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Theodore Clinton McIlvaine

G. G. Pohlman

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By

T. C. McIlvaine

and

G. G. Pohlman

Agricultural Experiment Station
College of Agriculture, Forestry, and Home Economics
West Virginia University
C. R. Orton, Director
Morgantown

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AN ACID-SOIL REACTION, resulting from the leaching of calcium and other bases, is often one of the principal factors limiting the production of many of the common field crops in West Virginia. The harmful effect of soil acidity on crop yields has been attributed, among other things, to excessive quantities of hydrogen-ion, soluble aluminum, manganese, or iron and to deficiencies of calcium, phosphorus, or other essential nutrients. It has been suggested that the exchangeable-calcium content or the percentage saturation with base (*4*) may be more closely related to crop growth than is the acidity of the soil. In the field it is usually impossible to isolate any individual cause of poor growth of plants on acid soils. In many cases the interaction of several factors may be responsible. However, since most of the causes are related, the measurement of hydrogen-ion concentration, expressed as pH, and the measurement of available calcium have come to be considered as fairly reliable indices of the need for lime applications.

The present study was started (1) to study the effect of the reaction of a particular soil on the yields of various crops and (2) to compare the effect of aluminum sulfate and sulfuric acid, used to acidify soils, on the yields of crops.

METHODS

The field work was conducted on Wheeling fine sandy loam soil having an initial reaction of about pH 6.0. Small plots or bins were made, using wood frames 3 ft. square and 10 in. deep. These were placed in the soil to a depth of 7 in. The surface 7 in. of soil was removed from each of these bins, thoroughly mixed, with various portions treated as shown in Table 1.

The treated soil was replaced in the frames in the fall of 1928. The following spring the bins were planted in quadruplicate at each reaction to measure the effect of reaction on growth of various crops. Additional crops were planted each year thereafter in order to measure the effect of reaction on as many different crops as possible.

Soil samples were taken each spring and fall to measure actual reaction of the soils growing each crop. The pH was determined by the quinhydrone electrode in 1929, 1930, 1931, 1932. Later determinations were made by means of the glass electrode, using 1 part of soil to 2½ parts of water.

Table 1—Treatments Used to Secure Desired Reactions*

Series	Desired pH	Treatment applied: Acid series: H_2SO_4 lb. per acre	Acid series: $CaCO_3$ lb. per acre	Aluminum: Aluminum sulfate lb. per acre	Aluminum: $CaCO_3$ lb. per acre
A	4.0	10,432		28,580	
B	4.5	6,160		28,580	4,960
C	5.0	3,652		28,500	7,720
D	5.5	1,772		28,500	9,380
E	6.0			28,500	9,580
F	6.5		2,068	28,500	13,520
G	7.0		4,138	28,500	18,760
H	7.5		8,276	28,500	24,820
I	8.0		16,552	28,500	38,620

*All soils were treated with $CaSO_4$ at the rate of 2000 lb. per acre following acid or lime treatment and with 500 lb. of 3-12-6 fertilizer. Sufficient soil was treated to fill 16 bins at each reaction in the acid series and 4 bins at each reaction in the aluminum-sulfate series.

EXPERIMENTAL RESULTS

Because of the change in methods of determining pH during the course of the experiment, it is not possible to make accurate comparisons of soil reaction. However, several noteworthy trends occurred. The soils treated with sulfuric acid (Series A, B, C, and D) became less strongly acid until 1932. The decrease was greatest on Series A and became progressively less as the rate of acid treatment decreased. The acid treatment probably removed some inert materials from the soil particles, exposing fresh surfaces which released bases to the soil solution for several years. The limed bins (Series F, G, H, and I) showed slight increases in pH in the first three years after treatment. During the later years of the experiment all the soils became more acid, but none of them reached the low value of pH 4.0 initially desired in Series A. The range in pH values in 1938 was 4.5 to 7.2 instead of 4.0 to 8.0 as originally desired.

The aluminum-sulfate treated bins showed increased pH for 3 to 4 yr. following treatment, after which the pH became lower in most cases. These bins, however, were usually somewhat higher in reaction than the acid-treated bins. The range in values in 1937 was 4.6 to 7.75.

The primary purpose of the experiment was to relate soil reaction to plant growth on a particular soil. However, as the experiment progressed it became evident that the effect of reaction as measured by pH was not always the same. Since exchangeable calcium is known to influence crop growth, the soil samples for 1929 and 1938 were analyzed for water-soluble and exchangeable calcium. The relationship between these and the soil pH is presented in Figure 1. Three different curves are evident from these results. Curve A shows the relationship in 1929 between the soluble calcium and pH on the soils treated with aluminum sulfate. Even at pH 4.1 the soil had 8.3 milliquivalent calcium, which represents 61.1 percent of the total exchange capacity. At reactions above pH 5.6 the water-soluble and exchangeable calcium total more than the exchange capacity. Curve B gives the relationship in 1929 between pH and available calcium in the acid-treated series. This also shows a high calcium content on the soils below pH 5.6, which are those treated with sulfuric acid.

The third curve shows the relationship between pH and available calcium in 1938. There was very little difference between the acid and alumnium series by this time, indicating that the excess soluble calcium, noted in 1929, had been leached out. How long it took to reduce the water-soluble calcium level is not known, but the evidence from pH changes and from yield trends would indicate that several years elapsed before an equilibrium was reached. The annual pH changes in both acid and aluminum series were fairly high until 1936, following which only small changes occurred.

Yield data for cowpeas and soybeans in 1936 indicate somewhat higher relative yields at low reactions than in 1938. However, the response was much greater than in 1929 or 1930. Therefore it may be expected that yields prior to 1936 may reflect not only the relationship with pH but also the added variable of abnormally high soluble calcium, except in the acid series at reactions above pH 5.6. From this it may

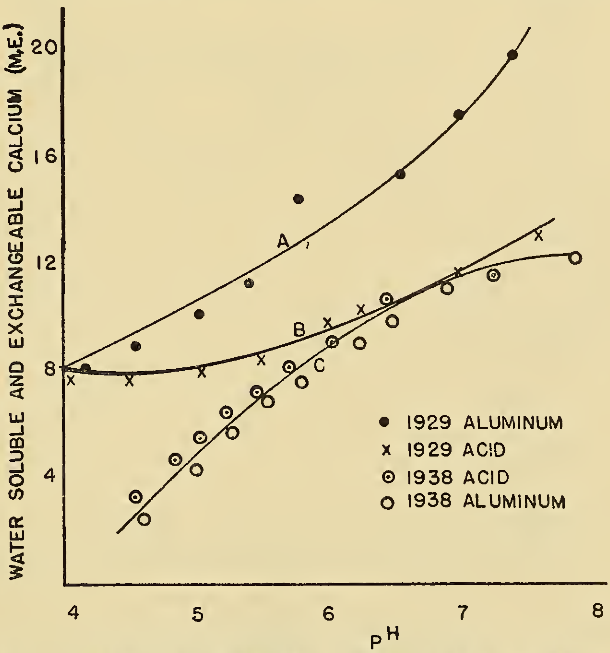

Fig. 1 — Relationship Between pH and Available Calcium

be reasoned that many of the curves may show greater acid tolerance and higher yields at low reactions (below pH 5.6) than would normally be expected on this soil. This may account for the apparent abnormality of some of the curves shown.

CROP YIELDS IN RELATION TO pH

Because of the variation in yield depending upon the season, all yields are expressed on a relative basis, the value of the highest-yielding plot being taken as 100.

CORN (F_1 hybrid) was grown in both acid- and aluminum-treated series in 1929, 1930, and 1941. Three plants were grown in each bin. Since the 1941 crop was affected by termites, only the results for 1929 and 1930 are given. At most reactions the yields were lower in 1929 than in 1930. However, when expressed on a relative basis the points make a fairly smooth curve as shown in Figure 2. These show a very rapid increase in yield with increasing pH up to about pH 5.0, after which there appears to be a slight but insignificant increase. In both 1929 and 1930 the corn on the most acid plots showed evidence of injury due to the high acidity. From the shape of the curve it would appear that the high calcium at reactions below pH 6.0 did not have much effect on yield. Therefore, the curve may be considered typical of what might be expected on this soil. Observations on other soils in West Virginia indicate very poor corn growth and yield below pH 5.0.

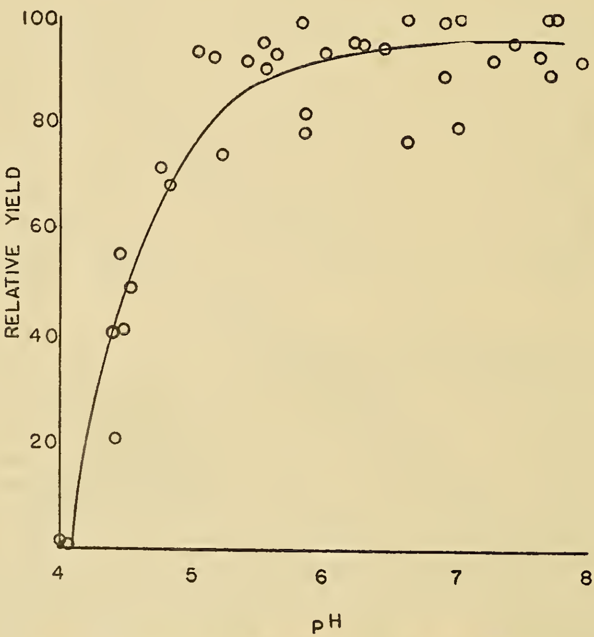

Fig. 2 — Corn Yields in Relation to Soil Reaction

WHEAT (Trumbull variety) was grown in the acid series in 1931 and 1932. Because of the fact that the grain was eaten badly by birds in 1931, the results are for straw only. The 1932 crop was harvested early to avoid damage. The relative yields are shown in Figure 3. Above pH 5.0 the general yield trend was upward with increasing pH, the highest yield being at pH 7.7 in 1931 and at 6.5 in 1932. The yields, except for the most acid reaction, were generally significantly lower below pH 6.1 than at the highest yield level. The yields between pH 4.5 and 4.9 were irregular and were not considered in drawing the curve. The high yield at pH 4.5 may have been due to increased plant-nutrient availability resulting from the acid treatment. The fact that the relative yield in 1932 was 12 percent lower at pH 4.5 than it was in 1932 would seem to indicate that this effect was decreasing and that a continued downward trend from pH 4.9 would be more normal.

BARLEY (Oderbrucker variety) was grown in the acid series in 1931 and 1932. The relative yields given in Figure 4 are for grain and straw. The general trend in both years is quite similar, with a rapid increase in yield up to about pH 5.1 followed by a more gradual increase up to a pH above 7.0. This increase was significant only in 1932. The curve is smooth and does not indicate any effect from the relatively higher calcium content at the more acid reactions.

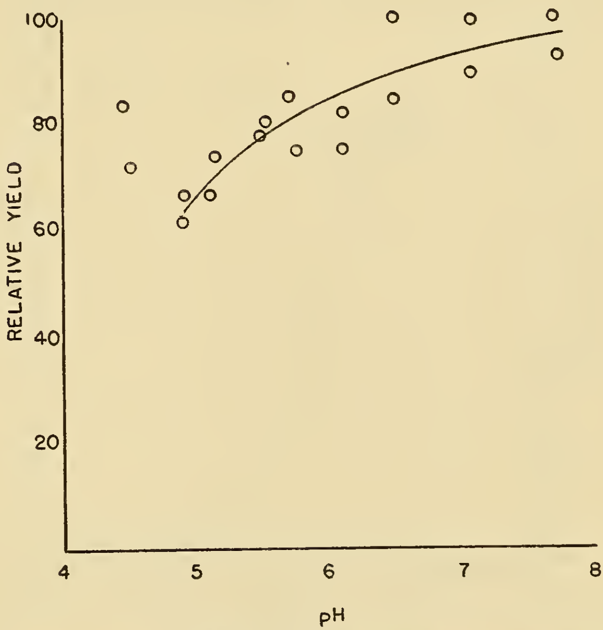

Fig. 3 — Wheat Yields in Relation to Soil Reaction (Points below pH 4.8 Omitted from Curve)

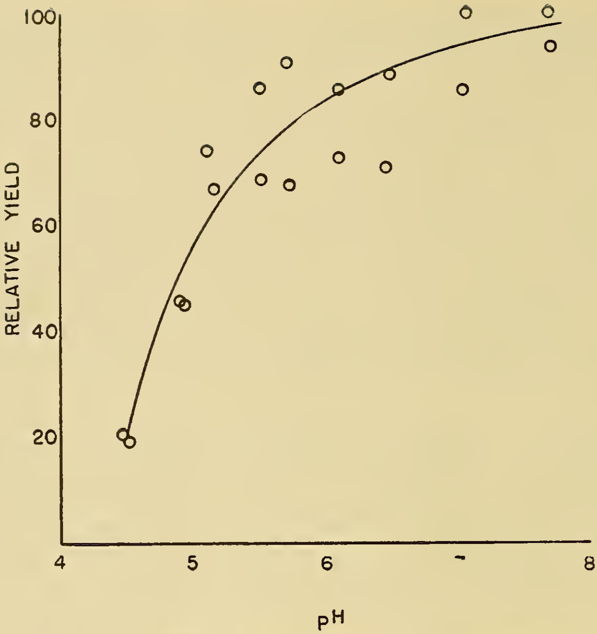

Fig. 4 — Barley Yields in Relation to Soil Reaction

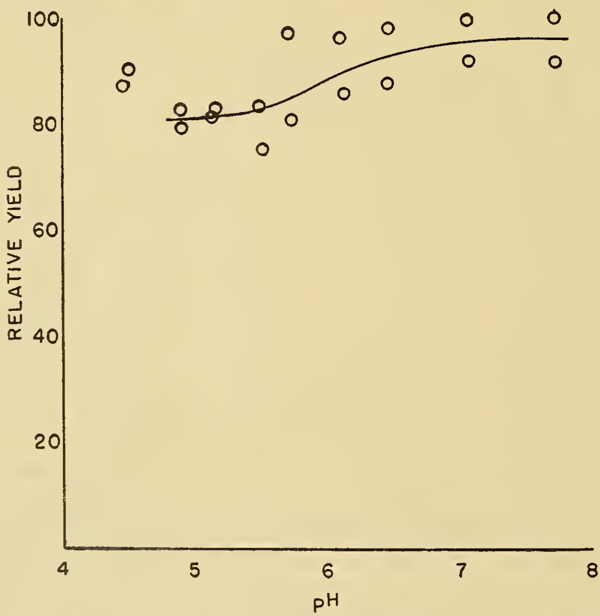

Fig. 5 — Rye Yields in Relation to Soil Reaction (Points below pH 4.8 Omitted from Curve)

RYE (Rosen) was grown in the reaction bins (acid series) in 1931 and 1932. The results are shown in Figure 5. The highest yields were obtained above pH 7.0, but, as shown by the graph, the yields were relatively high at all reactions. The relatively high yield at the most acid reaction was probably the result of the acid treatments, as previously mentioned. It further indicates that rye can utilize available calcium, even under strongly acid conditions.

ALFALFA was seeded in both acid and aluminum treated series in 1933 and yields taken in 1934. Relative yields at the various reactions are shown in Figure 6. Yields from both series were very similar and showed little growth below pH 5.6. The yield increased rapidly with increasing pH up to pH 7.1, after which there was little effect. The downward trend near pH 8.0 was not significant.

SWEET CLOVER was seeded in the acid series in 1933 and 1936, with yield records taken in the following year. The relative yields are shown in Figure 7. Yields were much lower in 1937 than in 1934, but relative yields were very similar, as shown by the curve. Yields were very low below pH 5.4 and increased rapidly up to pH 7. In both years the highest yields were obtained at the highest reactions.

RED CLOVER was seeded in 1933 and 1936, and yields were taken in the following year. Results are shown in Figure 8. Separate curves are shown for the 2 yrs.' results. Both show practically no growth below pH 4.8 and highest yields above pH 7.0. Yields were very low in 1937,

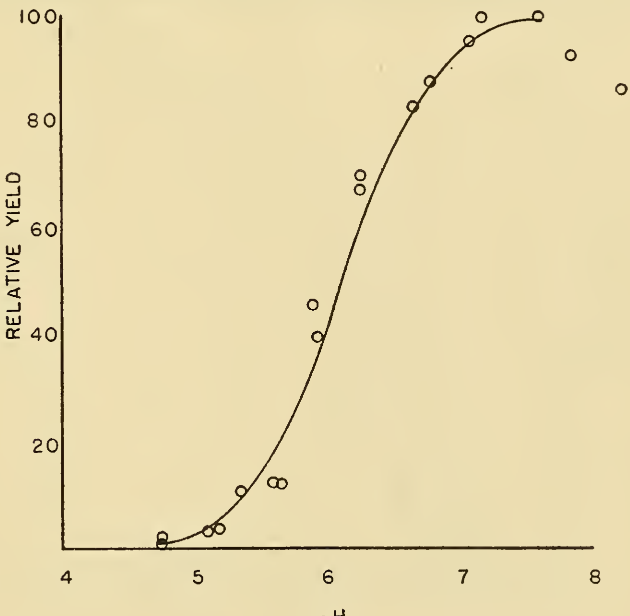

Fig. 6 — Alfalfa Yields in Relation to Soil Reaction

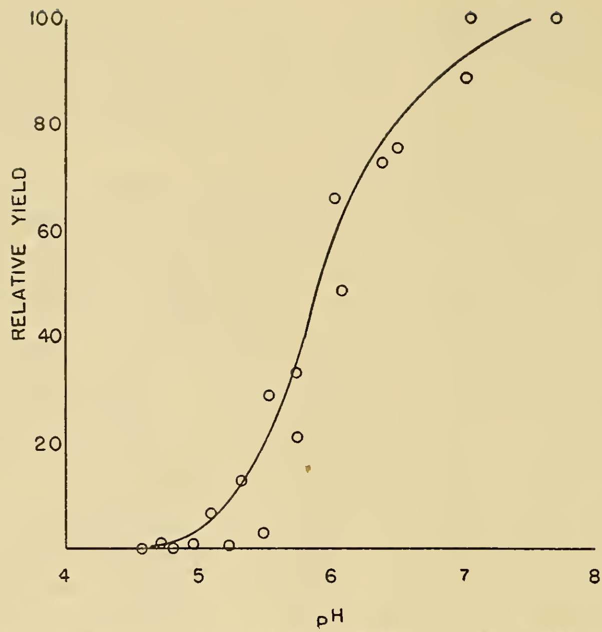

Fig. 7 — Sweet Clover Yields in Relation to Soil Reaction

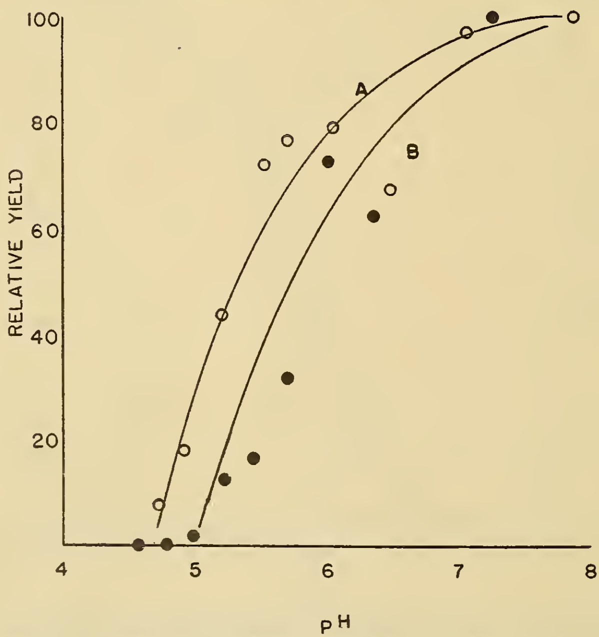

Fig. 8 — Red Clover Yields in Relation to Soil Reaction

partly as a result of a poor stand. This may be responsible for the fact that the curve is different from that of 1934.

ALSIKE CLOVER was seeded in 1933 and 1936. Yields were secured in 1934 and 1937. The relative yields shown in Figure 9 are very similar to those for red clover. Yields were low below 5.0 and increased steadily up to above pH 7.0. With alsike as well as with the red clover the 1937 results were markedly influenced by the stand, which may account for the different yield curve.

KOREAN LESPEDEZA was grown in the acid series in 1937. Although the stand and yield were only fair, there was a marked increase in yield with increasing pH to 6.8, as shown in Figure 10. Variability between replicates was so large that there was no significant difference in yield above 6.1.

SOYBEANS were planted in the acid series bins in 1929, 1930, 1936, and 1938, and in both acid and aluminum series in 1939. The Wilson variety was used in the first 2 yr., with Kingwa used in 1936, 1938, and 1939. The relative yields are given in Figure 11. Three separate curves are shown, all of which indicate the same trend but increasing sensitivity to acid conditions after the initial treatment. The results for 1929 and 1930 (Curve A) show the most marked increase in yield up to about pH 5 and more gradual but significant increases up to pH 6.2. The 1936 results (Curve B) show significant increases up to about 6.5. The 1938 and 1939 results (Curve C) show increased yields up to pH 6.5 - 7.0.

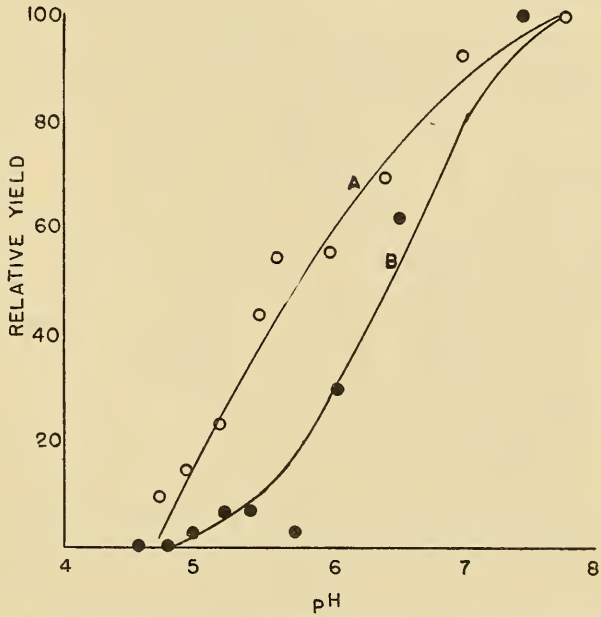

Fig. 9 — Alsike Clover Yields in Relation to Soil Reaction

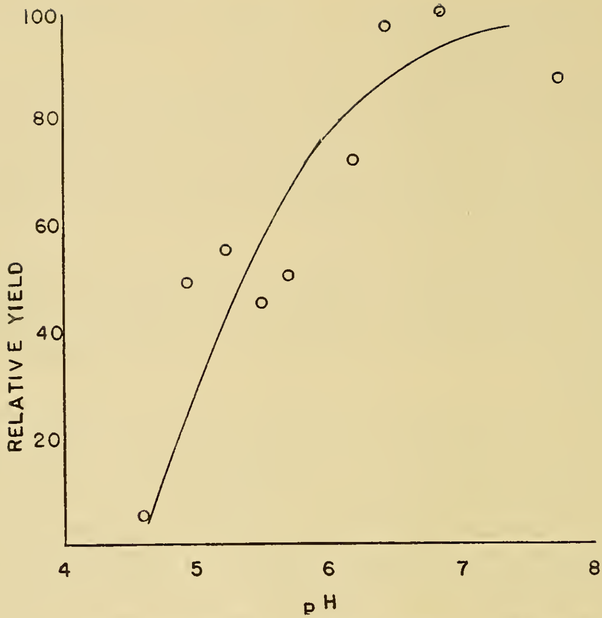

Fig. 10 — Korean Lespedeza Yields in Relation to Soil Reaction

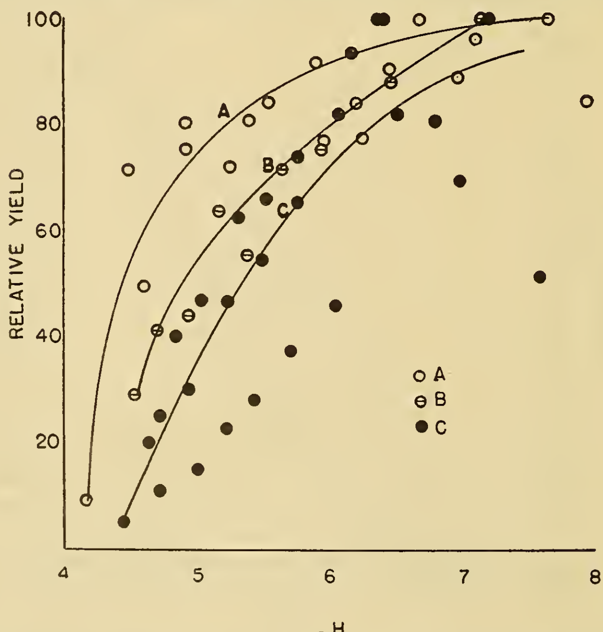

Fig. 11 — Soybean Yields in Relation to Soil Reaction

There were no significant differences in yields between the acid and aluminum series in 1939. The effect of high soluble calcium was very evident in 1929 and 1930 and to a lesser extent in 1936. The shape of all curves is similar, but it seems likely that Curve C more nearly represents the soil under normal conditions.

COWPEAS (Whippoorwill variety) were grown in the bins in 1929, 1930, 1936, 1938, and 1941. The results are shown in Figure 12. As with soybeans, these are divided into three curves. In 1929 and 1930 (Curve A) the highest yields were obtained at pH 5.0 to 5.1. In both years the yield at the highest reaction was significantly lower, indicating some injury from over-liming. This had largely disappeared by 1936 (Curve B), when the next cowpea crop was grown. The highest yield at pH 5.6 in 1936 was significantly different only from the yield at pH 4.5. However, as indicated by the curve, there was a downward trend in yield above pH 5.6. The 1938 and 1941 results, combined to give Curve C, show increased yields up to about pH 6.0, followed by little change at higher reactions. Here again the effect of the acid treatment is evident in giving relatively high yields at acid reactions. Curve C probably represents the yield trend under normal conditions in this soil.

SORGHUM was grown in the acid series in 1930, 1931, 1932, and 1939 and in the aluminum series in 1931 and 1932. Blackhull kafir was used in 1929 and 1930, Black Amber sorghum in 1931 and 1932, and Early Amber sorghum in 1939. The results are shown in Figure 13.

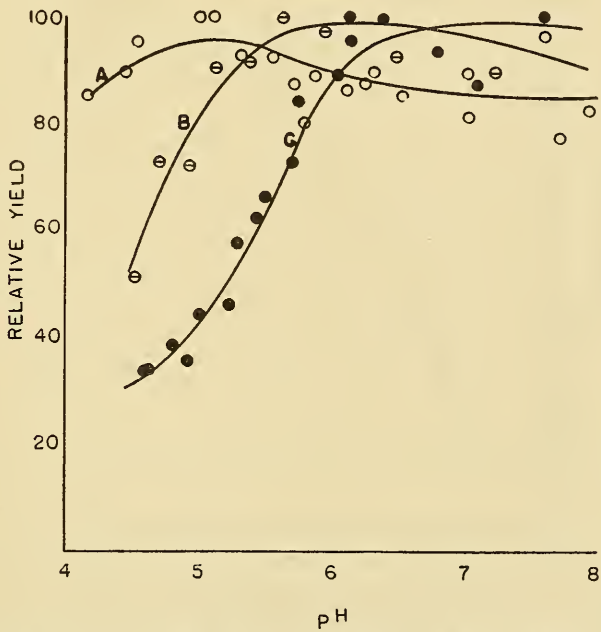

Fig. 12 — Cowpea Yields in Relation to Soil Reaction

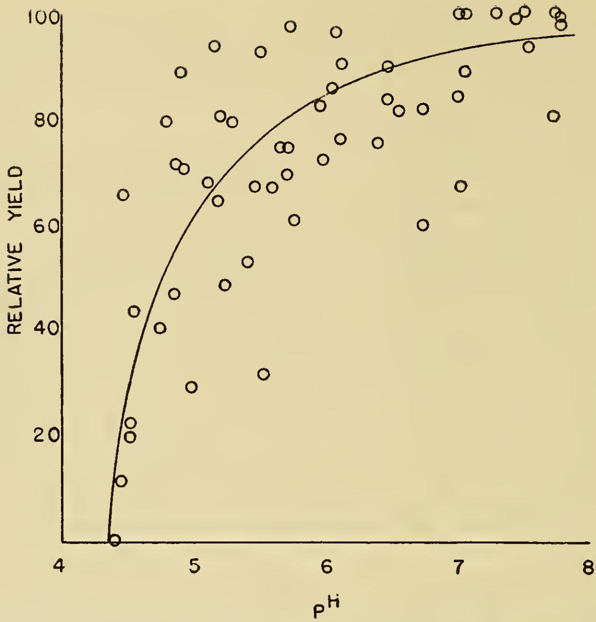

Fig. 13 — Sorghum Yields in Relation to Soil Reaction

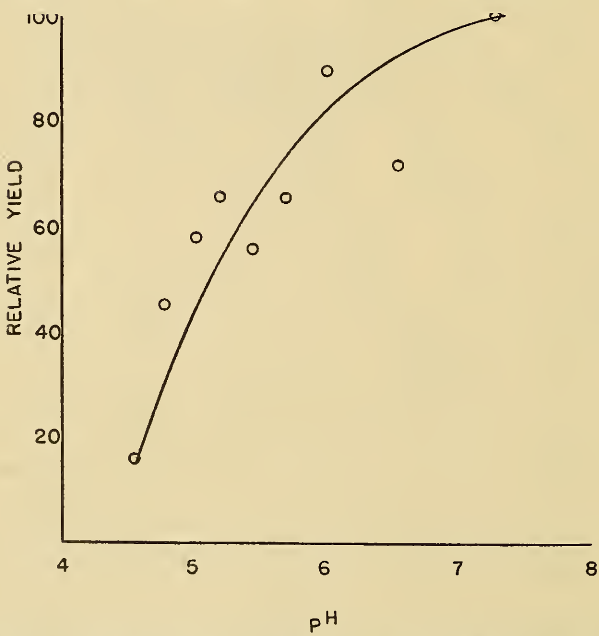

Fig. 14 — Sudan Grass Yields in Relation to Soil Reaction

Despite the different varieties used, the general trends were the same in all years, with the highest yields being secured at or near the highest reaction and in all cases above pH 7.0. The increases were not significant above pH 5.5.

SUDAN GRASS (Master Farmer variety) was grown in 1939. The yield trends shown in Figure 14 show marked increases up to about pH 6.0, with a further gradual increase up to 7.3, the highest value obtained in the bins at that time. However, the apparent increase above pH 5.7 was not significant.

GERMAN MILLET was grown in the reaction bins in 1939. The differences shown in Figure 15 are not significant, although the highest yield was obtained at pH 7.2.

TOBACCO (Burley Type) was planted in both acid and aluminum series in 1936 and in the acid series in 1937. The results are shown in Figure 16. In general the yield increases give a smooth curve, with the highest yield at about pH 7.2. The differences, however, above pH 5.6 were not significant.

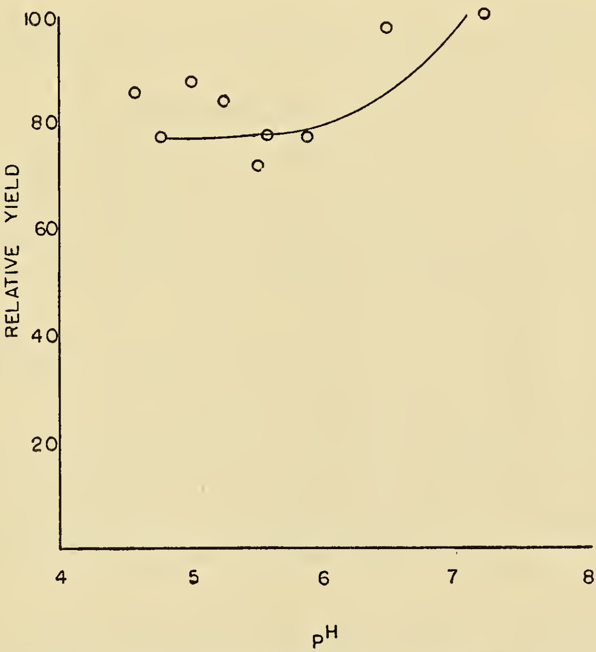

Fig. 15 — German Millet Yields in Relation to Soil Reaction (Points below pH 4.6 Omitted from Curve)

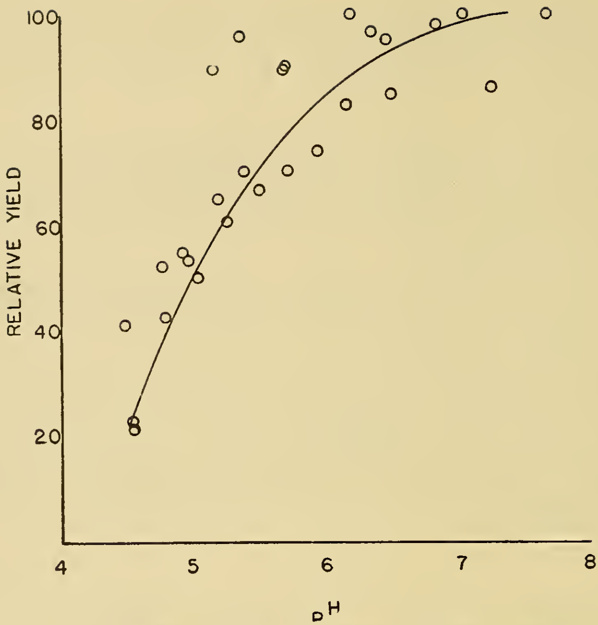

Fig. 16 — Tobacco Yields in Relation to Soil Reaction

DISCUSSION AND CONCLUSION

A great many references are to be found showing the effect of soil reaction on plant growth. Spurway (*6*) has recently reviewed these and has listed the optimum pH range for a large number of crops, as well as minimum and maximum pH limits for certain plants. The minimum pH for optimum growth and a comparison with the values reported by Spurway (*6*) are shown in Table 2.

In most instances the agreement is quite good, the greatest differences being with alsike clover and lespedeza, both of which showed relatively poor growth at low reactions in our tests.

Alsike clover has generally been considered as less sensitive than red clover to acid conditions. Bryan (*1*) secured slightly less growth of alsike clover at pH 5.0 than of red clover at the same reaction. Results at Ohio (*7*) show only a slight difference in these two crops at pH 5.0 and below. No explanation is apparent for the greater sensitivity of alsike clover noted here.

Sudan grass and cowpeas also showed somewhat greater sensitivity to soil reaction than shown by Spurway. On the other hand, barley showed somewhat greater tolerance in the present experiment. This may have been due to the high calcium content in the soil in 1931 and 1932.

Table 2—Minimum pH for Optimum Growth

Crop	Spurway	Lakin Results (a)
Alfalfa	6.2	6.7
Barley	6.5	6.2
Clover (Alsike)	5.5	6.4
" (Red)	6.0	5.9
" (Sweet)	6.5	6.6
Corn	5.5	5.1
Cowpeas	5.0	5.3 (b)
Lespedeza	4.5	5.8
Millet	5.0	--
Rye	5.0	--
Sorghum	5.5	5.2
Soybeans	6.0	6.0 (c)
Sudan grass	5.0	5.4
Tobacco	5.5	5.3
Wheat	5.5	5.9

(a) Based on significance at the 1% point.
(b) Average of 1938 and 1941 results.
(c) 1938 and 1939 results.

It has been shown by Papadakis (*3*) that different varieties of wheat vary in their tolerance to soil alkalinity. Similar differences probably occur in relation to acidity. However, there were no evident differences with the three varieties of sorghum. The differences in soybeans may have been related to variety, but it seems more probable that available calcium was responsible for the difference noted.

The decrease in yield at high pH values so frequently reported usually occurs during the first season following liming. Most workers attribute this to a temporary unbalance, since later crops are often not affected. Furthermore, such results appear only in certain soils. The only evidence of such a condition was with cowpeas, and even there it was not very marked. Apparently on this soil there was little overliming injury.

The role of soluble calcium in plant growth has been pointed out by Kelley (*2*) and recently summarized by Reed and Cummings (*5*). Its importance is unquestioned. But, since only one soil was used in this experiment, there was no opportunity to study in detail its effect on plant growth except as it was related to pH. As stated earlier, there may have been an influence of soluble calcium on the results secured during the first few years of the experiment.

The results presented here show a smooth growth curve relating pH to growth on a particular soil. Similar curves, with slightly different relationships, might be expected on other soils. The results, however, corroborate substantially the pH preferences of crops as shown by other investigators.

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