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Connecticut Agricultural Experiment Station
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CONNECTICUT AGRICULTURAL EXPERIMENT STATION

OFFICERS AND STAFF

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LIMING experiments in many tobacco sections have shown that lime may be injurious, beneficial or of no effect, depending upon local conditions with respect to soil acidity.

The determination of soil reaction as measured in pH values, where 7 pH is neutral, with units below 7 increasingly acid and above 7 increasingly alkaline, affords a reliable method for indicating the effects which soil acidity may produce upon the tobacco crop.

The amount of lime required to produce a desired decrease in soil acidity can be predicted from pH tests with a fair degree of accuracy, provided the factors indicated in this bulletin are used for calculating the effect of soil texture and organic content.

A survey of the conditions of Connecticut tobacco fields with respect to soil acidity have shown that while a majority of the fields range between 5.0 and 5.6 pH, many are more acid or less acid than these limits.

Crop conditions on these fields indicate that tobacco on fields more acid than 4.8 pH are likely to be adversely affected, both in yield and quality, by such degree of acidity. On fields less acid than 5.6 pH, injury due to black root-rot is prevalent.

These observations are confirmed by field and greenhouse experiments.

Liming soils which are strongly acid improves the character of the burn and the whiteness of the ash of tobacco grown on such fields.

Tobacco grown on strongly acid soils is abnormally high in content of manganese. There are indications that poor tobacco on these soils may be due to an abnormal concentration of soluble manganese in the soil and a consequent toxic effect upon the crop.

Liming the soil has reduced the absorption of potash by the tobacco plant, and has increased the necessity for liberal potash fertilization.

Some fertilizers, particularly sulfate of ammonia, increase soil acidity, while others, such as nitrate of soda, have the opposite effect.

Fields testing between 5.0 and 5.6 pH are in a satisfactory condition with respect to soil acidity. No lime should be used on such fields, and fertilizers which decrease soil acidity should be used with caution.

Fields more acid than 5.0 pH should not receive fertilizers with an acid tendency. At reactions between 4.6 and 5.0 pH, the equivalent of 1,000 lbs. of agricultural limestone per acre should correct the injurious degree of acidity on soils of average type for this section, while soils more acid than 4.6 pH may require as much as 2,000 lbs. per acre. Excessively sandy soils should be limed at somewhat smaller rates.

Fields between 5.6 and 6.0 pH may be made sufficiently more acid for protection against black root-rot by the selection of fertilizers with an acid tendency.

When the soil reaction is less acid than 6.0 pH, tobacco should not be grown. Other crops for a period of years, fertilized with acid-tending fertilizers may gradually restore a desirable degree of acidity.

Soil Reaction and Liming as Factors in Tobacco Production in Connecticut

By

M. F. Morgan, P. J. Anderson and Henry Dorsey*

Neutralization of the natural acidity of the soil by application of lime has a demonstrated value in the growing of many crops. The benefits thus derived have led to the inauguration of state wide liming campaigns in some sections. The publicity given to such propaganda involves the danger of creating the impression that liming is beneficial to all crops. However, it has been thoroughly demonstrated in the case of tobacco and potato crops that indiscriminate liming may be not only without benefit, but under certain conditions, positively harmful. On the other hand, it is a well-known fact that on some fields the application of lime has improved both the yield and the quality of tobacco. Such apparently contradictory evidence has not only confused the farmer, but also has confronted the agricultural scientist with the necessity of explaining such cases and of finding a method of indicating to the grower under what conditions he may expect beneficial results and why injury results at other times.

The principle effect of lime on soil is to change its reaction (degree of acidity). Since other substances which change soil reaction in the same direction have the same effect as lime upon the tobacco crop, it seems most likely that the reaction change produced by lime is primarily responsible for the effects observed on the crop. If this is a correct deduction, then the first and fundamental step in explaining these conditions and solving the difficulty is to answer the question:

1. *What is the optimum soil reaction for tobacco production?*

Corollary to this are the two questions:

2. *What is the effect of too much acidity?*
3. *What is the effect of too little acidity?*

The object of the present bulletin is to bring together the results of all the experimental work which has been done in the Connecticut Valley in trying to answer these questions, to summarize our present knowledge of the problem and to make it accessible to the growers and to other agricultural workers. Considerable data accumulated during recent years at Windsor, New

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Haven, and Storrs have not been published previously or only briefly presented in annual reports.

The steps followed in conducting the investigation were:

1. An extensive field survey in which the reaction of soil from over 2,000 tobacco fields has been tested.
2. Correlation of the reactions found with the condition of the tobacco grown on the fields.
3. Experimental plot tests with applications of lime and other soil amendments.
4. Greenhouse tests in pots.
5. Chemical analyses in the laboratory.

Previous Investigations

Until recent years no attempts have been made to determine the optimum degree of acidity of soil for tobacco production. Investigators in a number of states, however, have tried to measure the effects on the crop when soil acidity was partially or completely neutralized by application of lime. Without going into exhaustive detail, we present here the conclusions drawn from these liming experiments.

FIELD TESTS ON LIMING

Kentucky. On experimental fields in three different sections of the state two tons of limestone per acre were used where tobacco was grown in rotation with other crops. On the Lexington field there was no significant change in yield, on the Greenville field there was a decrease in yield while on the Mayfield soil there was an increase in one set and a decrease in the other. As a result of these tests Roberts, Kinney and Freeman (29) state that "Lime does not often benefit tobacco." The reaction of these soils before or after liming is not stated.

Tennessee. Mooers (20), in reviewing the results of six years of fertilizer tests on tobacco, states: "Liming was tested on several farms and at each place under a variety of fertilizer conditions, but no general conclusions can be drawn from the results except that tobacco does not appear to be very responsive to liming." During the next ten years, rotation experiments with tobacco, soy beans, wheat, grass and clover were tried at the Clarksville station on dark tobacco. In this rotation, two tons of ground limestone were applied to the wheat. At the end of the ten years (21) there was a difference in yield of only one per cent between the limed and unlimed tobacco. No records of the reaction of the soil are presented.

Ohio. Liming experiments on tobacco grown in a three-year rotation with wheat and clover were conducted at Germantown

(26) for 21 years. Lime was applied at the rate of 1,000 lbs. per acre (hydrated at first but limestone later) when fitting the land for tobacco. There were five pairs of plots in which lime was contrasted with no lime. When the yields were averaged at the end of 21 years it was found that in each of the five replications the yield of tobacco had been reduced. The reaction of this soil is not stated but since it "has been derived from glacial drift largely made up of limestone detritus" it may be inferred that it was not very acid at first. The fact that the depressing effect of lime was more noticeable during the latter part of the experiment indicates that root-rot may have played an important role here.

Maryland. Concerning an early experiment on liming in 1891 Patterson (27) states: "Lime injures the burning quality of tobacco and prevents its curing nicely." He finds the same effect also from magnesium salts.

In a later bulletin (28) Patterson also says: "Lime and magnesia compounds in small quantities seemed to produce but little effect, but in large quantities caused a growth that ripened unevenly and was hard to cure, yet with slightly improved combustibility, but on the whole, the application of lime immediately before planting of tobacco cannot be recommended."

In speaking of a later five-year series of experiments, Garner and Brown (16) state: "Where no nitrogen is supplied in the fertilizer, lime usually gives a considerable increase in yield, but where a nitrogenous fertilizer has been applied, no substantial benefit from liming is apparent. . . . . The effect of the lime in increasing the availability of the soils supply of nitrogen, however, is very marked and in fact, for this reason liming may produce a decidedly unfavorable effect on the quality of the tobacco crop under certain conditions. Farmers have frequently observed that liming a soil which is well provided with organic matter produces a dark colored and coarse textured leaf and the reason for this is that the lime makes available for the tobacco plant an excess of nitrogen. . . . While lime is not of great importance for the tobacco crop when supplied direct and even may be highly injurious, its direct action when applied to other crops may be highly beneficial."

New York. In experiments at Baldwinsville where 2,000 lbs. of burnt lime were applied once in four years there was an increase of 106 lbs. per acre in the cured tobacco. Collison and Harlan (10) state that the soils in this section are not abundantly supplied with calcium while a large part of what is present is not in carbonate form. The reaction of the soil is not stated.

Virginia. Green (17) speaking of results with suncured tobacco in rotation at Bowling Green says: "One half of each fertilizer plot is limed at the rate of 2,000 lbs. of burnt lime per acre once in the rotation. In none of our experiments at Bowling Green has lime given marked beneficial results. Where lime was used on the ten plots the average gross value of the tobacco was 24 cents per acre less than where lime was not used. Our experiments covering four years and involving about 190 individual fertilizer plots have not shown sufficient results to warrant the use of lime." Chemical tests showed that this land had little need of lime, yet he continued: "Some farmers a few miles distant from the experiment field report beneficial results from lime. Perhaps this condition is only local." On another field he obtained a slight benefit from liming. Further Virginia tests are reported in the next section.

North Carolina, Georgia and Virginia Flue-cured tobacco. Rather extensive experiments conducted at various places in these three states have been described by Moss et al (25). It will be sufficient to quote from their summary: "It would seem from the foregoing results that the use of ground limestone on the soils represented is not likely to give increases in the yield of tobacco unless the limestone carries a considerable quantity of magnesia . . . . . If potash salts carrying magnesia are used in quantities supplying 10-20 lbs. of magnesia per acre, under average conditions, little or no increase can be expected from the use of lime on tobacco. This is largely true at least with the fertilizer mixtures used in these tests, for in such mixtures, the phosphates used supply sufficient calcium for the plant food requirements of the tobacco crop. It is possible, however, that some tobacco soils are so acid as to require liming for best results independently of the plant nutrients in the soil." They warn against the excessive use of limestone on account of danger of root-rot and of liberation of ammonia. The actual degree of acidity on the plots is not stated except at Oxford, N. C., where it ranged from 5.66 to 5.98 pH before application of lime.

Canada. At the Ontario station when ground limestone was applied at the rate of 2,000 lbs. per acre for Burley tobacco, there was an average reduction of 158 lbs. per acre. Digges (12) states: "While the experiment has been conducted only one year and the results cannot be taken too conclusively, they very strongly indicate that liming . . . . . is undesirable from both the standpoint of yield and quality." At Farnham, Quebec, a liming experiment was conducted on tobacco in rotation with oats and clover at rate of 2,000 lbs. of air slaked lime per acre applied early in the spring before fitting for tobacco. Summing up this experiment Montreuil (22) says: "In every case lime has had the effect of cutting down the yield and did not improve the quality of the leaf." In a later experiment on this same field tobacco was grown continuously for three years (1925-27) with the same lime application as above. Slagg, Montreuil and Major (30) state concerning this experiment: "Significant decreases in yield and quality were secured wherever lime was applied during each of the three years of the experiment."

Connecticut. In the Poquonock experiments of 1892-96 where tobacco was grown continuously there were two pairs of plots contrasting lime at an annual rate of 300 lbs. per acre with no lime. Differences in yield, rank and fire-holding capacity of the tobacco were insignificant. No records of the soil reaction before or after liming were presented. Jenkins (18) drew no conclusion from this experiment but the data presented show that lime applied at this rate had no appreciable effect on the crop.

Massachusetts. Where tobacco was grown continuously and heavily limed (1 to 2 tons) each year, Anderson, Osmun and Doran (3) found the yield increased at first but later it was very much reduced and the roots were badly infested with the black root-rot organism.

Conclusions to be drawn from field liming tests in the principal tobacco growing sections of America. It is apparent from these published accounts that liming has been widely tested and that all the information which may be gained from routine lime plots is at hand. Briefly it is:

1. Lime may be injurious, beneficial, or neutral in its effect on tobacco.
2. Not only are the yield results different for the various sections but even in the same state the effect may be different, for example, Virginia.
3. On the same field liming may be beneficial at first but injurious later; for example, Ohio and Massachusetts.
4. Although results in most cases have been measured solely or mainly in yield, impairment of quality has also been mentioned in Maryland and in Canada.
5. None of the investigators mentions an improvement in quality.
6. No attempts have been made to correlate the effects observed with the changes produced in reaction of the soil, except for the Massachusetts experiments.
7. The injurious effects in a few of the more recent tests have been ascribed to promotion of black root-rot. In the most recent Canadian experiment it was suggested that the decrease in yield was due to lime without respect to root-rot. In Maryland it was thought that impairment of quality was due to too rapid liberation of nitrogen.
8. No explanation of beneficial effects is attempted but it is not believed that there was an actual shortage of nutrient calcium in any case, with the possible exception of the New York experiment.

BLACK ROOT-ROT AS AN EXPLANATION OF INJURIOUS EFFECT OF LIMING

Working in the Connecticut Valley in 1907 Briggs (7) was the first investigator to call attention to the fact that black root-rot was most severe where the land was made more alkaline by the use of such materials as lime, wood ashes, and carbonate of potash. He made no attempt, however, to measure the degree of acidity in question.

The same conclusion was reached by Beals (6) in Massachusetts from his field survey in 1915. This work was continued by

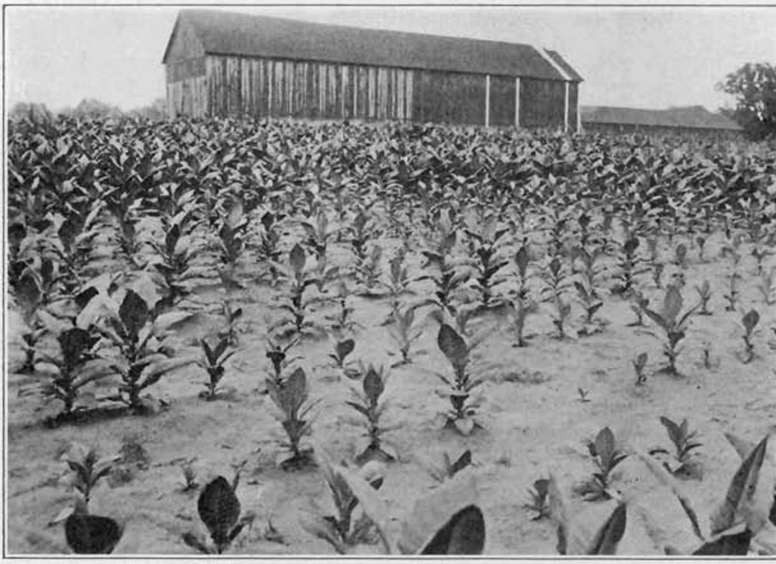


FIG. 66—Field of tobacco, showing black root rot on soil which is not sufficiently acid to prevent injury from this disease.

Chapman (9) who was the first to attempt to measure and correlate the soil reaction with root-rot. He determined the reaction of soils from a large number of tobacco fields by the Jones lime requirement method and by comparing the reaction with the condition of the tobacco on each field he came to the following conclusion:

"The tobacco soils of Massachusetts fall into three groups, as regards acidity. Soils with a lime requirement up to 3,000 lbs. per acre are not producing good crops, as a rule and are comparatively free from root-rot. Those with a lime requirement of from 3,000 to 8,000 lbs. CaO per acre are in good tobacco condition; but in this group pathogenic fungi are abundant in the soil, and the plants during certain seasons are very liable to suffer from root-rots, caused by some of these fungi. Soils with a lime requirement of 8,000 pounds CaO up are usually comparatively free from such fungi, and even in unfavorable seasons little disease is found, but the tobacco is perhaps of slightly inferior quality."

In pot experiments Johnson and Hartman (19) confirmed in general the conclusion of Briggs, Beals and Chapman that an acid soil checks the severity of the disease. Using the Truog method of determining lime requirement they found the disease much reduced in soils more acid than a lime requirement of 4.6 tons. They also showed, however, that the critical reaction shifted with the susceptibility of the variety, Burley being badly diseased at a reaction which inhibited disease on Connecticut Havana.

Anderson, Osmun and Doran (3) were the first to correlate severity of infection with soil acidity as measured by the hydrogen-ion method. Working with field plots artificially inoculated and limed, they came to the following conclusions at the end of five years:

1. The immediate effect of liming an acid soil was to increase the yield of tobacco.
2. If sufficient lime is added, black root-rot is ultimately promoted and there is consequently a reduction in yield.
3. Black root-rot is present in most soils but is more injurious in nearly neutral soils because the causal fungus, *Thielavia basicola,* grows more rapidly and vigorously in a nearly neutral medium.
4. In the field under experimentation, black root-rot caused little or no loss in soils more acid than pH 5.6. It caused severe loss on all soils less acid than pH 5.9. It should be understood that this critical region between pH 5.6 and 5.9 is an intermediate zone which may be shifted to a somewhat higher or lower position by variations in temperature and compactness of soil and by differences in the degree of infestation of the fungus in the soil.
5. As the soil becomes less acid, above pH 5.9, the loss from black root-rot increases.
6. After repeated applications of lime brought the soil reaction to a point favorable to the fungus, the omission of lime for two years, with tobacco grown continuously meanwhile, did not result in any immediate reduction in the severity of black root-rot.

Soil Reaction, Soil Acidity and Lime Requirement—Some Brief Definitions:

In the sense considered in this bulletin, the term "soil reaction" is used to indicate the degree of intensity of acidity or alkalinity which exists in the soil. It is now quite generally expressed in terms of "pH," on a scale where 7 pH (approximately) indicates the neutral point (neither acid nor alkaline) while lower units of pH, for example, 6 and 5 pH, indicate increasing degrees of acidity, while pH units above 7, such as 8 and 9, indicate alkalinity.

"Soil acidity" is a broader term, which includes not only the acid soil reaction, the intensity of which is measured in terms of pH, but the characteristic conditions of the soil which are related either directly or indirectly to such acid reaction.

Increasing degrees of soil acidity in a group of soils of varying reaction is usually evidenced by most, if not all the following conditions:

1. There is an increase in intensity of soil reaction, as indicated by pH values farther and farther below 7.
2. A decrease is to be found in the content of easily liberated (replaceable) lime and magnesia.
3. The more strongly acid soils may show a considerable concentration of soluble aluminum and maganese, with a consequent toxicity to the plant.
4. Carbonates of lime or magnesia when mixed with the moist soil are decomposed, with an absorption of the bases and an evolution of carbon-dioxide gas. The amount of lime which will be absorbed by the soil in this manner is greater on the more acid soils.
5. Nitrogen fixing bacteria which are free-living in well drained soils diminish or cease their activities and there is a decreasing effectiveness of legume bacteria and nitrifying organisms on the more acid soils.
6. In general, the rate of decomposition of soil organic matter is diminished at higher degrees of acidity.

It is not possible to say with assurance whether the other conditions are the cause or the result of the first one named, or that any or all of them are the result of some more remote soil processes which are evidenced only through these phenomena.

The "lime requirement" of a soil is commonly accepted as indicating the amount of lime, as burnt lime, hydrated lime, limestone or marl, which is required to bring the soil from its acid reaction to a condition of approximate neutrality, (7 pH.) It can be measured with a fair degree of accuracy by a number of chemical methods, and the results are expressed in terms of the number of pounds or tons of calcium oxide or calcium carbonate equivalent which the soil can absorb without becoming alkaline. The lime requirement of the soil is not the same as the lime requirement of the crop, since the crop may not require a neutral reaction and it may be desirable to maintain a certain degree of soil acidity.

A more complete statement in regard to the nature of soil acidity is given in Connecticut Agricultural College Extension Bulletin No. 101, while an exhaustive discussion of methods of measurement of soil acidity has been published by Conner, Morgan and Conrey (11).

A Study of Methods for Measurement of Soil Acidity

In the course of this survey four methods for the quantitative measurement of soil acidity were used. When the work was begun in 1925 the Stirlen double-wedge apparatus was the one immediately available for measuring pH values. This was used on two hundred soils. It was found that within the range of the bromthymolblue indicator (6.0-8. 6 pH) the data obtained were consistent with expected results. But soils of greater acidity, as measured by chlorphenol red, methyl red or bromcresol purple, tended to give results much nearer the same value—about 5.75 pH, than would be expected in a normal frequency distribution range. As soon as possible, a hydrogen-ion concentration apparatus for the electrometric determination of pH values, employing the gas chain hydrogen electrode, was set up and the "double-wedge" results were checked by this method. It was immediately apparent that the soils under investigation varied over a much wider range of pH values than had been found by the double-wedge method, and that soils below 5.75 pH were much lower in pH when measured by the hydrogen electrode. The following table shows a typical comparison of results by the two methods:

Table 1. Comparison of Double-wedge and Hydrogen Electrode Methods for Measurement of pH Values

Soil No.	Double-wedge	H.-Electrode
1	5.65	4.76
8	5.75	4.89
187	5.75	5.00
201	5.80	5.85
207	5.85	5.51
209	5.75	5.56
211	5.90	6.16
214	5.70	5.78
217	5.75	5.58
218	5.70	5.21
222	5.90	6.01
273	5.90	5.36
282	5.80	5.08
294	6.20	6.51
302	5.80	5.38

It was therefore decided to discard the double-wedge method.

At about this time the Morgan soil testing set (23) was developed by one of the authors and it was decided to make pH tests by both this and the electrometric apparatus, which was the procedure on about twelve hundred soils.

The gas chain hydrogen electrode was replaced by the more rapid and convenient quinhydrone electrode in the electrometric measurement, since the results of the two methods were found to be in close agreement.

The standard procedure finally adopted for determination of pH by the quinhydrone method is as follows:

> 10 gms. of freshly collected soil, 10cc of distilled water and approximately 10 mgs. of quinhydrone are stirred together for about one minute and the pH determined at once by means of a Leeds and Northrup Type K potentiometer, with the customary standard cell, storage battery and galvanometer. The half-cell used is the .01 N. HCl-.09 N. KCl quinhydrode half-cell described by Veibel (31). Connection with the half-cell was made by means of a saturated KCl agar bridge. Constant readings were obtained within a couple of minutes.

After several hundred soils had been tested independently by the Morgan soil testing set by the staff at the Tobacco Substation at Windsor and by the quinhydrone electrode at the Soils laboratory at the New Haven Station, a tabulation of 626 soils showed the following discrepancies between the results of the two methods:

.0—.1	pH—	239	soils
.1—.2	" —	165	"
.2—.3	" —	134	"
.3—.4	" —	54	"
.4—.7	" —	24	"

As a result of these comparisons, it was decided that the Morgan soil testing set was of satisfactory accuracy for general field use, but that the special features of this investigation necessitated the use of a standard method which was independent of the personal factor involved in colorimetric measurement. Hence the quinhydrone-electrode results were the ones selected for final tabulation, and in subsequent measurements this was used exclusively for determining pH values.

Since the earlier investigations of Chapman (9) were conducted prior to the general adoption of pH measurements in soil studies, and his conclusions were based on the Jones lime requirement method, it was desirable to compare the pH values with the results of this method. 650 soils were sent to the Connecticut Agricultural College and the lime requirements in terms of lbs. of $CaCO_3$ per 2,000,000 lbs. of soil were determined by the modified Jones method used by Dorsey (14).

An inspection of the data obtained on these soils by the two methods showed that while there is a general relationship between the two sets of results, there were many wide discrepancies. This is shown in the following table, which includes 25 soils obtained at random by selecting every tenth soil in the series:

TABLE 2. COMPARISON OF JONES LIME REQUIREMENTS AND pH VALUES

Soil No.	pH	$CaCO_3$ Requirement in lbs. per 2,000,000
660	6.16	1,290
470	6.07	2,258
530	5.93	1,774
650	5.86	2,258
600	5.85	1,935
560	5.83	2,580
520	5.70	4,193
370	5.59	3,708
590	5.57	2,903
620	5.55	2,903
540	5.50	3,386
630	5.48	3,870
550	5.39	2,580
390	5.38	4,515
430	5.28	2,580
670	5.22	5,483
510	5.10	1,935
440	5.04	4,031
480	5.03	3,581
490	5.03	2,903
420	4.95	3,870
380	4.92	7,095
570	4.89	3,548
540	4.86	5,966
500	4.52	3,870

These results are in agreement with the work of Carleton (8), who also pointed out that there was a general correlation when soils of the same textural classes were grouped together.

The soils included in our studies represented a considerable range of texture and organic content. The Jones method is essentially a measure of the absorption of the calcium-ion from a salt of a strong base (calcium) and a weak acid (acetic acid) thus leaving free acetic acid with a readily titratable acidity in direct proportion to the amount of calcium absorbed. It follows that the acidity thus measured depends not only upon the pH of the soil, but upon the absorptive surface of the soil. The latter will depend upon both the texture and the organic content of the soil.

The soils which had been tested for pH and lime requirement were examined carefully by a trained soil survey worker, who estimated the texture and relative amount of organic matter of 551 of these soils which had been preserved for future study. The pH and Jones $CaCO_3$ requirement were then graphically plotted, with a separate graph for each textural group, variations in or-

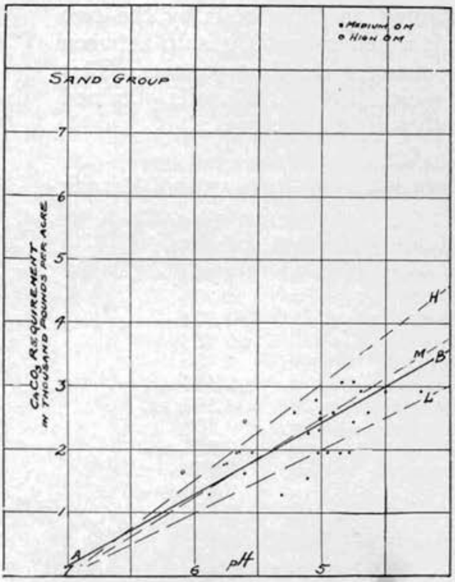


Fig. 67

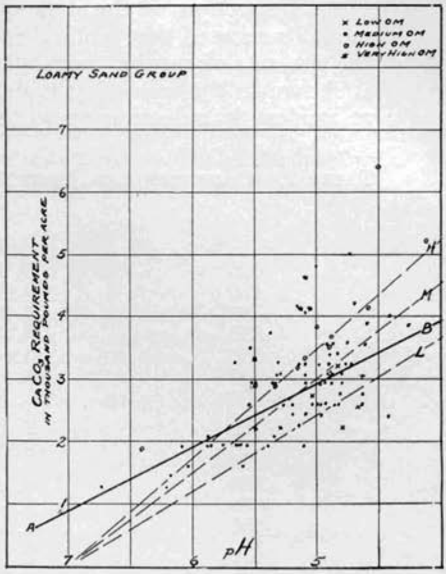


Fig 68

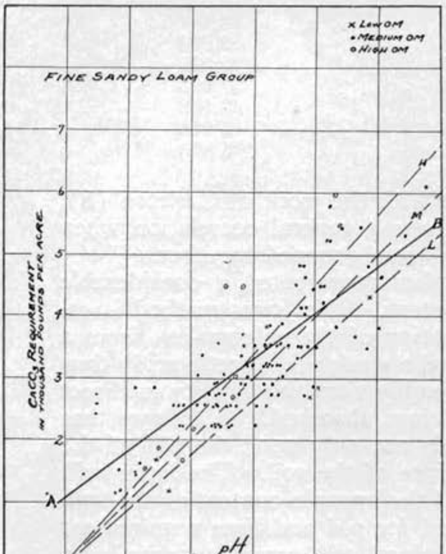


Fig. 69

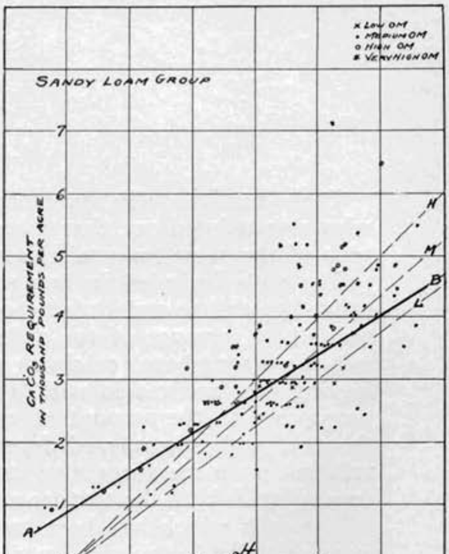


Fig. 70

The relationship between pH, lime requirement, soil texture and organic content.

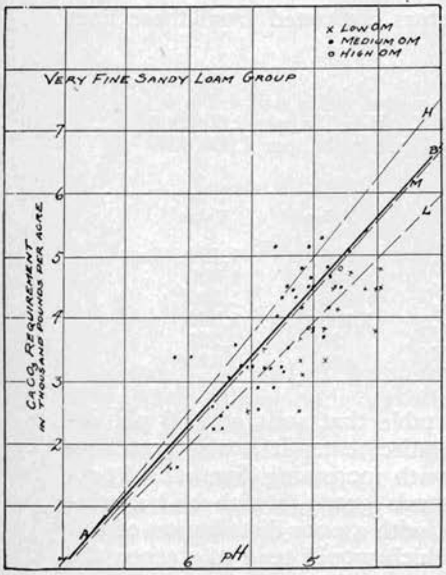


Fig. 71

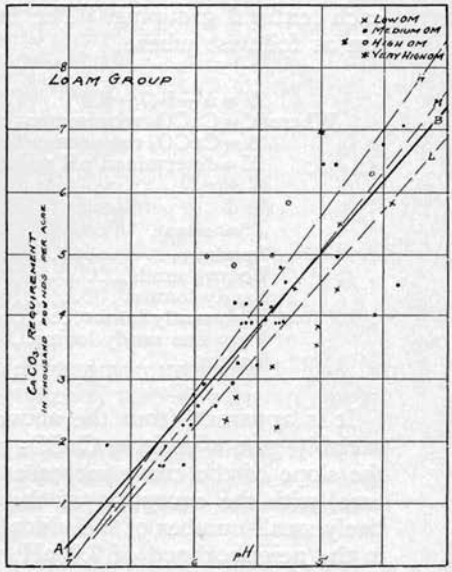


Fig. 72

The relationship between pH, lime requirement, soil texture and organic content.

ganic content being represented by symbols, for low, medium, high and very high amounts. It was immediately apparent that a definite correlation existed between pH and Jones lime requirement where soils of the same texture and organic content were compared. See figures 67 to 72.

Two groups of soil with more than a hundred individuals in each, the fine sandy loam and sandy loam groups, both with medium organic content, were selected for computation of correlation coefficient. The result are as follows:

Soil group	Correlation Coefficient
Fine sandy loam, medium organic content . . .	.757 ± .015
Sandy loam, medium organic content.	.856 ± .026

While a perfect correlation (1.000) is far from being attained, yet in consideration of the fact that the texture and organic content were estimated from observation rather than actually determined by mechanical analysis and laboratory method of organic matter determination, the results are in surprising agreement.

Figures 67 to 72 also show, as line AB, the mathematically determined regression lines for soils of average organic content in each textural grouping. The factors computed from these lines are as follows: where

$$Y = A - B(7 - X)$$

Where Y = $CaCO_3$ requirement at X pH in lbs. per 2,000,000
A = $CaCO_3$ requirement at 7 pH in lbs. per 2,000,000
X = determined pH value

Soil group	Value A	Value B
Sands....................	225	1,100
Loamy sands..............	925	1,000
Sandy loams..............	900	1,390
Fine sandy loams.........	1,100	1,500
Very fine sandy loams.....	25	2,225
Loams....................	400	2,325

It is apparent from the above table that soils at 7.00 pH invariably give a positive $CaCO_3$ requirement. It is also seen that the slope of the curve increases with increasing fineness of texture, with the exception of the sands group, which had a relatively small number of individuals, with a poor distribution of soil in the neighborhood of 7.0 pH, which would tend to steepen the slope of the regression line.

An inspection of the graphs shows that soils with high organic content give higher lime requirements at the same pH value than those of medium organic content, while the reverse is true of soil low in organic matter.

For the purposes of simplification, it appeared desirable to assign arbitrary values in definite units to indicate a straight line correlation between pH and lime requirement, with a zero line requirement at 7.0 pH, which would fit the distribution of points on the graphs to the maximum degree. After considerable trial and error, the following factors were selected, to be substituted in the equation $Y = 1{,}000K(7 - X)$:

Where Y = $CaCO_3$ requirement in lbs. per 2,000,000
X = determined pH value

Texture	Organic Content	Value of K
Sands..................	low	1.00
"	medium	1.25
"	high	1.50
Loamy sands...........	low	1.25
" "	medium	1.50
" "	high	1.75
Sandy loams...........	low	1.50
" "	medium	1.75
" "	high	2.00

Texture	Organic Content	Value of K
Fine sandy loams.......	low	1.75
" " "	medium	2.00
" " "	high	2.25
Very fine sandy loams...	low	2.00
" " " " ...	medium	2.25
" " " " ...	high	2.50
Loams................	low	2.25
"	medium	2.50
"	high	2.75
Silt loams.............	low	2.50
" "	medium	2.75
" "	high	3.00

Lines L, M and H, computed from these arbitrary values for low, medium and high organic contents, respectively, are shown on the graphs.

The degree of error in estimate of lime requirement from pH value by means of these lines as compared to the Jones lime requirements was computed for each soil studied. The results of these comparisons are as follows:

Error of estimate in lbs. $CaCO_3$ per 2,000,000	Percent of Soils
300 or less..........................	37.56
500 " "	68.96
1000 " "	90.19
1500 " "	96.91
2000 " "	99.45
2300 " "	100.00

Mean error of measurement: 509.2 lbs.
Standard deviation: 600.9 ± 12.21 lbs.

A similar type of correlation between pH values and lime requirement was attempted by Arrhenius (5), who gives the following table as the amount of hydrated lime in Kg per hectare (approximately the same as lbs. per acre) to change the soil reaction 1 pH unit in the alkaline direction:

Soils	Poor in Humus	Average Humus	Rich in Humus
Sandy..............	500	1000	1500–3000
Fine sandy..........	500–1000	1000–1500	2000–3000
Light clay..........	1500	2500	3500
Average clay........	2500	3500	4000
Heavy clay..........	3000	4000	4500

Humus soils with 15 per cent organic matter—4000–8000

It is believed that with soils of the types represented in these studies, the lime requirement can be estimated with reasonable accuracy for all practical purposes from determinations of pH values, using appropriate factors depending upon the texture and organic content of the soil. Accuracy within 1,000 lbs. CaCo per acre is sufficient, since rates of application of limestone are usually made to the nearest half ton quantity.

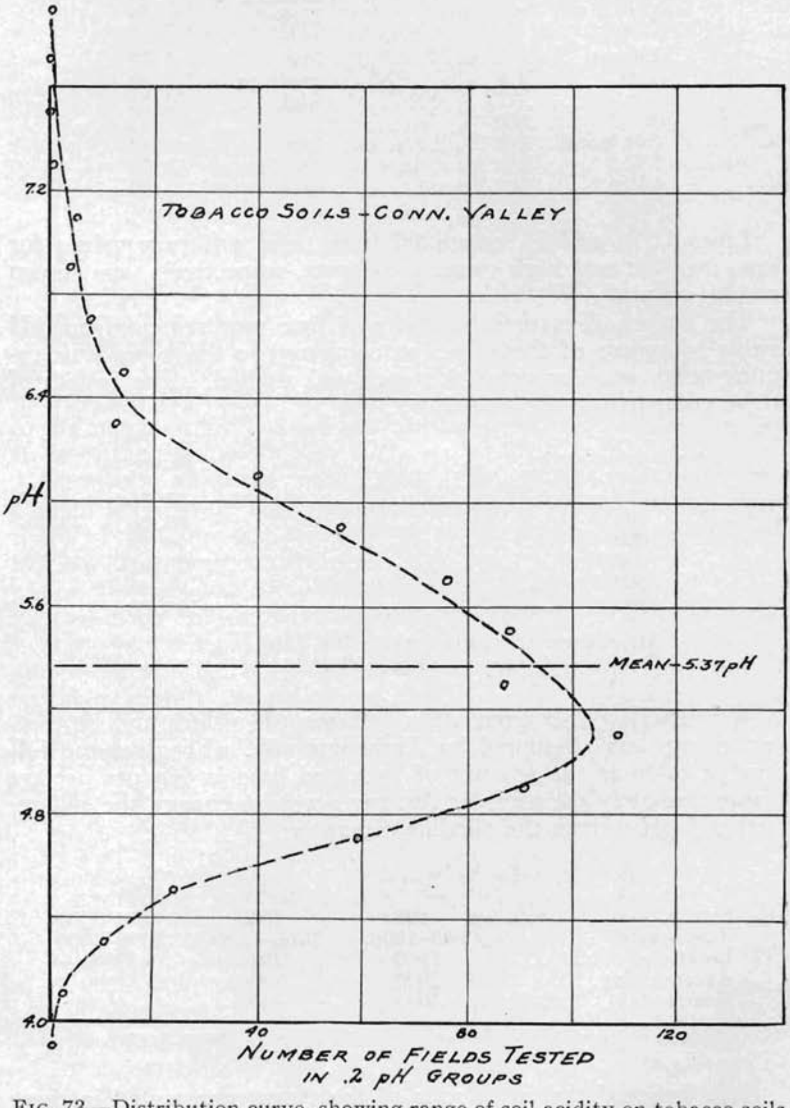


FIG. 73—Distribution curve, showing range of soil acidity on tobacco soils of the Connecticut Valley.

DISTRIBUTION OF SOIL ACIDITY IN THE CONNECTICUT VALLEY TOBACCO DISTRICT

The results of electrometric pH tests of soil samples from seven hundred tobacco fields* have been brought together and graph-

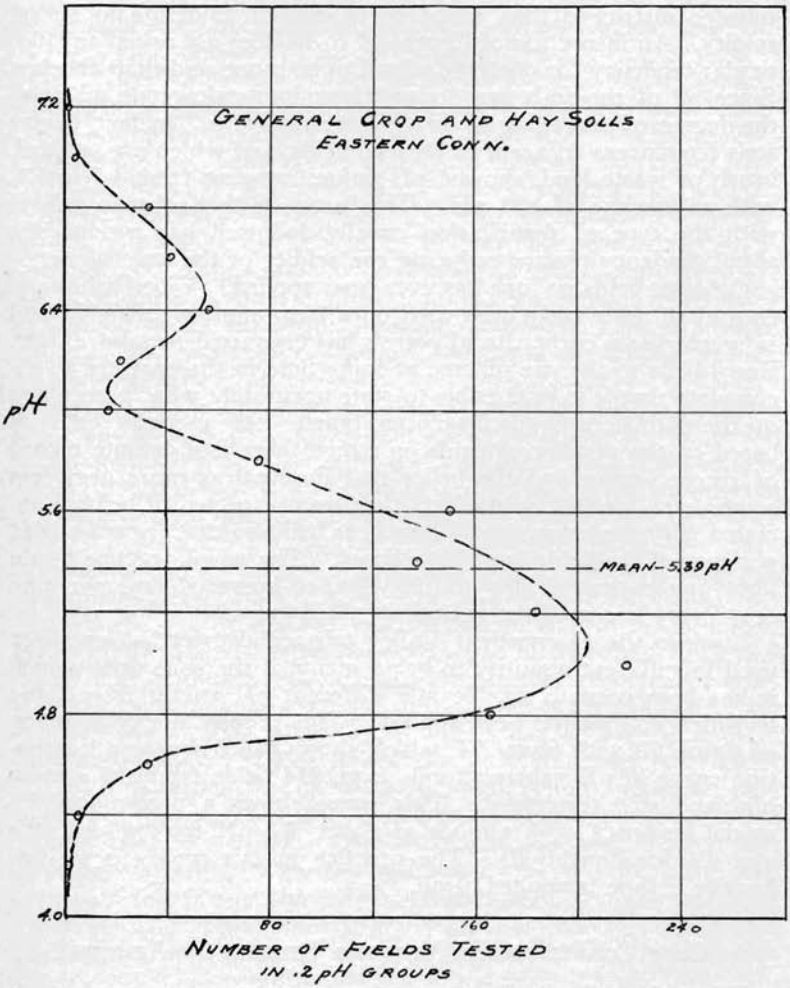


FIG. 74—Distribution curve, showing range of soil acidity on eastern Connecticut dairy farms.

*We are indebted to J. S. Owens, Extension Agronomist, Conn., Agr. College, and B. G. Southwick, County Agent, Hartford County, Conn., for assistance in collecting these samples.

ically plotted as a frequency distribution curve in figure 73. The soils ranged from 8.2 pH to 3.9 pH, with a pronounced modal point at 5.2 pH. The mean of all soils tested was 5.37 pH. Eighty-one per cent of the soils had pH values between 4.6 and 6.0 pH.

The prevailing condition of the soils of the Connecticut Valley tobacco district is thus found to be one of moderate to strong acidity. An inspection of figures 67 to 72 does not reveal any particular tendency for one type of soil to be more acid than another. Since all of the soils are derived from non-calcareous material, the degree of prevailing acidity is not surprising. In fact, twelve soils from areas adjacent to tobacco fields, and which are wooded, brush or waste land, showed pH values ranging from 4.7 to 5.4, with an average of 4.91 pH. This suggests that tobacco culture with the type of fertilization usually followed has produced a slight tendency toward reducing the acidity of the soil.

On most fields no lime has ever been applied. Wood ashes and cottonhull ashes have been used on a large number of fields, and in recent years carbonate of potash has been used to some extent. Records as to the use of lime at some time in the past are so incomplete that it is impossible to state accurately what percentage of these tobacco lands has been limed. As a rough estimate based on the number of fields on which there is a definite record of recent liming and the belief that liming was more prevalent some years ago before black root-rot was suspected of being associated with the heavy use of lime, it is believed that from 30 to 40 per cent of the fields have been limed. The usual practice was a light application of 500 to 1,000 lbs. of hydrated lime per acre once every two or three years.

Lime in the Connecticut Valley tobacco district has not been used in sufficient quantity to bring many of the soils upon which it has been used to significantly different pH values from those to which no lime has been applied. This is seen in a comparison of figure 73 with figure 74, which shows the frequency distribution curve of pH values of soils from 914 fields from the eastern highland of Connecticut. This curve shows a pronounced bimodal tendency, with a mode of about 5.1 pH for unlimed soils and 6.4 for limed soils. The practice in this region is to lime heavily if lime is applied at all.

Crop Conditions at Varying Degrees of Acidity

When the soil samples were taken notes were also made as to the condition of the crop. However, since the samples were taken at a time of the year when the land was bare, it was necessary to rely on the memory and statement of the grower as to whether the crop was good, fair or poor. In most cases where black root-rot was suspected, careful examination of the roots were made by an experienced pathologist.

An attempt has been made to tabulate the records of all the fields upon which there was an estimate of crop conditions. This is shown in table 3.

TABLE 3. CROP CONDITIONS AS RELATED TO SOIL ACIDITY

No. of Soils in Group	Reaction Range	Percentage of Soils in Group: No Black Root-rot Record: Very Good Crop	Fair Crop	Poor Crop	Black Root-rot: Moderate	Severe
54	6.4 pH or above	19	2	54	7	18
119	5.8 6.4 pH	44	16	35	3	2
406	5.2 5.8 pH	61	25	13	1	0
193	4.6 5.2 pH	54	26	20	0	0
71	Below 4.6 pH	36	24	40	0	0

Black root-rot infestation is particularly severe on soils above 6.4 pH. Entirely satisfactory crops are found on a decreasing percentage of the fields above 5.8 pH, and below 5.2 pH. However, the percentage of poor crops remained relatively low between 4.6 and 5.8 pH.

As indicated by these results, tobacco in the Connecticut Valley is practically safe from black root-rot troubles and produces best results under the moderately acid conditions ranging from 5.2 to 5.8 pH. Increasing acidity beyond 5.2 pH has adversely affected the crop, particularly below 4.6 pH.

FIELD EXPERIMENT WITH A VERY ACID SOIL

In the course of the soil reaction survey a field belonging to Mr. J. E. Phelps in Suffield was found to be unusually acid (3.9 pH). Although the soil was of a favorable type, was highly fertilized, and in earlier years had produced large yields of good tobacco, the crop in more recent years was very poor both in yield and quality. When first observed by the writers in 1925, there was only one spot in the field where growth appeared normal. On this spot the owner had burned stalks and the reaction was found to be 5.2 pH. Examination of the roots showed that no form of root-rot was responsible for the poor growth. The leaves of the plants showed the characteristic yellow spotting which we later associated with manganese toxicity. Since this combination of conditions led us to believe that the trouble was due to a too acid condition of the soil, a series of plots was laid out on this field in 1926 for the purpose of determining what benefit could be derived from applications of lime and also of superhosphate. Lime was applied at rates of 1,500, 3,000 and 5,000 lb. CaO per acre; superphosphate at rates of 1,000 and 2,000 lbs. per acre. The response to the higher applications of both lime and phosphate was very definite and striking. The tobacco on these was quite normal in size and appearance while the untreated plots were again abnormally stunted and the leaves showed the same spotting as on previous crops. The lower applications were beneficial but to a less degree than the higher ones. The experiment was repeated the following year on different plots with much the same results. The best tobacco was produced on the 1927 plots which were treated with a combination of 2,000 lbs. lime and 1,500 lbs. superphosphate.

Pot experiments with soil from the above field, conducted at the New Haven Station showed marked improvement in growth of Turkish tobacco from applications of lime, although heavy applications of phosphorus in the form of orthophosphoric acid, equivalent to 3,000 lbs. of superphosphate per acre, failed to show any response. Similiar results were obtained from the growth of barley on this soil.

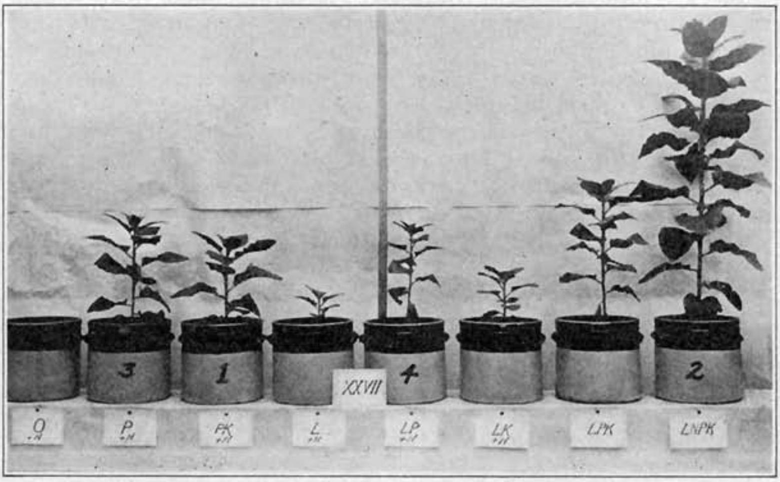
In experiments on the station farm it was learned that the tobacco leaves take up considerably more manganese (see Tobacco Station reports for 1927 (2) and 1928 (4)) from an acid soil. Apparently in a *very* acid soil, the amount of manganese absorbed becomes toxic. When the manganese in the soil is thrown out of solution by application of lime or supherphosphate, it is not absorbed in sufficient amount to interfere with growth and the plant develops normally. All tobacco contains a small amount of manganese, but experiments have failed as yet to show that this is essential to the plant.

There is also the possibility that alumina in these very acid soils may become toxic to tobacco. This substance also would be rendered insoluble by lime or superphosphate. This is another possible explanation of the benefit derived from liming such soils.*

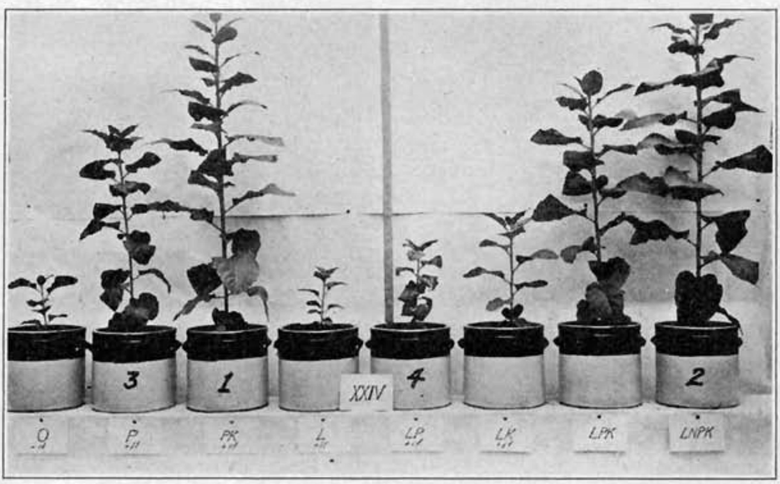
Pot Experiments With Tobacco Grown on Twenty-Four Connecticut Soil Types

Incidental to a study of the fertilizer and lime requirements of typical Connecticut Soils, Turkish tobacco, a strain of high uniformity and well suited in habits of growth to greenhouse conditions, was grown as a test crop to reveal soil differences. Certain phases of the results of these investigations, while summarized elsewhere (24), are of special interest in connection with the effect of soil reaction.

*During a recent visit to the tobacco sections of Cuba, one of the writers (Anderson) had occasion to test soils from many fields, which showed the same type of stunted growth and yellow mottled leaves which we have considered characteristic of manganese toxicity in the Connecticut Valley. All these soils uniformly tested below 4.6 pH, while adjacent soils where tobacco was normal tested above 4.6. Growers there have known for years that such a condition could be overcome by the application of lime.



A



B

FIG. 75—Greenhouse pot experiments with tobacco, showing effect of lime on two different soils. No. XXVII shows marked response to lime, comparing (2), with lime, (1) without lime, both completely fertilized. No response to lime is observed on No. XXIV. Note also that lime without potash—(4) has reduced growth and produced potash starvation symptoms on both series as compared to unlimed without potash—(3).

Twenty-four soils were studied in greenhouse pots, with various combinations of nitrogen, phosphorus and potassium, with and without lime. These soils represented most of the important soil types of the entire state. Only two of them were from old tobacco fields, the others being chiefly from old hay fields. Two crops of tobacco were grown on these soils in 1928, and with one exception, to be noted later, the results were similar for both crops. The results of the second crop, showing a comparison between the complete fertilizer—NPK—and the complete fertilizer and lime—LNPK—yields, are summarized in table 4.

TABLE 4. GROWTH OF TOBACCO ON LIMED AND UNLIMED SOILS IN GREENHOUSE POTS.

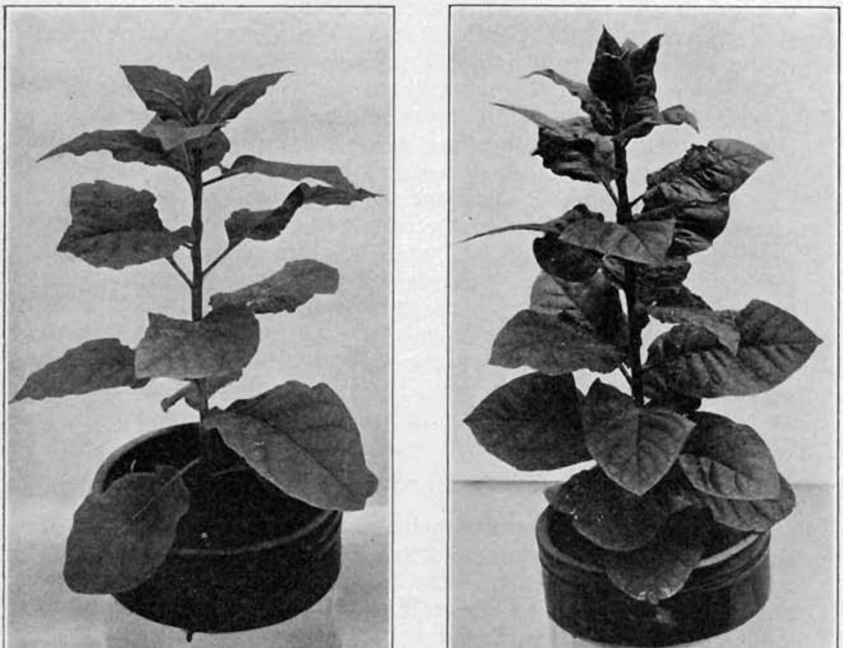
Soil Reaction NPK (pH)	Soil Reaction LNPK (pH)	Yield NPK compared with LNPK %	Pot Series
4.01	6.8	17.61	XXVII
4.55	6.86	79.63	XXXIV
4.59	7.23	29.44	XXXVII
4.73	6.62	47.45	XIX
4.73	6.71	69.71	XVII
4.75	6.92	92.25	XXXI
4.75	6.77	102.70	XXVIII
4.80	6.98	92.39	XXV
4.81	6.83	74.14	XVIII
4.88	6.82	115.43	XXXV
4.90	6.98	111.14	XV
4.91	6.66	120.79	XXX
4.91	6.40	112.56	XXXII
4.97	7.03	104.20	XXI
4.97	6.60	96.86	XX
5.05	7.16	125.86	XXIV
5.06	6.80	131.14	XXXIII
5.09	7.40	95.66	XIII
5.11	6.48	95.27	XVI
5.12	6.29	128.30	XIV
5.16	6.87	87.97	XXIX
5.18	7.16	122.21	XXVI
5.52	6.38	111.28	XXXVI
7.48	7.55	120.90	XXII

From the above table it is apparent that no consistent benefit from the use of lime is obtained at reactions above 4.88 pH, and one soil at 4.75 pH yields better without lime than when limed to 6.77 pH. Above 4.88 pH eleven soils gave reduced yields when limed, while four soils were slightly improved.

Black root-rot was not found on any of the limed soil, since only two of the soils had previously been cropped to tobacco, and these had not been infested in the field.

A most striking result in these experiments was the reduction in yield on limed pots when potash was not applied. With the exception of two soils which failed to show any response to potash, the yield was reduced on the LNP pots as compared with the NP pots, and the symptoms of potash hunger were much more apparent on the lime pots. It appears that where potash is a limiting factor in the soil, the correction of acid condition by the application of lime reduces the availability of the soil potash to the plant.

Two soils in the above experiment, both very strongly acid, exhibited peculiar physiological conditions on one or both crops



A—Series XXV, first crop. B—Series XXVII, second crop.

FIG. 76—Tobacco plants grown in complete fertilizer pots without lime on two very acid soils.

on the unlimed treatments. Series XXV, at a pH of 3.96 on the NPK pots during the growth of the first crop, produced plants having all their leaves very highly mottled over their entire surface. Certain patches on the leaves where the mottling was most pronounced were wrinkled and distorted and small spots of the tissue turned brown and fell out later. The plants were of fair size on the well fertilized plot in spite of the peculiar growth. This soil was examined for soluble aluminum and manganese during the growing period of the first crop, and the completely fertilized pots without lime showed 322 lbs. of aluminum and 816 lbs. of manganese per acre soluble in .5 Normal acetic acid.

The second crop on this soil did not show these abnormal effects. The growth was normal in appearance on the unlimed pots, though it showed a somewhat increased growth with lime. The acidity had become reduced from some unknown cause to 4.80 pH on the same pots which had formerly tested nearly 1.0 pH more acid. The soil was again analyzed for soluble aluminum and manganese, and showed that the soluble aluminum content was practically unchanged, while the soluble manganese content was reduced to 32 lbs. per 2,000,000. The abnormal plant grown in the NPK pot from this soil is shown as "A" in figure 76.

The other abnormal soil produced plants somewhat like those described above, but much more stunted and with the mottled condition of the leaves localized in certain areas where the tissue was much wrinkled and distorted and brown spots of considerable size developed. The lower leaves especially showed a "marbled" appearance. During the first crop the soil on the PK treatment showed a reaction of 3.96 pH, and the aluminum and manganese soluble in .5 N. acetic acid was 666 and 68 lbs. per 2,000,000 respectively. The second crop showed similar results. The PK treatment soil then was practically unchanged—4.01 pH, and the soluble aluminum and manganese was practically unchanged. The abnormal plant grown on the NPK pot from this soil is shown as "B" in figure 76.

The Effect of Fertilizers on Soil Reaction

In view of the influence which soil reaction may thus have on the growth and quality of the crop it is well to inquire what effect the continuous application of the ordinary tobacco fertilizer materials has on the reaction of our soils. The fertilizer plots at the Windsor station have offered opportunities for answering this question for a number of the substances. Some results have been published in the reports for 1927 and 1928. It will be sufficient here to merely refer to these and to results at other stations where similar tests have been made.

Cottonseed meal, castor pomace, linseed meal, tankage, hoof meal, horn meal. These organic ammoniates have had a tendency to make the reaction very slightly more acid. The change, however, is not pronounced and from a practical standpoint may be disregarded.

Dry ground fish on the Windsor plots made the soil somewhat more acid than the preceding materials but even here the change was small.

Urea for the first few weeks causes the soil to become more alkaline but after this it drops down until it is slightly more acid.

Nitrate of soda has the strongest tendency toward alkalinity of any of the ordinary ingredients of the tobacco mixture. This may be seen from the comparative reaction of four plots on the station farm at the end of the three years during which each plot received its nitrogen supply in a different carrier:

	pH
Cottonseed meal plot	5.08
Nitrate of soda plot	5.50
Sulfate of ammonia plot	4.64
Synthetic urea plot	4.92

Nitrate of lime has the same tendency as nitrate of soda but, according to a two year test at the station, to a somewhat less degree.

Sulfate of ammonia has a *pronounced* tendency toward acidification as indicated in the table above and as discussed fully in the tobacco station reports for 1927 and 1928. This is also supported by investigations at many other stations too numerous to cite at this time.

Carbonate, sulfate and nitrate of potash. Of these three most common sources of potash in the tobacco mixture, sulfate is reputed to make the soil slightly more acid, while carbonate is said to reduce the acidity. In a four year experiment at the tobacco station farm where each of these carriers was used on separate adjacent plots it was found that none of them had a measurable effect in changing the soil reaction during that time. In a greenhouse experiment, however, where the important factor of leaching was eliminated, it was found that carbonate reduced acidity by .3 of a pH unit.

Superphosphate (acid phosphate) *precipitated bone, bone meal and steamed bone* all make the soil slightly less acid.

Cottonhull ash theoretically should make the soil considerably less acid on account of the carbonates of calcium, magnesium and potassium contained. No tests covering a sufficiently long period, however, have been made.

Wood ashes has a strong alkaline tendency.

Manure. The effect of manure is to make the soil less acid. The degree of change on a coarse sandy loam may be judged by the reactions of the manure and adjacent plots at the tobacco station at end of third year of treatment.

Plot	Treatment	Reaction
M1	20 tons stable manure annually	5.85
C3	Adjacent no-manure plot	5.33
F6	" " "	5.33
M1-1	10 tons stable manure annually	5.60
C3-1	Adjacent no-manure plot	5.27
F5	" " "	5.17 pH
M2	20 tons "Adco" manure annually	5.59
C14	Adjacent no-manure plot	5.25
M2-1	20 tons "Adco" manure annually	5.50
C14-1	Adjacent no-manure plot	5.30

Effect of Lime on Combustion of Tobacco

On three fields at the Windsor station and at Poquonock, liming experiments have been conducted for several years. After fermenting the tobacco from the limed plots and adjacent unlimed plots, the combustion was compared on single leaves and on cigars made from tobacco from these plots. The tests were repeated for three years. (See the station reports for 1927 and 1928 for details.) Results in all cases have uniformly showed that heavy liming has:

1. Reduced the fire holding capacity of the leaves when tested singly (strip test), but
2. When on the cigar the fire holding capacity has been just as good or usually better than for unlimed tobacco.
3. In all cases lime makes the ash white.
4. The coal band is narrower, that is, the burn is closer and less irregular.
5. Too much lime causes the ash to flake.
6. The taste and aroma have been improved.

Altogether then, liming has been beneficial to the burn and the practice is to be recommended as long as the reaction of the soil is sufficiently acid that there is no danger of lime shifting it to a condition favoring root rot. If the soil tests 5.0 pH or below *and combustion is not satisfactory,* lime should be beneficial.

Effect of Liming the Soil on Composition of Tobacco

Tobacco from limed soils thus exhibits characters of combustion which are different from those of tobacco grown on soils which have not been limed. Some of these characters, particularly the whiteness of ash and closeness of burn are desirable; other, such as the "flaking" of ash and reduction in fire holding capacity on the leaf are objectionable. These differences in burn are correlated with changes which liming produces in the chemical composition of the leaf. In order to see to what extent such changes are produced, tobacco (of the crop of 1926) from limed and adjacent unlimed plots—which otherwise were identical in character of soil and previous treatment—was analyzed with respect to those elements which it was belived might be affected by liming. Three different series of plots were used in these analyses as follows:

Limed plots on Field VIII. Beginning with 1922 these plots were limed heavily each year. With the last application in the spring of 1925 they had received during these four years five tons of hydrated lime per acre and the reaction of the soil was slightly above 7.0 pH.

Thielavia series. These consisted of three plots. One half of each received an application of one ton of hydrated lime per acre each spring, beginning in 1924.

Poquonock field. Plots on this field were limed at the same rate as the Thielavia series, in the spring of 1925 and 1926.

TABLE 5. ANALYSES OF TOBACCO FROM LIMED AND UNLIMED PLOTS. CROP OF 1926. WATER-FREE BASIS.*

Plot No.	Grade	Lime	Total Ash	Percentage of minerals P_2O_5	K_2O	CaO	MgO	Mn_3O_4	Al_2O_3
FIELD VIII									
L	M	Lime	23.89	0.78	6.52	4.72	3.79	.01	.09
L1	M	Lime	23.05	0.73	6.38	4.82	3.58	.01	.08
L2	M	Lime	22.63	0.73	5.92	4.73	4.21	.01	.06
L3	M	Lime	22.90	0.74	6.06	4.79	3.89	.01	.08
L38	M	Lime	23.49	0.75	6.87	4.52	3.61	.01	.11
L39	M	Lime	21.83	1.05	6.37	4.13	3.12	.01	.08
C3-1	M	No lime	26.90	0.85	8.90	5.67	1.16	.10	.09
F6-1	M	No lime	28.15	0.87	8.36	6.55	1.19	.06	.21
N1-5	M	No lime	25.20	0.88	7.51	6.53	1.38	.06	.07
N1-6	M	No lime	25.22	0.93	7.62	6.13	1.29	.07	.07
POQUONOCK FIELD									
4A	All	Lime	24.57	0.77	6.79	4.98	3.11	.03	.17
15A	All	No lime	27.26	0.77	7.23	5.30	1.55	.21	.23
6A	All	No lime	28.19	0.85	7.80	5.84	1.18	.12	.31
THIELAVIA PLOTS									
T1A	M	Lime	22.83	0.72	5.12	5.53	3.49	.01	.08
T1B	M	No lime	24.78	0.84	6.67	6.11	1.56	.29	.14
T1A	S	Lime	25.33	0.62	4.18	6.38	4.54	.02	.11
T1B	S	No lime	27.43	0.76	6.62	7.04	1.57	.28	.31
T2A	M	Lime	23.86	0.82	6.10	5.37	3.13	.01	.05
T2B	M	No lime	24.63	0.84	7.37	5.62	1.18	.04	.11
T2A	S	Lime	25.70	0.60	5.52	6.00	3.15	.02	.14
T2B	S	No lime	26.82	0.75	7.10	6.42	1.18	.04	.13
T3A	M	Lime	23.83	0.69	5.73	5.15	3.58	.01	.11
T3B	M	No lime	25.43	0.85	6.81	6.19	1.62	.06	.06
T3B	S	No lime	27.49	0.68	7.17	6.89	1.59	.09	.17

The lime was not analyzed each year but it was commercial lime from western Massachusetts and unquestionably all of it had some magnesia in it. Some samples from that section have as high as 30 per cent MgO.

Results of the analyses presented in table 5 show that:

1. In every comparison, liming reduced the percentage of total ash, of calcium, phosphorus, manganese and potash. Aluminum was reduced in some cases but not in all.
2. In every case, liming approximately doubled the percentage of magnesium.

*Analyses by E. M. Bailey, Station Chemist.

In experiments with tobacco in Ohio, Ames and Boltz (1) also found that liming a soil reduced the percentage of calcium, potassium, manganese, phosphorus and sulfur but increased the magnesium.

Garner (15) found that magnesium salts are injurious to fire holding capacity of tobacco (more so than the calcium salts). He also found that all magnesium salts produce a white ash.

Apparently the white ash and reduced fire holding capacity which was found on our limed plots are due to magnesium rather than to calcium.

Effect of Lime on Composition of Tobacco from Greenhouse Pots at New Haven

In connection with the greenhouse studies at New Haven which have been described previously, composite samples of both the leaves and stalks from the tobacco grown on various combinations of fertilizer and lime were analyzed by the station chemist for certain constituents. The results are shown in table 6.

Table 6. Analyses* of Tobacco from Greenhouse Pots. Composite of 23 Connecticut Soils. Second Crop, 1928. Water-free Basis.

	Leaves Percentage of					
Treatment	Ash	CaO	MgO	Mn_3O_4	P_2O_5	K_2O
N	27.85	8.13	1.82	.21	.71	2.67
NP	25.08	8.28	2.08	.42	.77	1.57
NPK	25.36	6.78	1.71	.44	.57	4.98
LN	27.14	10.96	1.35	.07	.56	.94
LNP	27.46	10.96	1.15	.01	.85	.76
LNK	28.65	9.01	1.29	.02	.60	3.34
LPK	27.12	10.35	.96	.01	.65	2.20
LNPK	26.11	10.58	.94	.01	.57	1.85

	Stalks Percentage of					
Treatment	Ash	CaO	MgO	Mn_3O_4	P_2O_5	K_2O
N	15.42	2.85	.67	.02	.88	5.08
NP	10.49	1.93	.64	.05	.67	2.97
NPK	11.65	1.03	.29	.03	.55	5.54
LN	12.82	3.97	.65	tr.	.64	2.83
LNP	13.13	4.78	.60	.00	.72	1.56
LNK	13.71	2.16	.37	.00	.58	5.18
LPK	8.98	1.81	.22	.00	.57	2.90
LNPK	7.61	1.83	.21	.00	.44	2.33

An inspection of the data shows that the effect of lime, when applied to acid soils in the form of pure calcium carbonate (containing no magnesium) has been to very materially reduce the con-

*Analyses by E. M. Bailey, Station Chemist.

tent of potash, to slightly decrease the content of magnesium and to materially increase the content of calcium in all the comparisons where other fertilization has been the same. The increased content of lime in the tobacco from the limed pots may appear to be contradictory to the results at Windsor, where lime did not produce an increase in the calcium content of the plant, but materially increased the magnesium content.

However, it must be recalled that a magnesian limestone was the source of lime in the Windsor experiment.

A striking difference between unlimed and limed tobacco, as shown by the analysis of the plant, has been the presence of considerable maganese in the unlimed tobacco, while liming has practically eliminated this element from the plant. This is in complete accord with the Windsor results and is evidence that the poor production of tobacco on highly acid soils is associated with both a high concentration of manganese in the soil and plant.

Regulating the Soil Reaction for Tobacco

From all the data which have been accumulated during this investigation it is apparent that for the majority of soils in this section the optimum reaction is between 5.00 and 5.6 pH. The fact that *some* fields with a reaction as high as 6.00 or as low as 4.6 are producing satisfactory crops is probably due to the modifying influence of other factors which are not discussed here. It is also true that some fields which have the optimum soil reaction are not producing satisfactory crops—showing that soil reaction is by no means the only factor which determines the suitability of a field for tobacco.

The practical question to the grower then is: How can he keep his soil permanently within the optimum? If it is already optimum, how can he keep it from changing to an unfavorable higher or lower reaction? If it is too low (too acid) or too high (not acid enough) what measures can he adopt to correct it?

A certain amount of regulation can be accomplished by proper selection of the fertilizer materials. As indicated by the preceding statements, the effect of each of the ordinary tobacco fertilizer materials is fairly definitely established now. If the grower finds his soil to be near the upper limit of the optimum range, or above it, he should avoid the liberal use of any materials which tend to make it more alkaline and rather favor those with an acid tendency. In this connection, however, he should be cautious about the too liberal use of sulfate of ammonia, which of all the materials, has the most pronounced acidifying power, but which appears to have an adverse effect on combustion (see reports of the Tobacco Station for 1927 and 1928). If the soil tests near the lower limit of the optimum range, or below it, he should favor the materials with an alkaline tendency.

It will be observed, however, that most of the materials produce only very slight changes in the soil. If the field is *very much* too acid or too alkaline the effects of fertilizers are too slight and too slow; other more effective methods must be used.

If the soil is too acid, the remedy is simple: It may be corrected by applications of lime materials (limestone, burnt lime or hydrated lime). It does not seem to make much difference which of these is used as long as the actual amount of oxides of calcium and magnesium is the same and when they are ground to the same degree of fineness. Unless the soil is very acid (4.5 or below) the equivalet of 1000 lbs. per acre of limestone should be a sufficient amount to apply at one time. Below 4.5, the application may be doubled. If later tests show that the soil is still too acid, the treatment may be repeated after a year or two. Wood ashes is also a good material to use on the more acid soils.

However, when a soil has become too alkaline—usually due to a too liberal application of lime or ashes—and black root-rot has become troublesome, it is not a simple or easy matter to reduce it to the proper degree of acidity. Frequently it will be more profitable for the farmer to use this field for other crops for several years before raising tobacco there again. Due to the leaching of the alkaline elements these soils naturally become gradually more acid. Also during this period the root-rot fungus becomes less prevalent in the soil and this disease will be less troublesome when tobacco is raised again there.

Finely ground sulfur, or "inoculated sulfur", has sometimes been used to make the soil more acid. Experiments with this material in comparison with sulfate of ammonia are now in progress on three tobacco farms and a preliminary report is given in the Tobacco Station report for 1928 (4). Although it has been much more effective than sulfate of ammonia on the soils tested, it is too early to recommend its use since no determination of its effect on the quality of the tobacco has been made yet.

Aluminum sulfate is also being tested and appears promising but the tests have not progressed to a point where recommendations can be made.

In acidification experiments at the Massachusetts Station, Doran (13) used a number of mineral and organic acids and was able to increase both the soil acidity and yield of tobacco with sulfuric, nitric and phosphoric acid. Sulfur had the same effect.

As yet, none of these rapid acidifying agents have been used on a large scale in a practical way.

SUMMARY

A review of investigations in most of the tobacco growing sections of the United States and Canada show that lime has rarely produced material increases in the tobacco crop in field experiments, and that in some cases there is an injury from the use of lime, which is ascribed to the greater prevalence of black root-rot on the limed soils. Most of these field experiments have not given careful consideration to the degree of acidity which exists on the unlimed soils.

A study of methods for the determination of soil acidity as a factor in tobacco production in the Connecticut Valley has shown that there is a close correlation between pH values as determined by both colorimetric and electrometric (quinhydrone electrode) methods and the Jones lime requirement results, when the modifying effect of texture and organic content of the soil are properly evaluated. Correlation factors for various textural classes of different organic contents have been computed.

Over two thousand tobacco fields have been surveyed for soil reaction and the results of several hundred representative cases have been tabulated to determine the frequency occurrence of different degrees of soil acidity (pH values), as well as the character of tobacco grown at these reactions. A soil reaction of between 5 and 5.4 pH is of most frequent occurrence. There is a range between 3.9 and 8.2 pH, with a mean value of about 5.4 pH.

Tobacco fields between reactions of 4.8 and 5.6 pH have been found to produce the highest percentage of satisfactory crops. Below 4.8 the degree of acidity becomes an adverse factor, while above 5.6 pH the injurious effects of black root-rot are in evidence and there is some indication that even in the absence of black root-rot tobacco may be somewhat affected in an adverse direction by conditions of very slight acidity, neutrality or alkalinity.

Very acid soils - below 4.8 pH - have shown increased growth of tobacco when lime is added to a complete fertilizer treatment, in greenhouse experiments. In the field, on a very acid soil, producing poor tobacco even when liberally fertilized, tobacco has been much improved by applications of lime and superphosphate. On extremely acid soils, the injurious effects may be due to toxic manganese, alumium, or both.

Various fertilizers produce different effects on the reaction of the soil. Ammonium sulfate is conspicuous in increasing acidity, while nitrate of soda is the most effective in producing higher pH values (decreased acidity). Urea has a slight acid tendency and the effects of the organic ammoniates are probably very slightly in the acid direction. Manure and all the common carriers of phosphorus tend to decrease the acidity. Carbonate, sulfate and

nitrate of potash have produced little or no effect on soil reaction under field conditions.

Analyses of tobacco from unlimed and limed soils show that lime decreases the percentage of potash and manganese and that where magnesian limestone is used, there is an increase in the content of magnesium with a decrease in the calcium content. In pot experiments a pure calcium carbonate form of lime has increased the calcium content of the plant, with a slight reduction in the magnesium content.

Liming acid soils in experiments at Windsor has improved the character of the burn and the whiteness of the ash.

When soil conditions are too acid for satisfactory results, in case of tobacco at pH values below 4.8 pH, lime in some form is the cheapest and most effective means of reducing soil acidity.

Soils which are at an unsatisfactory reaction from the standpoint of black root-rot can be corrected to some extent by selecting acid-producing fertilizers, although reactions above 6.0 pH are difficult to change sufficiently in a short time, by any practical means now at hand. Further investigations concerning methods of making black root rot soils more acid are in progress.

Recommendations

Since the soil reaction is an important factor in the production of high grade cigar-leaf tobacco in Connecticut, it is desirable that the grower keep himself informed by means of soil tests as to the soil reaction conditions on his tobacco fields.

If the soil is at reactions between 5.0 and 5.6 pH, no lime should be used, and fertilizers tending to diminish the soil acidity should be used with caution. On soils testing below 5 pH the use of fertilizers tending to increase acidity should be avoided, while on many soils between 5.0 and 4.6 pH the occasional use of not more than 1000 lbs. per acre of agricultural limestone or its equivalent in other forms of lime should correct the too acid soil conditions which are present. Soils below 4.6 pH may be safely limed at the rate of 2,000 lbs. per acre, although on excessively sandy soils lighter applications should suffice. The soil should be tested the following year and if still too acid, more may be applied.

Fields with reactions above 6.0 pH are not safe for tobacco, and should be put in other crops until an acidity indicated by reactions of 5.8 or below can be developed through leaching and crop removal, with a consequent loss of lime and other basic materials from the soil.

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