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Effect of LIME LEVEL and SOIL pH on Selected Crops and Their Responses to Phosphate and Manure

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EFFECT OF LIME LEVEL AND SOIL pH ON SELECTED CROPS AND THEIR RESPONSES TO PHOSPHATE AND MANURE

E. E. BARNES[1], C. A. LAMB and G. W. VOLK

INTRODUCTION

The use of lime as a soil amendment extends back many centuries. According to Russell (5), the Latin writer Pliny described its use in Roman agriculture. Crops were improved, but the reasons for improvement were not understood. Little was known concerning the action of lime in the soil until after the science of chemistry, as it is known today, was developed.

The use of lime in England and France dates back to at least the sixteenth century. The form most commonly used in England was chalk while in France marl was more common. These two forms were easily pulverized and applied to the land. A little later, limestone was burned to make it fine; but pulverizing with machinery was only a relatively recent development.

Lime was used in colonial times in America. The practice was introduced by farmers who had used it in Europe. However, it was not until the establishment of Agricultural Experiment Stations in the middle of the 19th century, that any accurate tests were made of its effectiveness in increasing crop growth. Not until the end of the 19th century and the beginning of the 20th century were reports made by experiment stations on experiments conducted over a number of years. The Rhode Island (9) and the Pennsylvania (8) stations were among the first reporting favorably on the use of lime on acid soils at the turn of the century.

EARLY LIME WORK AT THE OHIO STATION

Experimental work on the use of lime was started at the Ohio Agricultural Experiment Station in 1900. That year the west end of one section of a five-year rotation fertility experiment was limed (6). From the start, excellent responses were noted. It was not known whether the good effects of lime were due to a change in soil reaction or whether they were brought about by furnishing calcium as a plant nutrient. To

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[1]Deceased.

investigate this matter another experiment was started in 1905, and reported (6) as the Lime and Floats Test. In this study rock phosphate and gypsum which contained calcium were compared with lime in different forms. The acid soil reaction was not greatly affected by the use of raw rock phosphate or gypsum. This experiment confirmed the fact that on acid soils such as this the primary cause of the good effect of lime on the growing of legumes was the change in the soil reaction from acid to neutral or alkaline.

Little was known at the time concerning the amounts of lime required to maintain a soil at a favorable reaction for the optimum growth of crops, or the relative efficiency of different forms of lime. These points were investigated in another experiment that was started in 1915 in which different forms of lime at different rates were compared. The description of this test was first published by Thorne (7) and titled Supplemental Liming Tests at Wooster. The experiment showed that the carbonate form of lime when finely ground was as effective as the burned form, if used at rates containing equivalent amounts of calcium.

These three experiments constituted the main experimental work on lime at the Ohio Agricultural Experiment Station prior to 1926. At that time two more experiments were instituted. One was designated as the Liming Materials Experiment, results of which have been published elsewhere (1, 2, 3, 4). The other, the Legume Reaction Experiment, is reported in detail here.

THE LEGUME-REACTION EXPERIMENT

FIRST PHASE (1928–1935)

The Legume-reaction Experiment[2] was designed to answer a number of questions concerning soil reaction and fertility conditions which enable crops to make maximum yields. The land used was systematically tiled and limed to bring the ranges to the desired reactions in 1928. Figure 1 shows the layout of the experiment.

Soil Reaction: The experimental area was divided, north to south, into five ranges. An attempt was made to adjust the different ranges to different reactions. The objective for Range I on the north was a pH value of 4.5. The normal reaction of this soil was about 5.2 so it was necessary to lower the reaction. This was done by applying aluminum sulfate. Range II was adjusted to pH 5.0 by adding a smaller amount of aluminum sulfate. Lime was added to all the plots of Ranges III, IV and V in amounts calculated to bring the reaction to

[2]Experiment designed by R. M. Salter.

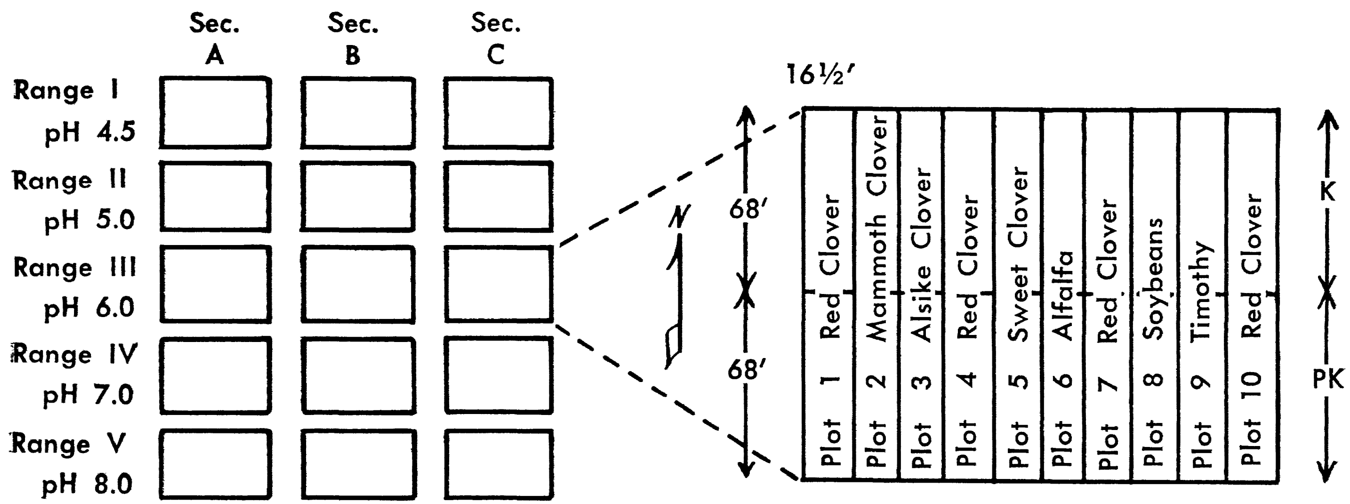

Fig. 1.—This is the plot layout used in the experiment. Plot areas were 16½′ × 136′.

pH 6.0, pH 7.0 and pH 8.0, respectively. The reaction of Range V never reached pH 8.0 on all the plots but in the course of 3 or 4 years most were above pH 7.5. The initial applications made on each range to adjust the reaction were: Ranges I and II, 2½ tons and ½ ton of aluminum sulfate per acre, respectively; Ranges III, IV and V, 1, 3 and 6 tons of calcium carbonate per acre, respectively. This initial treatment was found insufficient in many cases to bring the soil to the desired reaction and additional amounts of the amendments were added to each plot, if needed, during preparation of the land for corn. Thereafter, each time corn was grown, the plots were sampled individually and the amount of amendment indicated was added to adjust the reaction to the desired value.

Rotation: The area was further divided, west to east, into three sections and each section was divided into 10 plots. The rotation was corn, small grain, meadow on all the sections. On Section A the specific rotation was corn, winter wheat, meadow; on Section B it was corn, spring oats, meadow; and on Section C corn, spring barley, meadow. In the meadow year each section produced 7 different hay crops which had been sown in the preceding small grain with the exception of soybeans, as shown in Figure 1. Red clover was grown on four of the ten plots, while the other six hay crops were each seeded on one plot. All the sections were treated in the same way in the hay year.

Fertilization: For the purpose of fertilizer application, each range was split into a north and a south half. Both halves received 40 pounds per acre of muriate of potash (50% potash) on corn and 50 pounds on the small grains. The south half received in addition 200 pounds per acre of 20% superphosphate on corn and 400 pounds on the small grains. All fertilizers were broadcast.

ADJUSTMENT OF SOIL REACTION

In the fall of 1929, the plots were sampled by half plots on Sections B and C. The following year Section A was sampled in the same way. The reaction of all 100 samples on each section was determined using a quinhydrone electrode. The average reactions were:

	Sec. A (1930)	Sec. B (1929)	Sec. C (1929)	Average of 3 sections	Desired reaction
	pH	pH	pH	pH	pH
Range I	4.8	4.9	5.0	4.9	4.5
Range II	5.1	4.9	5.5	5.2	5.0
Range III	5.8	6.0	6.2	6.0	6.0
Range IV	6.8	6.9	6.8	6.8	7.0
Range V	7.3	7.1	6.9	7.1	8.0

With the exception of Ranges I and V, the reactions were rather close to the desired values. On neither Range I nor Range II had the application of aluminum sulfate reduced the pH as much as desired, and Range V had a reaction not much above neutrality. Sections B and C were given additional applications of amendments in the spring of 1930 and Section A in 1931, the amounts used being dependent on the actual reaction as shown by the samples taken by half plots.

The last sampling of the soils during the first phase of the experiment was done in the fall of 1933 (Sec. A), 1934 (Sec. C), 1935 (Sec. B). The average reactions at these times were:

	Sec. A (1933)	Sec. B (1935)	Sec. C (1934)	Average of 3 sections	Desired reaction
	pH	pH	pH	pH	pH
Range I	4.6	4.5	4.4	4.5	4.5
Range II	5.0	4.9	4.7	4.9	5.0
Range III	5.7	5.5	5.3	5.5	6.0
Range IV	7.1	6.6	6.3	6.7	7.0
Range V	7.7	7.5	7.5	7.6	8.0

Thus, by the end of the first phase of this experiment the desired reactions had been fairly well attained. The least satisfactory was Range III, where the reaction was 0.5 pH below the desired level. Also only a few plots of Range V ever attained a pH value of 8.0, but the average over the three sections was above 7.5.

Initially in 1926, and during the years 1929-1932 inclusive, amendments were added to the five ranges as shown in Table 1. In calculating limestone neutralized by applications of aluminum sulfate, 7 pounds of aluminum sulfate were assumed to be equivalent to 3 pounds of limestone.

CROP YIELDS

Corn: During the first phase of the experiment 5 crops of corn were grown. One year of the five (1930) was very dry, which reduced the corn yields materially. One corn crop was grown on Section A and two each on Sections B and C. In Table 2 average yields are tabulated by range and half plots.

Only on Ranges II, III and IV did the applications of phosphorus fertilizer increase corn yields over potash alone. In no case was the response to phosphorus large. Except on Range I, where alfalfa and sweetclover were very poor, corn yields were good following these crops. Corn after mammoth clover was superior to that after alfalfa and sweetclover on Range I, about equal to that after them on Range II, and only equal or inferior to that following alfalfa and sweetclover on Ranges III,

TABLE 1.—Initial and supplementary applications of lime and aluminum sulphate to adjust soil reactions

	Pounds per Acre							
	Range I		Range II		Range III		Range IV	Range V
	Limestone	Aluminum sulfate	Limestone	Aluminum sulfate	Limestone	Aluminum sulfate	Limestone	Limestone
Initial application	------	5,000	------	1,000	2,000	------	6,000	12,000
Applied as corrective	------	10,660	950	5,070	2,190	1,520	2,520	28,190
Total applied to each range	------	15,660	950	6,070	4,190	1,520	8,520	40,190
Pounds limestone equivalent added (+) or "removed" (—)	—6,710		—1,647		+3,540		+8,520	+40,190

TABLE 2.—Average yield of CORN produced during the first phase (5 years 1929-1933 inclusive)

Plot	Preceding Hay Crop	pH 4.5 Range I		pH 5.0 Range II		pH 6.0 Range III		pH 7.0 Range IV		pH 8.0 Range V	
		K North	PK South	K North	PK South	K North	PK South	K North	PK South	K North	PK South
		bu.	bu.	bu.	bu.	bu.	bu.	bu.	bu.	bu.	bu.
Average of 1, 4, 7, 10*	Red Clover	16.1	13.5	23.5	27.6	27.1	30.1	33.1	34.9	30.6	28.9
2	Mammoth	19.5	16.8	29.1	30.8	30.0	37.3	37.7	37.6	38.0	32.2
3	Alsike	17.1	14.4	24.8	29.4	29 6	33.8	35.0	39.1	33.0	30.4
5	Sweet Clover	12.4	15.0	28.3	31.9	31.7	38.9	41.7	43.7	39.3	39.0
6	Alfalfa	13.0	13.9	26.7	31.6	35.2	37.2	45.9	49.6	48.3	44.0
8	Soybeans	15.3	12.5	23.6	27.0	25.1	27.1	32.6	37.3	35.4	34.2
9	Timothy	11.3	9.2	19.7	20.2	25.7	22.6	30.6	31.6	28 8	29.6
Average		15.0	13.6	25.1	28.4	29.2	32.4	36.7	39.1	36.2	34.0
Average increase for phosphate		—1.4		+3.3		+3.2		+2.4		—2.2	

*Plot 1 of Section A—not included in averages.

IV and V. Corn after mammoth clover was consistently better than after red clover; alsike ranked slightly ahead of red clover in increasing corn yields in every comparison. Soybeans for hay had much the same effect on corn as red clover, and timothy rather consistently gave lowest corn yields. Yields of corn increased consistently from pH 4.5 through pH 7.0, but dropped off slightly at the highest pH.

Wheat: Wheat yields are presented in Table 3. The response to phosphates is outstanding. The effect was greatest on soils at pH 6.0 or lower; there was a somewhat lesser response at pH 7.0, and a marked decrease at the highest soil reaction. On the unphosphated end of the plots there was an increase in yield with increasing pH of the soil; on the phosphated end, maximum yields appeared to be reached at pH 7.0; there was no decrease in yield at the highest pH in the experiment. There was no outstanding advantage for any hay crop. However, on Ranges I and II where alfalfa and sweetclover were poor, these crops along with soybeans and timothy gave lowest wheat yields where phosphate was not applied. When phosphate was used, differences in the effects of various hay crops were small.

Oats: Oats yields are given in Table 4. The picture is different from that for wheat. Response to phosphate was greatest at pH 6.0 and decreased considerably at both higher and lower reactions. The general yield level without phosphate varied little on Ranges I, II and III, increased on Range IV and still more on Range V. When phosphate was used, there was a yield increase from Range I through Range III, but no differences on Ranges III, IV and V. The pattern of yield response to soil reaction appeared to change depending on the use of phosphatic fertilizers. Oats yields were less affected by low pH than were those of the other two small grains. The preceding hay crop apparently had little influence on the oats yields.

Barley: Table 5 gives the barley yields. At the lowest pH on Range I barley failed to head, and even on Range II the yields were very low. Without phosphate the yield about equaled the seed used. It is evident that barley is extremely sensitive to soil acidity. Response to phosphate was relatively large at pH 6.0. Higher yields were obtained with increasing pH, but response to phosphate fell off at neutrality and above. There was little effect of preceding hay crop except that red, mammoth and alsike clover appeared to be superior on Range III.

Hay: Hay crops were harvested, weighed and samples taken for separation into hay and weeds, and for moisture determination. Yields were then calculated to hay and weeds at 20 percent moisture content. Yields are given in Table 6. On Ranges I and II addition of phosphates had no appreciable effect on the yield of any hay crop. With

TABLE 3.—Average yield of WINTER WHEAT produced during the first phase (2 years, 1929 and 1932 on Section A)

Plot	Preceding Hay Crop	pH 4.5 Range I		pH 5.0 Range II		pH 6.0 Range III		pH 7.0 Range IV		pH 8.0 Range V	
		K North	PK South	K North	PK South	K North	PK South	K North	PK South	K North	PK South
		bu.	bu.	bu.	bu.	bu.	bu.	bu.	bu.	bu.	bu.
Average of 1, 4, 7, 10*	Red Clover	12.7	26.5	12.7	29 4	16.8	35.4	23.3	39.0	27.4	37.8
2	Mammoth	15.0	26.2	13.6	31 0	17.2	36.2	21.8	40.8	30.8	35.5
3	Alsike	10.2	25.3	11.5	30.1	16.9	36.1	22.9	40.0	28.8	41.9
5	Sweet Clover	5.3	25.0	9.3	27.6	11 6	34.9	22.3	40.8	29.0	42.1
6	Alfalfa	4.5	26.3	9.3	29.3	15.9	32.5	23.2	39.5	27.4	38.9
8	Soybeans	4.5	26.7	8.0	28.3	14 8	32.6	21.0	33.8	24.8	35.6
9	Timothy	7.3	27.0	10.0	29.8	12.9	28.5	22.3	32.2	27.5	34.6
Average		8.5	26.1	10.6	29.4	15.2	33.7	22.4	38.0	28.0	38 1
Average increase for phosphate		+17.6		+18.8		+18.5		+15.6		+10.1	

*Plot 1 of Section A—not included in averages.

TABLE 4.—Average yield of SPRING OATS produced during the first phase (2 years, 1931 and 1934 on Section B)

Plot	Preceding Hay Crop	pH 4.5 Range I		pH 5.0 Range II		pH 6.0 Range III		pH 7.0 Range IV		pH 8.0 Range V	
		K North	PK South	K North	PK South	K North	PK South	K North	PK South	K North	PK South
		bu.	bu.	bu.	bu.	bu.	bu.	bu.	bu.	bu.	bu.
Average of 1, 4, 7, 10*	Red Clover	36.1	44.2	37.0	48.2	35.9	53.6	44.8	54.4	50.9	56.3
2	Mammoth	37.7	44.3	36.4	49.9	39.4	57.8	40.3	55.8	51.3	58.9
3	Alsike	34.7	45.2	36.4	51.7	42.7	57.2	43.6	54.2	49.2	53.1
5	Sweet Clover	33.8	42.2	32.7	50.0	36.6	61.6	43.3	57.2	55.3	56.7
6	Alfalfa	37.5	40.8	36.7	50.5	32.0	53.4	45.3	59.2	51.4	54.1
8	Soybeans	35.6	44.4	30.3	54.1	29.8	57.5	43.6	57.4	51.4	59.1
9	Timothy	35.0	43.1	36.7	53.6	38.8	59.7	45.2	57.7	54.5	60.9
Average		35.8	43.5	35.2	51.1	36.5	57.3	43.7	56.6	52.0	57.0
Average increase for phosphate		+7.7		+15.9		+20.8		+12.9		+5.0	

*Plot 1 of Section A—not included in averages.

TABLE 5.—Average yield of SPRING BARLEY during the first phase (2 years, 1930 and 1933 on Section C)

Plot	Preceding Hay Crop	pH 4.5 Range I		pH 5.0 Range II		pH 6.0 Range III		pH 7.0 Range IV		pH 8.0 Range V	
		K North	PK South	K North	PK South	K North	PK South	K North	PK South	K North	PK South
		bu.	bu.	bu.	bu.	bu.	bu.	bu.	bu.	bu.	bu.
Average of 1, 4, 7, 10*	Red Clover	0.0	0.0	3.1	5.9	12.5	20.3	17.3	23.6	20.3	24.1
2	Mammoth	0.0	0.0	3.0	5.1	12.1	22.7	16.8	21.8	20.7	23.6
3	Alsike	0.0	0.0	2.4	7.0	12.2	21.1	16.9	22.5	19.8	21.7
5	Sweet Clover	0.0	0.0	2.2	3.9	6.4	17.0	17.2	21.5	19.1	23.6
6	Alfalfa	0.0	0.0	3.0	6.6	9.6	17.4	16.3	25.8	24.2	29.0
8	Soybeans	0.0	0.0	1.6	2.9	5.6	16.0	16.0	20.9	20.5	23.6
9	Timothy	0.0	0.0	3.8	6.4	9.8	17.8	17.2	22.2	21.4	23.3
Average		0.0	0.0	2.7	5.4	9.7	18.9	16.8	22.6	19.4	24.1
Average increase for phosphate		0.0		+2.7		+9.2		+5.8		+4.7	

*Plot 1 of Section A—not included in averages.

the exception of soybeans, all the crops responded well to phosphorus on Range III; sweetclover yields were doubled and alsike increased about 85 percent. All the clover and alfalfa responded well to phosphate on Range IV; soybeans and timothy did not. On Range V sweetclover yields were sizably increased by phosphate, but increases were only about half those obtained on Range IV. Alfalfa also showed a smaller response on Range V. Likewise, the other crops had little or no increase in yield for phosphate on Range V.

At the low yield levels obtained on the acid soil of Range I, soybeans produced more than twice the tonnage of any other hay. Timothy and mammoth clover yielded considerably less. Alfalfa and sweetclover gave very low yields. Soybeans still yielded the most hay on Range II, and the comparative yield pattern of the other crops not much changed. The clovers about doubled in yield, but were still very low on Range II. The increase was greatest on the phosphated end of the plots. Sweetclover and alfalfa improved somewhat, but were still the lowest yielding hays; timothy yielded almost twice as much as either on Range II.

On Range III there was a marked improvement in yield. Without phosphate, soybeans still produced the largest crop, but sweetclover yielded best on the phosphated soil. Alfalfa yields showed good increases over those on Range II; however, yield levels were not high.

Ranges IV and V produced fairly good hay yields. When phosphate was omitted, higher yields were obtained on Range V, but when phosphate was applied there was very little difference. Sweetclover yielded more than the other hays on Range V, and on Range IV when phosphate was used.

Red clover yielded less than mammoth, and not much different from alsike in all cases. The response of the three clovers was much the same for changes in pH or applications of phosphate. There was practically no response to phosphate on Ranges I and II, good responses on Range III and IV, but no effect on Range V.

Soybeans showed less effect from pH changes than any other crop, and there was apparently no response whatever to phosphate. Yields increased moderately from Range I through Range IV, but there was no clear indication of differences in soybean yields between Ranges IV and V.

Timothy, the only non-legume forage, yielded more than the clovers and alfalfa on Range I, about the same as them on Range II, but less at higher soil reactions. There was response to phosphate on Ranges III and IV, but little at either the high or low pH.

TABLE 6.—Hay yields 1928 to 1935

Plot	Crop	pH 4.5 Range I K North Hay	pH 4.5 Range I K North Weeds	pH 4.5 Range I PK South Hay	pH 4.5 Range I PK South Weeds
		Tons	Tons	Tons	Tons
Av. 1, 4, 7, 10*	Red Clover	0.26	0.19	0.22	0.16
2	Mammoth	0.47	0.20	0.24	0.20
3	Alsike	0.27	0.23	0.20	0.17
5	Sweet Clover	0.02	0.22	0.01	0.19
6	Alfalfa	0.06	0.22	0.07	0.14
8	Soybeans	1.00	0.24	1.00	0.20
9	Timothy	0.32	0.11	0.35	0.11

Plot	Crop	pH 5.0 Range II K North Hay	pH 5.0 Range II K North Weeds	pH 5.0 Range II PK South Hay	pH 5.0 Range II PK South Weeds
		Tons	Tons	Tons	Tons
Av. 1, 4, 7, 10*	Red Clover	0.31	0.19	0.34	0.22
2	Mammoth	0.49	0.15	0.45	0.22
3	Alsike	0.36	0.15	0.44	0.18
5	Sweet Clover	0.14	0.15	0.07	0.12
6	Alfalfa	0.31	0.18	0.26	0.15
8	Soybeans	1.15	0.11	1.21	0.13
9	Timothy	0.49	0.13	0.53	0.09

Plot	Crop	pH 6.0 Range III K North Hay	pH 6.0 Range III K North Weeds	pH 6.0 Range III PK South Hay	pH 6.0 Range III PK South Weeds
		Tons	Tons	Tons	Tons
Av. 1, 4, 7, 10*	Red Clover	0.62	0.30	0.80	0.38
2	Mammoth	0.89	0.29	1.08	0.34
3	Alsike	0.62	0.27	1.15	0.31
5	Sweet Clover	0.78	0.12	1.60	0.16
6	Alfalfa	0.95	0.21	1.17	0.31
8	Soybeans	1.21	0.07	1.22	0.13
9	Timothy	0.54	0.08	0.74	0.15

TABLE 6.—Hay yields 1928 to 1935—Continued

Plot	Crop	pH 7.0 Range IV K North Hay	pH 7.0 Range IV K North Weeds	pH 7.0 Range IV PK South Hay	pH 7.0 Range IV PK South Weeds
		Tons	Tons	Tons	Tons
Av. 1, 4, 7, 10*	Red Clover	1.14	0.34	1.43	0.39
2	Mammoth	1.31	0.34	1.74	0.35
3	Alsike	1.07	0.34	1.59	0.36
5	Sweet Clover	1.85	0.14	2.89	0 09
6	Alfalfa	1.99	0.28	2.76	0.33
8	Soybeans	1.46	0.10	1.53	0.13
9	Timothy	0.94	0.11	1.11	0.16

Plot	Crop	pH 8.0 Range V K North Hay	pH 8.0 Range V K North Weeds	pH 8.0 Range V PK South Hay	pH 8.0 Range V PK South Weeds
		Tons	Tons	Tons	Tons
Av. 1, 4, 7, 10*	Red Clover	1.51	0.28	1.43	0.42
2	Mammoth	1.89	0.25	1.55	0.37
3	Alsike	1.50	0.27	1.51	0.36
5	Sweet Clover	2.76	0.09	3.25	0.12
6	Alfalfa	2.60	0.23	2.76	0.39
8	Soybeans	1.53	0.11	1.43	0.13
9	Timothy	1.01	0.14	1.06	0.15

*Plot 1 of Section A not included in averages.

The total weight of weeds in hay gradually increased from Range II through Range IV. Percentagewise, however, the amount of weeds decreased. There was little difference between Ranges I and II, but where the hay increased considerably, weeds were in some degree suppressed. This was especially true for sweetclover and alfalfa, where Range I yields were almost nothing. There appeared to be fewer weeds on Range V when phosphate was applied, but this did not hold on the other ranges.

SECOND PHASE (1934–1946)

By the end of the crop year 1933 it had become clear that crops could not be produced successfully at reactions of pH 4.5 and 5.0. Also by this time the relation of pH to the efficiency of phosphate fertilizer had been established. Soybeans had proven to be an expensive source of hay, useful mainly as an emergency crop when hay was needed the same year the seeding was made.

In view of these facts, changes were made in the experiment, beginning in the spring of 1934 when Section A was planted to corn. Changes were initiated in Sections C and B in 1935 and 1936, respectively.

Reaction. It was decided no Range would be maintained at a reaction lower than pH 5.5. Range I was limed on the sod before plowing for corn with an amount of fine limestone calculated to raise the reaction to this level. Ranges II and III were similarly adjusted to pH 6.0 and pH 6.5, respectively. Range IV was kept at pH 7.0, and Range V left unlimed until the reaction fell below pH 7.5. Table 7 summarizes these changes and indicates the average amounts of limestone applied. Actual application varied, calculated from pH readings on individual samples from the half plot areas.

In Table 8 the actual reactions attained three and nine years after the initial liming are shown. The amounts of limestone applied during the nine years of the second phase is also given.

TABLE 7.—Changes in desired pH of ranges and amount of lime applied to effect the changes.

Range	Desired reaction		Average amount limestone applied
	First phase	Second phase	
	pH	pH	Lb/A
I	4.5	5.5	3940
II	5.0	6.0	3480
III	6.0	6.5	2680
IV	7.0	7.0	1760
V	8.0	7.5	----

The limesone applications made during the nine years of the second phase were on the average too small to maintain the reaction at the desired level on all except Range V. However the reactions given are those at the end of the second phase of the experiment, three years after the last liming. During the previous three years the desired reactions were more nearly realized than the figures would indicate. A review of selected plots on which the reactions had been satisfactorily maintained over the period showed that on this soil somewhat less than 300 pounds of calcium carbonate per acre per year were required to maintain a reaction of pH 6.0 or pH 7.0.

TABLE 8.—Soil reactions at the beginning and end of the second phase, and limestone applied during the period

Range	Desired Reaction	Average reaction at the beginning of the second phase (3 years after liming)				Limestone applied per acre during the second phase				Average reaction at the end of the second phase. (This phase covered 9 years)			
		Sec. A (1936)	Sec. B (1938)	Sec. C (1937)	Average	Sec. A	Sec. B	Sec. C	Average	Sec. A (1945)	Sec. B (1947)	Sec. C (1946)	Average
	pH	pH	pH	pH	pH	lb.	lb.	lb.	lb.	pH	pH	pH	pH
I	5.5	4.9	5.4	5.5	5.2	2,950	1,280	1,600	1,943	5.4	5.3	5.5	5.5
II	6.0	5.4	6.0	5.6	5.6	5,920	1,330	890	2,713	5.9	5.5	5.9	5.7
III	6.5	6.1	6.4	6.3	6.3	2,640	1,430	1,130	1,733	6.1	6.1	6.4	6.2
IV	7.0	7.0	7.4	7.2	7.2	3,320	770	360	1,483	6.4	6.8	6.7	6.6
V	7.5	7.6	7.7	7.7	7 7	1,660	80	590	777	7.8	7.4	7.8	7.6

Fertilizer. During the second phase of the experiment, the variable between north and south ends of the plots was changed from phosphate to manure. Determinations of "available" phosphate were made on both north and south ends of all plots. To bring these into balance 20 percent superphosphate was applied at 200 pounds per acre to the north ends. Throughout the second phase 150 pounds per acre of 0-14-6 was applied in the hill for corn, and 300 pounds per acre on the small grains on both ends of all plots. In addition, the south ends of all plots received four tons per acre of manure on the small grains, and four tons per acre on the corn.

Crops. There was only one change in the cropping system. Soybeans for hay were dropped and mixed hay substituted on plot 8. The mixture sown was four pounds alfalfa, four pounds red clover, two pounds alsike, and four pounds timothy per acre. Clarage corn was grown in the first phase, but replaced by W17 in 1936. Trumbull wheat, Wayne oats and Oderbrucker barley were grown throughout the experiment.

CROP YIELDS

Corn: Corn yields were considerably higher in the 13 crops of the second phase as is seen in Table 9. This was due in part to the drought of the early thirties which kept all corn yields low, and in part to growing a hybrid W17 after 1936. Corn yields on the unmanured area were remarkably uniform across Ranges I, II and III. There was about a 5 bushel increase on Range IV which was fairly well maintained to Range V. On the manured ends, crops were consistently 4 to 10 bushels higher. Greatest response to manure occurred on Range III, and decreased toward higher and lower soil reactions; differences in response are probably not statistically significant. Lowest yields consistently followed timothy, and at high pH values, best yields followed alfalfa. Corn after mixed hay, which contained considerable alfalfa, was also good. At pH 5.5 mammoth and alsike clovers were as good as alfalfa. At reactions lower than pH 7.0, corn after sweetclover without manure yielded less than after alfalfa.

Wheat: Average wheat yields are shown in Table 10 for the four crops of the second phase. The yield level was good, and not greatly different from the first phase. Winter wheat in Ohio is favored by dry winters, and matures early enough to escape most summer drought damage. Hence it did well in the dry period. Yields were about the same on Ranges I and II, increased on Ranges III and IV, but remained about the same on Range V. There was good response to manure at all soil reactions. Possibly least response was obtained at pH 5.5, and

TABLE 9.—Corn yields during second phase, 1934-1946 inclusive

Previous hay crop	Plot	pH 5.5 Range I		pH 6.0 Range II		pH 6.5 Range III		pH 7.0 Range IV		pH 7.5 Range V	
		North *	South *	North *	South *	North *	South *	North *	South *	North *	South *
		Bu.	Bu.	Bu.	Bu.	Bu.	Bu.	Bu.	Bu.	Bu.	Bu.
Red clover	Av. 1, 4, 7, 10	61.3	62.9	57.1	66.4	57.8	68.0	64.0	72.1	62.5	67.9
Mammoth clover	2	66.2	67.9	60.3	66.9	61.2	73.6	64.1	72.4	64.0	72.0
Alsike	3	65.2	66.6	61.7	66.9	58.4	72.9	64.8	71.6	64.9	66.4
Sweet clover	5	59.3	63.1	56.5	65.7	58.5	75.2	66.6	73.9	61.5	70.2
Alfalfa	6	63.7	66.1	62 8	72.1	66.9	76.7	69.7	79.2	68.8	74.5
Mixed hay	8	60.4	68.3	60 6	68 3	60.2	68.2	66 4	75.4	65 4	70.4
Timothy	9	46.8	56.2	50.0	60.3	50.6	61.3	62 2	67.7	55.3	63.4
Average		60.4	64.4	58.4	66.7	59.1	70.8	65.4	73.2	63.2	69.3
Increase from manure		+4.0		+8.3		+11.7		+7.8		+6.1	

*North no manure, South manured.

maximum at pH 6. and 6.5, but the differences were relatively unimportant. With one exception, lowest wheat yields followed timothy. At pH 6.0 or higher, best yields followed alfalfa. It appears that available nitrogen limited the wheat yields more than anything else.

Oats: Yields are given in Table 11 for the 4 second phase oat crops. In line with first phase results, the soil reaction within the pH 5.5 and pH 7.5 range had little effect on yields. The differences that occurred were probably due to poorer legumes at the lower pH. Lowest yields occurred on Range I, with the remaining Ranges about equal. There was response to manure at all reaction levels, but more at the lower pH's where legumes did not do so well and supplied less nitrogen. Poorest oats usually did not follow timothy. The picture was very erratic and no clear-cut effect of hay crop on oats yields was evident.

Barley: Table 12 gives the average yields for the four barley crops of the second phase. Here again there was poor production at the lower soil reactions. Yields increased up to pH 7.0, and leveled off. Increases were greater when manure was applied. Response to manure was good, and increased with pH up to pH 7.0. Barley on Range I with manure, yielded much the same as it did without manure on Ranges III, IV and V. When manure was not applied, barley after timothy was consistently among the low yielding plots. But when manure was used, the picture was not so clear cut. With moderate acidity, mammoth clover again proved as effective as any hay tested for increasing barley yield.

Hay: Hay crops were handled the same as in the first phase, and hay and weed yields for the first eight years of the second phase are given in Table 13. Red, mammoth and alsike clovers showed little effect of soil reaction on yield below pH 7.0; they were considerably higher in yield on Ranges IV and V. Sweetclover and alfalfa gave but slightly higher yields at pH 6.0 than at pH 5.5; however, yields increased gradually on Ranges III, IV and V. The mixed hay gave highest yields in every case. Apparently the combination of timothy, alfalfa and clovers had a flexibility not found in any one alone.

Response to manure was good at all soil reactions and for all hay crops. Response of timothy to manure was much the same on all ranges. Maximum response to manure for most crops came at pH 6.5 and pH 7.0. There were four cases where manure failed to increase the crop by at least one half ton per acre, and only two cases where the increase exceeded one ton per acre. In no case did the response at pH 7.0 exceed that at pH 6.5 for the same crop, and in most cases response was clearly less. Except on Range I, the amount of weeds was greatest

TABLE 10.—Average wheat yields in second phase (1935, 1938, 1941, and 1944 on Section A)

Previous hay crop	Plot	pH 5.5 Range I		pH 6.0 Range II		pH 6.5 Range III		pH 7.0 Range IV		pH 7.5 Range V	
		North *	South *	North *	South *	North *	South *	North *	South *	North *	South *
		Bu.	Bu.	Bu.	Bu.	Bu.	Bu.	Bu.	Bu.	Bu.	Bu.
Red clover	Av. 4, 7, 10	28.3	33.2	27.3	37.2	31.8	42.0	38.5	44.7	37.4	42.6
Mammoth clover	2	34.1	37.9	29.3	34.4	31.7	42.7	41.6	46.3	39.7	44.3
Alsike clover	3	31.6	34.6	26.8	36.7	33.5	43.0	39.6	45.8	38.2	43.8
Sweet clover	5	23.3	30.8	25.8	34.3	33.1	41.9	37.9	47.4	37.8	43.0
Alfalfa	6	26.9	33.8	29.6	39.9	41.0	45.6	42.9	47.5	41.6	49.8
Mixed hay	8	24.1	28.8	25 2	31.7	31.9	36.0	36.9	40.5	37.0	42.9
Timothy	9	21.3	29.4	21.9	29.0	24.9	30.9	28.9	36.7	29.2	35.1
Average		27.1	32.6	26.6	34.7	32.6	40.3	38.1	44.1	37.3	43.1
Increase from manure		5.5		8.1		7.7		6.0		5.8	

*North no manure, South manured.

TABLE 11.—Average oats yields second phase (1937, 1940, 1943, and 1946, on Section B)

Previous hay crop	Plot	Range I		Range II		Range III		Range IV		Range V	
		North	South	North	South	North	South	North	South	North	South
		Bu.	Bu.	Bu.	Bu.	Bu.	Bu.	Bu.	Bu.	Bu.	Bu.
Red clover	Av. 1, 4, 7, 10	58.6	64.8	59.2	64.3	60.7	65.6	62.5	64.8	61.6	64.1
Mammoth clover	2	54.7	65.4	59.1	65.7	57.0	67.0	59.2	65.5	59.1	66.9
Alsike	3	55.6	57.7	57.9	66.0	59.3	67.3	64.0	70.2	63.6	66.7
Sweet clover	5	53.4	64.3	57.1	64.9	65.7	67.8	65.8	68.0	61.4	67.5
Alfalfa	6	55.8	63.0	60.7	57.6	57.0	57.0	62.8	59.5	55.8	60.3
Mixed hay	8	53.0	59.0	57.8	58.7	58.7	62.9	59.2	60.4	58.9	65.1
Timothy	9	51.5	61.5	57.0	65.5	55.8	69.9	57.8	64.5	62.0	64.3
Average		54.7	62.2	58.4	63.2	59.2	65.4	61.8	64.7	60.7	65.0
Increase from manure		7.5		4.9		6.2		2.9		4.3	

TABLE 12.—Average barley yields second phase (1936, 1939, 1942, and 1945, on Section C)

Previous hay crop	Plot	Range I		Range II		Range III		Range IV		Range V	
		North	South	North	South	North	South	North	South	North	South
		Bu.	Bu.	Bu.	Bu.	Bu.	Bu.	Bu.	Bu.	Bu.	Bu.
Red clover	Av. 1, 4, 7, 10	15.7	23.6	19.3	28.8	24.6	33.0	25.1	34.5	22.8	35.2
Mammoth clover	2	17.8	23.6	20.8	23.2	22.2	30.9	25.0	34.2	23.7	34.6
Alsike	3	17.5	21.5	20.3	23.9	19.5	29.5	22.8	29.6	24.3	33.1
Sweet clover	5	14.4	18.8	15.2	23.5	16.7	27.2	18.9	31.5	18.4	33.2
Alfalfa	6	13.7	21.7	17.2	29.1	22.8	32.9	23.5	39.0	26.7	37.4
Mixed hay	8	13.1	23.5	18.4	29.2	23.7	35.3	23.4	33.6	23.0	34.7
Timothy	9	13.3	23.2	16.5	28.2	21.0	29.2	19.6	33.3	20.3	33.9
Average		15.1	22.3	18.2	26.6	21.5	31.1	22.6	33.1	22.8	34.6
Increase from manure		7.2		8.4		9 6		11.1		11.8	

TABLE 13.—Second phase. Hay yields 1936-1943 inclusive. 8 years

Plot	Crop	Range I			
		North		South	
		Hay	Weeds	Hay	Weeds
Av. 1, 4, 7, 10	Red Clover	1.85	0.22	2.49	0.25
2	Mammoth	1.77	0.17	2.22	0.12
3	Alsike	1.27	0.14	1.72	0.13
5	Sweet Clover	1.50	0.06	2.25	0.05
6	Alfalfa	1.15	0.18	2.07	0.21
8	Mixed hay	2.16	0.06	2.84	0.08
9	Timothy	0.49	0.08	1.22	0.22

Plot	Crop	Range II			
		North		South	
		Hay	Weeds	Hay	Weeds
Av. 1, 4, 7, 10	Red Clover	1.66	0.22	2.55	0.29
2	Mammoth	1.53	0.09	2.17	0.17
3	Alsike	1.07	0.08	1.91	0.20
5	Sweet Clover	1.54	0.07	2.46	0.12
6	Alfalfa	1.27	0.21	2.04	0.45
8	Mixed hay	2.15	0.11	3.12	0.12
9	Timothy	0.40	0.10	1.07	0.19

Plot	Crop	Range III			
		North		South	
		Hay	Weeds	Hay	Weeds
Av. 1, 4, 7, 10	Red Clover	1.64	0.30	2.42	0.48
2	Mammoth	1.60	0.23	2.45	0.27
3	Alsike	1.05	0.20	1.96	0.28
5	Sweet Clover	2.10	0.08	2.81	0.20
6	Alfalfa	1.42	0.34	2.30	0.61
8	Mixed hay	2.44	0.09	3.55	0.19
9	Timothy	0.62	0.15	1.47	0.25

TABLE 13.—Second phase. Hay yields 1936-1946 inclusive. 8 years—Continued

Plot	Crop	Range IV			
		North		South	
		Hay	Weeds	Hay	Weeds
Av. 1, 4, 7, 10	Red Clover	1.93	0.34	2.65	0.41
2	Mammoth	1.60	0.25	2.35	0.32
3	Alsike	1.24	0.27	1.90	0.35
5	Sweet Clover	2 07	0.07	2.91	0.09
6	Alfalfa	1.74	0.48	2.86	0.64
8	Mixed hay	3.01	0.07	3.85	0.12
9	Timothy	1.00	0.21	1.65	0.34

Plot	Crop	Range V			
		North		South	
		Hay	Weeds	Hay	Weeds
Av. 1, 4, 7, 10	Red Clover	2.32	0.24	2.94	0.38
2	Mammoth	2.36	0.26	2.52	0.25
3	Alsike	1.47	0.20	2.13	0.22
5	Sweet Clover	2.42	0.09	2.97	0.05
6	Alfalfa	2.48	0.33	3.15	0.46
8	Mixed hay	3.62	0.05	4.28	0.07
9	Timothy	0.94	0.20	1.50	0.40

where manure had been used. There was the least amount of weeds in the sweetclover, but the mixed hay was almost as free of weeds. The greatest weight of weeds per acre was found in the alfalfa.

SUMMARY AND CONCLUSIONS

The rotations grown do not indicate satisfactory performance at soil reaction below pH 6.0. Soybeans for hay, and oats for grain showed the greatest tolerance for acid soils; barley for grain showed the least. Of the forage legumes, mammoth clover ranked consistently high at low soil reactions. Of the legumes, alfalfa and sweetclover were most seriously affected by low pH. Except for barley, the grain crops apparently reached maximum production at about pH 7.0, and the higher soil reaction tended to depress the yields. The ideal range would appear to be pH 6.5 to pH 7.0 for these crops.

Phosphate was needed on this soil. Response of wheat to phosphate was greatest of the grain crops, being about 18 bushels per acre at pH 4.5, pH 5.0 and pH 6.0. At pH 7.0 to 7.5 response from phosphate decreased but was still considerable. Oats also showed good returns for added phosphorus, but maximum response was at pH 6.0; yield increases were much less as the soil became more acid or approached neutrality. Apparently phosphorus in the soil becomes more readily available as the soil pH increases with the result that the fertilizer has less apparent effect. With time this effect would likely decrease, since the phosphorus made available on this soil by liming might be exhausted after a few years. Barley followed the same general response pattern as oats, modified by the extreme sensitivity of the crop to soil acidity. Corn actually showed yield decreases for applications of phosphorus on Ranges I and V, and very minor response at the intermediate soil reaction. Hay crops responded to phosphorus only at pH 6.0 and above, and response decreased above neutrality.

When a moderate application of phosphate was used, and 8 tons of manure added each 3 years on half of the plots, corn gave consistently good response to the manure with a maximum at pH 6.5. In contrast, wheat yields were increased rather uniformly across all soil reactions. Oats gave a somewhat better response to manure on the more acid soils, probably because of the poorer legume growth on these ranges and the smaller amount of nitrogen available. Barley responded well with greatest increase at high soil pH. This probably resulted from the poor performance of the crop on acid soils. Hay responded well to manure at all soil reactions. Maximum response was obtained at pH 6.5 to pH 7.0.

Considering the experiment as a whole, the crops show characteristic responses to soil reaction, phosphate fertilizer and manure. In the great majority of cases a soil reaction of pH 6.5 to pH 7.0 appears to be optimum. Maximum yields and maximum response to fertilizer appear to be attained in this reaction range. A good program suggested by this experiment and supported by many others is to add a good grade of agricultural ground limestone to bring the soil reaction to about pH 6.5 to 7.0, and make supplementary applications whenever the reaction drops to pH 6.5 or slightly lower.