate of phosphorus application.

According to the Truog method, there was present as dilute acid-soluble phosphorus 36 pounds per acre of P_2O_5 in the Norfolk soil where no phosphorus was added. When 40 pounds of

P_2O_5 was added, theoretically there should have been 76 pounds of readily available phosphorus. The Truog method accounted for only 66 pounds at the end of one day. Apparently 10 pounds, or 25 per cent of the amount added, had been fixed within 24 hours. At the end of 7 days, 16 pounds or 40 per cent apparently had been fixed, and, at the end of 28 days, 22 pounds or 55 per cent. Data on phosphorus fixation are given in Table 3.

It is pointed out that at the end of 4 weeks approximately 54 per cent of the phosphorus added to the Norfolk soil at all rates of application of phosphorus had apparently been fixed; about 62 per cent and 70 per cent of that added to the Eutaw and Cecil soils, respectively, had been fixed. In the Cecil soil apparently 48 per cent of the amount added at the 80-pound application rate of P_2O_5 had been fixed within one day, as indicated by the Truog method. The other soils did not indicate as high a phosphorus-fixing capacity in such a short period.

TABLE 3. EFFECTS OF TIME, DIFFERENT SOILS, AND INCREASES IN APPLICATIONS ON FIXATION OF PHOSPHORUS

Amount P_2O_5 applied per acre	Dilute acid-soluble P_2O_5 found and apparent fixation by periods: P_2O_5 per acre 1 day after application			P_2O_5 per acre 7 days after application			P_2O_5 per acre 28 days after application		
	Amount found[1]	Apparent fixation[2]	Percentage fixed[3]	Amount found[1]	Apparent fixation[2]	Percentage fixed[3]	Amount found[1]	Apparent fixation[2]	Percentage fixed[3]
Lb.	*Lb.*	*Lb.*	*Per cent*	*Lb.*	*Lb.*	*Per cent*	*Lb.*	*Lb.*	*Per cent*
Norfolk soil									
0	36	----	----	36	----	----	36	----	----
40	66	10	25	60	16	40	54	22	55
80	92	24	30	82	34	43	74	42	53
120	110	46	38	102	54	45	90	66	55
160	142	54	34	128	68	43	110	86	54
Eutaw soil									
0	30	----	----	20	----	----	20	----	----
80	82	28	35	68	32	40	48	52	65
160	146	44	28	90	90	56	74	106	66
240	216	54	23	144	116	48	110	150	63
320	270	80	25	170	170	53	158	182	57
Cecil soil									
0	26	----	----	28	----	----	24	----	----
80	68	38	48	42	66	83	42	62	78
160	140	46	29	84	104	65	82	102	64
240	174	92	38	122	146	60	96	168	70
320	266	80	25	144	204	64	138	206	64

[1] Amount found by Truog method.
[2] Amount "fixed" according to Truog method.
[3] Percentage "fixed" of that applied.

RELATIVE RESPONSE OF VEGETABLE CROPS TO PHOSPHORUS, NITROGEN, AND POTASH

Since the use of commercial fertilizers began in the South, phosphorus, nitrogen, and potash have been the three principle elements supplied in what has been termed a complete fertilizer. Of the total plant food in a complete fertilizer, phosphorus has made up a larger proportion than either of the other two. This has been true also for the country as a whole.

Indication of the relative importance of the three elements is shown in the comparison of average relative yields of a large number of crops on several soils in the larger experiment, of which the phosphorus studies were a part. The relative yields for each rate of application of phosphorus, nitrogen, and potash are given in percentage of the yield from the maximum application. The total yield in pounds of all vegetables at each rate in a given series was used as a basis for calculting the percentage of the maximum. The data are presented in Tables 4, 5, and 6.

TABLE 4. RESPONSE OF VEGETABLE CROPS ON DIFFERENT SOILS TO INCREASES IN PHOSPHORUS APPLICATIONS

P_2O_5 applied per acre per year[1]		Yield in percentage of maximum rate		
Norfolk	Eutaw and Cecil	Norfolk soil[2]	Eutaw soil[2]	Cecil soil[2]
Pounds	*Pounds*	*Per cent*	*Per cent*	*Per cent*
0	0	31	14	8
40	80	73	75	72
80	160	91	89	92
120	240	100	98	98
160	320	100	100	100

[1] One-third of annual application applied to each of 3 crops.
[2] Average of 26 different vegetable crops on each soil.

TABLE 5. RESPONSE OF VEGETABLE CROPS ON DIFFERENT SOILS TO INCREASES IN NITROGEN APPLICATIONS

Nitrogen (N) applied per acre[1]	Yield in percentage of the maximum rate		
	Norfolk soil[2]	Hartsells soil[2]	Decatur soil[2]
Pounds	*Per cent*	*Per cent*	*Per cent*
0	27	33	40
30	58	62	65
60	79	81	81
90	93	95	93
120	100	100	100

[1] Amount per acre to each of 3 crops per year.
[2] Number of vegetable crops on Norfolk 27, on the Hartsells 11, and on the Decatur 12.

TABLE 6. RESPONSE OF VEGETABLE CROPS ON DIFFERENT SOILS TO INCREASES IN POTASH APPLICATIONS

Potash (K_2O) per acre per year[1]	Yield in percentage of the maximum rate			
	Norfolk soil[2]	Cecil soil[2]	Decatur soil[2]	Hartsells soil[2]
Pounds	*Per cent*	*Per cent*	*Per cent*	*Per cent*
0	85	89	82	82
45	117	99	93	92
90	94	103	95	101
135	100	100	100	100

[1]One-third of annual application applied to each of 3 crops.
[2]Average of 25 different crops on Norfolk and Cecil, 12 on Decatur, and 11 on Hartsells soil.

It is evident from these data that crop yields on soils not previously fertilized, or fertilized at low rates, are more completely limited by the absence of phosphorus, nitrogen, and potash in the order named. The results, however, show that maximum yields of vegetable crops are more quickly reached by relatively small applications of phosphorus than of nitrogen.

STUDIES DEALING PRIMARILY WITH PHOSPHORUS REQUIREMENTS AND ABSORPTION

PHOSPHORUS REQUIREMENTS OF DIFFERENT VEGETABLE CROPS ON DIFFERENT SOILS. Phosphorus content of the crop from the phosphorus rate producing the highest yield was taken to indicate the phosphorus requirement of that crop for maximum production. In determining the phosphorus content of the crop, the whole plant minus the fibrous roots was analyzed. Where the weights represented fruits, pods, roots, or tubers, in addition to the vines, separate analyses were made of the separate parts and a total weighted average was obtained.

The results represent the average of 4 years for most of the crops. In Table 7, the data are expressed as pounds per acre of P_2O_5 absorbed. The crops are arranged in order of decreasing magnitude of phosphorus requirement or phosphorus absorption. Significance should not be attached to small differences between crops. The object is to permit grouping into five broad classes —very high, high, medium, low, and very low-phosphorus requirements. In determining the amounts of phosphorus absorbed by crops, the average yield for all record years and the average analysis for 2 to 4 years were used.

TABLE 7. PHOSPHORUS ABSORBED AT MAXIMUM PRODUCTION, ARRANGED IN ORDER OF MAGNITUDE

Vegetables	Amount of P_2O_5 per acre absorbed by different vegetables on different soils			
	Norfolk soil	Eutaw soil	Cecil soil	Average
	Pounds	*Pounds*	*Pounds*	*Pounds*
Turnips	39.90	74.66	48.49	54.35
Chinese Cabbage	32.67	42.90	38.46	38.01
Collards	26.03	44.93	37.23	36.06
Tendergreen	21.73	45.53	30.18	32.48
Squash	33.44	30.72	31.42	31.86
Sweetpotatoes	30.37	26.21	32.22	29.60
Cabbage	23.25	34.82	29.67	29.25
Okra	21.08	33.15	24.86	26.36
Carrot	20.83	29.89	27.74	26.15
Lima Beans	25.06	24.53	20.69	23.43
Pepper	17.26	29.08	23.52	23.29
Eggplant	18.55	22.10	12.83	17.83
N. Z. Spinach	13.78	19.96	17.39	17.04
Tomato	15.74	19.46	14.73	16.64
Potato	14.88	17.20	15.18	15.75
Kale	12.38	17.71	13.93	14.67
Beans	15.20	17.61	11.13	14.65
Beets	10.16	15.64	16.89	14.23
Swiss Chard	10.63	7.19	20.96	12.93
English Peas	8.24	12.31	13.76	11.44
Endive	6.93	10.66	11.65	9.75
Onion	7.66	10.46	8.66	8.93
Radish	7.15	10.11	6.50	7.92
Lettuce, spring	6.63	6.70	10.17	7.83
Lettuce, fall	4.22	8.19	6.13	6.18
AVERAGE	17.75	24.47	20.98	21.07

The average P_2O_5 contained in the 25 crops on the three soils was 21.07 pounds per acre. The average ranged from 6.18 pounds per acre in fall lettuce to 54.35 pounds in turnips. Therefore, there was a wide difference in the phosphorus absorbed by different vegetables in producing the maximum yield under conditions of the experiment. Turnips was the only crop in the group having a very high phosphorus requirement. Chinese cabbage, collards, tendergreen, squash, sweetpotatoes, and cabbage, were in the group having a high phosphorus requirement. Onions, endive, radish, and lettuce were in the group that had a very low phosphorus requirement. Other vegetables were in intermediate groups. While the phosphorus requirement of the individual vegetables differed to some extent on the three soils, the range was not wide. Usually the highest phosphate requirement was found on the soil producing the highest yield.

PHOSPHORUS FEEDING CAPACITY OF DIFFERENT VEGETABLE CROPS ON DIFFERENT SOILS. By phosphorus-feeding capacity is meant the ability of a crop to absorb phosphorus from the natural supply in the soil or from phosphorus in less readily available forms. Phosphorus-feeding capacity of a given crop, as measured in this study, is indicated by the amount of phosphorus absorbed by the plant on plots receiving no phosphorus. The amounts of P_2O_5 absorbed by the different crops from the zero-phosphorus treatment are given in Table 8.

TABLE 8. PHOSPHORUS ABSORBED WITHOUT PHOSPHORUS APPLICATION, ARRANGED IN ORDER OF MAGNITUDE

Vegetables	Amount of P_2O_5 per acre absorbed by different vegetables on different soils			
	Norfolk soil	Eutaw soil	Cecil soil	Average
	Pounds	*Pounds*	*Pounds*	*Pounds*
Sweetpotatoes	20.57	26.21	9.67	18.82
Lima Beans	25.06	15.70	9.40	16.72
Okra	15.84	13.70	4.75	11.43
Potatoes	9.54	5.77	3.22	6.48
Turnips	14.62	2.60	.74	5.99
Carrots	7.05	7.84	2.80	5.90
Beans	7.76	5.13	1.67	4.85
Pepper	5.06	6.92	2.14	4.71
Cabbage	7.47	2.24	1.07	3.59
Eggplant	5.19	3.81	1.43	3.48
Squash	6.14	2.48	.26	2.96
Tomato, spring	3.63	2.60	.30	2.18
Chinese Cabbage	4.19	.97	.67	1.94
English Peas	1.52	2.94	1.26	1.91
Tendergreens	4.80	.12	.15	1.69
Radish	2.04	.71	.37	1.04
New Zealand Spinach	2.61	.24	.19	1.01
Onion	.76	1.01	.47	.75
Collards	1.81	.23	.19	.74
Beets	1.48	.19	.31	.66
Lettuce, fall	.44	.71	.39	.51
Lettuce, spring	.70	.30	.43	.48
Endive	.28	.78	.10	.39
Swiss Chard	.48	.23	.34	.35
Kale	.41	.20	.08	.23
TOTAL	149.45	103.63	42.40	98.51
AVERAGE	5.98	4.15	1.70	3.84

It will be noted that there was a very wide difference in the amount of phosphorus absorbed by the different crops and a very wide difference in the amount of phosphorus taken up by the same vegetable on the different soils. This indicates a difference both in the phosphorus-feeding capacity of the different crops and in the availability of the phosphorus in the three soils. It is pointed out that the three soils had received little or no phosphorus for many years before being placed in the field bins. The Cecil was a virgin soil and had never received any commercial phosphorus, while the Eutaw and Norfolk soils were from abandoned fields that had received no phosphorus for many years and then only in small amounts.

Two crops, lima beans and sweetpotatoes, are outstanding in their ability to absorb less readily available phosphorus from soil. These crops absorbed an average of about 18 pounds per acre of P_2O_5 from the soils. These were in marked contrast to endive, chard, lettuce, kale, or beets, which absorbed an average of about one-half pound each per acre of P_2O_5. The two crops in the first group, therefore, were able to absorb approximately 36 times as much phosphorus as the crops in the other group. As to relative phosphorus-feeding capacities of the other vegetables, okra was high; beans, cabbage, carrots, eggplant, peppers, potatoes, squash, tomatoes, and turnips were medium; Chinese cabbage, English peas, collards, onions, radishes, spinach, tendergreen, and beets were low; and lettuce, endive, Swiss chard,and kale were very low.

PHOSPHORUS-ABSORPTION EFFICIENCY OF DIFFERENT VEGETABLE CROPS. It is obvious that one crop might have a high-phosphorus requirement with either a high-, medium-, or low-phosphorus-feeding capacity. Another crop might have a low-phosphorus requirement with either a high-, medium-, or low-feeding capacity, while still another might have a medium-phosphorus requirement with either a low-, medium-, or high-phosphorus-feeding power.

To provide a convenient means of expressing relative efficiency of a crop to obtain its phosphorus needs from less available phosphorus of the soil, the term "absorption efficiency" is used and expressed as the absorption-efficiency index. This index is the reciprocal ratio of phosphorus absorbed at the rate giving greatest plant weight to phosphorus absorbed at the zero rate. Use of the reciprocal for index value means that the higher the index, the higher the ability of plant to obtain its phosphorus needs without phosphorus applications.

The average phosphorus absorption-efficiency indices are given in Table 9 for different vegetable crops on the three soils. The range is from 1.6 to 71.0.

Influence of the several factors in determining efficiency index is illustrated by collards and lima beans. The collard had a relatively high phosphorus requirement, an average of 36.06 pounds of P_2O_5 per acre on the three soils. The crop had a very low-phosphorus-feeding capacity, only 0.74 pounds of P_2O_5 per acre. Its phosphorus absorption efficiency, therefore, was very low. Lima beans had a medium-phosphorus requirement, 23.43 pounds

TABLE 9. PHOSPHORUS ABSORPTION EFFICIENCY OF DIFFERENT VEGETABLES

Vegetable	Amount P_2O_5 per acre absorbed[1]		Absorption efficiency index[2]
	At zero phosphorus rate	At phosphorus rate giving maximum plant growth	
	Pounds	*Pounds*	
Lima Beans	16.72	23.43	71
Sweetpotato	18.82	29.60	64
Okra	11.43	26.36	43
Potato	6.18	15.75	39
Beans, Snap	4.85	14.65	33
Carrot	5.90	26.15	23
Pepper	4.71	23.29	20
Eggplant	3.48	17.83	20
Tomato, spring	2.18	16.64	13
Radish	1.04	7.92	13
Cabbage	3.59	29.25	12
Turnip	5.99	54.35	11
Squash	2.96	31.86	9
Onion	.75	8.93	8
Lettuce, fall	.51	6.18	8
Lettuce, spring	.48	7.83	6
N. Z. Spinach	1.01	17.04	6
Tendergreen	1.69	32.48	5
Chinese Cabbage	1.94	38.01	5
Beets	.66	14.23	5
Endive	.39	9.75	4
Swiss Chard	.35	12.93	3
Collards	.74	36.06	2
Kale	.23	14.67	1.6

[1] Average of 2 to 4 years on each of 3 soils.

[2] Reciprocal ratio P_2O_5 absorbed at phosphorus rate giving maximum plant growth to P_2O_5 absorbed at zero-phosphorus rate.

of P_2O_5 per acre being absorbed by this crop when it made its greatest plant growth. The phosphorus-feeding capacity, however, of the lima bean was high, 16.72 pounds per acre of P_2O_5 being absorbed without the addition of a phosphatic fertilizer. This crop, therefore, had a very high absorption-efficiency index.

Under conditions of this experiment, sweetpotatoes and lima beans had very high absorption-efficiency index values. Okra, potatoes, and beans had high efficiency indices, while kale and collards had very low absorption-efficiency values. The indices of the other crops were intermediate.

Results from studies conducted preliminary to this investigation by Whitten[1] showed that (1) there were large differences in the amount of phosphorus contained in seed or vegetative parts used for propagation, (2) that this larger quantity of phosphorus gave larger root development in cultures lacking phosphorus, and (3) that these larger root systems absorbed more phosphorus on soils low in phosphorus than plants having small root systems. The data in Table 9 indicate that phosphorus-absorption capacity may be related to such quantitative factors as the root-absorption area as well as the qualitative factors of root absorption and chemical requirements (lime usually) of the plant as advanced by Truog *(40)*.

PHOSPHORUS ABSORPTION BY DIFFERENT VEGETABLES AT DIFFERENT RATES OF PHOSPHORUS APPLICATIONS. Amounts of phosphorus absorbed by each vegetable on each of the three soils when receiving each of the five treatments are given in Appendix Table I.

The crops in the table are arranged in order of the magnitude of total phosphorus absorbed on all soils for all phosphorus rates. No important significance is attached to the order other than to indicate the general relationship of each crop in respect to phosphorus absorption.

Data reveal large differences in amounts of phosphorus absorbed by the different crops, in amounts absorbed on different soils by the same crops, and in the relative amounts absorbed by different crops when receiving different rates of phosphorus.

Considering all rates of phosphorus applications on all three soils, turnips, sweetpotatoes, and lima beans absorbed large

[1]Whitten, T. P. The interrelation of phosphorus reserves in seeds, root development, phosphorus absorption, and plant growth. Unpublished thesis. Alabama Polytechnic Institute Library, 1935.

quantities of phosphorus. Lettuce, endive, and onions absorbed relatively small quantities. The amounts absorbed by the first group ranged from 8 to 10 times those absorbed by the second group.

The amount of phosphorus absorbed by beans and beets might be used to illustrate differences in absorption by different crops on different soils. At the rate of 160 pounds of P_2O_5 per acre, beans absorbed 15.2 pounds per acre of phosphorus on Norfolk soil but only 8.4 pounds on Cecil soil. At the same phosphorus application rate, beets absorbed only 10.2 pounds per acre of P_2O_5 on the Norfolk soil but 12.9 pounds on the Cecil soil.

Phosphorus absorption of sweetpotatoes and lima beans illustrate the differences between crops in the relative amounts absorbed at different rates of application. On Cecil soil with no phosphorus added, absorption by sweetpotatoes was only 9.7 pounds per acre of P_2O_5 and by lima beans 9.4 pounds. When 160 pounds per acre of P_2O_5 was applied to Cecil soil, sweetpotatoes absorbed 27.6 pounds, while lima beans absorbed 16.4 pounds. Thus, sweetpotatoes on Cecil soil treated with 160 pounds per acre of P_2O_5, absorbed 185 per cent more phosphorus than they did on the same soil but with no phosphorus added. On the other hand, the increased absorption of phosphorus by lima beans under identical conditions was only 74 per cent.

PHOSPHORUS UTILIZATION EFFICIENCY OF DIFFERENT VEGETABLE CROPS. The term utilization efficiency is expressed as the percentage of phosphorus absorbed by the plant in relation to the amount applied. In Table 10 are given the relative utilization efficiencies of different vegetable crops when supplied different amounts of phosphorus on different soils.

Data in the table reveal that there are (1) wide ranges in the utilization efficiency of different crops on the same soils, (2) wide differences in efficiency of the same crops on different soils, and (3) consistent differences in utilization efficiencies when different amounts of phosphorus are added.

It may be observed, for example, that relative utilization efficiencies of the different crops on Norfolk soil ranged from a low of 14 per cent for lettuce or 16 per cent for endive to 238 per cent for turnips when fertilized at 40 pounds per acre of P_2O_5 on an annual basis. Although not as extreme, similar differences occurred at the other phosphorus rates and on the other soils.

It may be noted also that the utilization efficiency of phosphorus absorption was consistently lower for higher phosphorus applications (Table 10). For example, the decrease of cabbage on Norfolk soil was from 105 to 79 to 58 to 47 per cent as the annual applications of P_2O_5 were increased from 40 to 160 pounds per acre. On Eutaw soil, the utilization efficiency of cabbage decreased from 76 to 33 per cent, and on the Cecil soil, from 50 to 28 per cent as the rates were increased from 80 to 320 pounds per acre of P_2O_5.

Since a number of vegetable crops have a high-phosphorus-absorption capacity, it is obvious that these crops might absorb more phosphorus than had been supplied, especially at a low rate of phosphorus application. The data show that this is true with several crops. At the annual rate of 40 pounds per acre, turnips absorbed 31.7 pounds of P_2O_5 on the Norfolk soil. This was 2.38 times as much phosphorus as its share (13.3 pounds) of the annual rate.

There are many factors that have a part in the final utilization efficiency of a crop. The final results involve interplay of phosphorus requirements, phosphorus-feeding power, and residual phosphorus from previous crops. The collard offers a good illustration of the interplay of these factors. At the lowest rate of phosphorus application, it had a utilization efficiency of 117 per cent on the Norfolk soil, 112 per cent on the Eutaw soil, and 72 per cent on the Cecil soil. This crop had a very low phosphorus-feeding capacity, as represented by an absorption of 0.74 pounds of P_2O_5 from the zero-phosphorus treatment on the three soils. It had a high-phosphorus requirement, as represented by 36.06 pounds per acre of P_2O_5 absorbed for the treatment giving maximum plant growth. Its phosphorus absorption index was very low; yet given a very small application of phosphorus, the crop absorbed 17 per cent more phosphorus than it received for its one-third of an annual application. In the case of turnips, the amount of phosphorus absorbed was 138 per cent more than was supplied at the low rate of application.

The phosphorus absorbed in excess of that supplied might come from the soil's natural phosphorus reserves or from unused portions of phosphorus applied to other crops in the rotation. The extent to which a crop might use the natural phosphorus of soil when presumably the more available phosphorus supplied from superphosphate is present has basic implications. It seems evident that when low-phosphorus applications are given, certain

TABLE 10. EFFICIENCY OF PHOSPHORUS UTILIZATION BY DIFFERENT VEGETABLE CROPS ON DIFFERENT SOILS FERTILIZED AT DIFFERENT RATES OF PHOSPHORUS

Vegetables	Percentage of P_2O_5 absorbed of that applied to different soils at different rates											
	Pounds of P_2O_5 per acre applied to Norfolk soil[1]				Pounds of P_2O_5 per acre applied to Eutaw soil[1]				Pounds of P_2O_5 per acre applied to Cecil soil[1]			
	40	80	120	160	80	160	240	320	80	160	240	320
	Pct.	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*
Sweetpotatoes	244	152	95	77	189	103	73	55	131	69	54	48
Turnip	238	123	95	75	157	117	93	61	102	84	61	49
Chinese Cabbage	141	110	82	61	96	62	46	40	72	56	48	33
Collards	117	86	65	47	112	79	59	42	72	58	47	35
Tendergreen	111	81	62	41	105	72	57	43	66	46	38	29
Okra	152	79	52	42	93	53	41	31	59	47	38	30
Lima Beans	195	94	62	48	81	46	29	23	54	31	24	19
Cabbage	105	79	58	47	76	51	36	33	50	40	30	28
Squash	94	87	64	63	48	30	34	29	34	40	33	29
Carrot	85	62	52	41	65	41	34	28	41	37	34	26
Pepper	86	51	43	31	60	37	31	27	52	30	27	22
Eggplant	101	65	45	35	63	28	28	22	23	17	12	12
N. Z. Spinach	63	43	32	26	50	32	25	21	43	27	22	14
Tomatoes, spring	77	48	35	30	47	26	24	16	25	23	18	15
Beans	89	46	36	29	42	26	21	17	23	16	12	10
Potatoes	83	46	34	28	36	26	19	16	26	18	16	14
Kale	32	32	30	23	28	25	21	17	26	20	15	13
Beets	38	24	20	19	18	16	17	15	25	24	19	16
English Pea	29	21	18	15	33	19	15	12	23	20	16	13
Swiss Chard	31	30	29	20	8	6	8	7	24	23	18	20
Radish	42	24	18	13	28	19	12	9	20	12	8	6
Endive	16	17	16	13	19	15	12	10	11	14	11	11
Onion	16	17	16	14	12	12	11	10	11	10	11	9
Lettuce, spring	23	22	18	12	8	7	8	6	10	11	9	10
Lettuce, fall	14	11	9	8	12	9	10	8	9	8	7	6
AVERAGE[2]	87	57	43	34	58	38	30	24	40	31	25	20

[1] Annual rates per acre.
[2] Calculated from total phosphorus absorbed at the differents rates.

crops continue to absorb phosphorus from the reserve supply of the soil. Furthermore, it seems likely that the application of a small amount of phosphorus supplies certain crops with enough phosphorus to enable them to absorb phosphorus from the less available supplies through mass root-soil relations made possible by increased root growth.

CROP RESPONSES TO PHOSPHORUS APPLICATIONS

The data reported thus far have dealt with various phases of phosphorus absorption and with differences in phosphorus requirements and feeding capacities of different crops. This phase of the study deals with the response of different vegetable crops to applications of phosphorus as expressed in yields of plant parts normally used for food.

YIELD OF DIFFERENT CROPS FROM PHOSPHORUS INCREMENTS. Yields of 26 vegetable crops at five rates of phosphorus applications on each of three soils are given in Appendix Table 2. Since these are the basic data from which a number of other tables are derived, they are analyzed in some detail statistically. In Appendix Table 3 are given the "F" value for differences in yield between different rates of phosphorus applications and the coefficient of variation for each set of data consisting of the yields of each crop on each soil for the years involved. The least significant difference between treatments for each set of data is presented in Appendix Table 4.

Three other sets of statistics derived from Appendix Table 2 are presented in Appendix Table 6. In this table are given the rates of phosphorus applications theoretically required for maximum yields, the theoretical rate for zero yields, and slope of the lines between the yield at the zero and the yield at the theoretical maximum rate of phosphorus application. These data were derived from equations for second degree polynomials, which were computed for each set of data.[2]

The data in Appendix Table 2 are expressed in Table 11 as "relative yields," i. e. yield of each crop from each rate of phosphorus application as percentage of the yield at maximum rate. The yields of any two vegetables or groups of vegetables at any of the lower rates of application may be compared in terms of the yields at the highest rate.

[2]Equations are available in mimeograph form upon request.

TABLE 11. RELATIVE YIELDS OF DIFFERENT VEGETABLES ON DIFFERENT SOILS FROM DIFFERENT PHOSPHORUS APPLICATIONS[1]

Vegetable	Relative yields from pounds of P_2O_5 per acre applied to Norfolk soil					Relative yields from pounds of P_2O_5 per acre applied to Eutaw soil					Relative yields from pounds of P_2O_5 per acre applied to Cecil soil					Average number crops
	0	40	80	120	160	0	80	160	240	320	0	80	160	240	320	
	Pct.	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	
Sweetpotatoes	94	99	102	89	100	100	94	97	98	100	57	94	98	109	100	4
Lima Beans	104	101	94	99	100	79	95	100	97	100	48	72	84	94	100	4
Okra	81	87	111	80	100	55	81	82	88	100	31	72	112	107	100	2
Radish	39	95	100	107	100	11	96	110	110	100	9	89	97	95	100	4
Turnip	44	87	97	96	100	8	85	100	106	100	2	79	93	103	100	4
Tendergreen	34	90	115	112	100	1	83	92	101	100	1	80	92	103	100	4
Tomatoes, spr.	29	74	92	96	100	30	92	100	116	100	4	61	98	105	100	4
English Peas	25	65	90	98	100	36	98	100	102	100	15	72	97	94	100	4
N. Z. Spinach	23	70	86	97	100	2	83	93	106	100	1	93	103	128	100	4
Chinese Cabbage	17	69	98	104	100	4	76	87	95	100	3	86	110	110	100	4
Potatoes	57	75	90	96	100	32	59	86	98	100	23	63	84	92	100	4
Carrots	33	60	83	102	100	35	70	83	95	100	14	51	88	98	100	4
Collards	10	71	94	102	100	1	76	91	97	100	1	73	96	99	100	4
Cabbage	40	74	98	100	100	8	76	92	94	100	4	65	92	96	100	4
Beets	16	76	90	99	100	2	46	75	94	100	3	56	98	98	100	3
Pepper	32	73	82	117	100	24	56	64	76	100	10	72	86	94	100	2
Eggplant	11	75	96	90	100	9	83	81	101	100	3	50	64	87	100	3
Beans	38	70	81	92	100	19	56	77	92	100	7	44	67	92	100	4
Squash	13	50	91	88	100	7	62	85	99	100	0	52	87	94	100	4
Kale	5	52	79	98	100	2	55	80	93	100	2	70	88	90	100	4
Onions	18	47	79	89	100	18	41	79	93	100	9	44	78	102	100	4
Endive	4	36	71	98	100	9	53	84	89	100	1	32	71	80	100	3
Swiss Chard	6	50	85	100	100	6	45	63	93	100	3	51	74	86	100	4
Tomatoes, sum.	23	42	73	85	100	6	39	71	102	100	4	47	71	66	100	3
Lettuce, spr.	9	52	83	95	100	4	32	54	88	100	5	32	60	77	100	4
Lettuce, fall	13	53	77	95	100	8	37	56	87	100	7	45	73	92	100	4
AVERAGE	31	69	90	97	100	20	68	84	97	100	10	63	87	96	100	

[1]Yield at each rate of phosphorus application in relation to yield of the maximum phosphorus rate.

Figures 1 to 5 graphically illustrate the response of different crops in yields to increments of phosphorus and certain factors that affect the nature of the response. Figures 1 to 3 are based on data from field bins, while Figures 4 and 5 are based on data from greenhouse experiments.

The data in Table 11 and Figures 1 to 5 reveal great differences in the yield response of different vegetables to different rates of phosphorus on different soils under different conditions. For example, the relative yields of a number of crops on Norfolk soil receiving 40 pounds per acre of P_2O_5 were nearly as high as the yields of the maximum rates, whereas the relative yields of several other crops were below 50 per cent. Sweetpotatoes produced about as much on Norfolk and on the Eutaw soils without added phosphorus as they did from any amount applied. The yield of lima beans on the Norfolk at the lowest rate used was practically the same as that from the highest rate.

Another observation of importance is the effect of soil type on the nature of the yield response and the corresponding yield curve. Lima beans, for example, on the Norfolk soil with no additional phosphorus gave relative yields as high as those from the highest application. On the other hand, the relative yield from the zero-phosphorus rate was 79 per cent on the Eutaw and 48 per cent on the Cecil soil. From the 80-pound rate of P_2O_5, the relative yield was 95 per cent on the Eutaw soil but only 72 per cent on the Cecil soil. The yields of sweetpotatoes on Norfolk and Eutaw soils were as high from the no-phosphorus treatment as from any of the amounts of phosphorus applied, but the yield on the Cecil at the zero-phosphorus rate was only 57 per cent as high as the maximum rate.

For the five rates of phosphorus application ranging from zero to 160 pounds per acre of P_2O_5, the average relative yields of 26 crops were 31, 69, 90, 97, and 100 per cent on the Norfolk. The average relative yields from applications ranging from 0 to 320 pounds per acre were 20, 68, 84, 97, and 100 per cent on the Eutaw soil and 10, 63, 87, 96, and 100 per cent on the Cecil soil.

Figures 1 to 5 illustrate the different types of curve and some of the factors affecting the type of curve. The relative yield curves for sweetpotatoes are given in Figure 3. On the Norfolk and Eutaw soils, the curves are straight and horizontal, whereas on the Cecil the curve is slightly convex. When crops give as high yields from no phosphorus as from different rates of phosphorus, straight line horizontal curves result.

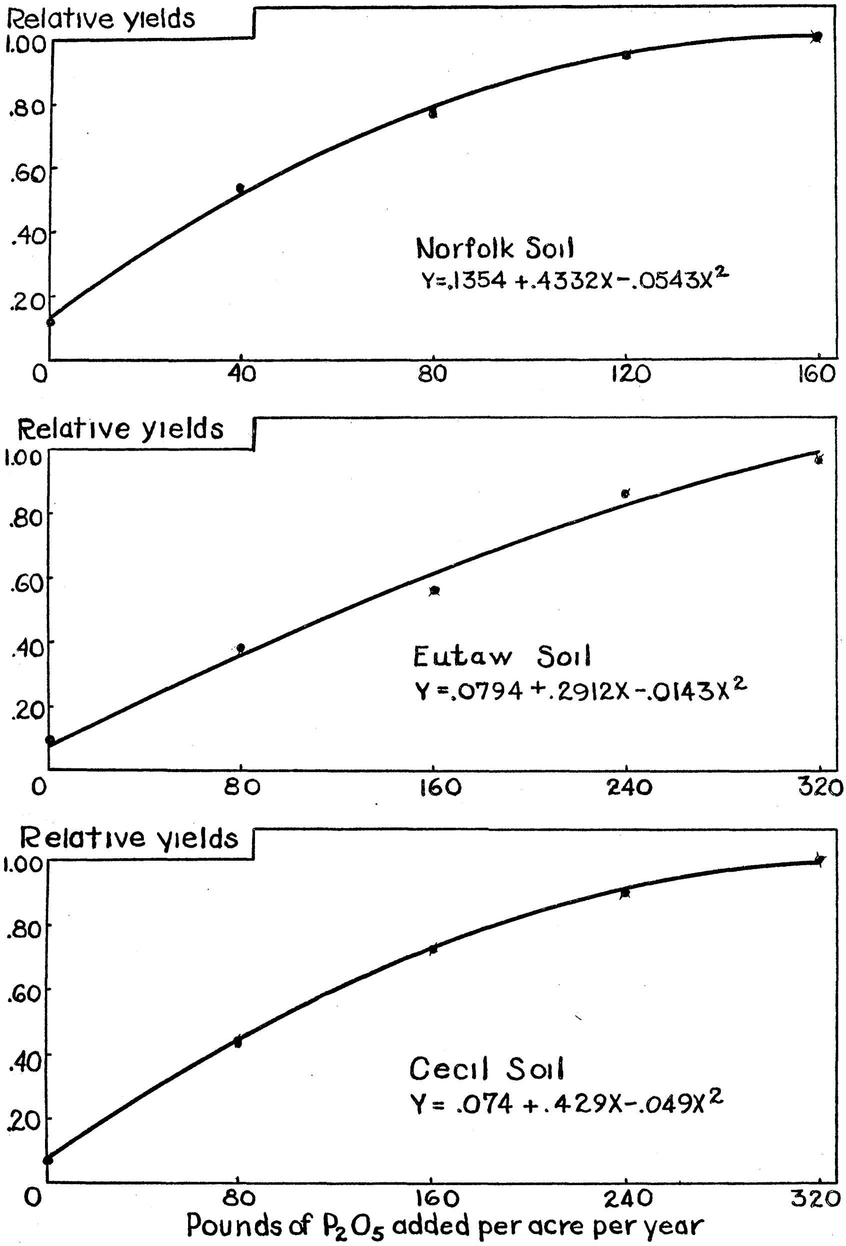

FIGURE 1. Relative yields of lettuce grown on different soils receiving different rates of phosphorus (4-year average) in experiments conducted in field bins. Treatment consisted of repeated applications of phosphorus.

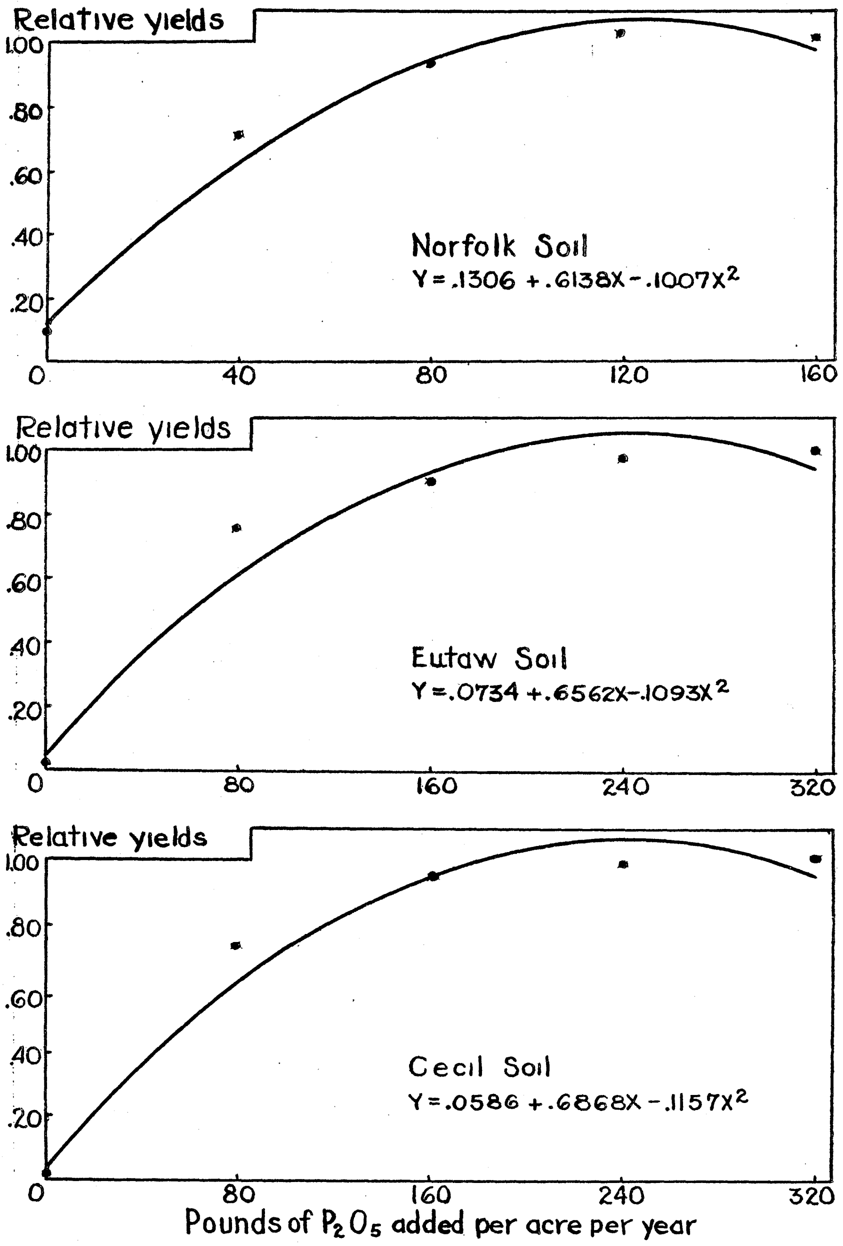

FIGURE 2. Relative yields of collards grown on different soils receiving different rates of phosphorus (4-year average) in experiments conducted in field bins. Treatment consisted of repeated applications of phosphorus.

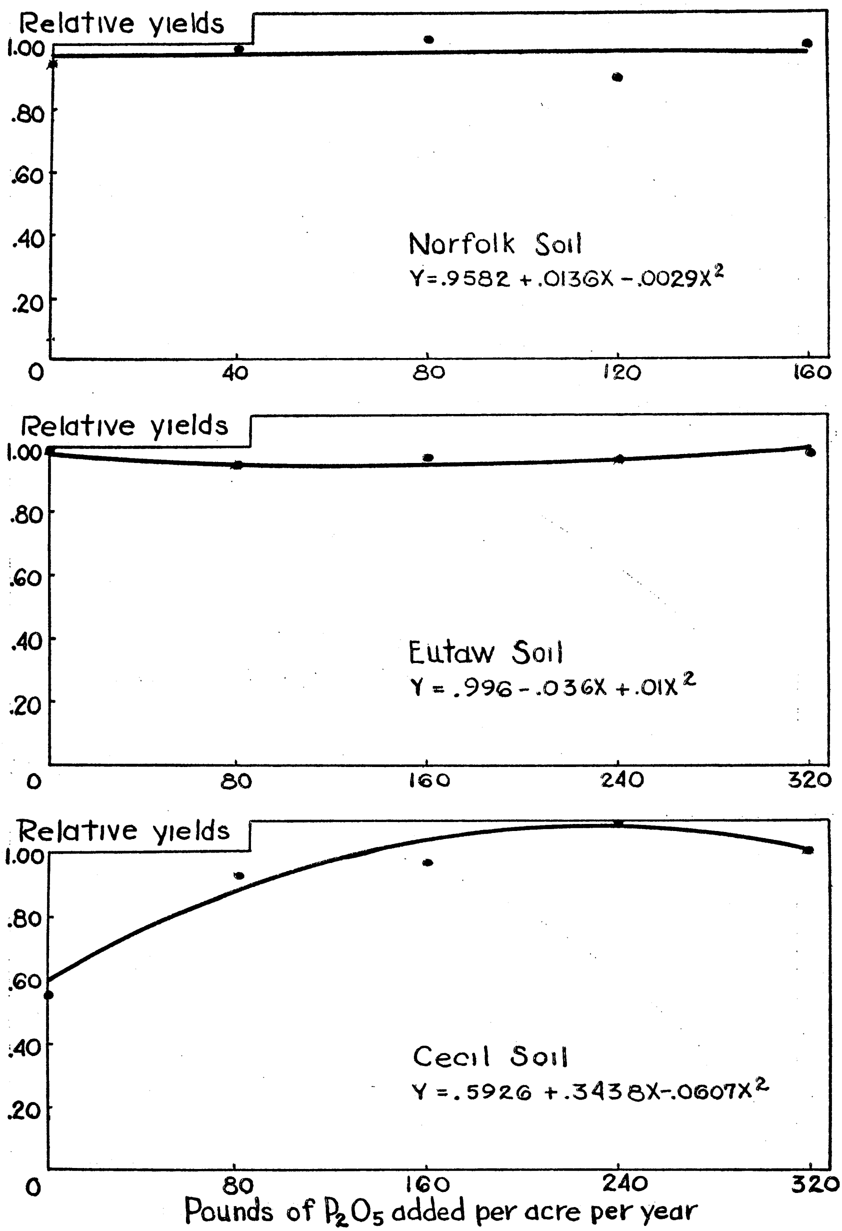

FIGURE 3. Relative yields of sweetpotatoes grown on different soils receiving different rates of phosphorus (4-year average) in experiments conducted in field bins. Treatment consisted of repeated applications of phosphorus.

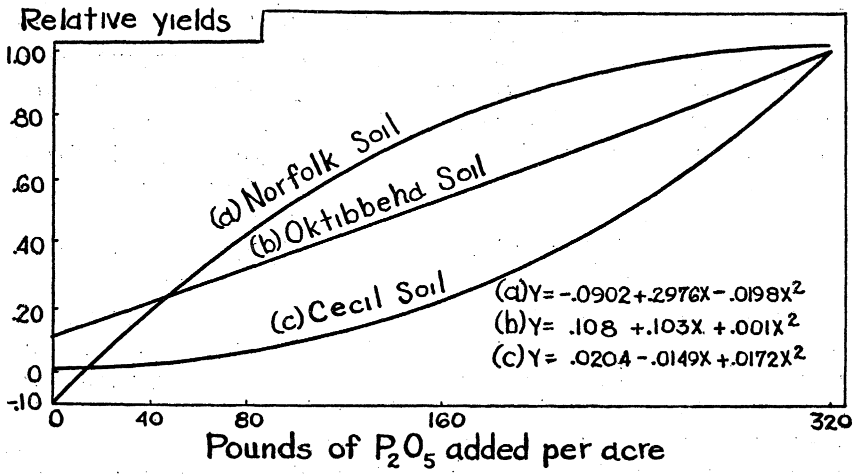

FIGURE 4. Relative yields of lettuce grown on different soils receiving different rates of phosphorus in experiments conducted in pots in the greenhouse. Treatment consisted of one application of phosphorus mixed with all soil in the pot.

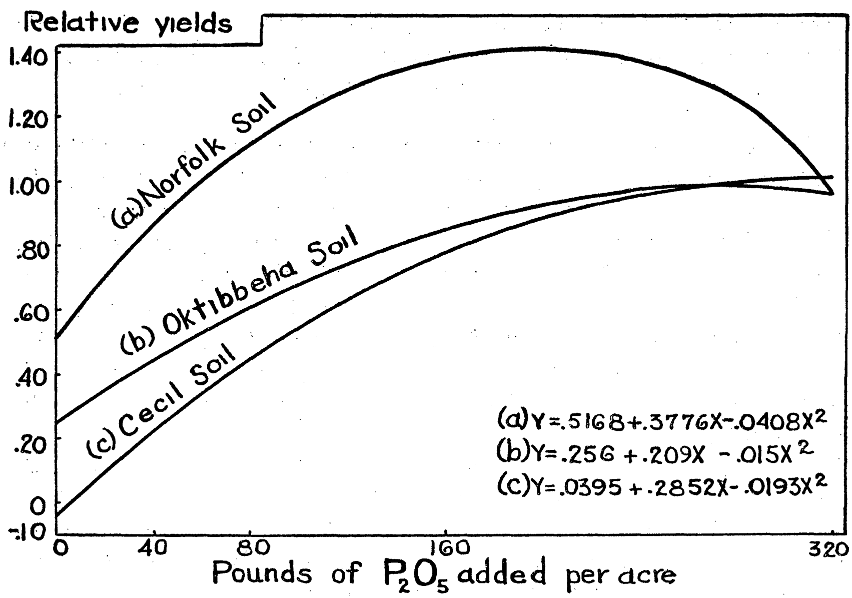

FIGURE 5. Relative yields of mustard grown on different soils receiving different rates of phosphorus in experiments conducted in pots in the greenhouse. Treatment consisted of one application of phosphorus mixed with all soil in the pot.

When crops make low yields without phosphorus but relatively high yields at low rates of application, highly convex curves result (Figure 2). Crops that give somewhat uniform increases for increases in phosphorus application give inclined, flat, or straight line curves (Figure 1). When crops give low increases in yield for low rates of application and high yield only from high applications, the curves are concave. No crop grown over a period of years in field bins gave concave curves.

A number of factors affect the convexity and concavity of curves. The effects of a number of factors are shown in Figures 4 and 5. Data in these graphs are from greenhouse experiments. The phosphorus was mixed with all the soil in the pots and only one application of phosphorus was given. The curve for relative yield of lettuce on Norfolk soil (Figure 4) is convex, on Oktibbeha soil almost straight, and on Cecil soil concave. The curve for the relative yield of mustard on Norfolk soil is highly convex and on Oktibbeha and Cecil soils slightly convex (Figure 5).

Figures 4 and 5 along with Figures 1 to 3 and the data in Tables 1, 2, 3, 7, 8, and 11 indicate that relative yield curves are more convex or less concave when crops absorb relatively low amounts of phosphorus at the zero rate and make high relative yields from low rates of phosphorus applications, when soils have low phosphorus-fixing capacity, and when phosphorus is applied repeatedly to the same soil and applied to a limited zone.

RELATIVE CAPACITY OF DIFFERENT VEGETABLE CROPS TO MAKE SATISFACTORY YIELDS AT LOW-PHOSPHORUS APPLICATIONS. In areas of highly specialized vegetable production, heavy applications of phosphorus are made. The amounts applied are often much in excess of phosphorus needs of the crops grown, and continued use of heavy applications results in accumulation of high or excessive amounts of phosphorus *(3, 5, 7, 8, 30, 43, 44)*. The situation is often quite different in many gardens and truck patches on farms where the rate of fertilization used is for field crops rather than vegetable crops. Hence, satisfactory production often depends upon the ability of the crop to grow with relatively small phosphorus applications.

In Table 12, the relative yields of different crops on different soils are given for the smallest phosphorus application made. The rates on an annual basis were 40 pounds of P_2O_5 per acre on Norfolk soil and 80 pounds on the two clay soils. Yield at the maximum phosphorus application is used as 100 per cent. The

TABLE 12. RELATIVE YIELDS OF DIFFERENT CROPS ON DIFFERENT SOILS AT LOW RATES OF PHOSPHORUS APPLICATIONS

Vegetable	Yield of lowest phosphorus rate in percentage of yield at highest rate on different soils		
	Norfolk soil	Eutaw soil	Cecil soil
	Per cent	*Per cent*	*Per cent*
Sweetpotatoes	99	94	94
Radish	95	96	89
Lima Beans	101	95	72
Tendergreen	90	83	80
Turnip	87	85	79
N. Z. Spinach	70	83	93
Okra	87	81	72
English Peas	65	98	72
C. Cabbage	69	76	86
Tomato, spring	74	92	61
Collards	71	76	73
Eggplant	75	83	50
Pepper	73	56	72
Cabbage	74	76	65
Potato	75	59	63
Kale	52	55	70
Beans	70	56	44
Carrot	60	70	51
Squash	50	62	52
Beets	76	46	56
Swiss Chard	50	45	51
Onion	47	41	44
Endive	36	53	32
Lettuce, fall	53	37	45
Lettuce, spring	52	32	32

relative yields ranged from a low of 32 to a high of 101 per cent. Sweetpotatoes, lime beans, collards, turnips, tendergreen, tomatoes, and okra are crops that produced between 70 and 100 per cent of the maximum yields from the lowest rate of phosphorus applied. Such response undoubtedly is one of the reasons why these crops are grown more commonly than other vegetables on farms in the Southeastern States.

EFFECTS OF PHOSPHORUS RATES ON EARLINESS OF MATURITY. Effects of phosphorus on earliness of maturity has been recognized by plant physiologists for many years. In Table 13 are presented early and medium-early yields of a number of crops, as expressed by percentages of total yields. Phosphorus had a decided effect on earliness with most crops. The most pronounced

TABLE 13. EFFECTS OF PHOSPHORUS RATES ON EARLINESS OF MATURITY

Vegetable		Percentage of total yield of early and medium-early harvests on different soils at different rates of phosphorus														
		Pounds P_2O_5 per acre applied to Norfolk soil					Pounds P_2O_5 per acre applied to Eutaw soil					Pounds P_2O_5 per acre applied to Cecil soil				
		0	40	80	120	160	0	80	160	240	320	0	80	160	240	320
		%	%	%	%	%	%	%	%	%	%	%	%	%	%	%
Beans	a[1]	7	14	21	27	30	21	24	31	30	32	5	14	23	20	23
	b[1]	39	44	59	66	67	66	75	78	79	82	56	62	72	71	73
L. Beans	a	22	26	28	29	29	21	34	33	38	33	14	11	15	15	15
	b	73	76	75	76	78	74	86	89	89	89	57	61	70	71	73
Tomatoes	a	6	21	26	26	27	2	20	15	18	15	0	11	10	8	7
	b	32	50	51	65	60	36	54	53	55	52	19	37	52	30	37
English Peas	a	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----
	b	68	67	57	47	47	76	46	38	39	35	78	60	60	60	58
Squash	a	7	15	31	28	24	14	29	33	35	32	0	14	19	19	17
	b	30	77	77	78	79	45	74	82	85	80	100	64	81	83	77
Tomatoes	a	3	6	4	8	8	3	8	13	11	9	0	3	4	2	3
	b	15	29	34	35	35	19	45	47	50	49	13	32	32	32	31
Pepper	a	23	25	28	28	31	14	24	28	23	30	7	27	21	24	25
	b	56	57	61	63	64	51	63	70	72	88	31	58	58	60	64
Okra	a	14	11	16	12	14	18	16	19	22	21	11	12	16	14	17
	b	44	44	49	49	46	54	50	54	60	56	46	44	50	46	55
Eggplant	a	0	8	16	15	16	0	13	18	21	16	0	4	12	17	20
	b	15	51	68	67	62	25	60	61	71	70	25	41	57	58	59

[1] a = early; b = early + medium-early.

difference occurred between no phosphorus and the low rate of phosphorus, although usually the increase in the percentage harvested as early or medium-early continued with each increment. Crops giving little response in total yield from phosphorus applications showed little effects of phosphorus on earliness. English peas proved to be the exception. On all three soils, English peas gave a higher percentage of early and medium-early harvest with the no-phosphorus treatment than with any rate of phosphorus.

EFFECTS OF ADDED MATERIALS ON PHOSPHORUS AVAILABILITY

EFFECTS OF LIME. Much work has been done on the influence of lime on availability of phosphorus and on factors responsible for increased availability. Parker and Tidmore *(27)* found much higher phosphorus in the soil solution on limed soil from plots in long continued experiments in Alabama, Illinois, Ohio, and Kentucky. Salter and Barnes *(33)* reported that liming of soils not receiving phosphorus gave response about as great as adding phosphate without lime. Investigators have attributed this to a reduction in soil acidity and an increase in the calcium ions in proportion to the iron and aluminum ions. At high acidity, more iron and aluminum salts are in solution. They unite with the phosphate present giving highly insoluble iron and aluminum phosphates. When lime is added, acidity is reduced, calcium ions are increased, and the more soluble calcium phosphates are formed.

Included in this experiment was one treatment containing lime. The phosphorus application to each soil in this treatment was at the maximum rate. A comparison of dilute acid-soluble phosphorus in the maximum-phosphorus rate with and without lime is given in Table 14.

The data show that there was a significant increase in the amount of dilute acid-soluble phosphorus on limed plots.

TABLE 14. DILUTE ACID-SOLUBLE PHOSPHORUS IN SOILS AS AFFECTED BY LIME

Soil type	P_2O_5 on limed and unlimed plots [1]							
	Amount in phosphorus maintenance plots [2]				Amount in phosphorus residual plots [2]			
	Without lime	With lime	Difference	Odds [3]	Without lime	With lime	Difference	Odds [3]
	p.p.m.	*p.p.m.*	*p.p.m.*		*p.p.m.*	*p.p.m.*	*p.p.m.*	
Norfolk	120	189	69	434:1	114	173	59	999:1
Eutaw	262	300	38	60:1	188	237	49	29:1
Cecil	204	280	76	73:1	159	254	95	999:1

[1] Comparison based on limed and unlimed plots receiving annually during first 9 years 160 pounds per acre P_2O_5 on the Norfolk and 320 pounds on the Eutaw and Cecil.

[2] Phosphorus maintenance plots received from the 10th through the 14th years one-half of the phosphorus rates of the first 9 years; the residual plots received no phosphorus after the 9th year.

[3] Odds as determined by Student's method using the phosphorus in limed and unlimed plots for each of the 5 years as pairs.

EFFECTS OF ORGANIC MATTER ON THE DILUTE ACID-SOLUBLE PHOSPHORUS. A number of investigators have pointed out that one of the many effects of organic matter is the increase in availability of phosphorus. Hester and Shelton *(19)* showed that a Norfolk fine sandy loam low in phosphorus and containing 3 per cent organic matter gave as high yields of lima beans as the same soil with three times as much phosphorus but containing only 1 per cent organic matter.

The effect of organic matter on phosphorus availability was investigated in the residual phosphorus study. Grain sorghum was grown in the summer and turned under on one-half of both

TALE 15. DILUTE ACID-SOLUBLE PHOSPHORUS IN SOILS OF RESIDUAL PLOTS AS AFFECTED BY ORGANIC MATTER

Rates of P_2O_5 applied per acre[1]	Dilute acid-soluble P_2O_5 on plots receiving and not receiving a green manure crop				Av. amount of green sorghum turned per a. per yr.
	No organic matter added	Organic[2] matter added	Difference	Odds	
Pounds	*p.p.m.*	*p.p.m.*	*p.p.m.*		Pounds
Norfolk soil					
0	26	26	0	NS	7,991
40	39	40	1	NS	10,895
80	65	64	−1	NS	14,294
120	87	89	2	NS	15,669
160	120	130	10	NS	12,657
Eutaw soil					
0	12	13	1	NS	14,218
80	34	37	3	NS	18,101
160	76	89	13	216:1	18,718
240	132	145	13	57:1	20,223
320	202	224	22	57:1	19,379
Cecil soil					
0	8	9	1	NS	4,611
80	22	25	3	NS	9,558
160	55	63	8	NS	16,181
240	102	107	5	NS	17,190
320	161	181	20	NS	17,373

[1] Amount of phosphorus applied per acre per year for 9 years of the first period; determinations for readily available phosphorus represent the average of the 5 years on residual phosphorus plots by use of Student's method with plots receiving and not receiving organic matter each year as pairs.

[2] Organic matter consists of crops of sorghum grown and turned under.

the phosphorus-residual and phosphorus-maintenance plots. The amounts of dilute acid-soluble phosphorus on each of three soils of the residual plots during the period of the study are given in Table 15.

The organic material supplied in amounts and by methods employed in this experiment affected the amount of dilute acid-soluble phosphorus little or none in the Norfolk and the Cecil soils. There was a small but significant increase in the indicated amount in the Eutaw soil.

STUDIES OF RESIDUAL PHOSPHORUS

AVAILABILITY OF RESIDUAL PHOSPHORUS AS MEASURED BY CROP YIELDS. In areas devoted to intensive production of commercial truck crops, liberal applications of fertilizers containing high percentages of phosphorus are added. It is known that phosphorus added to the soil becomes "fixed" and, therefore, is not readily lost by leaching. It is also known that while the added phosphorus thus fixed is less readily available to crops, much of it may be used by plants. It is still further known that crops remove only a portion of the phosphorus supplied. Hester *(20)*, Bryan *(5)*, Chapman *(8)*, Hawkins *(18)*, and Bushnell *(7)* have shown that high amounts of phosphorus do accumulate in the soil and are available later for use.

Data presented here provide considerable information on the subject of phosphate accumulation and its later availability to crops.

Although the phosphorus rates used in the experiment were not as high as those reported in some commercial vegetable-producing areas, there was a considerable accumulation over a 9-year period. This accumulated supply affected yields for an additional 5-year period, the harvested amounts varying with the rates applied and with type of soil. The index crops used were Irish potatoes in the spring and turnips in the fall.

Actual and relative yields of turnips are given in Table 16. The data are for each of the 5 years of the second period on each of the three soils. In expressing relative yields, the yields of plots on the three soils receiving the highest phosphorus-maintenance application are used as reference plots (100 per cent). Yields from all other plots are expressed as the percentages of yields of the corresponding reference plots.

Plots referred to as phosphorus-maintenance plots received each year during the residual study one-half as much P_2O_5 as was applied during the first period. The amounts of phosphorus applied to the lighter Norfolk soil at maintenance rates were 0, 20, 40, 60, and 80 pounds of P_2O_5 per acre per year divided equally between the spring and fall crops. The maintenance rates applied to the two clay soils were double those used on the Norfolk soil.

Because of fluctuation in yields by years, the relative yields show the value of residual phosphorus better than the actual yields. The relative yields of turnips on each soil by years are given in Figure 6.

On the Cecil and Eutaw plots that received 240 and 320 pounds per acre of P_2O_5 for the 9 years of the first period, relative yields of residual plots during the second period were within 10 per cent of the reference plot even at the end of 5 years.

On plots that had previously received 160 pounds per acre of

TABLE 16. ACTUAL AND RELATIVE YIELDS OF TURNIPS FROM RESIDUAL AND PHOSPHORUS MAINTENANCE APPLICATIONS

P_2O_5 per acre applied for 9 years[1]	Yields per acre by years[2]					Relative yields by years[3]				
	1943	1944	1945	1946	1947	1943	1944	1945	1946	1947
Lb.	*Lb.*	*Lb.*	*Lb.*	*Lb.*	*Lb.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*
Norfolk soil	Maintenance application of phosphorus[1]									
0	0	473	589	1,600	64	0	3	1	5	0.2
40	8,006	8,391	22,343	17,133	9,357	54	54	56	53	31
80	14,028	13,171	31,629	27,392	23,629	95	85	79	85	79
120	11,635	15,008	37,344	31,962	27,219	79	97	94	99	92
160	14,714	15,494	39,795	32,294	29,734	100	100	100	100	100
	Residual phosphorus[1]									
0	0	1,043	999	870	147	0	7	3	3	0.4
40	4,263	3,994	13,241	4,115	1,965	29	26	33	13	7
80	10,803	7,981	24,397	12,979	7,917	73	52	61	40	27
120	11,744	11,756	34,810	23,251	18,093	80	76	87	72	61
160	14,432	12,134	32,378	27,283	20,294	98	78	81	84	68
Eutaw soil	Maintenance application of phosphorus									
0	154	1,408	320	1,466	64	0.4	5	0.7	4	0.1
80	18,842	17,907	34,400	31,974	19,296	51	61	84	79	51
160	32,653	23,878	40,947	39,501	37,325	88	81	100	97	100
240	34,503	26,848	38,809	39,526	41,350	93	91	95	97	110
320	37,139	29,478	40,941	40,640	37,491	100	100	100	100	100
	Residual phosphorus									
0	269	684	448	1,587	288	0.7	2	1	4	0.7
80	12,141	11,411	18,438	14,541	11,782	33	39	45	36	31
160	29,939	23,719	32,742	31,437	31,347	81	80	80	77	84
240	34,752	26,170	42,988	38,502	35,488	94	89	105	95	95
320	35,788	29,690	39,488	42,752	43,149	96	101	96	105	115
Cecil soil	Maintenance application of phosphorus									
0	0	0	77	115	6	0	0	0.2	0.3	0
80	5,709	12,653	25,479	21,587	12,294	52	65	86	62	39
160	14,080	17,875	29,670	32,672	29,843	128	93	101	94	95
240	13,991	19,744	31,046	33,798	32,218	128	102	105	97	103
320	10,970	19,335	29,517	34,688	31,322	100	100	100	100	100
	Residual phosphorus									
0	0	205	13	326	6	0	1	0	0.9	0
80	1,709	2,445	8,756	1,843	403	16	13	30	5	1
160	10,656	15,910	27,981	24,378	15,942	97	82	95	70	51
240	11,750	18,016	33,504	31,059	29,965	107	93	114	90	96
320	11,475	20,364	32,096	32,653	30,125	105	105	109	94	96

[1] Rates applied annually for 9 years; no further application was made on the residual plots; and ½ of original rates were applied to phosphorus-maintenance plots.

[2] Yield of roots and tops.

[3] Relative yield in percentage of the yield of the reference plot, which received highest phosphorus application for 9 years and highest maintenance application for residual period.

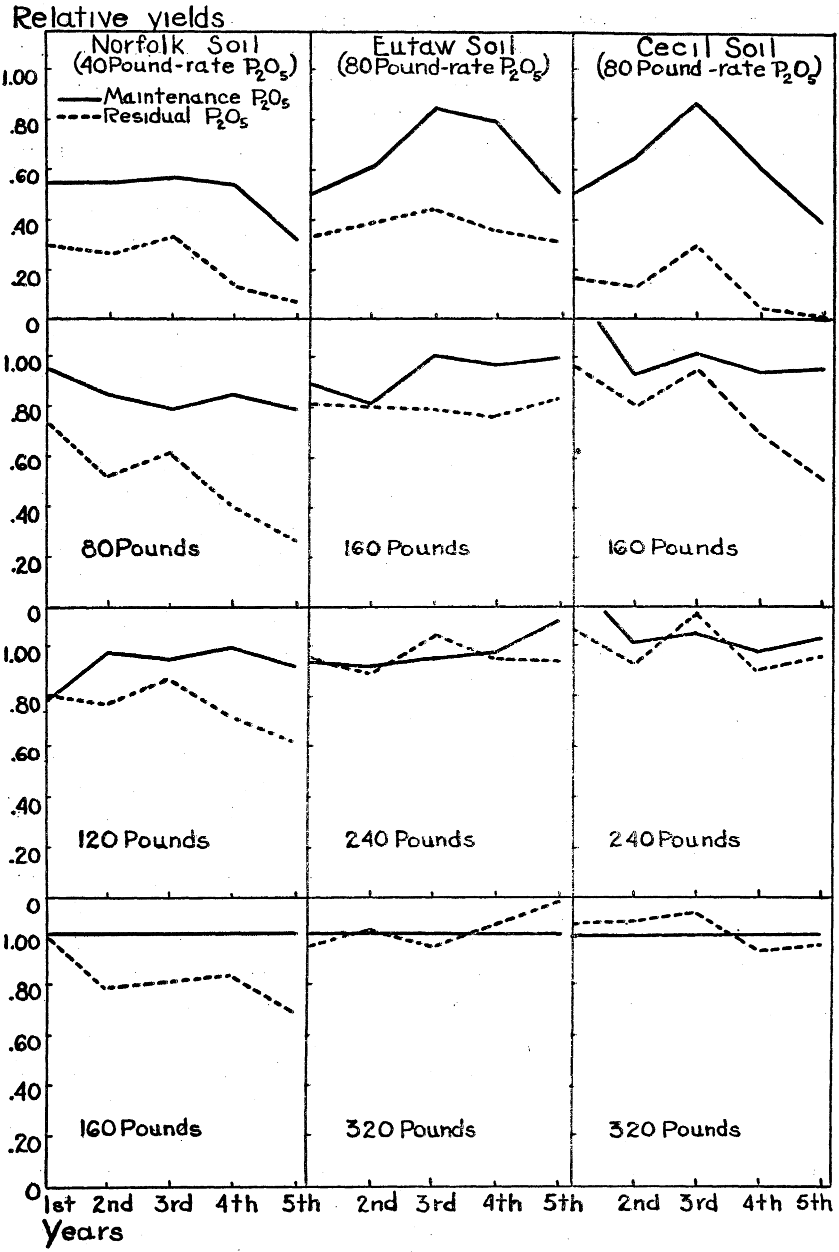

FIGURE 6. Relative yields by years of turnips from residual phosphorus. Phosphorus was applied for 9 years at indicated rates. Yields from residual phosphorus were measured from the 10th through the 14th year. Maintenance rates for the residual period were one-half of the rates used in the first period.

P_2O_5, the relative yields of the residual plots averaged about 83 per cent as high as the reference plots on Norfolk and Eutaw soils, and about 91 per cent on the Cecil soil for 3 years after phosphorus applications were discontinued. By the fifth year, yields of the residual plots on the Norfolk and Cecil soils had dropped to 68 and 51 per cent, respectively.

On residual plots that received lower rates of phosphorus during the first period, the decline in relative yields was more rapid. By the fifth year, the relative yields of the plots previously receiving 80 pounds of P_2O_5 per acre dropped from 73 to 27 per cent on Norfolk soil, and from 16 to 1 per cent on Cecil soil. On the other hand, there was practically no decline on the Eutaw soil.

AVAILABILITY OF RESIDUAL PHOSPHORUS AS MEASURED BY CHEMICAL METHODS. Indicated amounts of readily available or dilute acid-soluble phosphorus in soils from previous phosphorus applications are given in Table 17 and the indicated relative amounts are shown in Figure 7.

The dilute acid-soluble phosphorus during the residual period follows very closely the amounts of phosphorus added during the first period. Consistently, these amounts were higher in plots previously receiving higher applications of phosphorus during the first period. The amounts, likewise, were consistently higher on the plots receiving the phosphorus-maintenance applications during the residual period than companion plots receiving no phosphorus.

There was very little loss in the amounts of dilute acid-soluble phosphorus in either of the three soils during the 5 years of the residual study. This was true at the low rates as well as at the high rates of phosphorus application and on soils rated high as well as on those rated low in phosphorus-fixing properties.

These data and those on yields in the residual phosphorus studies give quantitative data on the amount and availability of phosphorus added to three soils. The retention of phosphorus often considered as a problem in phosphorus fertilization appears to be a favorable factor in fertilization of vegetable crops. While a relatively low percentage of the phosphorus added is used, nevertheless it is securely held by the soil for use at a later date.

Data on this phase of the study and on relative yields from different rates of phosphorus application would indicate that vegetable crops might make maximum or near-maximum yields

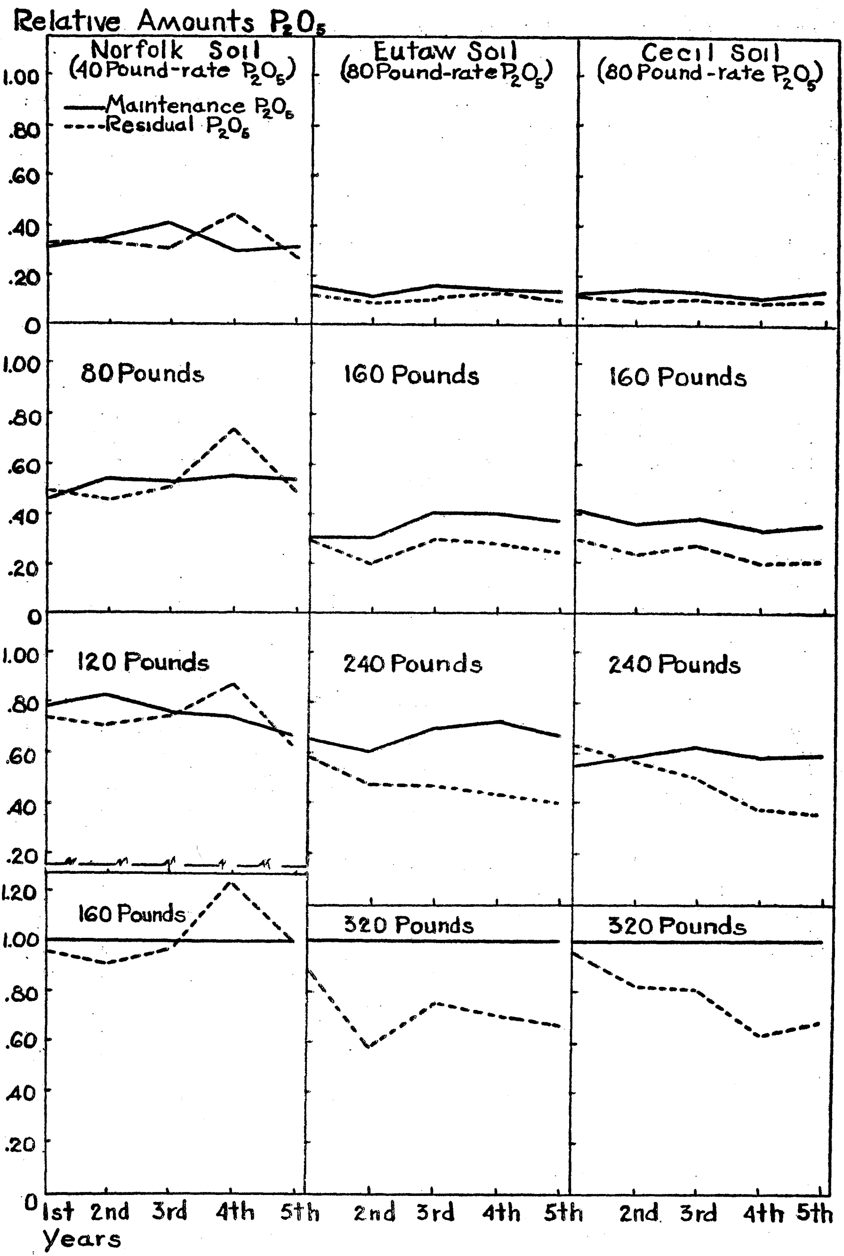

FIGURE 7. Relative amounts of dilute acid-soluble P_2O_5 by years from residual phosphorus. Phosphorus was applied for 9 years at indicated rates. Determinations for available P_2O_5 were made each year from the 10th through the 14th year. Maintenance rates of the residual period were one-half of the rates used in the first period.

TABLE 17. ACTUAL AND RELATIVE AMOUNTS OF DILUTE ACID-SOLUBLE PHOSPHORUS FROM RESIDUAL AND PHOSPHORUS MAINTENANCE APPLICATIONS

P_2O_5 per acre applied 9 years [1]	Amounts of P_2O_5 per acre by years [2]					Relative amounts of phosphorus by years [3]				
	1943	1944	1945	1946	1947	1943	1944	1945	1946	1947
Lb.	*p.p.m.*	*p.p.m.*	*p.p.m.*	*p.p.m.*	*p.p.m.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*
Norfolk soil	Maintenance application of phosphate [1]									
0	19	22	25	25	32	18	20	23	17	24
40	33	38	44	41	43	32	35	41	28	32
80	48	58	57	70	71	46	54	53	48	54
120	81	90	81	106	88	78	83	76	73	67
160	103	108	108	146	132	100	100	100	100	100
	Residual phosphorus [1]									
0	22	22	28	25	31	21	20	26	17	23
40	34	37	34	45	36	33	34	31	31	27
80	49	49	55	77	65	48	46	51	53	49
120	76	78	81	95	83	74	72	75	65	63
160	99	100	105	136	129	96	92	97	93	98
Eutaw soil	Maintenance application of phosphorus									
0	10	13	10	19	10	4	4	4	6	4
80	34	39	38	45	34	16	12	16	15	14
160	70	100	100	122	93	32	32	42	42	38
240	144	191	164	214	164	66	61	70	73	67
320	218	314	236	293	245	100	100	100	100	100
	Residual phosphorus									
0	7	11	10	16	9	3	4	4	6	4
80	28	31	28	40	28	13	10	12	14	11
160	64	68	75	84	61	29	22	32	29	25
240	127	149	114	132	101	58	48	48	45	41
320	194	187	182	212	164	89	60	77	72	67
Cecil soil	Maintenance application of phosphorus									
0	5	7	9	8	9	3	4	4	4	4
80	22	30	31	25	31	13	15	14	12	14
160	72	71	82	74	79	42	36	39	34	36
240	99	117	135	126	129	57	59	63	58	59
320	172	199	212	218	220	100	100	100	100	100
	Residual phosphorus									
0	3	7	10	7	8	2	3	5	3	4
80	20	21	25	21	22	12	11	12	10	10
160	51	49	59	45	48	30	25	28	21	22
240	108	114	108	84	81	63	57	51	39	37
320	163	166	173	141	152	95	83	82	64	69

[1] Rates applied annually for 9 years; no further application was made on the residual plots; and ½ of original rates were applied to phosphorus-maintenance plots.

[2] As determined by Truog's improved methods.

[3] Relative amount of phosphorus in percentage of the amount in the reference plots which received highest phosphorus applications for 9 years and highest maintenance applications for residual period.

on much less phosphorus than is now applied on land used continuously for vegetable crops. The data also indicate that on soils heavily fertilized with phosphorus, applications may be withheld for a few years without serious loss in yield.

CHANGES IN THE REQUIRED RATES OF PHOSPHORUS AFTER REPEATED APPLICATIONS. On a soil fertilized for the first time, only the phosphorus applied at that time plus the naturally available phosphorus of the soil is available to the crop. After phosphorus has been applied a few years, crops will draw on the residual phosphorus in addition to that added currently.

To obtain some measure of the change in phosphorus requirements of crops, the relative yields of a number of crops fertilized at different rates were averaged for each of the first 4 years. The crops for each period compared were identical. The results are presented in Figure 8.

The spread between the curves serves as a measure of the effects of residual phosphorus. The average relative yield of 15 crops was about as high or higher on the Eutaw soil and almost as high on the Cecil soil at the 160-pound rate of P_2O_5 by the fourth year as it was at the 240- and the 320-pound rates for the first and second years. The 80-pound rate of P_2O_5 on the Norfolk soil by the 4th year was giving a relative yield about as high as or higher than the 120- and 160-pound rates the first and second years.

These data suggest the advisability that current phosphorus applications be based on past applications to a given soil.

CHANGES IN SOIL PHOSPHORUS DURING THE INVESTIGATION

To obtain data on changes in soil phosphorus during the experiment, one of the five sets or sections of bins was chosen for detailed study. On this section, tabulations were made of all phosphorus added by fertilizers and all phosphorus absorbed and removed by harvested crops at each of the five rates of phosphorus application for the first 9 years. All plant residues from these crops remained on the plots. The data for phosphorus absorbed account only for the phosphorus in harvested crops, for which records of yield and phosphorus content were obtained. The actual amount absorbed, therefore, was in excess of the determined amounts to the extent of the crops grown but not recorded. (See footnote 3. Table 18).

An analysis was made in 1945 of the three soils in each rate

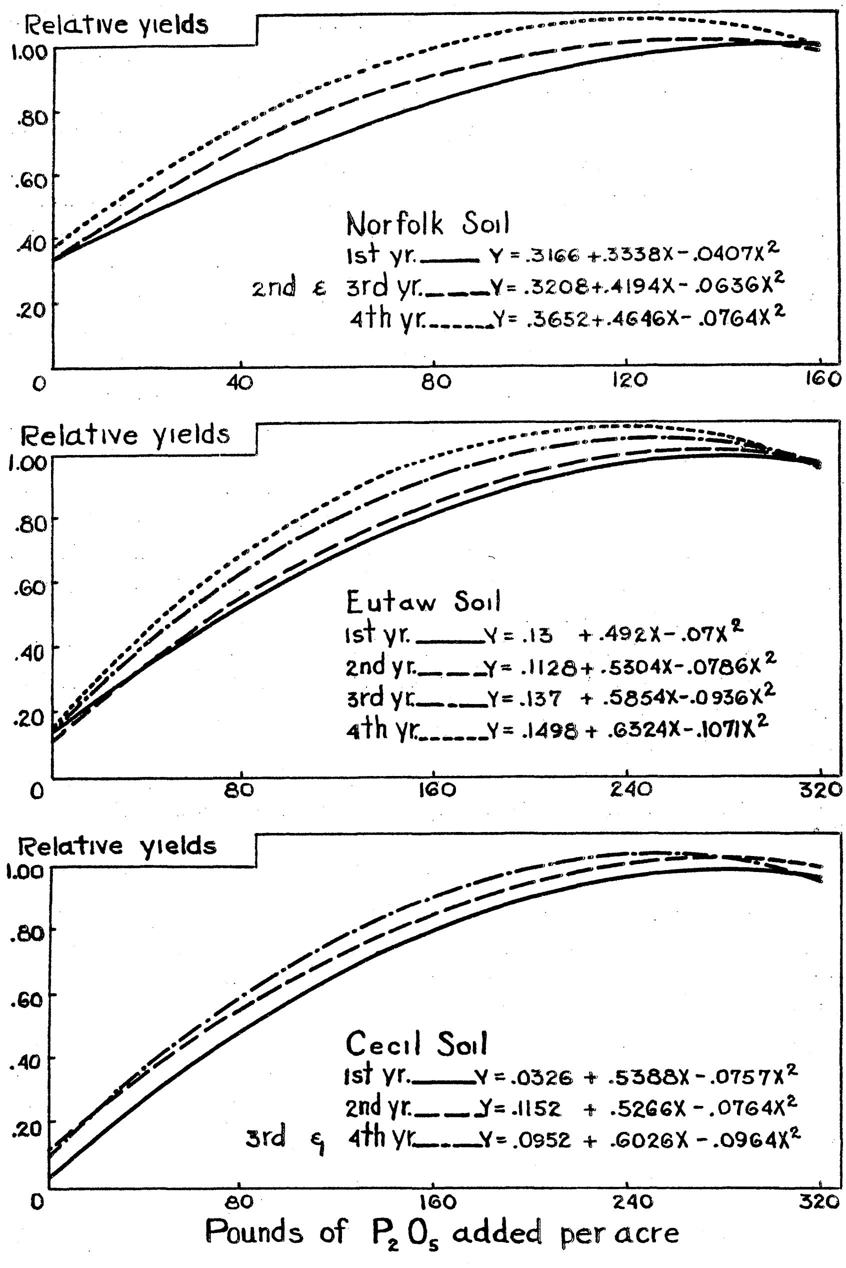

FIGURE 8. Average relative yields by years of 15 vegetable crops grown for the first 4 years on different soils receiving different rates of phosphorus.

TABLE 18. PHOSPHORUS ADDITIONS AND REMOVALS FOR THE 9-YEAR PERIOD, 1933-1942

Item	Amt. P_2O_5 added, absorbed, and removed from phosphorus applications at different rates per acre[1]				
	0 lb.	40 lb.	80 lb.	120 lb.	160 lb.
Norfolk soil					
P_2O_5 added 1933-1942[2], lb. per acre	0	360	720	1080	1440
P_2O_5 absorbed by harvested crops[3], lb. per acre	93	191	296	347	359
P_2O_5 removed from plots, lb. per acre	59	125	214	257	262
Net additions, P_2O_5, lb. per acre	–59	235	506	823	1178
Absorbed by harvested crops, per cent		53.0	41.1	32.1	24.9
Removed by harvested crops, per cent		34.7	29.7	23.8	18.1
	0 lb.	80 lb.	160 lb.	240 lb.	320 lb.
Eutaw soil					
P_2O_5 added 1933-1942[2], lb. per acre	0	720	1440	2160	2880
P_2O_5 absorbed by harvested crops[3], lb. per acre	56	230	333	420	461
P_2O_5 removed from plots, lb. per acre	24	161	247	314	343
Net additions, P_2O_5, lb. per acre	–24	559	1193	1846	2537
Absorbed by harvested crops, per cent		31.9	23.1	19.4	16.0
Removed by harvested crops, per cent		22.4	17.2	14.5	11.9
Cecil soil					
P_2O_5 added 1933-1942[2], lb. per acre	0	720	1440	2160	2880
P_2O_5 absorbed by harvested crops[3], lb. per acre	21	190	310	366	483
P_2O_5 removed from plots, lb. per acre	10	137	231	267	297
Net additions, P_2O_5, lb. per acre	–10	583	1209	1893	2583
Absorbed by harvested crops, per cent		26.3	21.5	16.9	16.8
Removed by harvested crops, per cent		19.0	16.0	12.4	10.3

[1] Data obtained from section B of the bins.
[2] Period from fall 1933 through summer 1942.
[3] Does not include phosphorus absorbed by one crop of eggplant destroyed by disease, one crop of Chinese cabbage killed by unexpected hard freeze, and one fall potato crop failure due to stand; all residues from these crops remained on the plots.

treatment to determine total and exchangeable phosphorus. Prior to 1945 the equivalent of 10 annual applications of phosphorus had been made. From the data, balance sheets were prepared. These data are presented in Tables 18, 19, and 20.

PHOSPHORUS ADDITIONS AND REMOVALS. In Table 18 are given the total amounts of phosphorus added from fertilizers and removed by crops. The amounts of phosphorus absorbed by the harvested crops are also given. The net additions, as given, represent the difference between the amounts of phosphorus added by fertilizer and the amounts removed from plots.

The removals of P_2O_5 from the bins of Norfolk soil were 59,

TABLE 19. PHOSPHORUS ADDED, REMOVED, LEFT IN SOIL, AND AMOUNT FOUND BY ANALYSIS [1]

Phosphorus (P_2O_5) applied per acre [2]	P_2O_5 per acre					
	Calculated amount in original soil [3]	Amount added 1933-44	P_2O_5 in soil plus amount added	Removed by plants 1933-44	Amount theoretically in soil	Amount found by analysis 1945 [4]
	Pounds	*Pounds*	*Pounds*	*Pounds*	*Pounds*	*Pounds*
Norfolk soil						
0	1,211	0	1,211	66	1,145	1,145
40	1,211	400	1,611	150	1,461	1,330
80	1,211	800	2,011	253	1,758	1,803
120	1,211	1,200	2,411	300	2,111	2,078
160	1,211	1,600	2,811	307	2,504	2,405
Eutaw soil						
0	1,212	0	1,212	34	1,178	1,178
80	1,212	800	2,012	183	1,829	1,646
160	1,212	1,600	2,812	285	2,527	2,190
240	1,212	2,400	3,612	352	3,260	2,958
320	1,212	3,200	4,412	390	4,022	3,582
Cecil soil						
0	1,753	0	1,753	11	1,742	1,742
80	1,753	800	2,553	149	2,404	2,144
160	1,753	1,600	3,353	249	3,104	2,628
240	1,753	2,400	4,153	292	3,861	3,051
320	1,753	3,200	4,953	326	4,627	3,899

[1] Data obtained from soil in section B of bins.

[2] This amount of P_2O_5 was applied each year for the first 9 years and one-half this amount was applied each year for the last 2 years. Ninety pounds of N and 45 pounds K_2O per acre per crop were used with all rates of P_2O_5.

[3] Caluculated from final analysis data by adding amount removed by plants.

[4] Data from analysis by Department of Agronomy and Soils, Alabama Agricultural Experiment Station.

125, 214, 257, and 262 pounds per acre for the 40-pound increments ranging from 0 to 160 pounds per acre. Removals from the Eutaw soil were 24, 161, 247, 314, and 343 pounds, and from the Cecil soil 10, 137, 231, 267, and 297 pounds per acre for 80-pound increments ranging from 0 to 320 pounds per acre.

It will be noted that the amounts of phosphorus removed from the plots receiving no phosphorus were 59 pounds per acre from Norfolk soil, 24 pounds from Eutaw soil, and 10 pounds from Cecil soil. These data give a fair indication of relative availability of natural phosphorus in the three soils.

When all additions and removals of phosphorus from the bins are taken into account, the net additions on the Norfolk ranged from —59 pounds per acre of P_2O_5 on the no-phosphorus plots to

1,178 pounds on the plots receiving 160 pounds per acre of P_2O_5; on the Eutaw soil, the range was from —24 to 2,537 pounds, and on the Cecil from —10 to 2,583 pounds per acre of P_2O_5.

Under conditions of the experiment that included adverse weather, disease, and crop failure, the removals expressed as percentage of the phosphorus added to the Norfolk soil ranged from 34.7 to 18.1 per cent as the rates increased from 40 to 160 pounds per acre of P_2O_5. The percentage removals from the Eutaw soil ranged from 22.4 to 11.9 per cent, and from the Cecil soil 19.0 to 10.3 per cent as the rate increased from 80 to 320 pounds per acre.

These data show, as do those presented earlier, that only a small part of the phosphorus added to the soil actually is removed in the used portions of the crops. They also show a decrease in the percentage of phosphorus used as the rates of phosphorus application increase.

TABLE 20. EXCHANGEABLE PHOSPHORUS, PERCENTAGE OF PHOSPHORUS SATURATION, AND ANION-EXCHANGE CAPACITY AS SHOWN BY ANALYSIS, 1945[1]

P_2O_5 applied		Exchangeable phosphorus		Phosphorus saturation	Anion-exchange capacity P_2O_5 per acre
Per year per acre[2]	Total amount (1933-44)	P per 100g	P_2O_5 per acre		
Pounds	*Pounds*	*Millimol*	*Pounds*	*Per cent*	*Pounds*
Norfolk soil					
0	0	0.38	675	19	3,477
40	400	0.48	853	25	3,477
80	800	0.61	1,083	31	3,477
120	1,200	0.69	1,225	35	3,477
160	1,600	0.85	1,509	44	3,477
Eutaw soil					
0	0	0.72	971	4.5	21,514
80	800	0.73	985	4.6	21,514
160	1,600	1.18	1,592	7.4	21,514
240	2,400	1.64	2,213	10.3	21,514
320	3,200	2.00	2,698	12.5	
Cecil soil					
0	0	0.35	522	5.8	9,045
80	800	0.55	820	9.1	9,045
160	1,600	0.87	1,297	14.4	9,045
240	2,400	1.15	1,715	19.0	9,045
320	3,200	1.38	2,058	22.8	9,045

[1] Data from analysis by USDA Bureau of Plant Industry, Soils, and Agricultural Engineering.

[2] This amount of P_2O_5 was applied each year for the first 9 years and one-half of this amount was applied each year for the last 2 years. Ninety pounds of N and 45 pounds K_2O per acre per crop were used with all rates of P_2O_5.

PHOSPHORUS BALANCE SHEET. The study of phosphorus additions and removals indicates that repeated applications of phosphorus for a number of years result in additions far in excess of removals. Investigations have universally shown that this surplus phosphorus is held by the soil. In 1945, total phosphorus determinations were made. In Table 19 data are given showing the total amounts of phosphorus added and removed during the period 1933-44, the amounts theoretically remaining at the end of the period, and the amounts found by analysis.

On plots receiving the highest phosphorus rate, the Norfolk was found to have 2,405 pounds per acre of P_2O_5, as compared with the theoretical amount of 2,504 pounds; the Eutaw, 3,582 pounds as compared with 4,022 pounds; and the Cecil, 3,899 pounds as compared with 4,627 pounds. Theoretical and indicated amounts showed about the same relationship for the other rates of application.

It is pointed out that the plots were enclosed by concrete walls as boundaries, which prevented run-off of a large portion of muddy water during heavy rains. This partially accounts for the relatively high recovery of phosphorus at the end of the period.

EXCHANGEABLE PHOSPHORUS AND DEGREE OF PHOSPHORUS SATURATION. In Table 20 are given the amounts of exchangeable phosphorus in the three soils after they had received the equivalent of 10 annual applications of phosphorus. The total anion-exchange capacity in terms of P_2O_5 for each soil and the percentage of phosphorus saturation are given. The Norfolk soil after receiving 10 applications of 160 pounds per acre of P_2O_5 had reached a phosphorus saturation of 44 per cent. Phosphorus saturation of the Eutaw soil after 10 applications of 320 pounds per acre of P_2O_5 was 12.5 per cent, and of the Cecil soil 22.8 per cent. The percentage of saturation ranged from 19 per cent to 44 per cent on the Norfolk, from 4.5 to 12.5 on the Eutaw, and from 5.8 to 22.8 on the Cecil soil.

DISCUSSION

DIFFERENCES IN PHOSPHORUS ABSORPTION BY PLANTS

The data resulting from this study show that great differences do exist among vegetables in regard to their ability or capacity to absorb phosphorus from soil in which there is only a limited amount readily available. These differences are striking. Data in Table 8 show an average absorption of P_2O_5 on three soils by the different vegetables, ranging from 0.23 pounds per acre for kale to 18.82 pounds for sweetpotatoes. Lieleland and others *(21)* found that Aiken clay loam soil near Paradise in the Sierra foothills had a very low amount of available phosphorus and a very high phosphorus-fixing capacity, which was about 10 times that of other apparently similar soils in California. While six different fruits showed no phosphorus response, the yield of such crops as cucumbers was increased 13.3 times and that of squash 29.4 times by the application of phosphorus.

The explanation offered by Truog *(41)* would attribute the differences largely to qualitative factors related to the chemistry of the material needed and used by the plant in its metabolism, in addition to the liberation of carbon dioxide by the roots. According to his explanation, plants absorbing large quantities of calcium had relatively high phosphorus-feeding power. Unpublished results from work preliminary to the study at the Alabama Station showed that large quantities of phosphorus in the seed or vegetative parts used in propagation gave larger root development in cultures lacking phosphorus, and that these larger root systems absorbed more phosphorus on soils low in phosphorus than plants with less phosphorus in the propagating parts.

Lima beans (Table 8) on soils receiving no phosphorus absorbed 16.72 pounds of P_2O_5 per acre under conditions where turnips absorbed 5.99 pounds and collards absorbed only 0.74 pounds. This comparison indicates that there are strong qualitative differences in the ability of crops to absorb phosphorus. Yet, the fact that turnips having a low phosphorus-absorbing power and a very high phosphorus requirement can develop a large root system with a very small application of phosphorus, absorb several times the amount applied, and make near-maximum yields would indicate that size of the root system is a factor to consider in the ability of a crop to absorb the required amount of phosphorus for full production.

The significant contribution of this study is the establishment of the facts that vegetable crops do differ greatly in their ability to absorb phosphorus, and that they may be grouped according to their capacities to absorb this element.

DIFFERENCES IN PHOSPHORUS ABSORPTION AS AFFECTED BY SOIL PROPERTIES

The three soils used in this experiment varied greatly in properties and characteristics, as shown in Tables 1 and 2.

The extent of differences in availability of phosphorus contained in the soils selected for use in this investigation may be seen from the data in Table 8. The total amount of phosphorus absorbed annually by the 25 crops on the Norfolk soil was equivalent to 149.45 pounds per acre of P_2O_5, on the Eutaw soil 103.63 pounds, and on the Cecil soil 42.40 pounds.

The Norfolk soil had a lower colloid content and could not absorb as much phosphorus as the Cecil soil; yet, it had more exchangeable phosphorus and a much higher percentage of its total anion-exchange capacity as exchangeable phosphorus than the Cecil soil. It, therefore, gave up over three times as much phosphorus to the crops grown than the Cecil soil. Although the percentage of phosphorus saturation in the Eutaw soil was somewhat smaller that that in the Cecil soil, indicating that the phosphorus might be more tightly held, this soil with about 67 per cent more exchangeable phosphorus released 103.63 pounds or twice as much as the Cecil soil.

The amounts absorbed by the same crops on soils receiving enough phosphorus to give maximum yield were quite different than the amounts absorbed on the same soils receiving no phosphorus. The amounts removed annually by 25 crops fertilized at rates to give maximum production were equivalent to 444 pounds per acre of P_2O_5 on the Norfolk, 612 pounds on the Eutaw, and 525 pounds on the Cecil soil, Table 7. The Cecil had thus released more phosphorus than the Norfolk soil. There was usually an average of 30 to 40 per cent more exchangeable phosphorus in the Cecil than in the Norfolk soil at maximum crop-production levels, although the percentage of phosphorus saturation was still much lower on the Cecil than on the Norfolk soil.

Data from the investigation reveal that differences exist in the ability of different crops to absorb phosphorus from different soils, as shown in Table 8. Many investigators *(2, 17, 21, 26, 31)* found that plants vary in capacity to obtain less readily available phosphorus from the soil. Where no phosphorus was added, turnips absorbed 14.62 pounds per acre of P_2O_5 on the Norfolk soil, but absorbed only 0.74 pounds on the Cecil. Carrots by contrast absorbed only 7.05 pounds per acre of P_2O_5 on the Norfolk soil but absorbed 2.8 pounds on the Cecil soil. The carrot, therefore, had absorbed only one-half as much phosphorus as the turnip on the Norfolk but 4 times as much on the Cecil soil. In the order of phosphorus absorbed, turnips would rank 4th on the Norfolk but 11th on the Cecil soil, while carrots would rank 8th on the Norfolk soil and 5th on the Cecil.

Phosphorus Utilization Efficiency as Affected by Rates of Phosphorus Application on Different Soils

The total amount of phosphorus absorbed per acre annually by 25 crops increased on each soil as the amount of phosphorus applied was increased (Appendix Table I). The percentage of phosphorus added that was absorbed, however, decreased on each soil as the amount of phosphorus applied increased (Tables 10, 18, 19, 20). It is obvious that the principle of diminishing returns applies to the absorption of phosphorus and its use by the plant. To the grower this fact is of economic importance.

As the rates of phosphorus increase, the total amount of phosphorus, the amount of exchangeable phosphorus, and the percentage of phosphorus in exchangeable form in the soil increases (Table 20). These factors all tend to increase the amount of phosphorus available to plants. Plants, however, are inherently able to use only so much phosphorus. There develops, therefore, a quantity of phosphorus in the soil in excess of plant needs. While yields may continue to increase because of this excess amount of phosphorus, increases are made at increasingly higher costs and at increasingly lower efficiency from a standpoint of phosphorus utilization by the plant.

At the lowest rate of phosphorus application, especially on the Norfolk soil, there was a high percentage of utilization. This was 87 per cent for the 25 crops, and a number of crops absorbed considerably more phosphorus than was applied. Many plants on soils with a low-fixation capacity may make extremely efficient use of the phosphorus when applied at low rates, but this efficiency in utilization is greatly reduced at higher rates of phosphorus application (Table 10). The average percentage of phosphorus absorbed of that added on the Norfolk soil decreased from 87 to 34 per cent as the amount applied increased from 40 to 160 pounds per acre of P_2O_5. The decrease on the Eutaw soil was from 58 to 24 per cent, and on the Cecil soil from

40 to 20 per cent. These decreases have a definite bearing on the cost of production per unit under light and heavy applications of phosphorus.

Two additional points should be made with reference to diminishing returns from phosphorus at high rates of application. One applies to the plant's performance; both points apply to the economics of production. The points may be illustrated by data in Table 11 and Appendix Table 1. Potatoes may be used as an example. As the phosphorus was increased on Norfolk soil, relative yields increased from 75 to 90 to 96 to 100 per cent. The increases in phosphorus application were in the ratio of 1 : 2 : 3 : 4. The relative increases in yield were 20, 28, and 33 per cent. For an increase in phosphorus application of 300 per cent, there was an increase in yield of 33 per cent.

In addition to the very great difference in increased rates of phosphorus application and crop yields, there is a difference due to what amounts to a luxury consumption of phosphorus by plants receiving high rates of phosphorus. The work of Wright [3], conducted with vegetable crops as preliminary to this investigation, showed a higher percentage of phosphorus in plants grown at higher phosphorus rates. Thus, plants grown at higher rates of phosphorus not only gave increases in yields far below increases in the phosphorus applied but required increased amounts of phosphorus for each pound of yield made.

YIELDS OF DIFFERENT VEGETABLE CROPS AS RELATED TO OTHER FACTORS

The data in Table 8 and Appendix Table 1, and in Table 11 and Appendix Table 2 show a close relationship between the capacity of crops to absorb phosphorus and the actual and relative yields made. Crops absorbing high amounts of phosphorus from no-phosphorus or from low-phosphorus applications made high yields without phosphorus and with small applications of phosphorus. Relative yields of these crops were also correspondingly high at the zero- and low-phosphorus rates. Crops shown in Table 8 and Appendix Table 1 are arranged in order of phosphorus absorption; in Table 11 they are, likewise, arranged

[3]Wright, Lawrence. A study of the relationship between available soil phosphorus, soluble plant phosphorus, and growth of different vegetable crops on different soil types. Unpublished thesis, Ala. Poly. Inst. Library, 1932.

generally in order of relative yields made at zero- and low-phosphorus rates. The orders are very similar. As would also be expected, the amount of phosphorus absorbed and the relative yields at corresponding phosphorus rates were both highest on the Norfolk soil and lowest on the Cecil soil. The relationship of phosphorus-absorption capacity and yields is natural, since crops with high phosphorus-absorption capacities absorb more phosphorus, which in turn is converted into greater yields.

AVAILABILITY OF RESIDUAL PHOSPHORUS

Data presented in Tables 18 and 19 show quantitatively the additions, removals, theoretical accumulation, and actual accumulation of phosphorus on different soils where different amounts of phosphorus had been added over a period of 9 to 11 years. In Table 17 and Figure 7 are given quantitative data on the indicated availability of accumulated phosphorus by chemical tests. Data on the availability of accumulated phosphorus to plants are given in Table 16 and Figure 6. Figure 8 shows relative yields of crops from first and later applications of different rates of phosphorus. These data show that large quantities of phosphorus are added to the soil in excess of what is used by crops and that the excess phosphorus accumulates and is later available to crops for a period of years. They also show that the rates of fertilizer application may be reduced on land that has grown truck crops for a number of years and that has received repeated applications of high rates of phosphorus.

Economy and conservation in the use of phosphorus may be effected by greatly reducing the amount of phosphorus applied on land that has received large applications over previous years, and by reducing moderately, after several applications, the amount applied to land not previously used for production of truck crops. The fixation of phosphorus by soils, a factor considered a few years ago as wasteful of phosphorus, may yet prove a factor in its conservation provided erosion can be controlled.

SUMMARY

Experiments reported in this publication measured differences among vegetable crops in their phosphorus requirement, phosphorus - absorption capacity, phosphorus - absorption and phosphorus-utilization efficiencies, and response to increased applications of phosphorus on Norfolk sandy loam, Eutaw clay, and Cecil sandy clay soils.

The phosphorus requirement of different crops for maximum production ranged from 6.18 pounds per acre of P_2O_5 for fall lettuce to 54.35 pounds for turnips.

The phosphorus-feeding capacity of different crops, as measured by the amount of phosphorus absorbed with no phosphorus added, ranged from a low of 0.23 pounds per acre of P_2O_5 for kale to a high of 18.82 pounds for sweetpotatoes.

The phosphorus-absorption efficiency of different crops, as measured by the reciprocal ratio of P_2O_5 absorbed at the phosphorus rate giving maximum yield to the P_2O_5 absorbed at the zero-phosphorus rate, ranged from a low of 1.6 for kale to a high of 71 for lima beans.

The phosphorus utilization efficiency of different crops was measured by the percentage of phosphorus absorbed of the phosphorus added. This efficiency ranged from a low of 6 per cent for fall lettuce grown on the Cecil soil and fertilized at the highest phosphorus rate to a high of 244 per cent for sweetpotatoes grown on the Norfolk soil and fertilized at the lowest phosphorus rate.

The percentage of phosphorus absorbed of that added was highest on the Norfolk and lowest on the Cecil soil. Percentages absorbed on each soil were highest at the lowest rate of phosphorus application and were lowest at the highest application rate. The average absorption percentage of 25 crops ranged from 87 to 34 per cent on the Norfolk soil, from 58 to 24 per cent on the Eutaw soil, and from 40 to 20 on the Cecil soil.

Vegetable crops varied greatly in relative yields obtained from different rates of phosphorus applications expressed in percentage of the yield from the highest rates. Two crops, the sweet-

potato and the lima bean, gave yields about as high without phosphorus and from low rates of applications as from the highest rates used. Relative yields of a number of crops were 90 per cent as high from the lowest application as from the highest applications, whereas relative yields of others were only 50 per cent as high.

The type of response of a given crop was affected by type of soil. Average relative yields of 26 different vegetable crops grown without phosphorus on the Norfolk sandy loam were 31 per cent, on the Eutaw clay 20 per cent, and on the Cecil clay 10 per cent of the average yields from the highest rates used. Average relative yields of the 26 crops from an application of 80-pounds per acre of P_2O_5 were: 90 per cent on the Norfolk soil, 68 per cent on the Eutaw soil, and 63 per cent on the Cecil soil.

The p. p. m. of dilute acid-soluble phosphorus, as determined by chemical test, were increased on the three soils by the addition of lime but only on one soil by the addition of organic matter.

Repeated applications of different rates of phosphorus over a period of 9 years resulted in accumulation of large quantities of phosphorus in the soil. Chemical tests indicated that considerable quantities of accumulated phosphorus were in a readily available form. The yield of turnips as an index crop showed that sufficient quantities of readily available phosphorus accumulated from the higher rates of applications of phosphorus during the first 9 years to give maximum or near-maximum yields over the next 5 years.

Based on average relative yields of 15 different vegetables, the Norfolk soil produced about as much by the fourth year from repeated applications of 80 and 120 pounds per acre of P_2O_5 as it did from 160 pounds per acre the first year. Relative yields on the Eutaw and Cecil soils, likewise, were about as high from four annual applications of 160 pounds per acre of P_2O_5 as those from 240 and 320 pounds per acre the first year.

Analysis of soil for total phosphorus after the equivalent of 10 annual applications accounted in a large measure for phosphorus additions, phosphorus removals, and original soil phosphorus. Analyses accounted for 96 per cent of the phosphorus in the Norfolk soil, 89 per cent in the Eutaw soil, and 84 per cent in the

Cecil soil in the plots receiving the highest phosphorus applications.

After the equivalent of 10 annual applications of phosphorus at the highest rates had been made, the phosphorus saturation percentages of total anion-exchange capacity for the three soils were: Norfolk, 44 per cent; Eutaw, 12.5 per cent; and Cecil, 22.8 per cent.

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APPENDIX

APPENDIX TABLE 1. ABSORPTION OF PHOSPHORUS BY DIFFERENT CROPS ON DIFFERENT SOILS RECEIVING DIFFERENT RATES OF PHOSPHORUS

Vegetable	P_2O_5 absorbed per acre by different crops on different soils receiving different rates of phosphorus														
	Pounds of P_2O_5 per acre applied to Norfolk soil					Pounds of P_2O_5 per acre applied to Eutaw soil					Pounds of P_2O_5 per acre applied to Cecil soil				
	0	40	80	120	160	0	80	160	240	320	0	80	160	240	320
	Lb.	*Lb.*	*Lb.*	*Lb.*	*Lb.*	*Lb.*	*Lb.*	*Lb.*	*Lb.*	*Lb.*	*Lb.*	*Lb.*	*Lb.*	*Lb.*	*Lb.*
Turnips	14.6	31.7	32.9	38.0	39.9	2.6	41.9	62.2	74.7	64.8	.7	27.2	44.8	48.5	52.3
Sweetpotatoes	20.6	24.4	30.4	28.4	30.9	26.2	37.9	41.2	43.8	44.2	9.7	26.1	27.6	32.2	38.4
Collards	1.8	15.6	23.0	26.0	25.1	.2	29.9	42.1	47.0	44.9	.2	19.1	31.1	37.8	37.2
Chinese Cabbage	4.2	18.8	29.4	32.7	32.3	1.0	25.5	32.9	37.1	42.9	.7	19.3	29.8	38.5	35.0
Tendergreen	4.8	14.8	21.7	21.7	22.0	.1	27.9	38.5	45.5	46.1	.2	17.6	24.3	30.2	30.6
Okra	15.8	20.2	21.1	20.6	22.2	13.7	24.8	28.0	33.0	33.2	4.6	15.8	24.9	30.3	32.5
Lima Beans	25.1	26.0	25.1	24.7	25.6	15.7	21.7	24.5	23.1	24.5	9.4	14.5	16.4	19.1	20.7
Cabbage	7.5	14.0	21.2	23.3	25.1	2.2	20.4	27.5	28.9	34.8	1.1	13.4	21.4	24.4	29.7
Squash	6.1	12.5	23.1	25.8	33.4	2.5	12.9	15.8	26.8	30.7	.3	9.0	21.3	26.3	31.4
Carrot	7.1	11.3	16.6	20.8	22.0	7.8	17.3	22.0	27.0	29.9	2.8	10.8	19.8	27.4	27.7
Pepper	5.1	11.4	13.7	17.3	16.6	6.9	16.0	19.8	24.7	29.1	2.1	13.8	16.0	21.6	23.5
Eggplant	5.2	13.5	17.3	17.9	18.6	3.8	16.8	14.8	22.1	23.1	1.4	6.1	8.8	10.0	12.8
N. Z. Spinach	2.6	8.4	11.5	12.9	13.8	.2	13.3	17.0	20.0	22.8	.2	11.5	14.4	17.4	15.2
Tomatoes, spr.	3.6	10.3	12.7	14.1	15.7	2.6	12.5	13.8	19.5	17.5	.3	6.6	12.1	14.7	16.2
Potatoes	9.5	11.0	12.2	13.7	14.9	5.8	9.6	13.9	15.3	17.2	3.2	6.9	9.4	12.6	15.2
Beans	7.8	11.9	12.0	14.2	15.2	5.1	11.2	13.7	17.1	17.6	1.7	6.1	8.4	9.9	11.1
Kale	.4	4.3	8.6	11.8	12.4	.2	7.5	13.1	16.5	17.7	.1	6.8	10.4	12.3	13.9
Beets	1.5	5.0	6.4	8.1	10.2	.2	4.9	8.7	13.5	15.6	.3	6.6	12.9	14.9	16.9
English Peas	1.5	3.9	5.7	7.4	8.2	2.9	8.7	10.2	12.3	13.2	1.3	6.1	10.4	12.5	13.8
Swiss Chard	.5	4.1	8.1	11.5	10.6	.2	2.2	3.4	6.5	7.2	.3	6.5	12.5	14.3	21.0
Radish	2.0	5.6	6.4	7.2	7.1	.7	7.5	10.1	9.7	9.3	.4	5.2	6.4	6.1	6.5
Endive	.3	2.2	4.4	6.5	6.9	.8	5.0	7.9	9.2	10.7	.1	3.0	7.7	9.1	11.7
Onion	.8	2.2	4.6	6.2	7.7	1.0	3.2	6.5	9.1	10.5	.5	2.8	5.5	8.7	9.4
Lettuce, spr.	.7	3.0	5.9	7.4	6.6	.3	2.1	3.7	6.2	6.7	.4	2.7	5.7	7.5	10.2
Lettuce, fall	.4	1.9	2.9	3.7	4.2	.7	3.3	4.8	7.7	8.2	.4	2.5	4.1	5.4	6.1
Total	149.5	288.1	376.9	424.6	447.2	103.6	383.9	495.8	596.2	622.3	42.4	265.8	406.2	491.6	539.0

APPENDIX TABLE 2. YIELDS OF DIFFERENT CROPS ON DIFFERENT SOILS RECEIVING DIFFERENT RATES OF PHOSPHORUS APPLICATIONS

Vegetable	Mean yields per acre on different soils receiving different amounts of phosphorus														
	Pounds of P_2O_5 per acre applied to Norfolk soil [1]					Pounds of P_2O_5 per acre applied to Eutaw soil [1]					Pounds of P_2O_5 per acre applied to Cecil soil [1]				
	0	40	80	120	160	0	80	160	240	320	0	80	160	240	320
Beans, bu.	72	132	153	175	190	53	152	211	250	273	10	66	98	136	148
Beans, Lima, bu.	213	207	193	203	205	167	200	211	205	211	96	145	170	190	201
Beets, lb.	1,815	8,445	9,912	10,958	11,066	286	7,829	12,662	15,969	16,948	447	9,352	16,322	16,316	16,624
Cabbage, lb.	10,860	20,080	26,820	27,360	27,260	2,860	27,000	32,520	33,120	35,400	1,280	19,380	27,500	28,880	30,020
Carrots, lb.	6,028	10,825	14,999	18,464	18,166	8,346	16,441	19,620	22,383	23,559	3,234	11,671	20,005	22,300	22,809
Chinese Cabbage, lb.	6,184	24,943	35,347	37,685	36,203	1,489	31,223	36,002	38,908	41,146	962	26,731	34,087	34,118	31,077
Collards, lb.	1,549	10,613	13,970	15,164	14,929	256	20,445	24,505	25,978	26,908	172	14,098	18,755	19,247	19,441
Eggplant, lb.	2,230	15,745	20,104	18,882	20,868	2,333	20,824	20,133	25,269	24,940	519	9,229	11,846	16,020	18,409
Endive, lb.	392	3,360	6,668	9,228	9,398	1,568	9,369	14,763	15,599	17,538	181	4,831	10,690	11,979	14,987
English Peas, lb.	591	1,553	2,153	2,354	2,405	1,301	3,532	3,609	3,679	3,599	571	2,780	3,780	3,640	3,887
Kale, lb.	410	4,178	6,420	7,889	8,079	251	6,182	8,951	10,377	11,169	132	5,939	7,324	7,705	8,525
Lettuce, spr., lb.	756	4,227	6,820	7,787	8,169	393	3,023	5,009	8,253	9,349	755	4,309	8,192	10,444	13,599
Lettuce, fall, lb.	536	2,236	3,273	4,014	4,246	725	3,598	5,365	8,316	9,611	506	3,103	5,027	6,386	6,914
N. Z. Spinach, lb.	4,471	13,370	16,300	18,396	19,027	511	24,216	27,341	31,047	29,244	261	16,415	18,172	22,575	17,584
Okra, lb.	3,669	3,937	5,039	3,596	4,520	3,587	5,252	5,312	5,693	6,482	1,443	3,386	5,245	4,994	4,676
Onions, lb.	1,205	3,145	5,236	5,962	6,665	1,856	4,368	8,365	9,789	10,581	876	4,067	7,243	9,481	9,306
Pepper, lb.	5,257	12,009	13,501	19,224	16,490	7,387	17,090	19,600	23,104	30,405	2,015	14,639	17,511	19,318	20,467
Potatoes, bu.	93	123	147	158	164	79	148	216	245	251	45	123	165	180	196
Radish, lb.	2,617	6,404	6,772	7,234	6,736	1,042	9,138	10,502	10,483	9,524	573	6,025	6,523	6,400	6,733
Squash, lb.	2,374	9,284	16,832	16,355	18,542	1,096	10,280	14,118	16,464	16,650	8	6,661	11,124	12,063	12,806
Sweetpotatoes, bu.	469	495	511	447	500	453	428	440	444	453	227	376	392	436	399
Swiss Chard, lb.	807	7,158	12,288	14,403	14,447	560	3,983	5,543	8,195	8,781	643	10,559	15,380	17,905	20,738
Tendergreen, lb.	4,149	10,921	13,903	13,514	12,096	142	17,457	19,521	21,421	21,134	161	12,246	14,148	15,746	15,308
Tomatoes, spr., lb.	6,988	17,548	21,867	22,977	23,815	5,552	17,071	18,641	21,592	18,625	634	10,684	17,180	18,408	17,576
Tomatoes, sum., lb.	3,367	6,268	10,862	12,647	14,912	1,020	7,022	12,889	18,401	18,110	455	5,728	8,613	8,009	12,084
Turnips, lb.	13,648	27,224	30,359	29,985	31,152	3,438	36,225	42,529	45,108	42,583	835	26,858	31,672	35,106	34,207

[1] Pounds of P_2O_5 per acre per year, 1/3 to each of 3 crops.

APPENDIX TABLE 3. STATISTICAL VALUES ON CROP YIELDS

Vegetable	"F" values for differences in yields between rates of phosphorus applications on different soils [1]			Coefficient of variation		
	Norfolk soil	Eutaw soil	Cecil soil	Norfolk soil	Eutaw soil	Cecil soil
				Pct.	*Pct.*	*Pct.*
Bean	195**	36**	43**	7.06	9.14	15.40
Beans, Lima	6.0	.94	245**	4.28	10.61	9.18
Beets	84.6**	59.12**	26*	15.34	7.30	11.52
Cabbage	7.41	22.12*	36.88**	8.40	3.72	5.78
C. Cabbage	142.00**	7.28	5.69	10.93	10.56	9.40
Carrots	144.6**	79.0**	68.82**	6.14	13.96	20.49 [2]
Chard	20.5*	1.32	107.0**	20.43 [2]	44.25 [2]	10.22
Collards	9.0*	14.3*	23.46*	17.79	5.75	10.29
Eggplant	1.99	1.35	4.90	14.96	22.89 [2]	29.87 [2]
Endive	65.5**	19.20*	76.5**	11.81	12.90	5.71
Kale	3.77	14.6*	12.7*	39.48 [2]	20.45 [2]	5.32
Lettuce, spr.	11.97*	604**	52**	22.31 [2]	12.52	10.47
Lettuce, fall	61.61**	481.56**	22.84*	22.48 [2]	10.64	28.62 [2]
Okra	19.3*	2.65	3.61	5.94	18.72	15.34
Onion	467.7**	43.89**	529.4**	10.58	13.80	8.25
Peas, English	4.59	.70	172.0**	12.93	4.69	5.76
Pepper	6.26	13.15*	14.0*	32.79 [2]	21.46 [2]	16.54
Potato	23.23*	17.0*	31.00**	14.29	15.95	7.24
Radish	1.06	3.88	.59	18.88	8.65	18.80
Spinach, N. Z.	4.83	2.23	.97	25.64 [2]	25.46 [2]	32.44 [2]
Squash	34.92**	3.20	10.59*	17.48	16.18	17.72
Sweetpotato	2.30	.44	1.47	11.25	12.68	14.46
Tendergreen	2.1	16.19*	84.9**	12.52	7.47	8.59
Tomato, sum.	4.09	.73	1.60	14.98	13.55	21.00 [2]
Tomato, spr.	37.3**	42.26**	11.21*	22.59	19.98	29.13 [2]
Turnip	2.3	5.6	57.95**	4.51	7.82	6.84

[1] *Significant at .05 degree level; **significant at .01 degree level.
[2] Figures considered too high for high confidence except when "F" values are highly significant.

APPENDIX TABLE 4. STATISTICAL DATA ON CROP YIELDS

Vegetable	Unit per acre	Least significant difference between treatments for different crops on different soils — 5 per cent level		
		Norfolk soil	Eutaw soil	Cecil soil
Beans	Bushels	10.14	38.28	26.31
Beans, Lima	Bushels	12.70	31.61	7.18
Beets	Pounds	594	2,320	3,128
Cabbage	Pounds	5,786	3,482	3,558
Carrots	Pounds	1,331	1,605	2,800
Chard	Pounds	3,406	8,844*	1,877
Chinese Cabbage	Pounds	2,196	7,193	6,579
Collards	Pounds	3,079	3,820	2,512
Eggplant	Pounds	7,194	10,390*	8,372*
Endive	Pounds	1,572	3,591	2,192
Kale	Pounds	4,173	2,578	1,360
Lettuce, spr.	Pounds	2,310	534	2,436
Lettuce, fall	Pounds	519	567	1,590
N. Z. Spinach	Pounds	5,222*	8,789*	10,433*
Okra	Pounds	652	1,569	1,956
Onion	Pounds	316	1,875	493
Peas, English	Pounds	819	326	173
Pepper	Pounds	5,772*	6,998*	3,061
Potatoes	Bushels	20.91	52.53	26.09
Radish	Pounds	1,487	1,468	1,851
Squash	Pounds	3,112	7,465	3,809
Sweetpotatoes	Bushels	85	70	93
Tendergreen	Pounds	4,260	2,165	650
Tomatoes, spr.	Pounds	6,198*	9,952*	12,072*
Tomatoes, sum.	Pounds	2,699	3,765	3,528
Turnips	Pounds	5,033	7,209	2,158

*Differences too large to establish high confidence in data.

APPENDIX TABLE 5. STATISTICAL DATA FOR YIELDS OF TURNIPS IN RESIDUAL PHOSPHORUS PLOTS

Soils	Year	Statistical values for crop yields by year on different soils [1]		
		Coefficient of variation	"F" values—difference between treatments [2]	Least significant difference between treatments at .05 level
		Per Cent		*Pounds per acre*
Norfolk				
	1943	43.77 [3]	1.06 [3]	11,597 [3]
	1944	14.40	12.25	3,750
	1945	12.92	10.82	9,018
	1946	13.90	20.86	7,258
	1947	25.32 [3]	10.28	10,349 [3]
Eutaw				
	1943	12.60	11.91	8,794
	1944	7.61	23.88	4,250
	1945	8.78	12.49	7,494
	1946	6.97	28.34	5,747
	1947	12.70	14.60	9,651
Cecil				
	1943	18.39	10.62	4,371
	1944	24.41 [3]	4.73	9,126 [3]
	1945	10.54	15.03	6,797
	1946	15.91	13.67	9,990
	1947	10.26	51.00	5,523

[1] Data for yields in residual and phosphorus-maintenance plots used in determining statistical value.

[2] "F" values required for significance at .01 level = 7.00 and at .05 level = 3.79.

[3] Figures considered unsatisfactory for high confidence.

APPENDIX TABLE 6. THEORETICAL RATE OF PHOSPHORUS APPLICATION FOR MAXIMUM YIELDS, FOR ZERO YIELDS, AND SLOPE OF LINE FROM YIELD AT ZERO RATE TO THEORETICAL MAXIMUM RATE FOR DIFFERENT VEGETABLE CROPS ON DIFFERENT SOILS[1]

Vegetable	Phosphorus rate per acre for maximum yield			Phosphorus rate per acre for zero yield			Slope of line between yield at zero rate and yield at maximum rate		
	Norfolk soil	Eutaw soil	Cecil soil	Norfolk soil	Eutaw soil	Cecil soil	Norfolk soil	Eutaw soil	Cecil soil
	Lb.	*Lb.*	*Lb.*	*Lb.*	*Lb.*	*Lb.*	*Pct.*	*Pct.*	*Pct.*
Beans	164	336	392	— 49	— 40	— 14	14	19	20
Beans, Lima	92	232	344*	no pt.	—283*	—141*	— 3	7	12
Beets	124	320	248	— 14	— 4	— 4	27	25	33
Cabbage	124	240	248	— 35	— 18	— 9	21	30	31
Carrots	160	304	288	— 32	— 79	— 20	18	16	24
Chinese Cabbage	120	248	216	— 12	— 14	— 8	30	30	41
Collards	120	240	240	— 8	— 9	— 7	31	33	34
Eggplants	120	248	384*	— 11	— 22	— 12	29	28	20
Endive	184	296	424*	— 1	— 17	— .4	23	24	20
English Peas	136	216	240	— 21	— 60	— 25	22	25	28
Kale	108	288	256	— 4	— 6	— 11	26	26	29
Lettuce, spr.	148	856*	848*	— 7	— 8	— 14	25	15	15
Lettuce, fall	160	816*	352*	— 12	— 22	— 13	22	15	21
N. Z. Spinach	136	232	216	— 21	— 10	— 6	22	35	44
Okra	112	400*	232	—171*	—224*	— 38	5	8	28
Onions	180	376*	320	— 18	— 31	— 11	19	19	24
Pepper	136	960*	256	— 27	—103	— 22	22	10	27
Potato	160	312	296	— 85	— 62	— 46	11	18	20
Radish	112	216	224	— 31	— 18	— 21	24	38	33
Squash	144	264	248	— 10	— 13	— 3	24	28	25
Sweetpotatoes	92	112	224	—640*	no pt.	—111*	.4	— 2	18
Swiss Chard	140	416*	320	— 4	— 14	— 10	28	19	23
Tendergreen	108	232	232	— 21	— 10	— 8	31	35	35
Tomatoes, spr.	128	224	248	— 26	— 42	— 5	22	29	34
Turnips	120	224	232	— 43	— 15	— 9	18	35	35

[1]Results based on annual applications of phosphorus (P_2O_5), with three crops being grown per year on same area.
*Figures considered unsatisfactory for high confidence.