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Appendix

Agricultural Lime

Reevaluation of Missouri Limestone Recommendations Incorporating Recent (1993—1999) Soil Test Results

John Stecker and James R. Brown

The current recommendations for correction of adverse soil acidity have been in use for about 30 years. The basis for these recommendations is the empirical relationship between two indices of soil acidity: pH_s and neutralizable acidity as measured by the Woodruff Buffer. The relationship was established from a soil test database of samples analyzed in the early 1970s. A larger more current soil test database is now available from which to examine soil-lime interactions.

Computing advancements since 1970 have vastly improved the ability to include more complex factors in recommendation calculations. Our improved understanding of soil-plant interrelationships as pertaining to liming and changes in cropping practices may also effect a need for revised recommend-ations. As a review of the basis of lime recommendations used by the Soil Testing Laboratory, this section has three objectives: 1) review the development of current recommendations, 2) compare the relationship between NA and pH_s as used in the current recommendations to that of a current data-base, and 3) consider potential changes that could update or improve lime recommendations. Questions to be evaluated include: 1) Should lime recommendations be based on percentage base saturation rather than pH_s and NA? 2) Should the "needed ENM" calculation be a function of pH_s, NA, and CEC? 3) Should Soil Regions continue to be included in the lime recommendation? 4) May a measure of extractable aluminum as it relates to NA improve recommendations for low pH_s soils (for example $pH_s <$ 4.8)?

Development of current lime recommendations

The current algorithm of lime recommendations by the University of Missouri Soil Testing Lab was developed by T. R. Fisher in 1972. The *Soil Test Interpretations and*

Recommendations Handbook (Buchholz, 1992) shows the algorithm as presently used. Fisher did not publish a detailed description of the development of his equations. However, in a letter to the Agronomy Department Soil Testing Com-mittee dated July 20, 1972, he provided a brief description of three equations (Equations 1, 2, 3) that relate NA to pHs for the purpose of making lime recommendations. Each of equations 1, 2, and 3 assumes a different relationship between NA and pH_s. Fisher's letter and a description of his methods were pub-lished by J. R. Brown in Agronomy Miscellaneous Publication 84-03 (Brown, 1984). Included were tables that compared lime requirements calculated from the different equations at various pH_s and NA values. As a basis for his recommendation equations, Fisher used a database of about 30,000 soil samples analyzed by extension soil testing laboratories during 1970 and 1971.

Equation 1 was based on a linear relationship between pH_s and NA even though the actual relation-ship was curvilinear. Equation 1 consistently underestimated lime requirements on low pH_s soils.

$$ENM = 400 * \left(NA - \frac{NA}{14 - 2 * pH_s} \right)$$

Equation 2 was based on the assumption that on average NA occupied 6% of the soil's CEC with a pH_s of 6.5 (Equation 2a) and 13.5% with a pH_s of 6.0 (Equation 2b). The assumptions were not accurate across all CEC groups (see Figure 1), and as a result some soils would not be given a lime requirement despite having a pH_s value less than optimum for plant growth.

$$ENM = 400 * [NA - (0.06 * CEC)]$$

$$ENM = 400 * [NA - (0.13 * CEC)]$$

Equation 3 is similar to Equation 1, but it was based on a quadratic relationship between NA and pH_s. Fisher's database (Figure 2A) and that of the 1990's database (Figure 2B) show this to be an accurate assumption. The constants a, b, and c in Equation 3 are obtained from the quadratic equations fitted to the curves in Figure 2A. The presently used lime recommendation equations are variations of Equation 3.

$$ENM = 400 * \left[NA - \frac{NA}{a - b * (pH_s) + c * (pH_s)^2} \right]$$

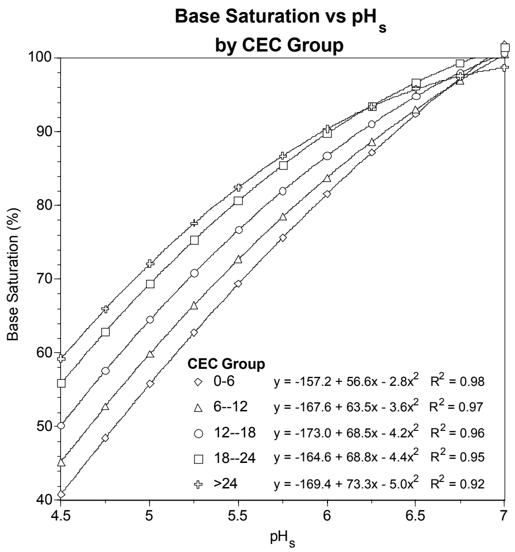

Figure 1.Percent soil base saturation versus pH_s

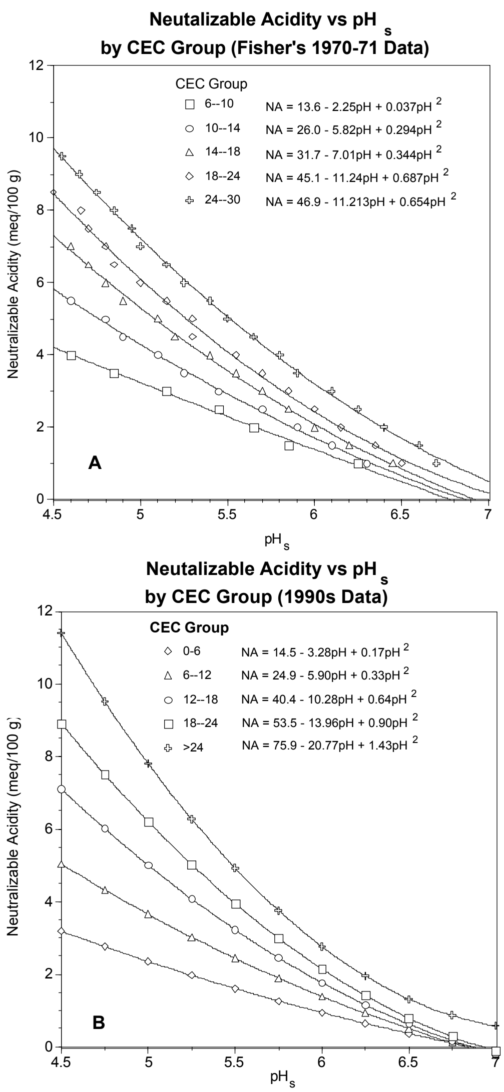

Figure 2. NA versus pH_s as varied by CEC group for A) 1970-1971 and B) 1993-1999 data sets.

Fisher's development of Equation 3 began with a mathematical description of a portion of the NA versus pH_s curve (Equation 4). A graphical example is given in Figure 3. The objective was to describe the portion of the curve (an amount of NA) from NA_o (NA observed) to NA_d (NA desired) and from the observed pH (pH_o) to the desired pH (pH_d). If NA = 0 then $pH_d = pH_v = pH_s$ 7.0.

$$\frac{dNA_o}{dpH_o} = C\left(pH_v - pH_o\right) \quad \text{Equation 4}$$

where C is a constant

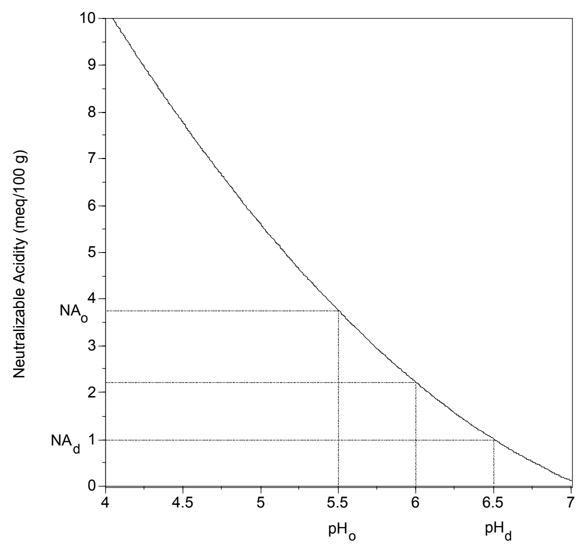

Figure 3. Graphical representation of the calculation of lime requirement (NA) from a NA versus pH_s curve. NA_o is the observed NA, NA_d is the NA at the desired pH_s, pH_o is the observed pH_s and pH_d is the desired pH_s.

Following integration, substitution and rearrangement, Equation 5 is obtained (see Brown, 1984 or Appendix A of this document for a complete description). The denominator in Equation 5 is a quadratic equation, which describes the NA versus pH_s curve. Fisher then could substitute coefficients from NA versus pH_s curves obtained from soil test data into Equation 5 (coefficients l, m, and n).

$$NA_d = \frac{NA_o}{l - m * pH_o + n * pH_o^2} \quad \text{Equation 5}$$

The amount of NA to neutralize (NA_l) is represented in Equation 6.

$$NA_l = NA_o - NA_d \quad \text{Equation 6}$$

The final step was to convert the equation into units of effective neutralizing material (ENM), which resulted in Equation 3. In the final algorithm, there were three variations of Equation 3 (Equations 7, 8 and 9), each of which was based on a different target pH_s (6.0, 6.5, and >6.5). With a target pH_s greater than 6.5, the quadratic part of Equation 3 drops out resulting in Equation 7.

$$ENM = (400) * (NA) \quad \text{Equation 7—for a target } pH_s > 6.5$$

$$ENM = 400 * \left[NA - \frac{NA}{41.425 - 10.307 * (pH_s) + 0.629 * (pH_s)^2} \right]$$

Equation 8—for a target pH_s of 6.5

$$ENM = 400 * \left[NA - \frac{NA}{19.109 - 4.802 * (pH_s) + 0.297 * (pH_s)^2} \right]$$

Equation 9—for a target pH_s of 6.0

The precise dataset used by Fisher is now unavailable, so we are unable to recalculate precisely the coefficients in his recommendation equations (Equations 1, 2 and 3). Yet among the family of CEC group curves in Figure 2A, the coefficients from the 18-24 CEC group essentially match those in Equation 8. The 12-18 CEC group of the 1990's data set resulted in similar coefficients. For a target pH_s of 6.0 (Equation 9), integration of a smaller area of the NA vs pH_s curve results in smaller coefficients.

Evaluation of prospective changes to lime recommendation algorithm

Following the preceding review of data and the methods used to develop the current lime require-ment recommendations, it is appropriate to review potential changes that would update or improve recom-mendations. Some considerations are issues that were originally considered by Fisher, but perhaps were not implemented because of limited computing capabilities. It is not our intent to promote one method over another; rather we want to review the legitimate alternatives to the presently used algorithm.

Use of Percent Base Saturation

Fisher originally explored the possibility of using average percent saturation of the soil exchange complex with NA as a means of making lime recommendations (see Equation 2). His objection to this approach was that occasionally no lime recommendation would be given for samples with pH_s values less than 5.6 or 6.1. As evident in Figure 1, there is a good relationship between base saturation and pH_s. At a target pH_s of 6.5, there is a small range (about 5%) in the percent base saturation across CEC groups. For the 12 to 18 CEC group, the percent base saturation is 95%. Similarly, there is a good relationship be-tween NA and percent base saturation (R^2 between 0.93 to 0.98 across CEC groups). Thus it would be feasible to substitute a measure of base saturation for NA and use the current algorithm to calculate lime requirement. As Fisher noted, there would still be the problem of some soils not receiving a lime recommendation despite the observed pH_s being less than the target pH_s.

Varying Recommendations by CEC Group

The relationship between NA and pH_s is not the same across all soils as shown in Figure 2. As cation exchange capacity increases, it tends to buffer the release of protons from the exchange complex of the soil. The CEC groupings used in Figure 2 illustrate the differences in NA as related to CEC groups, which suggests that CEC may be included in equations used to calculate lime requirements.

In trying to follow Fisher's development of equations 8 and 9, he apparently used coefficients from the 18-24 meq/100 g curve to represent an average of the NA vs pH_s relationship. Using both the 1970's (Table 12) and 1990's databases (Table 13), we attempted to contrast lime requirements that result from Fisher's equations as varied by CEC group. Although the NA groups do not perfectly overlap between the two datasets, this exercise provides an opportunity to analyze the contribution that grouping soils by CEC would make toward improving lime recommendations.

In Tables 12 and 13, lime recommendations were calculated by substituting coefficients generated from curves in Figure 2 into Equation 8. Table 12 was generated from Fisher's 1970 and 1971 dataset (see

Figure 2A), and Table 13 from the 1993 to 1999 data set (see Figure 2B). Each pH_s range reflects an appropriate range in NA for the CEC group. For each CEC group, the Curve Coefficient column was generated using coefficients taken from the quadratic equations that describe the curves (in Figure 2). The second column was generated using Equation 8, which remember represents an average CEC (18-24 meq/100g). In Table 12 there is no 18-24 CEC group for comparison, because this is the CEC group on which it is assumed that Fisher based Equation 8. The coefficients are essentially identical

.

Table 12. Lime recommendations using coefficients from curves generated by 1970-1971 data set CEC groups that were substituted into Equation 8.

CEC Groups												
	6-10			10-14			14-18			24-30		
NA	pHs	Curve Coeff†	Avg Coeff‡	pHs	pHs	Curve Coeff	pHs	Curve Coeff	Avg Coeff	pHs	Curve Coeff	Avg Coeff
		lb ENM/acre			lb ENM/acre			lb ENM/acre			lb ENM/acre	
1.0	6.25	0	146	6.30	13	125	6.45	0	41	6.70	0	0
1.5	5.85	245	374	6.10	191	293	6.20	195	247	6.60	166	0
2.0	5.65	411	555	5.90	385	481	6.00	408	441	6.40	384	146
2.5	5.45	588	746	5.70	584	679	5.85	597	623	6.25	577	366
3.0	5.15	798	961	5.45	805	895	5.70	791	814	6.10	777	587
3.5	4.85	1005	1175	5.25	1008	1099	5.55	989	1011	5.90	1001	842
4.0	4.60	1202	1381	5.10	1199	1293	5.40	1189	1211	5.80	1186	1029
4.5	4.30	1409	1594	4.90	1406	1501	5.20	1406	1428	5.65	1393	1249
5.0	4.10	1599	1795	4.80	1589	1690	5.10	1593	1617	5.50	1601	1469
5.5				4.60	1798	1900	4.90	1809	1835	5.40	1794	1665
6.0				4.45	1996	2101	4.80	1999	2028	5.25	2004	1884
6.5				4.25	2206	2311	4.70	2192	2222	5.15	2200	2083
7.0				4.15	2396	2505	4.60	2385	2418	5.00	2410	2301
7.5							4.45	2591	2626	4.95	2596	2484
8.0							4.30	2796	2834	4.85	2795	2686
8.5							4.20	2992	3032	4.75	2995	2889
9.0							4.00	3208	3249	4.65	3196	3093
9.5										4.55	3397	3297
10.0										4.45	3598	3501
Average Difference#			163			100			31			-131

†Curve coefficients used from curves shown in Figure 2A and substituted into Equation 8.
‡Average coefficients used by Fisher in Equation 8—approximately that of the CEC group 18-24.
#Average ENM difference between the Curve Coefficients and the Average Coefficients (Fisher's 18-24 CEC Group) across all pH_s values.

Because of the similarity of curve slopes, there is little difference in ENM recommendations between CEC groups. For CEC groups with values less than the presumed 18-24 meq/100 g in Fisher's Equation 8, lime requirements (Curve Coefficient column) are slightly less than recommended by Equation 8 (Avg. Coefficient column). At greater CEC values, lime requirements of the CEC groups are slightly greater than that of the average. The greatest discrepancies between CEC group recommendations and the average CEC recommendation are with the low CEC groups. The curve of the 6-10 CEC group deviates from the other CEC groups by being more linear

(small value for the squared term). However, because of the relatively small NA values that are associated with the low CEC soils, ENM recommenda-tions differ only slightly. A direct comparison of CEC-group curves between the two datasets is not possible, because the data were not identically grouped. However there appears to have been little change. An exception is the largest CEC group. The curve for the >24 group (1990s data set) is more strongly curvilinear than the 24-30 group

(1970s data set). This may be due to improved precision of lab techni-ques. The 1970s' dataset consisted of significant numbers of samples that were run in county labs, while

Table 13. Lime recommendations using coefficients from curves generated by the 1993-1999 dataset CEC groups that were substituted into Equation 8.

	CEC Groups														
	0-6			6-12			12-18			18-24			>24		
NA	pH_s	Curve Coeff[†]	Avg Coeff[‡]	pH_s	Curve Coeff	Avg Coeff	pH_s	Curve Coeff	Avg Coeff	pH_s	Curve Coeff	Avg Coeff	pH_s	Curve Coeff	Avg Coeff
		lb ENM/acre			lb ENM/acre			lb ENM/acre			lb ENM/acre			lb ENM/acre	
1.0	6.25	0	146	6.30	0	125	6.45	0	41	6.50	0	2	6.70	0	0
1.5	5.85	69	374	6.10	96	293	6.20	126	247	6.35	76	152	6.60	59	0
2.0	5.65	226	555	5.90	293	481	6.00	345	441	6.15	326	362	6.40	282	146
2.5	5.45	402	746	5.70	498	679	5.85	538	623	6.00	533	551	6.25	486	366
3.0	5.15	633	961	5.45	729	895	5.70	738	814	5.85	744	748	6.10	703	587
3.5	4.85	860	1175	5.25	937	1099	5.55	942	1011	5.70	958	950	5.90	953	842
4.0	4.60	1068	1381	5.10	1128	1293	5.40	1149	1211	5.55	1173	1155	5.80	1148	1029
4.5	4.30	1291	1594	4.90	1340	1501	5.20	1376	1428	5.40	1387	1362	5.65	1371	1249
5.0	4.10	1488	1795	4.80	1522	1690	5.10	1567	1617	5.20	1619	1587	5.50	1594	1469
5.5				4.60	1736	1900	4.90	1792	1835	5.10	1815	1779	5.40	1796	1665
6.0				4.45	1937	2101	4.80	1986	2028	4.90	2042	2002	5.25	2017	1884
6.5				4.25	2151	2311	4.70	2182	2222	4.80	2240	2196	5.15	2221	2083
7.0				4.15	2341	2505	4.60	2379	2418	4.70	2440	2393	5.00	2441	2301
7.5							4.45	2591	2626	4.60	2640	2590	4.95	2631	2484
8.0							4.30	2801	2834	4.45	2852	2801	4.85	2836	2686
8.5							4.20	3001	3032	4.30	3064	3011	4.75	3042	2889
9.0							4.00	3222	3249	4.20	3265	3210	4.65	3248	3093
9.5													4.55	3455	3297
10.0													4.45	3661	3501
Average Difference[#]			299			167			55			-19			-125

[†]Curve coefficients used from curves shown in Figure 2A and substituted into Equation 8.
[‡]Average coefficients used by Fisher in Equation 8—approximately that of the CEC group 18-24.
[#]Average ENM difference between the Curve Coefficients and the Average Coefficients (Fisher's 18-24 CEC Group) across all pH_s values.

the 1990s data came from only two labs (Columbia and Portageville). With the elimination of the county labs, potentially more NA would have been measured on low pH_s soils. Subsequently, a greater curvilin-earity resulted in the 1990's dataset curves. Nevertheless, lime recommendations generated from the 1970s' and 1990s' datasets were relatively similar. The small differences due to CEC are not large enough to justify the inclusion of CEC groups in the algorithm.

Varying Recommendations by Soil Region

Soils across Missouri vary considerably with respect to weathering and parent material (see Appen-dix B), and these differences affect the nature of reserve acidity. In general, weathering of soils in the state increases to the south and east from the northwest corner of the state. Soil regions were established in the recommendation algorithm in order to provide region-specific lime recommendations. Present recommendations vary only by the target pH_s for forage legumes in the Cherokee Prairie, Ozark and Ozark Border regions (Soil Regions 6, 7, and 8).

Each NA versus pH_s curve for any CEC group shown in Figure 2 could be considered an average, comprising a group of curves that result from individual soil regions. An example of a family of curves by soil region for two CEC groups is shown in Figure 4. At lower pH_s values and the larger CEC groups, the NA values of some soil regions diverge from the "pack" of curves of other soil regions. In particular, curves of Soil Regions 6 and 7 lie above those of other soil regions. For Soil Regions 6 (Ozarks) and 7 (Ozark Border), the greater NA per pH_s may be a consequence of increased activity of soil aluminum. As was observed with the different CEC groups, the similarity of curve slopes as varied by soil region would result in little difference in ENM recommendations.

Is There a Need for a Measure of Extractable Aluminum?

The activity of soil aluminum increases appreciably at pH_s values of 4.5 or lower. At such low pH_s values, aluminum activity in soil solution becomes toxic to plant growth. In Missouri the problem of low pH_s and toxic aluminum is mostly isolated to the highly weathered Ozark soils. Even when the surface soil acidity is reduced by application of liming materials, the subsoils remain highly acidic. The present lime recommendations account for the acid subsoils by increasing the amount of lime recommended for legumes. The increase in lime requirement results from an increase in the desired pH_s. The hoped-for-effect is that the greater amount of lime will neutralize some of the subsoil acidity. The effectiveness and efficiency of such an increased lime application toward alleviating aluminum toxicity can not be quantified, but Kroth and Mattas (1981) showed that the liming effect will move downward given time.

It must be remembered that the NA measurement is an index of reserve acidity, and may not accur-ately represent acidity that results from soil aluminum. A measurement of extractable aluminum may indicate the potential for additional reserve acidity. Yusef (1986) and Syed Rastan (1995) both showed that neither KCl extractable aluminum nor two times that amount of aluminum was a satisfactory estimate of lime requirement. Syed Rastan (1995) had promising results from aluminum extracted with 0.33 M $LaCl_2$. As with any index such as the laboratory measurement of NA, field calibration is necessary to determine the actual effectiveness of the limestone amount recommended by the NA measurement.

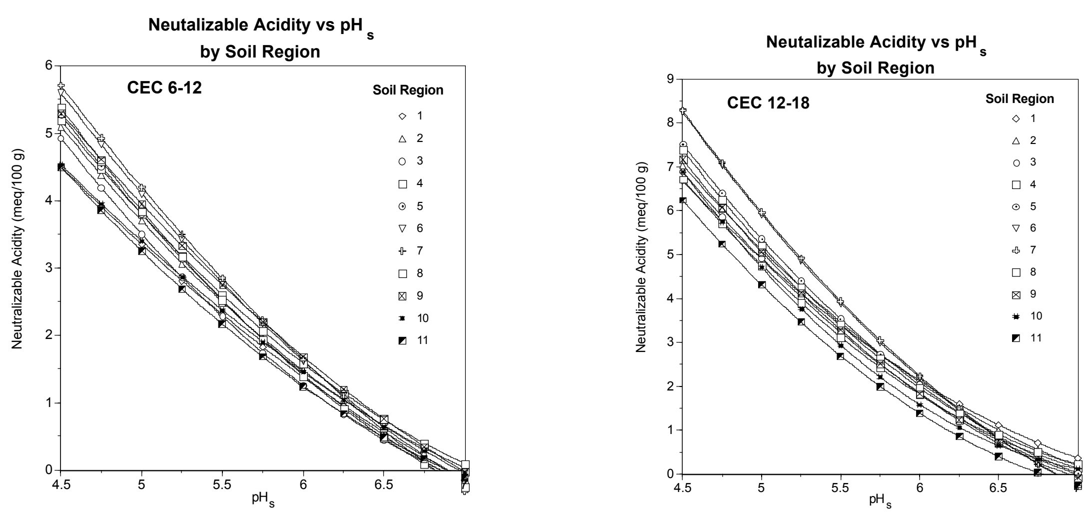

Figure 4. Soil Region effect on NA vs pH_s curves for a) 6-12 CEC and b) 12-18 CEC. 1993 to 1999 data set.

Summary and Recommendations

The current lime recommendation algorithm used by the University of Missouri Soil Testing Lab-oratory has not changed in 30 years since implementation. The essence of the algorithm is that NA and pH_s are measured in the laboratory, and then an empirical relationship between the two is used as the basis for determining the amount of limestone to apply. The algorithm is not varied by soil CEC. Soil test results collected from 1993 to 1999 indicated that the relationship between NA and

pH_s is essentially un-changed relative to the data set used in 1972 when the current algorithm was developed. The algorithm was developed such that differences in the NA versus pH_s relationship due to CEC or Soil Region do not dramatically affect limestone recommendations. Thus we do not propose the inclusion of CEC in a new algorithm. We feel that the work by Kroth and Mattas (1981) justify retaining the separate recommend-ation for legumes grown in Soil Regions 6, 7, and 8.

With each curve of NA versus pH_s examined, there was a considerable scatter of data points around the fitted curve. Identifying the sources of such scatter may lead to modifications in the algorithm that improve recommendations. Some soils may be more buffered against limestone applications. That is, the NA versus pH curve for some soils may have a greater slope or greater curvilinearity than expressed by the recommendation equations. Similarly, different liming materials may vary in their neutralization of soil acidity to a target pH. For example some liming materials may be somewhat self-buffered through reduced dissolution. Some soils may also have large amounts of extractable aluminum, and the NA measurement may not accurately express all of the reserve acidity.

This review of the basis of liming recommendations and its historical background provide the necessary information to answer the questions posed at the start of this section of the paper.

1. Should lime recommendations be based on percentage base saturation rather than pH_s and NA?

   No. Percentage base saturation is calculated from the sum of the milliequivalents of basic cations divided by the CEC. The estimate of basic cations in the soil comes from the soil tests for potassium, calcium, and magnesium, all extracted with 1 M ammonium acetate. The estimate of NA, which is obtained using the Woodruff buffer, is necessary to get the CEC. Thus, no test would be eliminated by using the percentage base saturation method for making recommendations. As yet, there is no quick test method to substitute for the Woodruff buffer as a measure of NA unless there was a significant increase in turn-around time for soil testing.

2. Should the "needed ENM" calculation include CEC in addition to pH_s and NA?

   Probably not. The review using the 1993-1999 data set showed minimal ENM differences (fractional ton of limestone) in recommendations when CEC was included in the algorithm between the current algorithm and the algorithm including CEC. If however, improved precision in calculated quantities is desired, then computing capabilities make this a simple change.

3. Should soil regions continue to be included in lime recommendations?

   A qualified yes. The review using the 1993-1999 dataset suggests using the soil regions added little to the value of the lime recommendations. However, the ultisols of the highly weathered Ozark region have profound effects on rooting depths due to high levels of aluminum. For this reason it seems desirable to continue to use a separate algorithm for soil regions 6 and 7. The curves in Figure 4 showed that Region 7 was somewhat different from the other regions. Histor-ical data have been presented that showed downward movement of the liming effect with time on highly acid soils.

4. May a measure of extractable aluminum as it relates to NA improve recommendations for low pH_s soils?

   Not at this time. Research by Yusef and Syed presented in this paper is not adequate to support inclusion of an extractable aluminum soil test on low pH_s soils. There were no field data on which to base recommendations, even though both former students showed that such a test is feasible. Syed's work suggested that 0.33 M $LaCl_2$ had potential for a test, but requires field calibration; greenhouse results are inadequate for calibration. Addition of an aluminum test to the soil testing program would increase the turn-around time for results and require some laboratory improve-ments to be able to analyze for aluminum.

No-tillage culture of crops was virtually unknown when the present limestone recommendations were developed. The assumption of the present recommendations is that all liming material is evenly distributed throughout the depth of tillage. Thus a target pH should be achieved uniformly in the tillage depth. As all row crops have a target pH_s of 6.1 to 6.5, application of lime only to the soil surface will likely violate the assumption of reaching a target pH_s with the recommended amount of lime. The NA versus pH_s curves show soil, particularly high CEC soils, to be more buffered at pH_s near or above 6.5. So it seems likely that no-till lime recommendations would require modification.

The average relationship between NA versus pH_s (across all soils) seems to be well defined and provides a good basis for making limestone recommendations. Future directions for liming research should evaluate the impact of extractable aluminum, examine the effects of different liming materials and the response of different soils to effect changes in pH_s. The principles of recommending lime based on laboratory measurement of NA and pH_s seem well based. However, further field calibration of these indices remains ever necessary.

Conservation Tillage Systems and Liming Materials

Gene Stevens and David Dunn

Objective:

(1) Determine the soil depth that surface applied lime in conservation tillage systems will neutralize soil acidity on clay and silt loam soils.
(2) Evaluate calcitic (white) lime and dolomitic (red) lime materials in no-till and strip-till corn/soybean rotation systems.

Current status/importance of research area:
The adoption of conservation tillage systems continues to increase across Missouri. However, no-till and strip-till farmers have expressed concern that lime may need to be incorporated with conventional tillage equipment to neutralize soil acidity below the 0 to 2-inch soil depth. Research at the University of Tennessee Milan Experiment Station showed that surface applied lime on a no-till field effectively increased soil pH in the soil profile. However, this study was conducted on a loessial silt loam soil with good internal drainage. Whether the same would be true on a poorly drained Sharkey clay soil is not known. Solubility of the liming material may also be a factor. Tests with conventional till cotton at the University of Missouri Delta Center showed that dolomitic lime increased soil pH slower than calcitic lime, but both types of lime resulted in the same amount of cotton yield increase.

Research activities in 2002:

Tests were conducted at two locations. Fields on the University of Missouri-Delta Center with Dubbs silt loam (average pH_{salt} 5.2) and Tiptonville silt loam soils (average pH_{salt} 5.3) were used. (We have another field with pH 4.5 to add to the study in 2003.) Soybeans were planted at one site and corn at the other. A split-plot design was used with no-till, strip-till and conventional till main plots. Soil pH_{salt} and Woodruff buffer pH were used to determine the recommended amount of ENM needed to raise the pH to the 6.1 to 6.5 range. Liming materials were obtained from local dealers and tested for ENM value. Sub-plot treatments were the recommended rate of calcitic (white) lime, recommended rate of dolomitic (red) lime, and an untreated check. These will be surface applied in the Spring of 2002 before any tillage was done.

At planting, soil cores were collected from the 0 to 36-inch soil depth. The cores were cut into 2-inch increments and tested for soil pH and extractable Mn. During the season, soil samples were collected and tested from the 0 to 2-inch, 2 to 4-inch, and 4 to 6-inch soil depths. Soybeans or corn leaf tissue samples were collected at the beginning of reproduction. Samples were tested for Mn and Al contents in the tissues. Plots will be mechanically harvested for yield.

Results in 2002:

Generally, both red and white lime increased soil pH and reduced the availability of Mn which is often toxic to crops at low soil pH levels. Lime incorporated with tillage reacted faster and affected soil to a greater depth than when tillage was not used. An unexpected effect of tillage was found in untreated check plots. In both soybeans and corn, soil pH values were slightly higher in untreated check (no lime) conventional till plots as compared to untreated check no-till plots.

In the soybean test in late July, no-till plots with white lime had higher pH values than plots with red lime or no lime at the 0 to 2-inch depth(Figure 1). In conventional till plots, there was no difference at the 0 to 2-inch depth between lime treatments but plots with white lime treatments had high pH values at the 2 to 4-inch, and 4 to 6-inch depths (Figure 2). In no-till plots, we found small differences in Mn levels between lime treatments at the 0 to 2-inch depth (Figure 3). In the conventional till plots, the untreated check had consistently higher Mn levels than red or white lime treatments (Figure 4).

Soybean

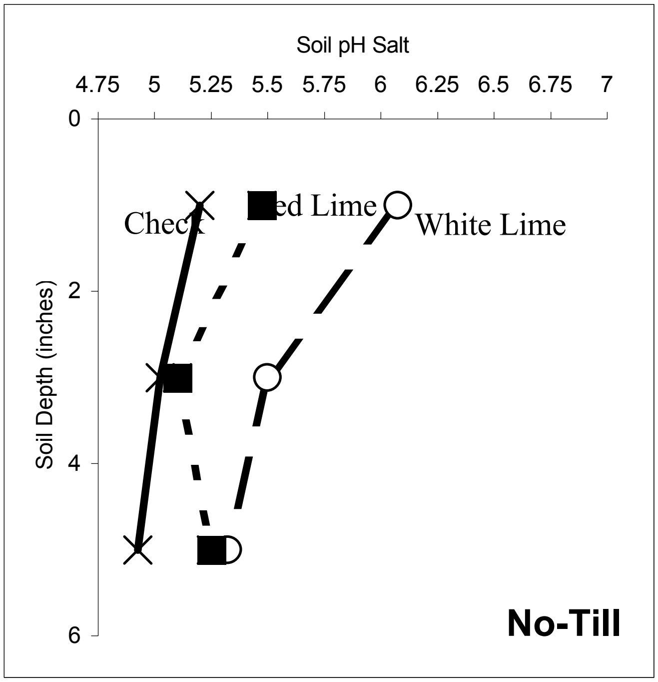

Figure 1. Effects of liming treatments on soil pH in no-till soybeans.

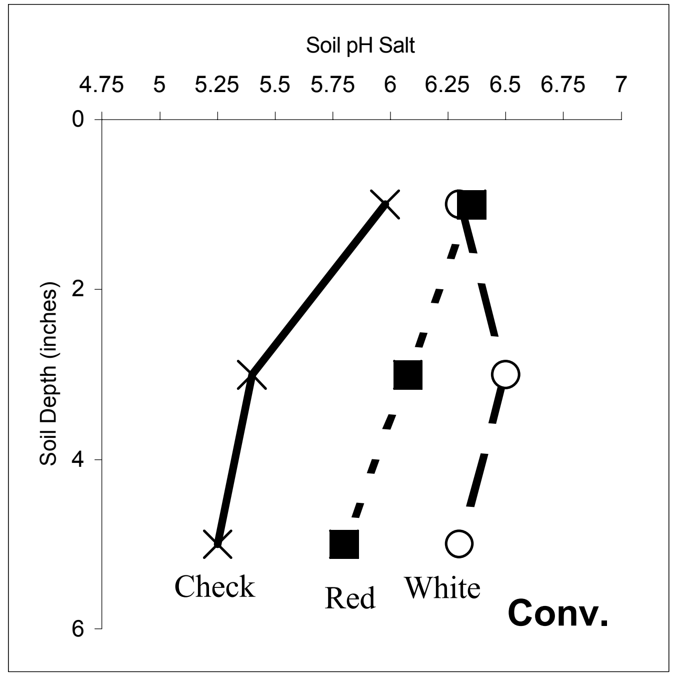

Figure 2. Effects of liming treatments on soil pH in conventional till soybeans.

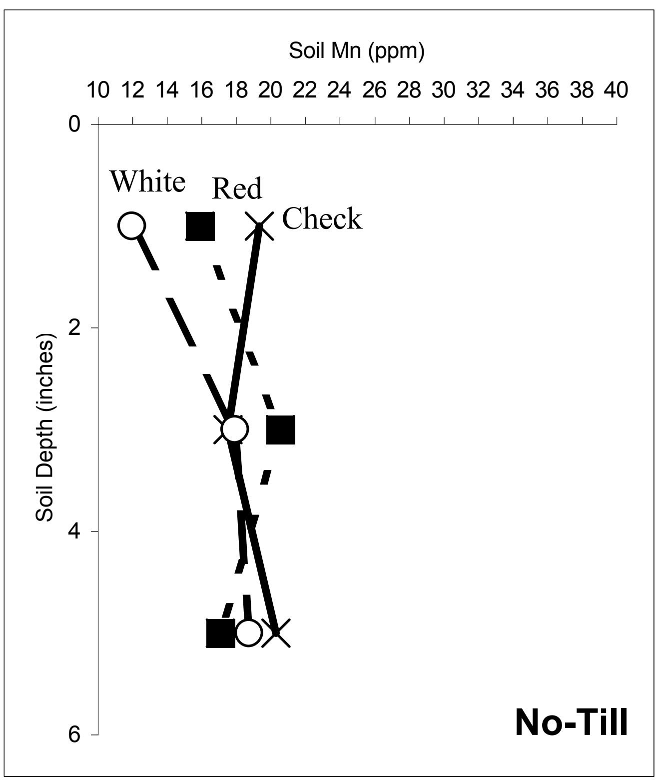

Figure 3. Effects of liming treatments on soil Mn in no-till soybeans.

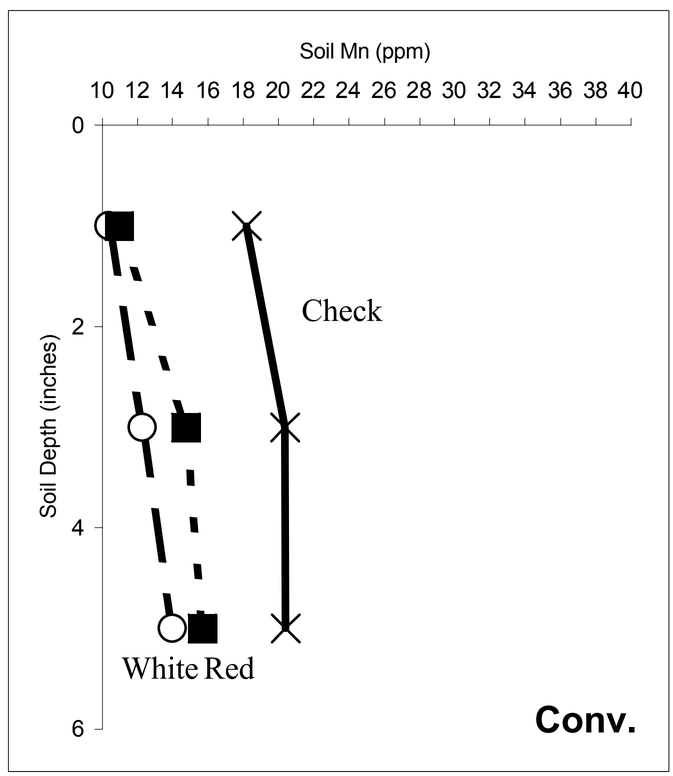

Figure 4. Effects of liming treatments on soil Mn in conventional till soybeans.

Similar results were found in the corn experiment (Figures 5-8). White lime increased soil pH more than red lime and but both liming treatments lowered soil Mn levels as compared to the untreated check. In no-till plots, soil pH was most affected by lime in the 0 to 2-inch depth.

Corn

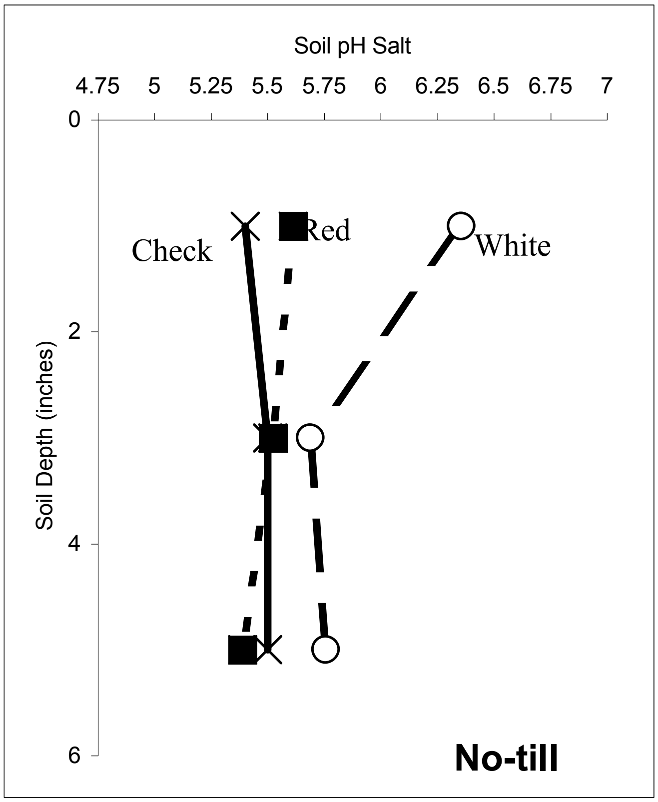

Figure 5. Effects of liming treatments on soil pH in no-till corn.

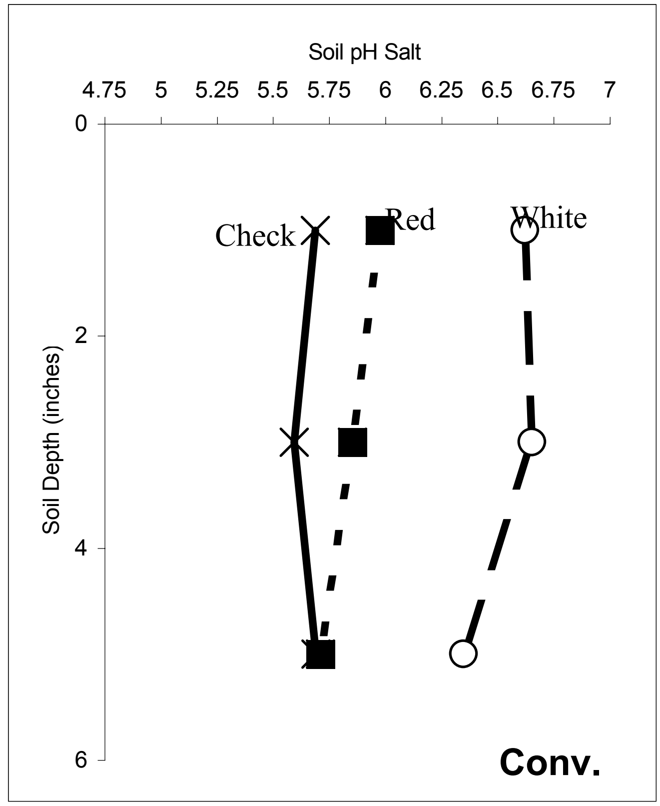

Figure 6. Effects of liming treatments on soil pH in conventional till corn.

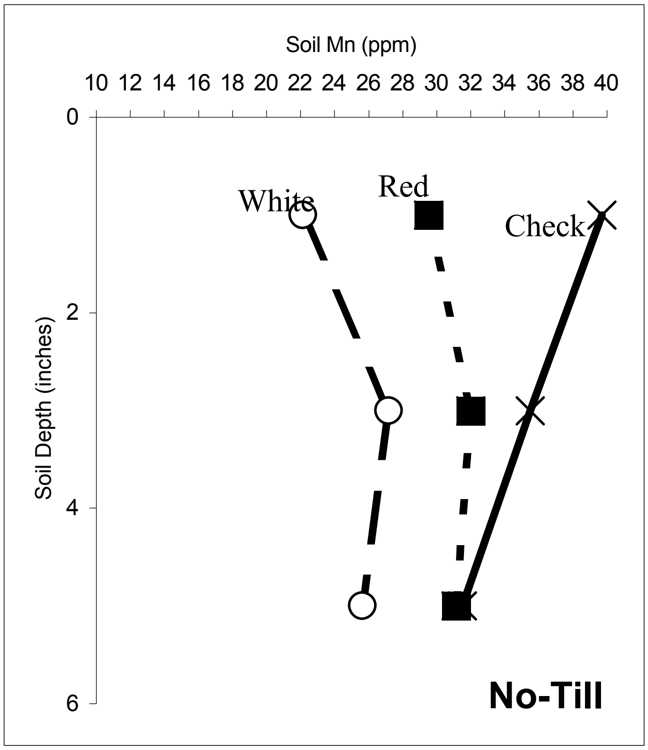

Figure 7. Effects of liming treatments on soil Mn in no-till corn.

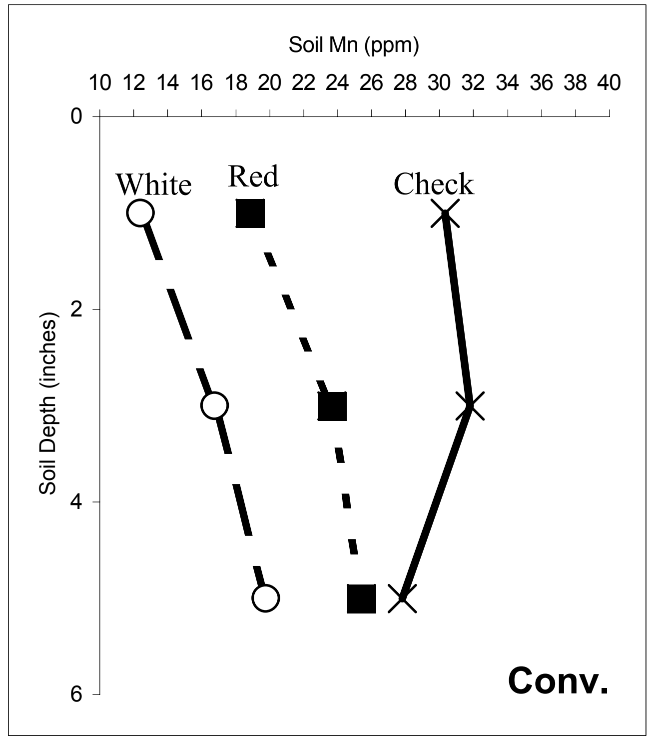

Figure 8. Effects of liming treatments on soil Mn in conventional till corn.

Soybean yields were not significantly increased by lime applications (Table 1). However, yields were increased numerically in strip-till and conventional tillage plots as compared to the untreated check. (In other lime tests that we have conducted often the trend is for higher yields with lime the first year with statistically significant effects found in year 2 and 3.) In no-till plots with white lime, yields were reduced compared to the untreated check. This may have been due to a micronutrient deficiency resulting from a concentrated amount of lime at the soil surface. This indicates that there may be a danger to putting all the lime on the soil surface in one year in a no-till cropping system.

We did not find significant effects from tillage or lime in corn yields. Overall, corn yields were low because irrigation was not available at the corn site (Tables 2 and 3.) Water was probably the most limiting productivity factor in the corn in 2002.

Table 1. Effect of lime and tillage on soybean yields in 2002.

Tillage	Lime	Yield	
		bu/acre	
Strip-till	Red	48.8	ab
Strip-till	White	46.9	ab
Strip-till	None	44.0	ab
No-till	Red	52.4	a
No-till	White	36.5	b
No-till	None	51.1	a
Conventional	Red	54.8	a
Conventional	White	49.5	ab
Conventional	None	43.5	ab

Table 2. Average effect of tillage on corn yields averaged across lime treatments.

Tillage	Yield	
	bu/acre	
Strip-till	105.6	a
No-till	94.9	a
Conventional	95.0	a

Table 3. Average effect of lime on corn yields averaged across tillage treatments.

Lime	Yield	
	bu/acre	
Red	95.6	a
White	99.7	a
None	100.1	a

Budget for 2003:

Expenses	
	2003
Res. Specialist salary (0.4)	$12,360
Fringe benefits	$3,090
Supplies	$1,030
Plant analysis	$721
Travel	$515
Total	$17,716

No-till lime management and soil pH effects on herbicide carryover

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Objective:
Evaluate yield loss due to carryover of pH-sensitive herbicides at different surface soil pH levels in a no-till soybean-corn rotation.

Methods:

- The experiments were conducted at Bradford Farm east of Columbia.
- No-till soybean-corn rotation. Both crops are grown each year.
- Experimental treatments are five lime/acid treatments in combination with four herbicide treatments for each crop.
  - Lime/acid treatments are:
    - high rate lime (about 3 tons/acre)
    - low rate lime
    - no treatment
    - low rate acid (iron sulfate was used)
    - high rate acid (equivalent to high lime rate).
- Lime and acid treatments were surface-applied.
- Lime and acid treatments created a wide range of soil pH values in the surface inch. For example, soil salt pH (normal MU test) ranged from 4.4 to 7.1 in May 2001.
- Herbicide treatments for each crop are shown in Table 1. These herbicides were chosen because their chemistry is pH-sensitive, with greater potential for carryover at high or low pH.
  - Increased potential for carryover at high pH: Atrazine, Peak, Classic
  - Increased potential for carryover at low pH: Atrazine, Pursuit, Scepter

Table 1. Herbicide Treatments applied in 1999 & 2001.

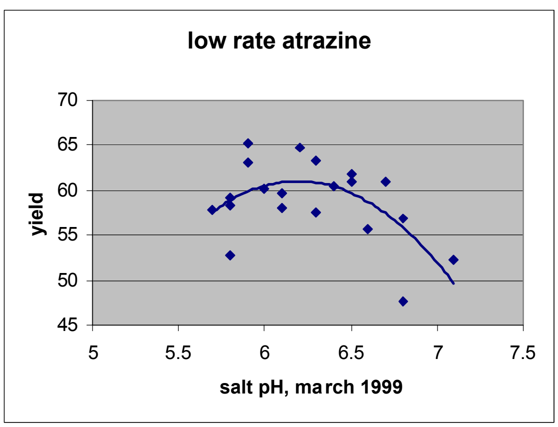
Corn		Soybean	
Herbicide	Rate (lb/ac)	Herbicide	Rate (lb/ac)
Atrazine	1.25	Pursuit	0.063
Atrazine	2.5	Scepter	0.125
Peak	0.018	Classic	0.04
Untreated		Untreated	

- This study has a two-year cycle. In the first year of the cycle, the herbicide treatments in Table 1 were applied to each crop. In the second year of the cycle, the rotation crop was grown and yields were analyzed to see whether they were affected by herbicide carryover from the previous year.
- Herbicide treatments were applied in 1999 and 2001.
- Yield effects of herbicide carryover were evaluated in 2000 and 2002.

- Soil pH also influences herbicide efficacy. We wanted to focus on pH effects on carryover, and eliminate differences in weed control between plots. We did this by growing Roundup Ready crops and controlling weeds in all plots with postemergence Roundup applications.

Results for soybean:

- Soybean yields were good in both harvest years. Average yield in 2000 was 58 bu/acre, and in 2002 was 49 bu/acre.
- In both 2000 and 2002, there was evidence of atrazine carryover effects on soybean yield.
  - In 2000, both atrazine treatments (1.25 lb/acre and 2.5 lb/acre) resulted in soybean yields that were sensitive to soil pH.
    - A curved line best described this relationship (Figure 1) with 95% confidence, while soybean yields in the control and Peak treatments were not influenced by soil pH.
    - Yields were most clearly reduced at high soil pH values, but they also appeared to be reduced at low soil pH.
- There are reasons why atrazine carryover damage might be expected at either low or high soil pH values:
  - At low pH, atrazine is strongly adsorbed to soil particles, making it less available for breakdown.
  - At high pH, atrazine is extremely soluble in the soil solution, producing potentially toxic effects even when concentration in the soil as a whole is very low.
- With the 2.5 lb/acre rate of atrazine, average soybean yield was 59 bu/acre from salt pH 5.7 to 6.5, and 54 bu/acre with pH above 6.5, a yield difference of 5 bu/acre.
- Dry conditions from July 1999 to April 2000 may have favored herbicide carryover. Herbicide breakdown is usually slower under dry conditions.



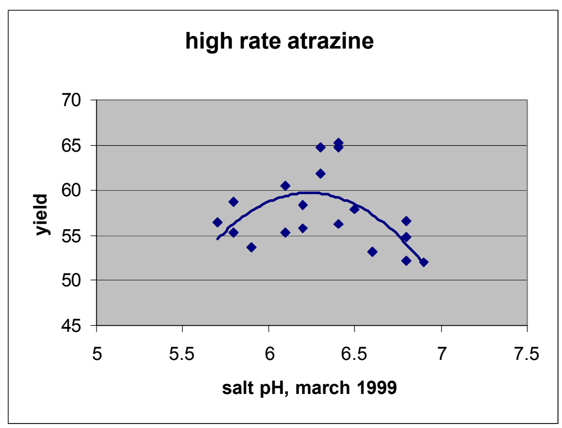


Figure 1. Soybean yield in 2000 was affected by soil pH in plots that had received atrazine (either 1.25 or 2.5 lb ai/acre) in 1999. For both atrazine treatments, yields were reduced at high soil pH and possibly also at low soil pH. The curved (quadratic) line best described the observed yields (95% confidence for both graphs). Soil pH measurements were taken in March 1999 (shortly before atrazine applications were made) in the top inch of soil, which is the main zone of atrazine activity.

  - In 2002, soil pH affected soybean yield in plots that had received the 2.5 lb/acre rate of atrazine, but not with the 1.25 lb rate.

    - Lower yields were seen with low soil pH values, especially below salt pH of 5.2 (Figure 2), but the reduction was only about 1.5 bu/acre (95% confidence). There was also some indication of yield reduction at low pH in 2000.
    - Unlike 2000, we did not see any yield reduction at high soil pH in 2002.
- Peak treatments did not result in pH-sensitive carryover damage. However, soybean yields in 2000 were reduced by 3 bu/acre when Peak had been applied the previous year, regardless of soil pH. No yield reduction was seen in 2002, in fact, plots receiving Peak in 2001 yielded 1 bu/acre more than control plots.
- Overall, herbicide carryover had much greater impact on soybean yield in 2000 than in 2002. This is probably related to the dry weather from July 1999 to April 2000, which created a poor environment for herbicide breakdown.

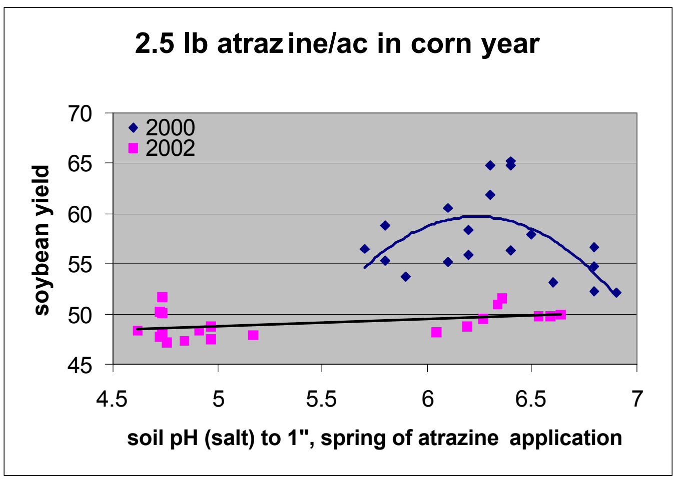


Figure 2. Soil pH effects on soybean yields compared for 2000 and 2002 in plots that had received 2.5 lb atrazine/acre the previous year. In 2000, yield was reduced at high soil pH (54 bu/acre above pH 6.5, 59 bu/acre below) and perhaps also at low pH, while in 2002 yields were reduced only at low pH and the yield reduction was smaller (1.5 bu/acre). Both effects are statistically significant with 95% confidence.

Results for corn:

- Corn yields were not as good as soybean yields, but were representative of many Missouri cornfields. In 2000, average corn yield was 132 bu/acre. In 2002, yields were limited by drought stress and average yield was 101 bu/acre.
- We did not see any effect of Pursuit, Scepter, or Classic treatments from the previous year on corn yield in either 2000 or 2002.

Economic analysis:

Results from 2000 suggest a soybean yield loss of around 5 bu/acre following atrazine when soil salt pH is above 6.5 (approximate water pH of 7.0) in the top inch. An estimate of the economic impact of this yield loss for Missouri:

> (5 million total acres of soybean) x (50% following corn) x (Atrazine applied to 80% of corn acres) x (50% no-till) x (15% of no-till acres have pH above 6.5 in surface inch) x (5 bu/acre lost) x ($5.50/bu) = $4.1 million/year lost income to Missouri soybean producers

The estimate of 15% of no-till acres with pH above 6.5 in surface inch is very rough. Most no-till ground that is limed probably falls into this category for a year, so if liming happens once every 6 or 7 years, about 15% of no-till fields will have high surface pH.

Economic loss based on 2002 results would be much smaller, possibly $1.2 million/year (similar calculation but 1.5 bu/acre yield loss and estimating that 15% of no-till acres have low surface pH due to surface N applications).

Conclusions:

- Soybean yield was affected by carryover of herbicides (particularly atrazine) and soil pH in both 2000 and 2002, but effects were much greater in 2000. This was probably due to drought in 1999/2000, which favored herbicide carryover. Yield reductions due to atrazine were seen at both low and high soil pH.
- Corn yield was not affected by herbicide carryover or soil pH in either 2000 or 2002.
- The economic impact of pH-related herbicide carryover in Missouri is difficult to assess at this point. Results from 2000 suggest that it could be a multi-million dollar problem, but this year's results show that the impact can be much smaller.
- Avoiding over-liming may be important for soybean profitability when atrazine is used in a no-till soybean-corn rotation. Small, frequent lime applications may be appropriate. Variable-rate lime applications may also be justified.

Acknowledgements

We gratefully acknowledge the Missouri Fertilizer & Ag Lime Council for providing funding for this project. Thanks are also due to Tom Anderson, Larry Mueller, Eric Feutz, and Cheryl Holman for their help in making this project happen.

Nitrogen Management

Evaluating Fall N Applications for Corn

Peter Scharf, Larry Mueller, and Gary Lesoing
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Objectives:

The objective of this study is to evaluate fall N applications in production cornfields over several weather years. This will include:

a. Tracking how much fall-applied N is lost from production cornfields
b. Determining how much yield potential is lost
c. Determining the economics of additional spring N applications

Accomplishments for 2002:

- Fifteen experiments were established in production cornfields that had received NH_3 applications in fall 2001 (Figure 1 and Table 1). Most of these experiments were in west-central Missouri, near the Missouri River, and in the claypan region of northeast Missouri. Fall 2001 applications of NH_3 in Missouri were at the highest levels in many years, and these regions were among the highest in the state. Two experiments were established in Vernon County because it is a higher-risk area for loss of fall-applied N than the rest of the state. NH_3 was applied after November 10 in all but one of the experiments. Six fields had N-Serve added to the NH_3.

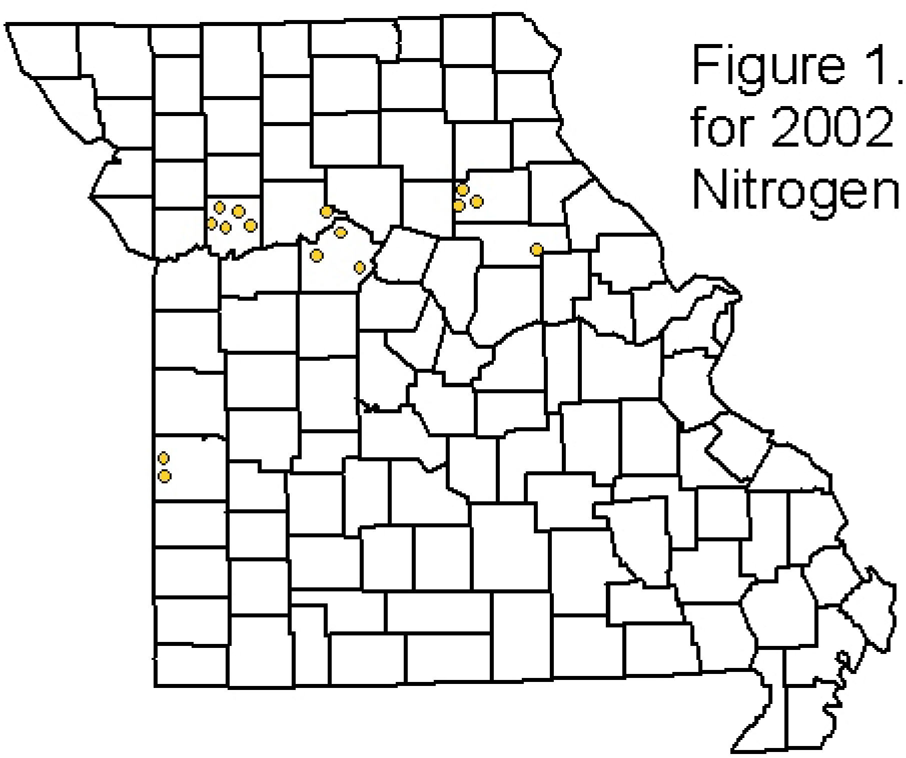

Figure 1. Locations for 2002 Fall Applied Nitrogen Trials

Table 1. 2002 LOCATIONS FOR FALL APPLIED NITROGEN TRIALS

COUNTY	LOCATION	SOIL SERIES	HYBRID
Vernon	Deerfield	BardenSilt Loam	Pioneer 35N05
Vernon	Hong	Parsons Silt Loam	[a]
Carroll	DeWitt	Leta Silty Clay	Asgrow RX730
Saline	Blackburn	Higginsville Silt Loam	Asgrow 686RR
Saline	Miami	Higginsville Silt Loam[b]	Pioneer 33P67
Saline	Napton	Higginsville Silt Loam	Pioneer 32P76
Ray	Dockery	Grundy Silt Loam	Stone E7S
Ray	Knoxville	Grundy Silt Loam	Stone E7S
Monroe	Madison	Putnam Silt Loam	NK-67T4
Audrain	Martinsburg	Mexico Silt Loam	Pioneer 34B23
Monroe	Middle Grove	Mexico Silt Loam	Mycogen 6888
Ray	Morton	Sibley Silt Loam	Pioneer 33P67[c]
Ray	Richmond	Zook Silty Clay Loam	Stone L3
Ray	Wood Heights	Grundy Silt Loam	Fielder's Choice 20010[d]
Monroe	Woodlawn	Putnam Silt Loam	NK-7070

[a] Not all background data was collected for the Hong location since we missed harvesting it.

[b] Plot has two soil series-Higginsville Silt Loam and Sibley Silt Loam.

[c] Plot has two hybrids-Pioneer 33P67 and Pioneer 33P77.

[d] Plot has two hybrids-Fielder's Choice 20010 and Fielder's Choice 20012.

Results:

Soil sample results

Soil samples were taken in all experiments to a three foot depth in April and May. These samples were analyzed for nitrate and ammonium (Table 2).

- Four of five fields sampled in April had considerably more N than we expected to find. A normal background rate of soil N, before any fertilizer is applied, is about 50 lb N/acre. On average, the soil N levels that we found in April were 125 lb N/acre higher than the NH_3 application rate used by the producer. We also measured about 125 lb N/acre in an unfertilized field in Saline County in a separate experiment. This implies that soil N levels prior to fertilization were high, but the reason for these high soil N levels is not clear.

- Ammonia converts to ammonium in the soil, and then converts to nitrate in a temperature-dependent process. Most of the N was still in the ammonium form in April samples taken in Saline and Carroll Counties, despite an unusually warm fall up to mid-December. Of these four fields, three had received N-Serve, which helps to keep the N in the ammonium form. In both of the Vernon County experiments, most of the ammonium had converted to nitrate by April, demonstrating the reason that fall N applications are riskier there: milder climate allows faster conversion to nitrate, which is the N form prone to loss.
- Conversion of ammonium to nitrate occurred quickly in late April and early May. Most of the N was in the nitrate form in all May samples except those from the Dockery and Middle Grove locations. N-Serve was used at both of these locations. The other four locations where N-Serve was used had most of their N in the nitrate form by May. The Middle Grove location had the lowest pH (salt pH 5.3) of any of the fields where N-Serve was used. Both N-Serve and low pH slow down the conversion from ammonium to nitrate.
- Application date did not appear to have any effect on the amount of N converted to nitrate for either the April or May soil sample timings. Nitrogen was applied on or after November 10 in all but one field
- The four Saline/Carroll locations that were sampled in late April were re-sampled in late May because of high rainfall after the initial sampling date. Between late April and late May, the ammonium-N was mostly transformed to nitrate-N, and an average of 81 lb N/acre was lost from the top three feet of soil. Despite this large loss of available N, only the Napton field appeared likely to be short of N and experience yield loss. This is because three of the fields had higher-than-expected N levels in April.
- For soil samples taken during May 21-24, only the Napton and Richmond locations had less soil N than what had been applied as fertilizer. This means that N loss in these fields was greater than the initial N content of the soil prior to fertilization, which is typically 50 lb N/acre but seems to have been higher this year at many locations.

Table 2. Fall N applications and spring N samples for 2002 experiments.

COUNTY	LOCATION	NITROGEN APPLICATION RATE, LB/AC	APPLICATION DATE [a]	N-SERVE	SAMPLING DATE	AMMONIUM 0-36" LB/AC	NITRATE 0-36" LB/AC	TOTAL N 0-36" LB/AC
Vernon	Deerfield	150	12/5/01	No	4/17/02	36	293	329
Vernon [b]	Hong				4/17/02	62	176	232
Carroll [c]	DeWitt	180	11/15/01	Yes	4/26/02	185	36	221
					5/22/02	31	163	194
Saline [c]	Blackburn	180	11/21/01	Yes	4/29/02	180	138	318
					5/22/02	40	201	241
Saline [c]	Miami	175	12/15/01	Yes	4/26/02	235	64	299
					5/22/02	13	193	216
Saline [c]	Napton	140	12/04/01	No	4/26/02	206	66	272
					5/22/02	9	127	136
Ray	Dockery	140	11/10/01	Yes	5/21/02	150	128	278
Ray	Knoxville	140	11/25/01	No	5/21/02	51	139	190
Monroe	Madison	175	12/15/01	No	5/23/02	22	240	262
Audrain	Martinsburg	150	11/15/01	No	5/24/02	12	208	220
Monroe	Middle Grove	180	11/16/01	Yes	5/16/02	157	96	253
Ray	Morton	150	10/15/01	No	5/23/02	50	177	227
Ray	Richmond	150	12/15/01	No	5/21/02	30	114	144
Ray	Wood Heights	150	12/15/01	No	5/21/02	39	123	162
Monroe	Woodlawn	150	11/15/01	Yes	5/22/02	13	145	158

[a] When dates were given as ranges the midpoint was used.
[b] Not all background data was collected for the Hong location since we missed harvesting it.
[c] Four locations were sampled on April 26th and again on May 22nd. Twelve inches of rain were recorded at the nearby weather station at Marshall between these sampling dates.

<u>Yield response to supplemental spring N</u>

When fall-applied N is lost, there is potential for yield loss, and for yield response to supplemental spring N. We applied either 0, 50, or 100 lb N/acre to small plots in the experimental fields between planting and emergence. In each field, six plots received no spring N, six received the 50 lb N/acre rate, and three received the 100 lb N/acre rate. These small-plot experiments were hand-harvested before the cooperating producers harvested the surrounding field, with the exception of the Hong location where we missed harvesting ahead of the producer.

- We saw significant (90% confidence) yield responses to supplemental spring N at two of the 14 harvested locations–Miami and DeWitt (Table 3). These two locations had a number of things in common:
  - Both were among the highest fall N rates applied.
  - Both received N-Serve mixed with the fall-applied N.
  - Neither appeared to be in danger of serious yield loss based on soil samples taken on May 22. Based on expected soil N levels of 50 lb N/acre above the fertilizer application rate, both were only a little below the expected level.
  - Both had high yield potential (above 160 bu/acre and among the four highest-yielding sites) when 100 lb spring N/acre was applied.
  - Both gave considerably higher yields with 100 lb/acre of additional N than with 50 lb/acre.
  - These two locations are close to each other.
- Among regions, the Saline/Carroll County region had both the biggest apparent N losses and the biggest yield response to N.
  - We expect yield response to be a result of N loss, but corn yield did not respond to spring N applications at Napton, the site with the biggest apparent N loss by May 21-24.
  - The sites where yield responded to N, Miami and DeWitt, had apparent N losses of only about 10 and 30 lb N/ac, respectively, by May 22.
  - Precipitation patterns may help to explain what happened.
    - Between April 26 and May 22, the weather station at Marshall recorded 12.0 inches of rain, while the station at Brunswick recorded 9.8 inches. Napton is closer to the Marshall station. The greatest apparent N loss may have occurred there because of greater rainfall.
    - Between May 23 and June 15, the weather station at Marshall recorded 4.4 inches of rain, while the station at Brunswick recorded 9.0 inches. Brunswick is very close to the DeWitt experiment, and also close to the Miami experiment. DeWitt and Miami are the two experiments where corn yield responded dramatically to supplemental spring N. One explanation for why corn yields responded at these locations is that heavy rains after the May 22 soil samples led to high N losses.
- Supplemental spring N

applications would have easily paid for themselves at the Miami and DeWitt locations.

- 65 and 39 bu/acre yield responses to 100 lb N/acre would generate $130 and $78/acre, respectively, with $2.00/bu corn.
- Applications would cost about $25/acre (100 lb N/acre x $0.20/lb N + $5/ac application cost).
- Predicting that these were the two fields where corn yield would respond to supplemental N would have been difficult.

- Yield response to supplemental spring N may have been limited by drought at other locations. Many areas (particularly, in this study, the fields in Ray County) had little rainfall from mid-June through July. Even if significant N losses occurred, the remaining N may have been sufficient to support the drought-lowered yields.

Yield response to zinc

Zinc treatments were also included in these experiments because of promising results in 2001 in another set of experiments. We did not find any sites with yield response to zinc among the 14 fields in this study. Further discussion of these results may be found in the report, “Refining Soil Test Recommendations for Corn,” by Peter Scharf, John Lory, Manjula Nathan, and Bill Wiebold.

Table 3. Yields From 2002 Fall Applied Nitrogen Trials.

COUNTY	LOCATION	YIELD WITH FERTILIZER TREATMENT:			
		CHECK	+ 50 N	+ 100 N	ZN
Vernon	Deerfield	126	123	123	125
Vernon	Hong [a]				
Carroll	DeWitt	141	156	180†	137
Saline	Blackburn	127	123	127	112
Saline	Miami	96	119*	161***	86
Saline	Napton [b]	155	155	162	
Ray	Dockery	85	89	90	92
Ray	Knoxville	87	91	91	94
Monroe	Madison	160	149	155	160
Audrain	Martinsburg	100	100	106	99
Monroe	Middle Grove	170	173	167	170
Ray	Morton	108	97	95	98
Ray	Richmond	66	59	52	66
	Ray	Wood	63	59	6762
Monroe	Woodlawn	122	123	121	98

*** This yield is greater than the yield of the check with greater than 99.9% confidence.

* This yield is greater than the yield of the check with greater than 95% confidence.

† This yield is greater than the yield of the check with 90 to 95% confidence.

[a] No harvest data from the Hong location.

[b] Zn treatments were not applied at the Napton location

Summary and Conclusions:

- Despite a mild winter, fall NH_3 applications remained mostly in the ammonium form until April, except for the two Vernon County locations, where they had converted to nitrate.
- There was little potential for over-winter N losses, even where N had converted to nitrate, because of a dry winter.
- Fall N converted rapidly from ammonium to nitrate between late April and late May, except in two of the six fields where N-Serve was used.
- High soil N levels were found in soil samples taken in April.
- The weather turned wet in late April, and for four fields sampled in both late April and late May, an average of 81 lb N/acre was lost during this period.
- Samples taken in late May suggested that N availability was still good at most locations.
- There was no yield response to supplemental spring N at the location that had the largest apparent N loss (about 55 lb/acre) by late May.
- There were large yield responses (65 bu/acre and 39 bu/acre) to supplemental spring N in two experiments.
  - Both had small apparent N loss according to soil samples taken in late May.
  - Both were near the experiment that had the largest apparent N loss by late May.
  - Both were near each other and near a weather station that recorded 9 inches of rain between May 22 (when soil samples were last taken) and June 15.
- The best explanation for the yield response at these locations is that large amounts of N were lost after the soil samples were taken due to excessive rainfall.
- These two fields may have needed additional N even if they had been fertilized just before planting instead of in the fall.

Acknowledgements

We gratefully acknowledge the Missouri Fertilizer & Ag Lime Council for providing funding for this project.

Nitrogen fertilization strategies for annual ryegrass pasture

Robert L. Kallenbach and Richard J. Crawford, Jr.
Plant Sciences Unit and the Southwest Research and Education Center
University of Missouri

Accomplishments for Year 1:

- A three-year field trial studying the effects of nitrogen rate and date of application on the yield and quality of annual ryegrass began in August, 2002. This replicated (4x) experiment has 16 treatments; four N rates at planting (0, 50, 100, and 150 lb/acre of N) followed by the either 0, 50, 100, or 150 lb/acre of N in late winter. The table below describes the rate and date of N applications for treatments.

Treatment	N at planting	N in Late winter
	--------- lb N /acre ---------	
1	0	0
2	0	50
3	0	100
4	0	150
5	50	0
6	50	50
7	50	100
8	50	150
9	100	0
10	100	50
11	100	100
12	100	150
13	150	0
14	150	50
15	150	100
16	150	150

- We established the annual ryegrass in to a conventionally tilled seedbed at the Southwest Research and Education Center near Mt. Vernon, MO in late August of 2002 (Fig. 1). The seeding rate was 30 lb/acre of pure live seed. After seeding, the autumn fertilizer treatments were applied.

Fig. 1. Planting annual ryegrass at the Southwest Research and Education Center near Mt. Vernon, MO. The annual ryegrass was planted into a conventional seedbed in late August of 2002. The stand established well but dry weather conditions in autumn have limited growth so far.

- Soil samples to a 40-inch depth were taken prior to seeding using a hydraulically operated soil probe. The probe diameter was 1.5 inches. Samples were split into three depth classes (0-10, 10-20, and 20-40 inches) and then analyzed for NH_4 and NO_3 content. Initial results showed that plots had equal ($P>0.05$) levels of pre-experiment NH_4 and NO_3.

- As planned, we started collecting forage growth data in the autumn of 2002 and this will continue through May of 2003 for the first year. Dry autumn weather at this location has limited forage growth to date. So far, all treatments have produced approximately 1500 lb/acre of dry matter which is less than 30% of what we would normally expect by this time. The lack of a response to N fertilizer is also abnormal as studies conducted in other states show that annual ryegrass responds quite favorably to N. Likely, the dry weather this autumn is responsible for this response. However, we expect that once the entire season's data has been collected (usually complete by late May), we will see a substantial response to N fertilization.

- Forage quality samples show that annual ryegrass is excellent forage. Samples collected to date show that annual ryegrass has a crude protein content of 28% and acid detergent fiber values less than 17%. In short, few other forages can produce such excellent quality feed for winter grazing.

- More than 1,000 individuals had the opportunity to view this new research project as part of various extension education programs and field days conducted at the Southwest Research and Education Center. As we develop more comprehensive data over the next three years, we will be able to extend our results even further.

Objectives for Year 2:

- Over the next year we will continue our research on N fertilization of annual ryegrass. Because annual ryegrass is planted in August and harvested through winter and early spring, we are only partway through the first year of data collection. As outlined in our original proposal, the tasks in the table below will be conducted over the next year.

- In addition, we will be fully analyzing our field data from the first year next summer. We are most interested in refining N recommendations for annual ryegrass so that maximum economic productivity can be obtained by forage-livestock producers. In addition, we would like to understand more about the fate N applied at relatively high rates to annual ryegrass. Work from other regions suggests that annual ryegrass can capture nearly all of the N applied to the surface. This may make it an ideal crop for operations with a large amount livestock manure.

- We will continue to integrate our findings into the curriculum of the Missouri Grazing Schools, grazing workshops statewide, and at the Southwest Research and Education Center Field day. These outreach efforts can be expected to reach more than 1,000 producers, agency staff, and agri-business personnel. Additionally, as more comprehensive data are collected, we will start work on a new guidesheet about annual ryegrass fertilization. In addition we will prepare articles to be published in statewide and national magazines such as Missouri Ruralist, Graze, Stockman Grass Farmer and scientific journals.

Harvest plots for forage yield and retain subsamples for forage quality analysis	Ongoing as forage growth dictates. Anticipate 5 to 7 harvests per year.
Apply N to plots receiving late winter fertilizer	3/1/03
Take five, 3 inch diameter cores from each plot & count the number of tillers	4/15/03
Take soil cores from each plot to determine residual soil N	6/1/03
Analyze samples taken to date for forage quality	7/31/03
Prepare seedbed for annual ryegrass planting (Year 2 of study begins)	8/20/03
Take soil core samples to a 40-inch depth for initial soil nitrogen determinations (Year 2)	8/31/03
Plant annual ryegrass at 30 lb/acre (Year 2)	9/1/03
Apply N fertilizer to plots receiving an autumn application (Year 2)	9/1/03
Take five, 3 inch diameter cores from each plot & count the number of tillers (Year 2)	10/10/03
Harvest plots for forage yield and retain subsamples for forage quality analysis (Year 2)	Ongoing as forage growth dictates. Anticipate 5 to 7 harvests per year.

Budget:
As requested last year, our budget for the second year of studies is as follows.

Year 2

Salary and Benefits	
Research Specialist (25% of $31,500)	$ 7,875
Benefits for Research Specialist	$ 1,969
Total Salary and Benefits	$ 9,844
Operating Expenses	
Seed, fertilizer, bags, repair parts for harvester and other field supplies	$ 1,850
NIR charges for forage quality analysis (approx. 300 samples @ $1 each)	$ 300
Forage quality wet chemistry for NIR calibration (60 samples @ $11 each)	$ 666
Soil N analysis (66 samples @ $8 each)	$ 528
Travel to SWC (mileage, lodging, and meals for six trips per year)	$ 1,464
Total Operating Expenses	$ 4,808
Equipment	
None requested	$ 0
Total Equipment	$ 0

Total Proposal Request for Year #2 ***$14,652***

Improved Nitrogen Fertilizer Recommendations for Soils Incorporating a Simple Measurement of Soil Physical Properties

Peter Motavalli and Stephen Anderson
Environmental Soil Science Program, University of Missouri

Accomplishments for Second Year:

- A two-year field trial was continued in 2002 at the Bradford Agronomy Center in which 2 levels of surface compaction were imposed (0, 2x passes of a tractor-pulled filled 500 gallon water tank) and 5 rates of N fertilizer (0, 75, 125, 175, 250 lbs N/acre as ammonium nitrate) broadcast applied pre-plant in a factorial design. The tractor (Model 504 International Harvester) and the water wagon had axle loads of 2.8 tons and 3.2 tons, respectively. The water wagon had 7.1 inch-width front and rear radial tires under an inflation pressure of 32 psi. The water wagon was pulled twice over the soil so that coverage of wheel-tracked soil was uniform over the whole compacted area. All treatments were applied in 4 replications to an adjoining area to the 2001 plots and this new area had been planted to corn the previous three years. Fallow plots receiving N fertilizer rates of 0 and 250 lbs N/acre were also established to separate the effects of soil and plants on the fate of applied N fertilizer.

- Soil physical properties measured during the initial growing season in which N fertilizer was applied were soil bulk density, soil hydraulic conductivity, soil pore size distribution, soil penetrometer resistance to a depth of 12 inches and changes in soil water content at depths of 4 and 8 inches. Soil water content was monitored using time domain reflectometry (TDR). The effects of compaction on N recovery of applied N fertilizer were evaluated by periodic soil sampling to determine ammonium-N and nitrate-N to a depth of 12 inches in 4 inch increments and by determination of crop N uptake.

- Surface compaction imposed in April, 2002 before planting significantly increased soil bulk density to a depth of 4 inches and soil penetrometer resistance to a depth of 12 inches (Fig. 1A and B). Averaged over all the years of treatments, surface compaction increased soil bulk density an average of 0.17 g/cm^3 in the 0 - 4 inch depth and 0.08 g/cm^3 in the 4 – 8 inch cm depth and penetrometer resistance (measured using a proving-ring dial gauge cone penetrometer from ELE International/Soiltest, Inc.) an average of 365 lb/in^2 in the 0 - 2 inch depth, 276 lb/in^2 in the 2 – 4 inch depth, and 145 lb/in^2 in the 4 – 8 inch depth. Surface compaction also significantly decreased total porosity in both the 0 – 4 and 4 – 8 inch depths and significantly increased the proportion of micropores (<5 µm pore radius) and decreased the proportion of coarse mesopores (25 – 500 µm radius) and macropores (>500 µm radius) in the 0 – 4 inch depth. The decreases in porosity and the proportion of macropores from surface compaction would be expected to affect the fate of applied N fertilizer by reducing drainage and causing poorer aeration.

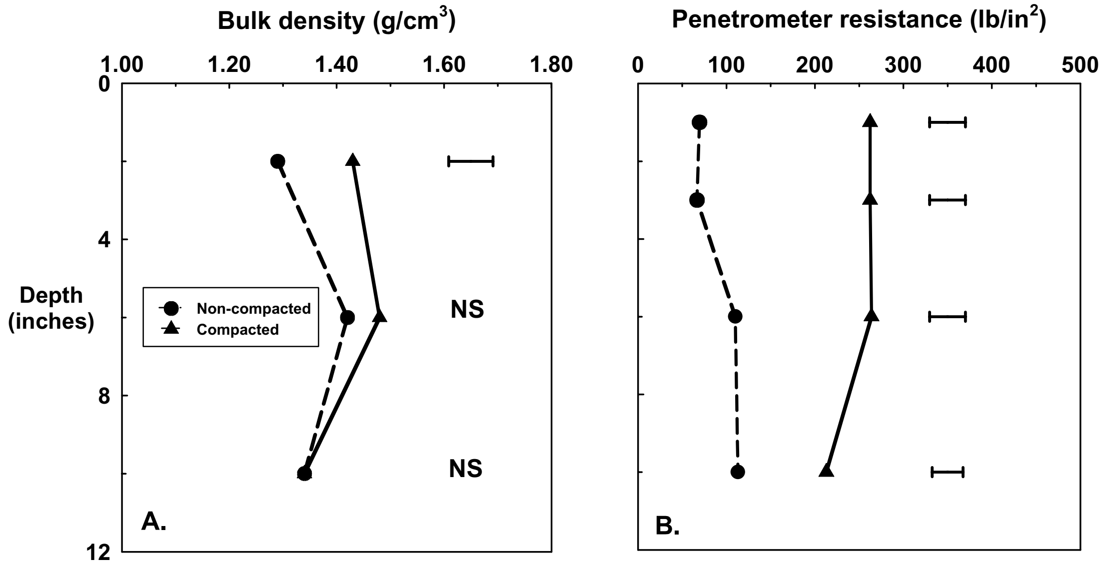

Figure 1. Soil bulk density (A) and penetrometer resistance (B) after surface compaction in a claypan soil in 2002. Bars indicate $LSD_{(0.05)}$ and NS = not significant.

- A separate comparison of four soil cone penetrometers, selected to represent a wide range of costs and capabilities, was conducted in the early summer of 2002. The soil penetrometers that were compared were the Profiler 3000 (Veris Technologies), the Investigator Soil Compaction Meter (Spectrum Technologies, Inc.), the Soil Compaction Tester (Dickey-john Corporation), and the proving-ring dial gauge cone penetrometer (ELE International/Soiltest, Inc.). The Veris instrument had the additional capability of measuring soil electrical conductivity (EC), a property which may be used to assess relative clay content. In general, the Spectrum penetrometer gave lower and the Veris instrument higher CI values compared to the ELE/Soiltest penetrometer under compacted conditions (Fig. 2A and B). Higher observed CI at lower depths for the Veris and Dickey-john penetrometers was attributed to shaft friction.
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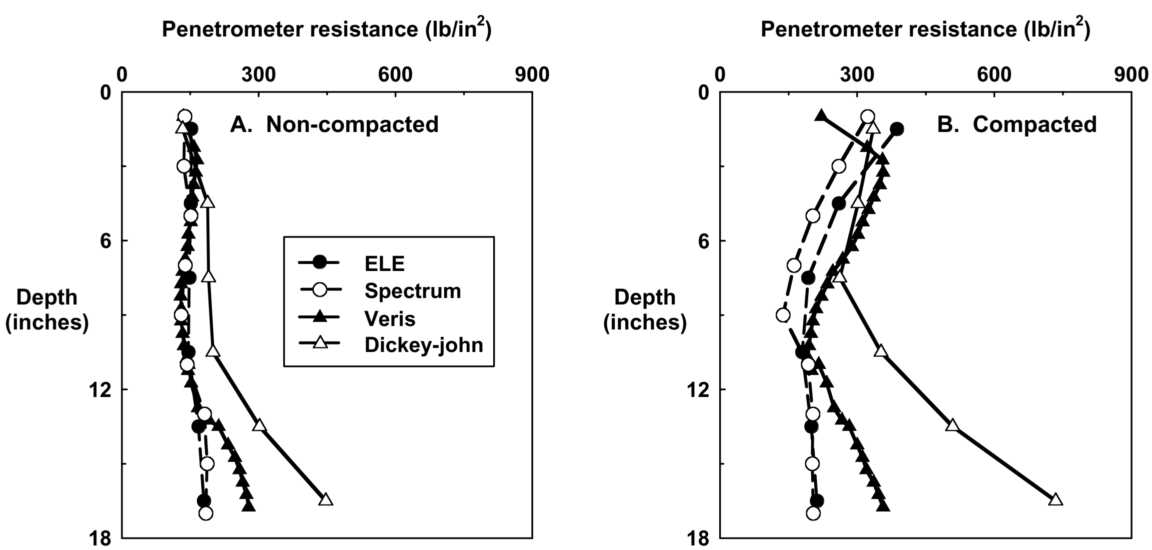

Figure 2. A comparison of soil penetrometer resistance by depth measured by several soil cone penetrometers in treatments of (A) the non-compacted treatments and (B) the compacted treatment.

- Corn grain yields and N uptake in 2002 significantly increased with increasing rates of pre-plant N fertilizer applications in compacted treatments, but were relatively low, probably a result of heavy windstorms knocking corn plants down late in the season (Table 1). The heavy winds especially increased lodging of corn in the non-compacted treatments. Continuous corn over the several seasons of the experiment also may have caused reduced yields. Early season observations showed a large negative effect on growth due to compaction. However, compaction only caused a significant statistical decrease in yield at the 125 lb N/acre fertilizer rate and had no effect on N uptake at any level of applied N.

Table 1. Corn grain yields and N recovery of pre-plant N fertilizer applications at Bradford Agronomy Center in compacted and non-compacted plots during the 2002 season.

	Grain yield			N uptake		
N Rate	Non-compacted	Compacted	$LSD_{(0.05)}$	Non-compacted	Compacted	$LSD_{(0.05)}$
lb/acre	bu/acre			lb N/acre		
0	51	30	NS†	46	35	NS
75	91	42	NS	30	38	NS
125	78	45	28	69	40	NS
175	86	57	NS	71	48	NS
250	94	89	NS	58	65	NS
$LSD_{(0.05)}$	NS	33		27	16	

†NS = not statistically significant at the $P < 0.05$ probability level.

- Soil inorganic N (ammonium + nitrate N) sampled to a depth of 12 inches in June and September (after harvest) in the fallow plots did not indicate an increased loss of applied fertilizer N (Fig. 3A and B) due to compaction but did show leaching of applied N to the 12 inch depth. This result is consistent with what was observed in 2001. Higher surface inorganic N with compaction is possibly because of reduced water infiltration in the compacted soil reducing leaching losses.

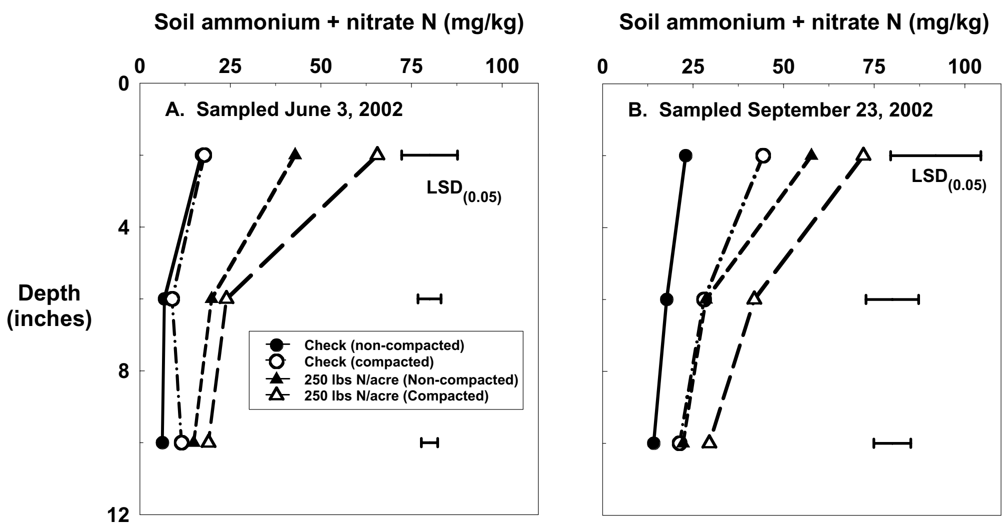

Figure 3. Soil inorganic N at two different sampling dates in the fallow plots.

- A research article comparing methods to assess soil compaction using soil cone penetrometers for possible use in soil fertility evaluation was produced and submitted in 2002 to the peer-reviewed journal, *Soil & Tillage Research*.

- The M.S. graduate student is conducting laboratory/greenhouse experiments to compare methods of assessing compaction and the effects of compaction on corn N efficiency with three soils with sandy, silt loam and clay textures obtained from the University of Missouri Delta Center. These studies will be the major part of the M.S. thesis research of the graduate student funded from this project. We anticipate these experiments will be completed by March, 2003.

Conclusions

- Although the use of the soil cone penetrometer was more sensitive to changes in soil physical properties due to surface compaction compared to measurements of soil bulk density, the routine use of soil cone penetrometers may be complicated by the effects of natural and management-induced variations in soil properties, such as soil water content, and by differences in cone penetrometer design and operation. Standardization of recommended soil sampling conditions and of characteristics of penetrometer design and operation that affect measured cone index (CI) would facilitate use of cone penetrometers for soil fertility evaluation under different environmental conditions. Based on current technology, we also recommend adding the capacity of soil penetrometers to measure soil water content and texture (e.g. through TDR and soil EC technology). However, the current cost of these additional features for penetrometers may discourage their use for routine soil testing.

- For utilization of soil bulk density and penetrometer resistance in soil fertility evaluation among the diverse soil conditions in Missouri, we are evaluating the use of *relative* bulk density and penetrometer resistance based on a standardized laboratory test of the maximum density and penetrometer resistance achieved for a given soil or category of soils (e.g. defined by soil texture).

- Consistent decreases in corn grain yields and N uptake due to surface compaction were not observed during 2001 and 2002 despite observed early season differences in crop growth and yellowing possibly due to N deficiency. This lack of response was attributed to heavy precipitation during 2001 and strong winds promoting lodging in the non-compacted treatments in 2002. Continuous corn grown over several years also may have contributed to reduced overall yields. Increasing amounts of applied N fertilizer increased grain yields in both compacted and non-compacted areas.

- On-going laboratory/greenhouse experiments to compare methods of assessing compaction and the effects of compaction on corn N efficiency with three soils with sandy, silt loam and clay textures under controlled environmental conditions are being conducted to determine the feasibility of adjusting N fertilizer recommendations based on relationships between soil bulk density, soil penetrometer resistance, soil water content, soil texture, and observed changes in N fertilizer efficiency with increasing soil physical restrictions.

Publications and Presentations Based on Project:

Motavalli, P.P., S.H. Anderson, P. Pengthamkeerati and C.J. Gantzer. Submitted. Use of soil cone penetrometers to detect the effects of compaction and organic amendments in claypan soils. Soil & Tillage Research (Peer-reviewed journal article).

Motavalli, P.P. 2001. Soil compaction and nitrogen efficiency. University of Missouri Crop Management Conference (November 28-29, 2001), Columbia, MO (Presentation to agricultural professionals).

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University of Missouri, Columbia, MO
(Field Day).

Motavalli, P.P. and R.J. Miles. 2001. Soil characteristics and compaction, Crop Injury Diagnostic Clinic (July 24-27, 2001) and Pioneer Sales Representative Crop Clinic (July 31, 2001), Bradford Agronomy Center, University of Missouri, Columbia, MO (Workshop for agricultural professionals).

Motavalli, P.P. 2001. Soil compaction and nitrogen availability, ARC Extension Tour (June 28, 2001), Bradford Agronomy Center, University of Missouri, Columbia, MO (Field day for UM extension professionals).

The influence of nitrogen rate and pasture composition on the toxicity, quality and yield of stockpiled tall fescue

Robert L. Kallenbach and Robert L. McGraw
Plant Sciences Unit, University of Missouri

Accomplishments for Year 1:

- A three-year field trial studying the effects of nitrogen rate and pasture composition on the toxicity, quality, and yield of stockpiled tall fescue began in August, 2002. The study has 10 treatments; five rates (0, 50, 100, 150 and 300 lb/acre) of N applied in August and two pasture types (tall fescue with or without red clover). The study is replicated six times.

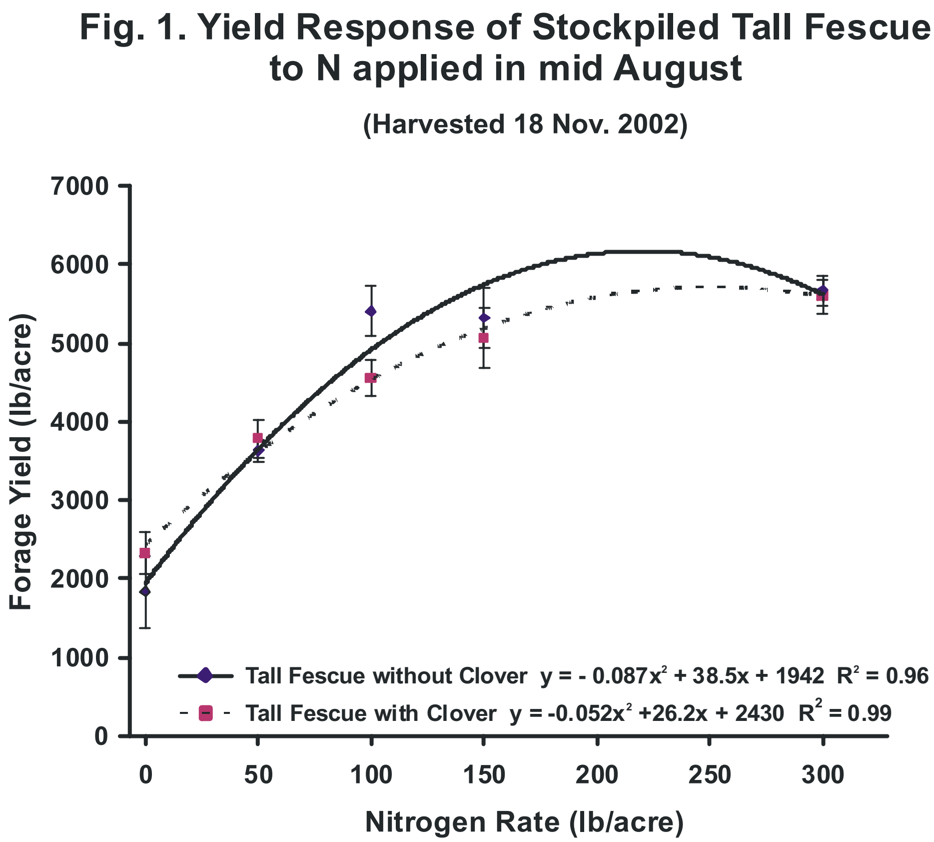
- We established the study in an existing endophyte-infected tall fescue/red clover pasture at the Forage Systems Research Center (FSRC) near Linneus, MO. Before the treatments were applied, the stand was approximately 30% red clover and 70% tall fescue. For the tall fescue treatments without clover, existing red clover plants were killed in the spring of 2002 by spraying 2,4-D and Remedy. The forage in all treatments was clipped to a 3-inch stubble height in early August prior to starting the study.

- Soil samples were taken to a 40-inch depth prior to applying fertilizer treatments using a hydraulically operated soil probe. The probe diameter was 1.5 inches. Samples were split into three depth classes (0-10, 10-20, and 20-40 inches) and then analyzed for NH_4 and NO_3 content. Initial results showed that plots had equal ($P>0.05$) levels of pre-experiment NH_4 and NO_3.

- As planned, we began to harvest forage on a monthly basis starting in mid-November of 2002. Forage harvests will continue monthly from November to March each year.

- Because this project examines forage yield, quality and toxicity of stockpiled tall fescue over winter, we are only part-way through the first year. As a result, we have only limited data to report at this time. However, some preliminary results are:

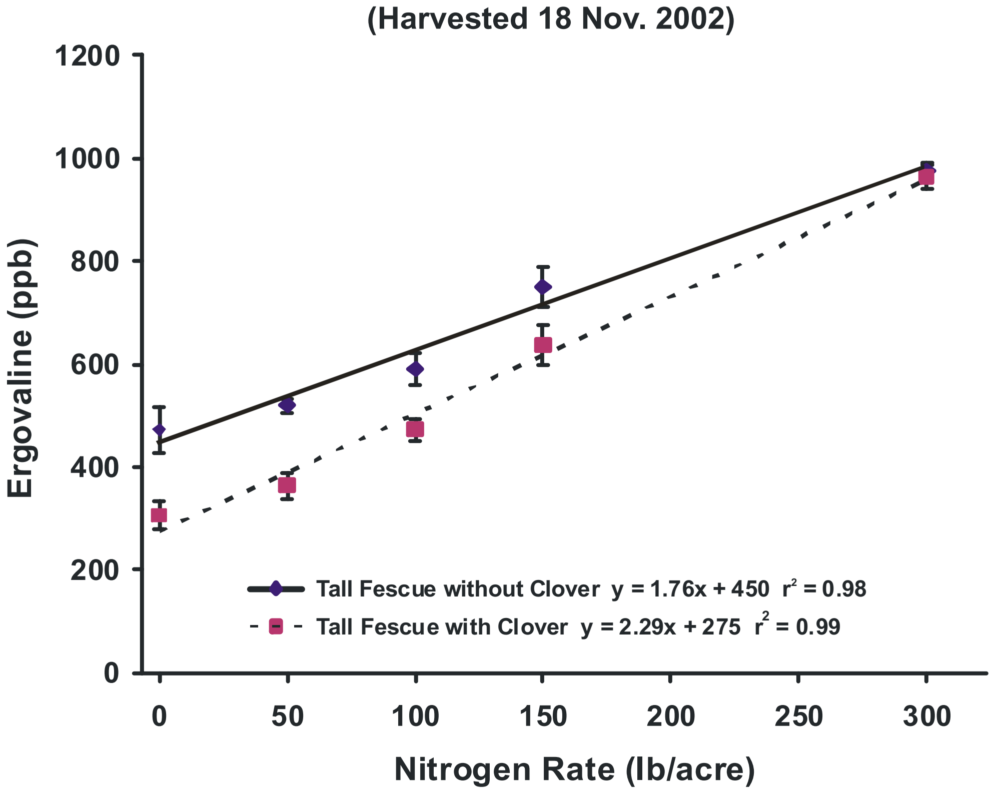
  - Forage yields in November increased substantially when N was applied in August, despite the dry growing conditions in the autumn of 2002. Regardless of whether plots contained red clover, a nearly linear response to N rates up to 100 lb/acre was observed. Rates above 100 lb/acre showed either little or no increase forage yield (Fig. 1). Although many producers limit late-summer or fall applications of N to 50 or 60 lb/acre, our data show that even in dry years rates up to 100 lb/acre give yield responses.



- Our data suggest that when previous moisture conditions cause limited on-farm hay supplies, a late summer N application might be more cost effective than previously thought. Although we have only one year of data, the preliminary results are promising; however, long-term studies are necessary to develop accurate recommendations.

- Ergovaline is the principal toxin in infected tall fescue and this compound causes metabolic problems for almost all classes of livestock. The ergovaline content of stockpiled tall fescue increased linearly with N rate (Fig. 2). When no nitrogen was applied, ergovaline levels were approximately 175 ppb lower in mixed tall fescue/red clover treatments in than treatments where no red clover was present. However, the benefit of red clover declined as N rates increased. Likely this is due to the lower percentage of red clover in the mixed sward as N rates increased.

Fig. 2. Ergovaline Content of Stockpiled Tall Fescue in Response to N Applied August



- The ergovaline concentrations we found are approximately 25 to 50% lower than those reported by Rottinghaus et al. (1991) for spring-grown tall fescue. However, the ergovaline concentration in all treatments was in excess of the 150 ppb threshold for livestock reported by Stamm et al. (1994). This suggests that while stockpiled forage has lower ergovaline levels than tall fescue during the growing season, it still is a potential problem for livestock owners in winter and that N fertilizer management plays an important role.

- More than 300 individuals have seen this research as part of various extension education programs conducted at the Forage Systems Research Center. In addition, the research plots have been used as part of Dr. McGraw's *Forages* class at the University of Missouri.

Objectives for Year 2:

- Over the next year we will continue our research on the impact of N on stockpiled tall fescue. As outlined in our original proposal, the tasks in the table below will be conducted over the next year.

Continue to harvest appropriate sub-subplots for forage yield and retain subsamples for forage quality and ergovaline analysis (Year 1)	1/15/03, 2/15/03 and 3/15/03
Seed 5 lb/a of red clover on appropriate plots to maintain grass/legume mix.	3/1/03
Take soil cores from each sub-plot to determine residual soil N.	3/19/03
Harvest all sub-subplots for forage yield and retain subsamples for forage quality and ergovaline analysis. (This should measure the residual effects)	5/19/03 and 7/24/03
Count the legume plants in six, 1.0 $ft.^2$ quadrats in each plot	5/25/03 and 8/12/03
Take soil core samples to a 40-inch depth for soil nitrogen. (Year 2 starts)	8/13/03
Apply N fertilizer for second years of experimentation. Treatments are 0, 50, 100, 150 and 300 lb/acre of actual N. (Year 2)	8/14/03
Analyze samples taken to date for forage quality and ergovaline content	8/30/03
Harvest appropriate sub-subplots for forage yield and retain subsamples for forage quality and ergovaline analysis (Year 2)	11/15/03, 12/15/03, 1/15/04, 2/15/04 and 3/15/04

- In addition, to completing the tasks outlined above, we will be analyzing our field data more fully. Specifically, we are interested in determining the rate and extent of forage degradation over winter, with a special focus on ergovaline concentrations. Based on previous data published by Kallenbach et al. (2003), ergovaline levels are expected to drop over winter in stockpiled tall fescue. Although the influence of N rate on this process is unknown, we would like to develop prediction equations that could guide producers, fertilizer dealers, crop consultants and other about the potential toxicity and use of stockpiled tall fescue in winter.

- We will continue to integrate our findings into the curriculum of the Missouri Grazing Schools and the annual Winter Grazing Workshops at Linneus and Mt. Vernon. These outreach efforts can be expected to reach more than 1,000 producers, agency staff, and agri-business personnel. Additionally, as more comprehensive data are collected, we will start work on a new guidesheet about stockpiling tall fescue as well as prepare articles to be published in statewide and national magazines such as Missouri Ruralist, Graze, Stockman Grass Farmer and scientific journals.

Budget:
As requested last year, our budget for the second year of studies is as follows.

Year 2

Salary and Benefits	
Research Specialist (25% of $31,500)	$ 7,875
Benefits for Research Specialist	$ 1,969
Total Salary and Benefits	$ 9,844
Operating Expenses	
Fertilizer, bags, repair parts for harvester and other field supplies	$ 1,000
NIR charges for forage quality and ergovaline analysis (900 samples @ $1 each)	$ 900
Forage quality wet chemistry for NIR calibration (45 samples @ $11 each)	$ 495
Ergovaline analysis (wet chem. for NIR calibration 45 samples @ $25 each)	$ 1,125
Soil N analysis (366 samples @ $8 each)	$ 2,928
Travel to FSRC (mileage, lodging, and meals for 8 trips per year)	$ 1,100
Total Operating Expenses	$ 7,548
Equipment	
None requested	$ 0
Total Equipment	$ 0

Total Requested for Year #2 ***$17,392***

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Stamm, M.M., T. Delcurto, M.R. Horney, S.D. Brandyberry, and R.K. Barton. 1994. Influence of alkaloid concentration of tall fescue straw on the nutrition, physiology, and subsequent performance of beef steers. J. Ani. Sci. 72:1068-1075.

Evaluating Grain Sorghum Nitrogen Fertilization Recommendations

Progress Report for Second Year (2002)

Gene Stevens and David Dunn

Objectives:

(1) Improve grain sorghum yields by testing nitrogen fertilizer rates with different plant populations.
(2) Develop tissue N content, and chlorophyll meter thresholds in grain sorghum for applying midseason N by fertigation.

Procedure:

Nitrogen experiments were conducted on two soil types at the University of Missouri-Delta Research Center at Portageville, Missouri. A randomized complete block design with four replications was used in each test. Grain sorghum was planted on 30-inch rows in each of the tests. Plots were 10 feet wide and 35 feet long.

Plant population. In the first experiment, the effect of plant population on yield response to early-season N rates was determined. This test was conducted on Tiptonville silt loam and Sharkey clay soils. Both field were planted in soybeans in the previous year. Grain sorghum was planted at a high seeding rate (150,000 seeds per acre). After emergence, plots were evenly thinned by hand to low and high plant populations (35,000 and 105,000 plants per acre). Five N rates were tested at each plant population. Early-season N treatments were applied at rates of 0, 50, 100, 150, and 200 lb N/acre (ammonium nitrate) when grain sorghum was 4 inches tall.

We added a second test in 2002 on the Tiptonville silt loam site to determine the effect of uniformity of plant population on nitrogen response. Treatments were included with 3-foot, 6-foot and 9-foot skips in the rows.

Nitrogen timing. In the second experiment, we collected data to calibrate midseason tissue N contents and Minota SPAD chlorophyll meter to grain sorghum yield response to N applied through a sprinkler irrigation system. This test was conducted on a Tiptonville silt loam soil. The field was planted in soybeans in the previous year. Before planting grain sorghum, ammonium nitrate was applied at the rates of 0, 25, 50, and 75 lb N/acre. Each preplant N rate had additional N applications with 0 and 30 lb N/acre by fertigation (32% UAN+ AGROTAIN) at stem elongation (late vegetative), and milk stages. Before making the fertigation N application, grain sorghum leaves was sampled from each plot. Each sample was tested for tissue nitrate content and digested for total N using a Hach Digesdahl abd SPAD chlorophyll meter.

Accomplishments for first year (2002):

Grain sorghum plots with evenly thinned low population treatments compensated for reduced stand by making larger heads. At the low N rates, grain sorghum yields were 10 to 15 bushels higher in the high population treatments than the low population treatments (Figure 1 and 2). However, the higher N rates (100 lb N/acre) increased tiller numbers and head size in low population treatments which compensated for the reduced stand.

However, we found that when grain sorghum plots were not thinned evenly leaving 3, 6, and 9 foot skips, it was more difficult for the heads to compensate for all of the reduced stand (Table 1 and Figure 3). The lowest yields occurred with three 9 foot skips in 50 foot plot rows (Figure 4).

In the fertigation study, grain sorghum yields increased with preplant N fertilizer, but no significant yield response was found to mid-season N fertigations (Figure 5).

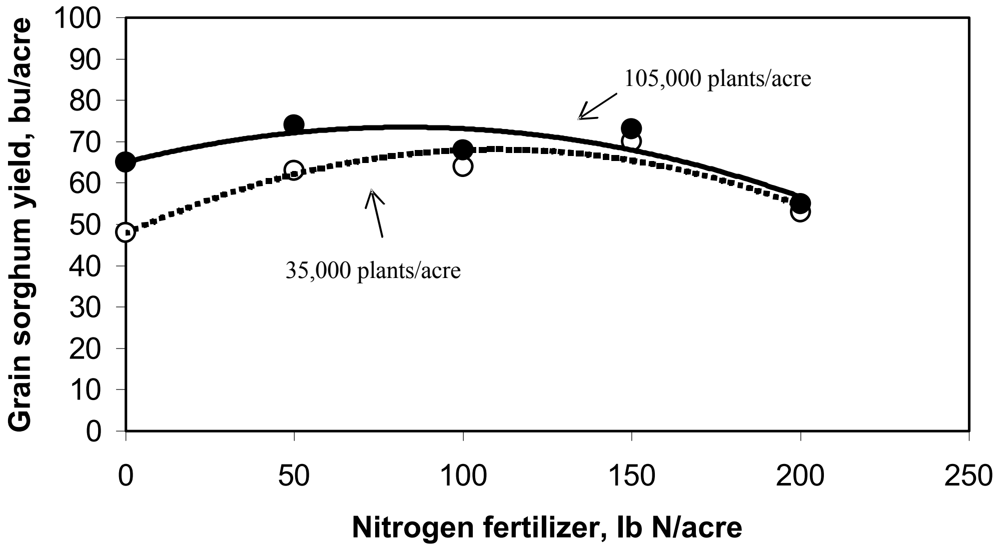

Figure 1. Grain sorghum yields on Tiptonville silt loam soil following cotton as affected by nitrogen fertilizer rate and grain sorghum plant population in 2002.

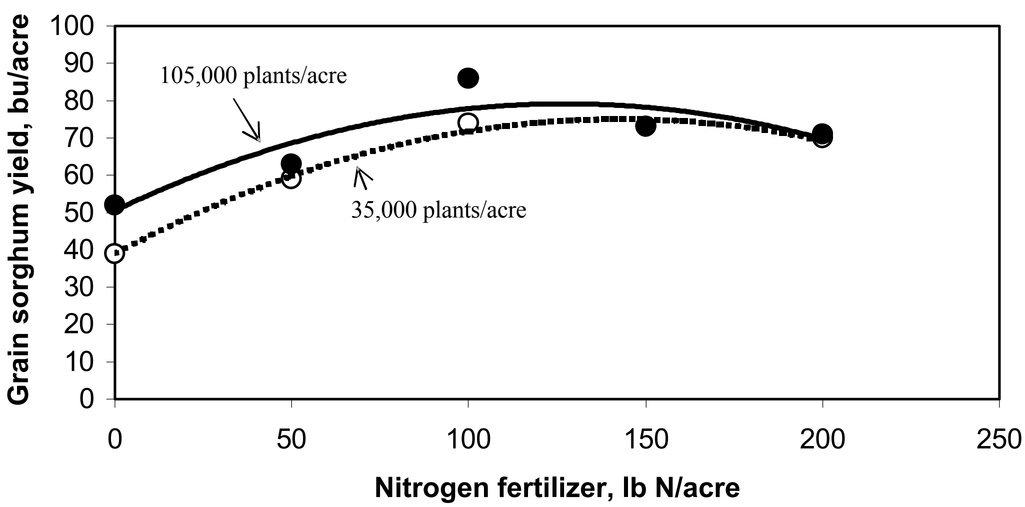

Figure 2. Grain sorghum yields on Sharkey clay soil following cotton as affected by nitrogen fertilizer rate and grain sorghum plant population in 2002.

Table 1. Effect of length and number of skips in grain sorghum rows on head size and yield response to nitrogen fertilizer in 2002.

Plants per acre	Length of skip (feet)	# skips in 50 foot plot row	lb N/a	Fresh wt. per head (grams)	Yield, bu/Acre
105,000	0	0	45	66	101
98,700	3	1	45	68	106
92,400	3	2	45	67	103
86,100	3	3	45	66	102
92,400	6	1	45	67	104
79,800	6	2	45	68	100
67,200	6	3	45	71	81
86,100	9	1	45	66	86
67,200	9	2	45	61	82
48,300	9	3	45	69	79
105,000	0	0	90	70	104
98,700	3	1	90	68	83
92,400	3	2	90	74	108
86,100	3	3	90	71	105
92,400	6	1	90	66	109
79,800	6	2	90	68	93
67,200	6	3	90	68	87
86,100	9	1	90	69	103
67,200	9	2	90	66	83
48,300	9	3	90	65	80
105,000	0	0	135	72	110
98,700	3	1	135	69	101
92,400	3	2	135	65	108
86,100	3	3	135	74	93
92,400	6	1	135	64	106
79,800	6	2	135	68	100
67,200	6	3	135	70	96
86,100	9	1	135	65	96
67,200	9	2	135	76	92
48,300	9	3	135	72	82

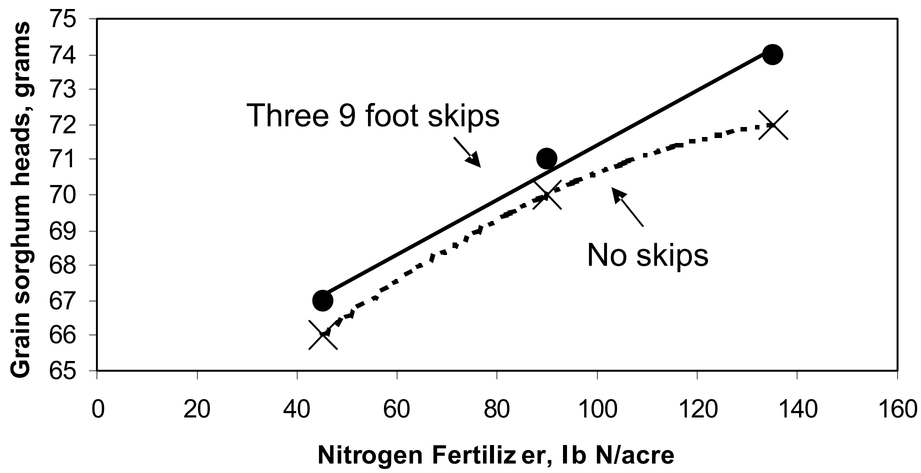

Figure 3. Fresh weights of grain sorghum heads as affected by nitrogen rate and three 9-foot skips in the 50-foot plot rows.

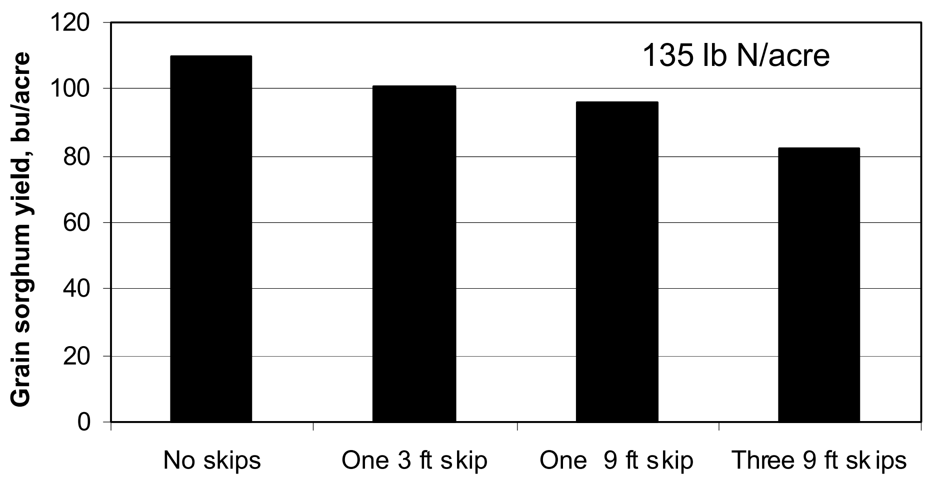

Figure 4. Grain sorghum yields with varying lengths and number of row skips per 50 feet.

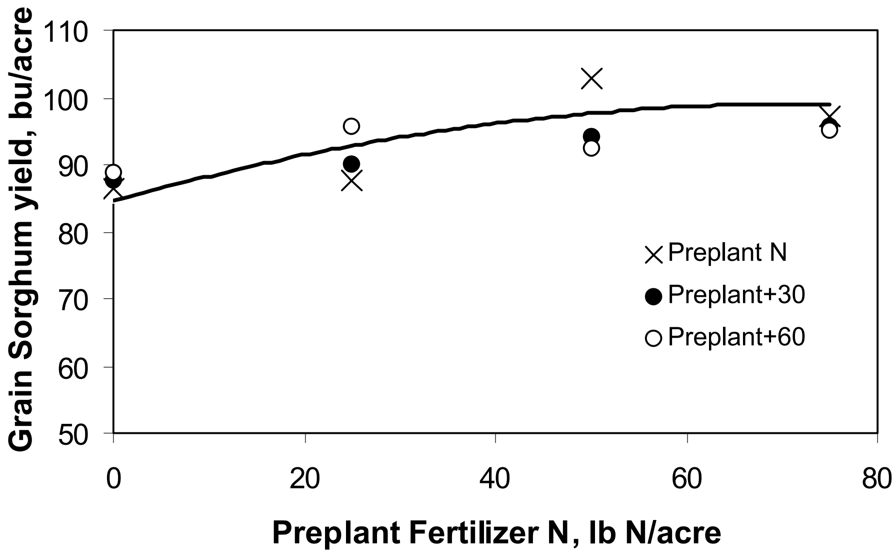

Figure 5. Grain sorghum yields with preplant N only and preplant plus 30 and 60 lb N per acre fertigations through a sprinkler irrigation system.

Objectives for Third Year (2003): We will continue with the original objectives as shown on the first page.

Budget for 2003: We are requesting the amount submitted in the original budget for 2003 ($8,657).

Potassium Management

RESPONSE OF MODERN COTTON VARIETIES TO MID-SEASON POTASSIUM FERTILIZATION

Bobby Phipps, Gene Stevens, David Dunn, and Andrea Phillips
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Abstract

Six potassium treatment combinations were evaluated. Treatments were twenty-five pounds of K applied preplant and a control. Foliar application of five pounds K at first square, five pounds K at first square + seven days, and no foliar K were evaluated in both combinations of preplant fertilizer. The results supported the soil test recommendation of twenty-five pounds of potassium per acre. The data did not support the foliar application of potassium. The varieties responded as expected.

Introduction

Cotton is an important crop in Southeast Missouri and the relatively short growing season encourages producers to plant cotton varieties that mature quickly. These varieties achieve maximum yields by setting relatively greater number of bolls in a shorter time. This increased boll load per day requires that nutrients be available to the plant in greater rates per day. Potassium is an essential nutrient for cotton production because it is involved in maintaining plant water status, cell turgor pressure, and controlling the opening and closing of stomata. The opening of the stomata controls the availability of CO_2 and potassium has an indirect control over photosynthetic activity. Potassium is also involved in cellulose synthesis. Eighty-five percent of K movement in the soil is by diffusion. Since diffusion is a relatively slow process, K fertilization is required to maintain high levels of exchangeable K. Rapid plant growth and uptake may deplete K around the root surfaces. During peak flowering a cotton crop may require 3 to 4 lbs. of K per day and this may be larger than Southeast Missouri soils are capable of supplying.

Methods and Materials

A two-year cotton study was conducted on a field at the University of Missouri-Delta Center Lee Farm (36^{o}N, 89^{o}W) in Pemiscot County, Missouri in 2001and 2002. The eight varieties of cotton were planted on a Tiptonville silt loam soil in May of each year. Soil samples of the study area were collected from the 0 to 15-cm depth before planting. Each year the soil test recommendation for K for this area was for a maintenance fertilization of 25 lbs./a of K_2O. Forty-two lbs./acre of KCl was applied in April each year to plots scheduled for pre-plant K. The nitrogen recommendation was 100 lbs. N/a. Urea-Ammonium nitrate 32% liquid fertilizer was applied in a ¼ at planting and the remainder applied at first-square. Other than potassium fertilization the standard practices for cultivating dry- land_cotton in Southeast Missouri were employed.

The experimental design was a split plot with potassium treatment as main plot with variety as the sub-plot. The main plot K treatments are listed in table 1. These applications were made using a Schwiess 4 row self-propelled high clearance sprayer on July 20 And July 31, 2001. The cotton varieties were STV 373, DP 1218BR, FM 958, FM 819, DP 436RR, PSC 355, STV 474, and BXN 47.

Plant height was measured three times during the growing season, in mid July and mid August. Cotton petiole samples were collected from the fourth fully expanded leaf down. These samples were collected following each potassium application. The petioles were dried, ground, digested using H_2SO_4 and H_2O_2, and analyzed by atomic absorption.

In early October of each year the two middle rows of each strip were mechanically harvested and the seed cotton weighed and recorded. The seed cotton was ginned using a 20-saw Continental gin stand preceded by an inclined cleaner and feeder extractor. The gin stand was followed by one stage of lint cleaning. Lint samples from each plot were sent to the International Textile Research Center for fiber quality analysis using a high volume instrument.

Statistical analyses of the data were preformed with SAS 6.1.2 (1990) using General Linear Modeling procedures. Fisher's Protected Least Significant Difference (LSD) was calculated at the 0.05 probability level for making treatment mean comparisons.

Results and Discussion-2001

For both years significant differences were found among the eight varieties. Plant height was as expected with STV 474 and BXN47 being the taller varieties and the later maturing. As expected DP436RR was the shortest and cutout first as shown by the reduced number of nodes per white flower. Closely related lines of STV 373, STV474 and BXN47 all had large numbers of bolls. STV474 had a high yield while BXN, the Buctril resistant version of STV474 yielded 109 pounds less for the two-year average. The micronaire of DP1218BR and PSC355 was high as expected. However STV474 would be expected to be even higher. FM958 produced very long fiber length of 1.161 which was to be expected. The high strength of FM958 and FM819 was high as expected. All of the varieties had excellent fiber strength. As expected varieties with reduced fiber strength had improved elongation. In 2001 trash content was high in FM958 as expected since it is an okra leaf variety. PSC355 had higher trash content than expected even though it is pubescent. For 2002 trash content of FM819 was the greatest. The difference in petiole potassium was very different in STV474 and BXN47 for 2001. In 2002 this difference was not as great. STV474 is the recurrent parent of BXN47. These two lines are very similar other than the engineered gene.

In 2001 no significant differences were found among the treatments for yields or fiber properties. The plant height was increased by the twenty-five pound application of potassium before planting. The later applications of potassium produced erratic results. Maturity was delayed by the application of potassium before planting as shown in the reduced nodes above white flower. Foliar applications gave inconsistent results. The petiole potassium was increased with the pre-plant application of potassium. Boll number and gin turnout were not significantly influenced by the fertilization. Lint yields were not significantly different but were numerically improved with the addition of pre-plant potassium. Lint yields were very high, especially considering the field had not been irrigated. No significant differences were found for any of the fiber properties, however trash appeared to be increased slightly with the pre-plant application. This would be expected with the delayed maturity.

In 2002 there were significant differences found among the treatments for yield and all fiber properties. There was also a significant interaction between treatment and variety for yield and fiber properties in 2002. Plant height at peak-bloom was not affected by K treatment. At cut out however, the treatment of 25 lbs K pre-plant + two midseason K foliar sprays produced significantly shorter plants than the other treatments. The petiole potassium was significantly increased with the pre-plant application of potassium. Potassium levels for the second sampling date closely track the total K application rates. Boll numbers at harvest were not significantly affected by K treatments in 2002. Lint yields were high considering that the plots were not irrigated in
.
2002, and that this area had been in continuous cotton cultivation for at least 45 years. Significant differences between lint yields were observed among K treatments in 2002 (LSD = 43). These yields were erratic among the treatments however. The numerically highest yield were for the 0 lbs K pre-plant + two foliar K sprays (1044 lbs/a). The 25 lbs K pre-plant + two foliar K sprays was lowest yielding treatment (996 lbs/a). Gin turn out was not effected by K treatment. Micronaire was affected by K treatment generally increasing as applied K increased. A significant difference was observed with the application of pre-plant K. Average micronaire levels were equivalent for all foliar K treatments that received the same pre-plant K. Micronaire levels were significantly greater for treatments receiving 25 lbs/acre pre-plant K. This indicates a delay in maturity with increasing K rates. Staple length was significantly shorter for the 25 lbs K pre-plant + two midseason K foliar sprays treatment. This combined with the high average microaire levels for this treatment could be evidence of water stress. Fiber strength was generally decreased by K applications. The strongest fibers were from the untreated check (32.23) while the weakest were from the 25 lbs K + one foliar spray treatment (31.53). Differences in elongation results while significantly different from one another were eratic in terms of K treatment. Trash content was increased with increasing K rate. As with micronaire a significant difference was observed with the application of pre-plant K. Average trash contents were generally equivalent for all foliar K treatments that received the same pre-plant K. Trash content was significantly greater for treatments receiving 25 lbs/acre pre-plant K. This also indicates a delay in maturity with increasing K rates. The differences found in fiber properties were not great enough to affect returns to producers in 2002.

Table 1. Potassium treatments and application dates for 2001.

Treatment #	Pre-plant K	Peak bloom K	Peak bloom K
1	0	0	0
2	0	5	0
3	0	5	5
4	25	0	0
5	25	5	0
6	25	5	5

Table 2. Average plant growth parameters as effected by K treatments averaged across all varieties.

Treatment #	Plant Height (peak bloom)			Plant Height (cut out)		
	2001	2002	2-year average	2001	2002	2-year average
1	20.2	24.5	22.3	30.4	33.6	33
2	19.8	24.4	22.1	28.8	33.8	31.3
3	20.6	24.5	22.5	29.1	34.3	31.7
4	20.6	25.1	22.9	30.1	34.3	32.2
5	22.0	25.1	23.5	31.1	34.2	22.7
6	21.7	25.1	23.4	29.8	32.3	31
LSD=0.05	1.2	NS		1.5	1.1	

Table 3. Average plant growth parameters as effected by varieties averaged across all K treatments.

Variety	Plant height (peak bloom)			Plant height (cut out)		
	2001	2002	2-year average	2001	2002	2-year average
STV 373	21.0	26.0	23.5	30.9	34.3	32.6
DP 1218BR	22.0	26.8	24.4	31.5	35.3	33.4
FM 958	19.2	22.1	21.7	27.2	32.	29.6
FM 819	21.0	24.1	22.5	29.6	31.5	30.6
DP 436RR	19.6	22.9	22.2	26.9	31.6	29.2
PSC 355	20.4	26.2	23.3	29.1	35.4	32.2
STV 474	21.0	24.8	22.9	31.6	34.9	33.2
BXN 47	22.2	25.3	23.7	32.5	35.0	33.7
LSD=0.05	1.3	1.1		1.7	1.3	

Table 4. Average petiole K % as effected by K treatments averaged across all varieties.

Treatment #	Petiole K% (peak bloom)			Petiole K% (peak bloom + 10 days)		
	2001	2002	2-year average	2001	2002	2-year average
1	4.94	5.51	5.23	4.89	1.50	3.20
2	4.79	5.50	5.15	4.97	1.81	3.39
3	4.79	5.80	5.30	5.41	2.07	3.74
4	5.04	7.76	6.40	6.01	2.05	4.03
5	5.23	5.45	5.34	5.19	2.30	3.75
6	5.23	6.23	5.73	4.99	2.35	3.67
LSD=0.05	0.44	0.56		NS	0.24	

Table 5. Average petiole K % as effected by varieties averaged across all K treatments.

Variety	Petiole K% (peak bloom)			Petiole K% (peak bloom + 10 days)		
	2001	2002	2-year average	2001	2002	2-year average
STV 373	5.38	6.21	5.79	5.46	2.30	3.88
DP 1218BR	4.57	5.31	4.94	4.70	1.86	3.28
FM 958	4.73	5.66	5.20	5.37	1.91	3.64
FM 819	5.81	5.61	5.71	5.08	2.03	3.55
DP 436RR	4.56	5.59	5.08	6.15	1.88	4.02
PSC 355	4.24	5.34	4.79	4.32	1.93	3.13
STV 474	5.52	6.07	5.79	5.64	2.12	3.88
BXN 47	4.16	5.87	5.02	5.27	2.10	3.64
LSD=0.05	0.51	0.65		NS	0.28	

Table 6. Average cotton lint yield parameters as effected by K treatments averaged across all varieties.

Treatment #	Boll #			Seed Cotton Weight			Lint Yields lbs/acre			Gin turnout		
	2001	2002	2-year average	2001	2002	2-year average	2001	2002	2-year average	2001	2002	2-year average
1	7.52	8.85	8.16	11.40	12.28	11.84	1018	1005	1012	.401	.37	.38
2	8.39	9.40	8.90	10.99	12.40	11.69	982	1015	999	.401	.37	.38
3	7.99	9.10	8.54	11.15	12.66	11.91	1006	1044	1025	.406	.37	.39
4	8.84	9.05	8.94	11.34	12.62	11.98	1022	1034	1028	.404	.37	.38
5	7.72	8.85	8.29	11.70	12.22	11.96	1043	1009	1026	.400	.37	.38
6	8.69	8.54	8.61	11.43	12.17	11.80	1023	996	1009	.402	.37	.38
LSD=0.05	NS	NS		NS	0.51		NS	43		NS	NS	

Table 7. Average cotton lint yield parameters as effected by varieties averaged across all K treatments.

Variety	Boll #			Seed Cotton Weight			Lint Yields lbs/acre			Gin turnout		
	2001	2002	2-year average	2001	2002	2-year average	2001	2002	2-year average	2001	2002	2-year average
STV 373	9.38	9.20	9.29	10.72	11.95	11.34	977	996	987	.409	.38	.40
DP 1218BR	7.93	9.35	8.64	11.61	11.67	11.64	1070	968	1019	.413	.37	.39
FM 958	7.02	7.95	7.49	11.41	13.42	12.42	1015	1015	1015	.400	.37	.38
FM 819	6.60	8.50	7.55	11.16	11.28	11.22	990	990	990	.398	.37	.38
DP 436RR	7.76	8.75	8.25	11.52	12.73	12.13	976	975	976	.380	.34	.36
PSC 355	8.66	8.25	8.45	11.64	13.24	12.44	1010	1074	1042	.390	.36	.38
STV 474	9.38	9.55	9.47	11.62	13.11	12.37	1083	1109	1096	.418	.38	.40
BXN 47	8.82	10.56	9.69	11.00	11.58	11.29	1005	969	987	.410	.37	.39
LSD=0.05	1.33	1.16		0.64	0.61		64	49		0.01	0.01	

Table 8a. Average fiber quality parameters as affected by K treatments averaged across all varieties.

Treatment #	Micronaire			Length			Strength		
	2001	2002	2-year Average	2001	2002	2-year Average	2001	2002	2-year Average
1	4.78	4.46	4.62	1.143	1.139	1.141	31.39	32.23	31.81
2	4.79	4.49	4.64	1.145	1.138	1.142	31.62	31.86	3.174
3	4.82	4.46	4.64	1.142	1.143	1.143	31.39	32.19	31.79
4	4.81	4.56	4.68	1.140	1.141	1.140	31.42	31.88	31.6
5	4.82	4.57	4.64	1.148	1.144	1.146	31.33	31.53	31.43
6	4.79	4.61	4.70	1.145	1.129	1.136	31.50	31.98	31.74
LSD=0.05	NS	0.07		NS	0.008		NS	0.54	

Table 9a. Average fiber quality parameters as affected by varieties averaged across all K treatments.

Variety	Micronaire			Length			Strength		
	2001	2002	2-year Average	2001	2002	2-year Average	2001	2002	2-year Average
STV 373	4.61	4.22	4.42	1.146	1.162	11.54	29.76	30.41	30.09
DP 1218BR	5.12	4.69	4.91	1.100	1.101	11.00	29.70	29.68	29.19
FM 958	4.77	4.53	4.65	1.161	1.162	11.61	33.91	34.94	34.43
FM 819	4.54	4.31	4.42	1.179	1.177	11.78	34.24	34.75	34.59
DP 436RR	4.80	4.52	4.66	1.157	1.146	11.51	30.31	30.60	30.46
PSC 355	4.99	4.94	4.96	1.137	1.121	11.29	32.28	32.62	32.45
STV 474	4.85	4.56	4.70	1.130	1.112	11.22	30.48	30.94	30.71
BXN 47	4.73	4.38	4.55	1.141	1.135	11.38	30.85	31.21	31.03
LSD=0.05	0.07	0.08		0.009	0.009		0.38	0.62	

Table 8b. Average fiber quality parameters as affected by K treatments averaged across all varieties.

Treatment #	Elongation			Uniformity			Trash			+b		
	2001	2002	2-year Average	2001	2002	2-year Average	2001	2002	2-year Average	2001	2002	2-year Average
1	5.73	5.11	5.42	84.03	83.08	83.55	2.2	2.4	2.3	8.31	8.65	8.48
2	5.72	5.13	5.43	83.87	82.79	83.33	2.1	2.4	2.3	8.28	8.84	8.57
3	5.82	5.15	5.48	83.85	82.84	83.34	1.9	2.7	2.3	8.21	8.77	8.49
4	5.74	5.06	5.40	83.87	83.09	83.48	2.2	2.6	2.4	8.22	8.77	8.49
5	5.76	5.12	5.44	84.20	82.97	83.58	2.3	2.5	2.4	8.24	8.86	8.55
6	5.74	5.31	5.53	83.98	83.23	83.61	2.2	2.9	2.6	8.22	8.77	8.49
LSD=0.05	NS	0.13		NS	0.22		NS	0.2		NS	0.16	

Table 9b. Average fiber quality parameters as effected by varieties averaged across all K treatments.

Variety	Elongation			Uniformity			Trash			+b		
	2001	2002	2-year Average	2001	2002	2-year Average	2001	2002	2-year Average	2001	2002	2-year Average
STV 373	5.70	4.98	5.32	83.48	82.64	83.04	2.2	2.4	2.3	8.57	8.98	8.78
DP 1218BR	6.15	5.54	5.85	83.90	82.65	83.28	1.5	2.1	1.8	8.50	9.13	8.82
FM 958	4.40	3.76	4.08	83.93	83.04	83.49	2.0	2.5	2.3	7.89	8.25	8.07
FM 819	4.59	4.24	4.42	84.26	83.20	83.73	2.6	3.2	2.9	7.31	8.04	7.68
DP 436RR	6.35	5.68	6.02	84.27	82.98	83.63	1.7	2.3	2.0	7.94	8.65	8.30
PSC 355	6.90	6.30	6.60	84.70	83.53	83.46	2.8	2.9	2.9	8.36	8.92	8.64
STV 474	6.07	5.46	5.76	83.63	82.92	83.28	2.3	2.4	2.4	8.67	9.21	8.94
BXN 47	5.86	5.19	5.53	83.56	82.95	83.26	2.0	2.7	2.4	8.72	9.15	8.93
LSD=0.05	0.14	0.17		0.36	0.26		0.4	0.3		0.14	0.18	

Conclusions

The data supports the soil test recommendation of twenty-five pounds of potassium per acre to be applied before planting. This is shown by plant height, maturity, petiole potassium, and lint yield. There was little benefit shown with later applications of foliar potassium. The varieties did perform very near to what would be expected from historical data.

Acknowledgement

This research is made possible by a grant from the Missouri Fertilizer and Lime Board

Refining the Soil Test Procedure for Potassium to Improve the K Recommendations for Missouri Soils.

Manjula Nathan , Peter Scharf, Department of Agronomy and Peter Motavalli, Environmental Soil Science Program, University of Missouri

Objectives:

1. To determine the relationship between the ammonium acetate extractable potassium (K) and tetraphenyl boron extraction method in predicting soil K availability for soybean and corn in Missouri soils.

2. To determine the effect of soil moisture content on the two methods of extraction in predicting soil K availability.

3. To examine the relationship between the two different soil K extraction procedures and yield response.

Methodology:

- Soil samples (136) received by the soil testing labs collected through out the state of Missouri as well as samples collected from soil K calibration studies and as well as the K fertilizer management and K fixation studies conducted by the co-investigators were used in the study.
- Soil samples were analyzed for plant available K by the ammonium acetate extractable K
- (routine method used currently by MU soil Testing Lab) and tetraphenyl boron K extraction procedure.
- The effect of soil moisture content on the above extraction procedures on predicting K availability was evaluated by making wet and dry measurements of extractable K by both extraction procedures.
- The effect of alternate wetting and drying on soil test K values using both extraction methods were studied in selected Missouri soils used in K fixation study (conducted by CO-PI and PI.). These soils were treated with 300 lbs of K2O/Ac and incubated at field capacity for five months. Following incubation these soils were subjected to alternate wetting and drying cycles for a period of five weeks. At the end, soil K was measured in check and K treated soils using both extraction procedures.
- The relationship between the two soil test K extraction procedures and yields are plotted with the yield data collected by CO-PI's from the K calibration and K management studies.

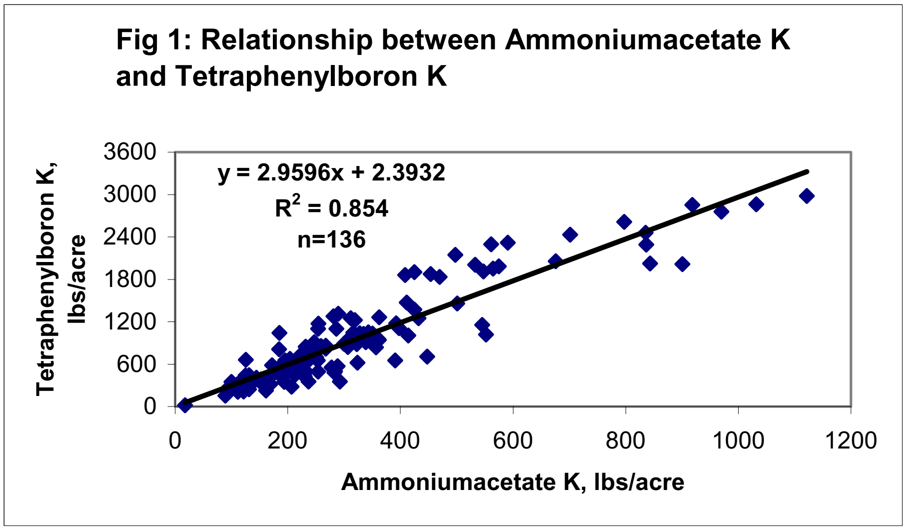


Table 1: Soil moisture effects on extractable soil K by both methods in selected Missouri soils.

Region and Soil Type	NH_4OAc-K* ppm				$NaBPh_4$-K** ppm			
	Wet	Dry	Increase	% incr.	Wet	Dry	Increase	% incr.
Ozarks-Creldon	67	82	14	21	125	137	12	10
Bootheel-Commerce Silty Clay Loam	243	247	5	2	927	1149	223	24
River Bottom-Haynie	408	429	21	5	1343	1572	229	17
Loess and Drift-Higginsville	170	187	17	10	580	648	68	12
Claypan-Mexico 2 Silt Loam	122	138	17	14	311	414	102	33
Claypan-Putnam Pasture	149	165	16	11	288	291	3	1
Bootheel-Sharkey	235	256	21	9	731	984	253	35
Loess and Drift-Grundy1 Silt Loam	199	213	13	7	586	661	75	13
Loess and Drift-Marshall Silt Loam	224	240	16	7	869	1122	253	29
Claypan-Mexico 1 Silt Loam	144	176	32	22	405	593	188	46
Osage-Parsons Silt Loam	115	121	7	6	290	293	3	1
Claypan-Putnam Cropland	507	517	10	2	753	1093	340	45
Means	215	231	16	10	601	746	146	22

* Ammonium acetate K
** Tetraphenylboron K

Table 2: Effect of wetting and drying cycles on extractable soil K by both methods in selected Missouri Soils.

Region and Soil Type	Ammonium acetate K	Tetraphenyl boron K
	Increase in soil test K in lbs/acre	
Ozarks-Creldon	117	250
Bootheel-Commerce Silty Clay Loam	90	154
River Bottom-Haynie	157	353
Loess and Drift-Higginsville	100	241
Claypan-Mexico 2 Silt Loam	71	146
Claypan-Putnam Pasture	103	195
Bootheel-Sharkey	26	143
Loess and Drift-Grundy1 Silt Loam	130	142
Loess and Drift-Marshall Silt Loam	98	70
Claypan-Mexico 1 Silt Loam	129	135
Osage-Parsons Silt Loam	141	160
Claypan-Putnam Cropland	213	184
Means	114	181

Fig. 2: Relationship between the increase in soil test K values for soils applied with 300 K2O lb/acre after incubation and alternate wetting and drying cycles

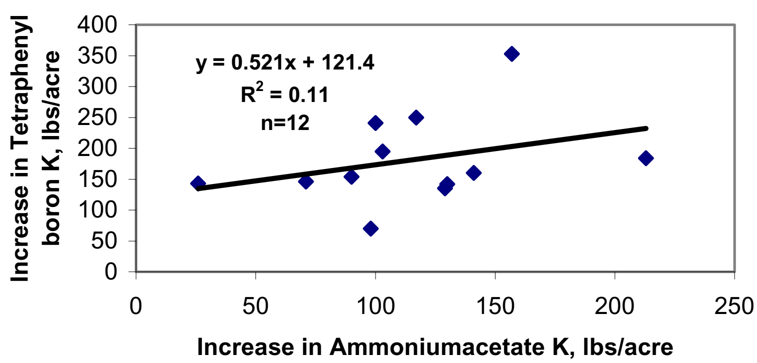


Fig. 3: Relationship between the Ammoniumacetate K and relative soybeans yields at Novelty

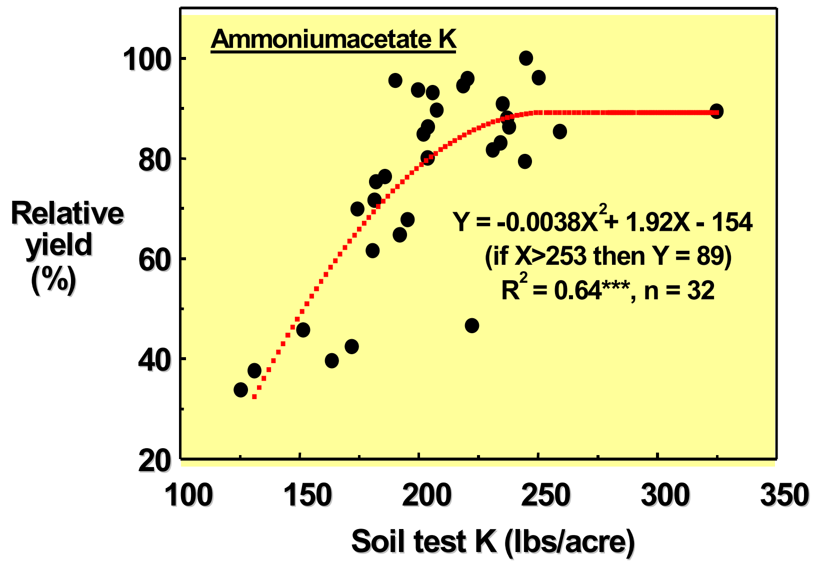
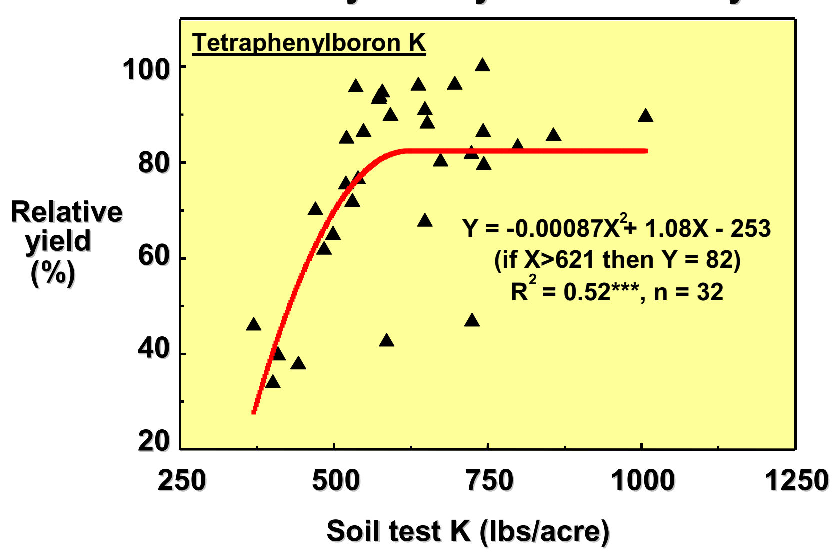


Fig. 4: Relationship between the Tetraphenylboron K and relative soybeans yields at Novelty



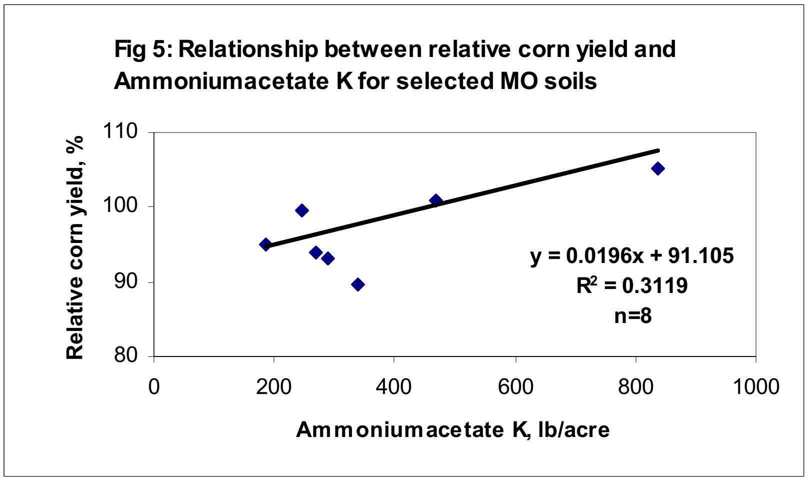


Fig 5: Relationship between relative corn yield and Ammoniumacetate K for selected MO soils
Relative corn yield, %
110
100
90
80
0
200
400
600
800
1000
Ammoniumacetate K, lb/acre
y = 0.0196x + 91.105
R^2 = 0.3119
n=8

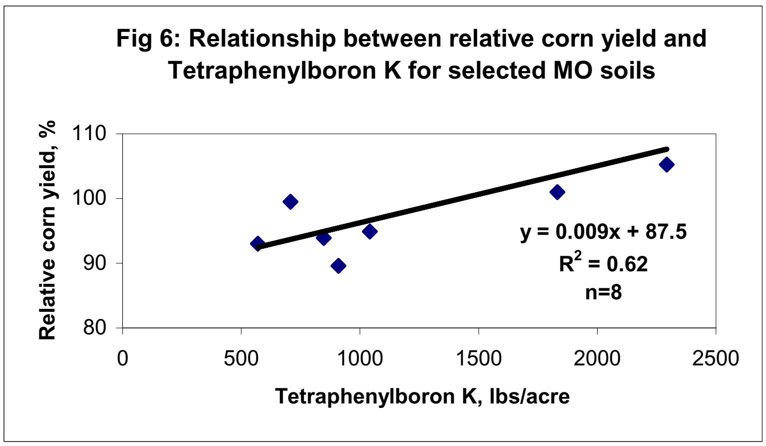


Fig 6: Relationship between relative corn yield and Tetraphenylboron K for selected MO soils
Relative corn yield, %
110
100
90
80
0
500
1000
1500
2000
2500
Tetraphenylboron K, lbs/acre
y = 0.009x + 87.5
R^2 = 0.62
n=8

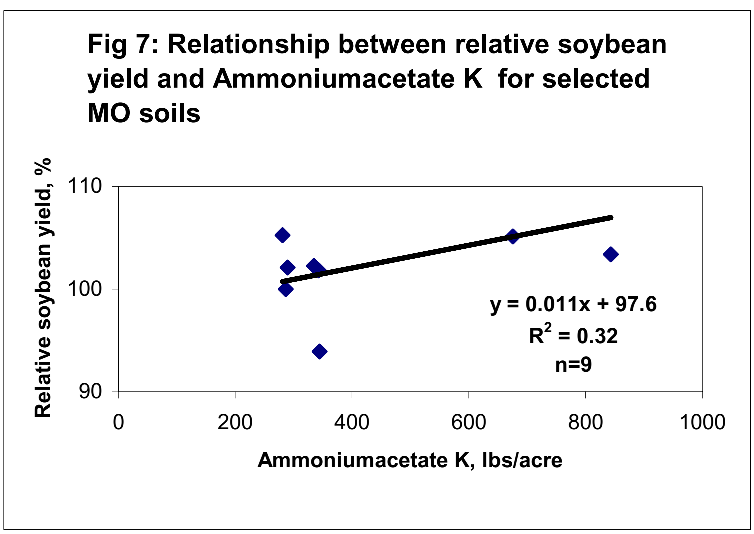
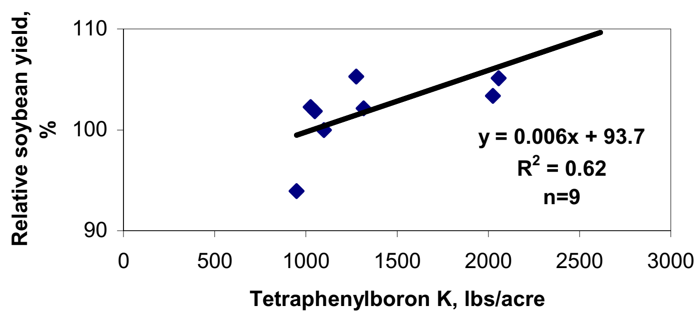


Fig 7: Relationship between relative soybean yield and Ammoniumacetate K for selected MO soils
Relative soybean yield, %
110
100
90
0
200
400
600
800
1000
Ammoniumacetate K, lbs/acre
y = 0.011x + 97.6
R^2 = 0.32
n=9

Fig. 8: Relationship between relative soybean yield and Tetraphenylboron K for selected MO soils



Results:

1. Tetraphenyl boron method extracted more soil test K than the ammonium acetate method in Missouri soils (Fig 1, Table 1).
2. There was a significant correlation between the ammonium acetate extractable K and tetraphenyl boron extractable K ($P >= 0.001$, $R^2=0.85$) for all Missouri soils (Fig 1).
3. Significant correlations were observed between the ammonium acetate extractable K and tetraphenyl boron K at Novelty and for K response study sites selected throughout Missouri (Fig 1).
4. The yield response from sites selected throughout the state of Missouri were better correlated with tetraphenyl boron extractable K than ammonium acetate extractable K (Fig 5, 6, 7, 8) but it was not the case at the Novelty site (Fig 3 and 4).
5. The ammonium acetate extractable K and tetraphenyl boron extractable K values were higher in dried soils than wet soils (Table 1). However, the percentage increase in soil K values was not consistent between these methods for the same soil. Further investigations are necessary to explain this data.
6. There was no consistency in the increase in soil test K values measured by both extraction methods (Table 2 and Fig. 2) in selected Missouri soils treated with 300 lbs of K2O/acre (incubated for a period of five months, followed alternate drying and wetting cycles for five weeks). Thus no conclusions can be drawn on the effect of wetting and drying cycles on extractable K by these two extraction procedures at this time.

Effect of Potassium Fertilization on Leafhopper Tolerance and Persistence of Alfalfa

C. Jerry Nelson (Agronomy), Rob Kallenbach (Agronomy) and Wayne Bailey (Entomology)

Objectives:

1. Determine effect of K-fertilization on leafhopper tolerance.
2. Measure effect of glandular hairs on leafhopper tolerance.
3. Evaluate interaction of K-fertilization and glandular hairs on alfalfa persistence.

Accomplishments for 2002:

We Finally Have an Excellent Stand of Alfalfa!

A 28-acre field of alfalfa was planted in fall 2000 at the Forage Systems Research Center near Linneus in North Central Missouri. The soil on the upper area is a Lagonda silt loam that slopes to an Armstrong silty clay loam. The replicates were arranged to account for slope and soil type. The entire field was limed and P was applied according to soil test recommendations. Within the field, eight blocks (four replicates of two alfalfa varieties) of 2 acres each were planted for the experiment. One variety (normal) did not have glandular hairs whereas the other variety (PLH resistant) had glandular hairs that deter potato leafhoppers (Fig. 1). Sub-plots were 1) no insecticide (control), 2) insecticide applied at economic threshold (IPM standard), and 3) insecticide applied regularly (scheduled spray). Insect treatments were subdivided into K treatments of 0, 100, and 300 lbs/acre, half applied after the first harvest and half applied after the fourth harvest in mid-September. All plots received P (75 lbs/acre) after the fourth harvest.

Our goals were to begin the insect control and K treatments in the spring of 2001, but we had severe winter heaving of the alfalfa that led to the death of 70 to 90 % of the stand, making it unusable for research. We reestablished the site in spring of 2001 using an herbicide to control weeds. We had good emergence, but later the stand was uneven as there was some washing in the plot areas due to heavy rains shortly after seeding that left several rills and potentials for some small gullies. In late spring, 2001 we tilled the area to reduce the potential of alfalfa autotoxicity and reestablished the experiment on September 5, 2001. We focused on locating the experiment on a field area that was less subject to erosion. We also retested the soil fertility level, and topdressed the plot area with 400 lbs of 0-46-0 to increase seedling vigor and the potential for getting good ground cover to enhance survival over winter. In addition, we planted winter wheat at a low rate as a companion crop. The purpose was to utilize the fibrous root system from the wheat to reduce soil erosion and to provide additional canopy cover to aid in reducing the freezing and thawing of the soil which leads to winter heaving.

Figure 1. Electron micrograph of a leafhopper among glandular hairs on an alfalfa leaf. The hairs are multicellular extensions of epidermal cells, and can be upright or flat. The upright hairs are the most effective in conferring resistance. The sticky exudates from the hair ends and the physical structure of the upright hairs are deterrents to egg laying and feeding by the leafhoppers. Some nymphs actually are entrapped by the sticky hairs and cannot move. Photo from Ranger and Hower. 2001. Crop Science 41:1427.

We had good alfalfa emergence and evaluated the stands throughout the fall of 2001 (Fig. 2). The unusually warm weather during October and November was favorable for development of the alfalfa seedlings and their potential to overwinter. The seedlings entered winter with more than six leaves, a stage that allows plants to develop good winter hardiness and a root system that tolerates normal freezing and thawing. We had a good stand in spring 2002, and were able to initiate the experiment with the insect and K treatments beginning with the first harvest (Fig. 3). Since no funds from the Fertilizer and Lime Council were expended during 2001, we requested a no-cost extension as part of the mid-term report in July 2001, and the annual report in January 2002. The extension was granted. Year 1 was 2002. We are now ready to go to Year 2 (2003).

Figure 2. Generalized views of alfalfa seedlings at the experimental plot area in late October 2001 after seeding in early September 2001. Wheat was planted at a low seeding rate to help control erosion and to help reduce winter heaving of the alfalfa. Views are of plot area from the SE (upper left), SW (upper right). NW (lower left) and a close-up (lower right) showing a dime placed among the small, but established alfalfa plants interspersed among the thin stand of wheat plants. The wheat plants helped reduce soil erosion and modulate soil temperature to aid in over wintering of the alfalfa. Photo in lower right is of a thinner spot in the field to show individual plants. The stand averaged more than 19 plants per sq. ft. in June 2002, when counted after undercutting with a sod cutter and counting individual plants.

Figure 3. Plot area in late June 2002, just prior to the second harvest. Note the stand has filled in well. Bare strips in photo on left indicate where sod was cut for plant counts after the first harvest. The right photo shows a corner of a plot of the normal variety with no spray (left of flag) and the PLH-resistant variety with no spray (right of flag). Note color change.

Plant Counts during 2002

The alfalfa stands looked good for both varieties in spring, 2002, when the plant density was counted (Table 1). We placed 0.1 x 0.1m quadrats on the ground and counted the plants within nine quadrats per plot on April 1. The overall density was calculated to be about 15 plants/sq.ft., a density that is quite good for a newly established stand. The K and leafhopper treatments did not begin until after the first harvest so there was no effect on plant density due to K or insect control. We did note, however, that the plant density of the PLH-resistant variety was about 30% lower than the normal variety. The seed of the PLH-resistant variety was coated (adding 30% in weight) so the pure live seed planted per unit of “seed” weight was also lower. One advertised advantage of coating is that germination and seedling survival are improved, so the same seeding rate should give a similar stand. That did not occur here, and the perceived value of the seed coating was not realized. This result should be tested further under Missouri conditions.

Plant density was determined again after the first and fourth harvests. For these plant counts, however, we used a sod cutter to undercut strips from each plot (Fig. 3), after which plants were lifted from the strips and counted (Table 1). The densities after the first harvest were greater than in April suggesting that more plants had emerged, but this was not the case. Earlier we became aware of the difficulty in discerning if a “plant unit” as seen from above ground is, in fact, a single plant or consists of two or more closely spaced plants that form an intermingled crown.

Previous experiments at the Southwest Center had indicated that the above-ground counting method consistently underestimated the correct plant density as often two, three and, in some cases, up to five plants grew very close together to form a plant unit. Recognizing this may be a factor in the evaluation of the effects of K and leafhoppers on plant persistence we compared the plant density data obtained from counting the plant units that were lifted with the sod cutter (from two 1.5 x 3.0 ft. areas per plot) with the total number of plants after separating the plants that make up each unit (Fig. 4). Data indicate the densities are underestimated by counting from above ground, and that the number of plant units consisting of two or more actual plants increases with plant density. This shows the value in the sod cutter methodology for this study.

Table 1. Effects of potato leafhopper control treatments, potassium fertilization rates, and varieties (PLH-resistant vs. normal) on plant density, stem density, stems per plant, and weight per stem on several dates in 2002.

Summary of treatments	Plants on 4-01	Plants on 6-11	Plants on 9-23	Stems on 9-23	Stems/plant on 9-23	Weight/stem on 9-23
	no./sq. ft				no.	g
Insect treatment						
No spray	15.4	20.3	18.9	47.2	2.68	0.44
IPM spray	15.1	18.3	18.6	45.9	2.57	0.43
Scheduled spray	15.6	18.7	17.9	46.9	2.74	0.42
Pr > F*	0.84	0.56	0.66	0.83	0.28	0.74
LSD (0.05)**	NS***	NS	NS	NS	NS	NS
K treatment						
0 lbs/acre	14.7	18.2	17.8	47.9	2.80	0.40
125 lbs/acre	15.0	18.5	18.4	46.8	2.66	0.44
250 lbs/acre	16.4	20.7	19.1	45.3	2.53	0.45
Pr > F	0.20	0.18	0.58	0.36	0.12	0.24
LSD (0.05)	NS	NS	NS	NS	NS	NS
Variety						
PLH resistant	17.9	22.3	21.0	48.6	2.39	0.41
Normal	12.8	15.9	15.9	44.8	2.94	0.45
Pr > F	0.01	0.01	0.01	0.01	0.01	0.20
LSD (0.05)	1.4	2.3	1.8	2.4	0.21	NS

* Probability values at 0.05 or lower indicate means are significantly different
** LSD indicates the difference among means that is needed to be statistically different
*** NS = not significant

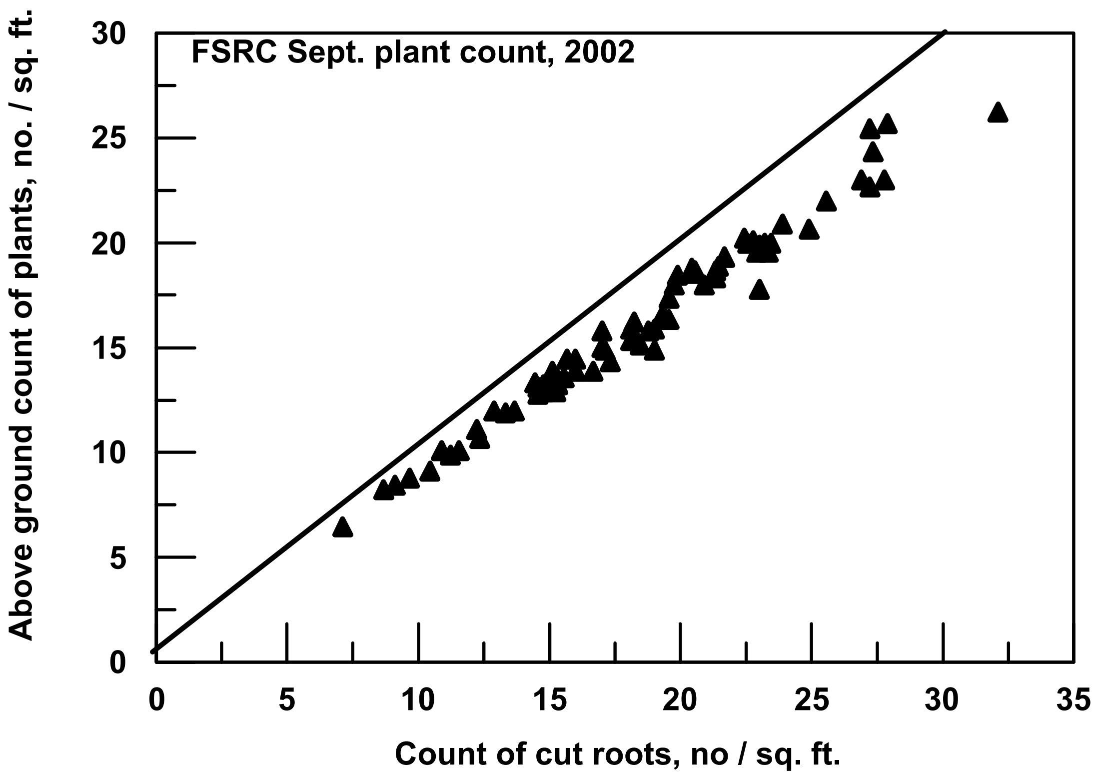


Figure 4. Relationship between number of plant units (some units have more than one plant) counted from above ground compared with number of plants found after sod cutting and separating plants within a unit. The 1:1 ratio (diagonal line) is not followed because only 76% of the plant units counted from above actually consisted of one plant, whereas 19% consisted of two plants, 4% consisted of three plants, and 1% consisted of four plants that were coexisting in close proximity even though they appear as one plant from above.

We are further researching the relationship between above ground counts and those from the sod cutter. We want to learn if single plants within a unit of two or more die one at a time, eventually thinning the "plant unit" to one and finally no plant, or if the multiple plant unit dies as an entity, with the units with higher numbers of plants dying early in the stand life and those with only one surviving the longest. The K and leafhopper study at FSRC alone cannot answer this question, but will be a valuable data set to verify how plant units of various numbers survive.

Similar to the April count, plant densities after the first and fourth harvests did not differ due to the K or leafhopper treatments, but as with the above-ground count, the PLH-resistant variety had about 30% fewer plants than the normal variety. We counted stems per plant allowing us to calculate stems per sq.ft. (Table 1). We calculated the weight (yield) per stem using yield data for the fourth harvest. Despite the 30% lower plant density, by mid-September the crowns of the PLH-resistant variety had expanded to have only 8% fewer stems per sq.ft., mainly because the lower plant density was offset by having 23% more stems per plant. In other studies we found that alfalfa plants in stands with low densities tend to develop larger crowns and support more stems. We expect stems per sq.ft. to stabilize at about 35 for both varieties until plant density is reduced to about four plants per sq.ft., after which the crown spread will not offset the continued plant loss and yield will begin to decrease. K influences the ability of the crown to spread.

We expected little effect on plant density due to K fertilization or leafhopper control this early in the experiment as the young plants are vigorous and are thinning mainly due to plant competition for light. As the stands thin, however, the ability of the crown to spread or compensate becomes compromised due to K deficiency, and detrimental effects from leafhoppers will be more evident.

Alfalfa Yields in 2002

Alfalfa yields were not affected by K fertilization rate in 2002 (Table 2), mainly because only half the K was applied after first harvest, and it did not have a major influence during the lower yielding periods of summer. The rest of the K was applied after the last (fourth) harvest. We expect to see the K response next year as nutrient removal continues to decrease soil K levels. Our earlier research shows that K stimulates crown development, especially over winter.

Table 2. Effects of potato leafhopper control treatments, potassium fertilization rates, and varieties (PLH-resistant vs. normal) on yield of alfalfa at each of four harvests in 2002. Total annual yield is also shown.

Summary of treatments	Yield 1 6-10	Yield 2 7-08	Yield 3 8-09	Yield 4 9-10	Total Yield
			t/a		
Insect treatment					
No spray	2.52	0.77	0.87	0.96	5.12
IPM spray	2.46	0.84	0.84	0.93	5.07
Scheduled spray	2.67	0.79	0.87	0.92	5.24
Pr > F*	0.65	0.29	0.22	0.45	0.81
LSD (0.05)**	NS***	NS	NS	NS	NS
K treatment					
0 lbs/acre	2.55	0.80	0.91	0.91	5.17
125 lbs/acre	2.61	0.80	0.85	0.95	5.21
250 lbs/acre	2.49	0.80	0.82	0.95	5.05
Pr > F	0.56	0.99	0.19	0.64	0.72
LSD (0.05)	NS	NS	NS	NS	NS
Variety					
PLH resistant	2.61	0.83	0.86	0.95	5.25
Normal	2.49	0.77	0.86	0.93	5.04

Pr > F	0.07	0.01	0.77	0.55	0.07
LSD (0.05)	NS	0.05	NS	NS	NS

* Probability values at 0.05 or lower indicate the means are significantly different
** LSD indicates the difference among means that is needed to be statistically different
*** NS = not significant

The leafhopper population was non-existent or low prior to the first harvest. After the first harvest, the population of adults and nymphs increased rapidly (Fig. 5), but in the no-spray treatment (control) the PLH-resistant variety had only 35 to 62% as many leafhoppers as did the normal variety. The glandular hairs of the PLH-resistant variety deter adults and egg laying and interfere with mobility and feeding by the nymphs. Some oscillations occurred in the leafhopper populations, mainly due to weather events. There were few leafhoppers found during regrowth after the third harvest. This is generally the case in Missouri. We counted both the adults and the nymphs (immature, non-mobile stage; Fig. 1), and found most of the changes in population were due to the adult component that consisted of about 84% of the total leafhoppers in the sweeps.

The scheduled spray treatment did an excellent job of leafhopper control (Fig. 5). Leafhopper populations had increased to exceed the IPM threshold only 7 days after the first harvest (small plants have a low threshold), the time of year when there is most leafhopper influx and egg laying. The single insecticide application in the IPM treatment controlled the leafhoppers until the second harvest date. The IPM threshold for the control variety was reached 13 days after the second harvest and was high again at 24 days, but not above the threshold. Therefore, the number of sprays was reduced from four with the scheduled spray to only two when based on IPM.

The K fertilization treatment did not affect leafhopper populations. But the PLH-resistant and the normal variety differed in the no-spray treatment during the second harvest when populations were high. The leafhopper populations developed rapidly shortly after the first harvest and reached the highest levels. Yield of the second harvest was 0.67 tons/acre for the normal variety with no spray compared with 0.88 tons/acre for the PLH-resistant variety with no spray, showing the value of the glandular hairs. In the third harvest the leafhopper population developed slower, did not reach the same level, and did not affect alfalfa yield (both yielded 0.87 tons/acre).

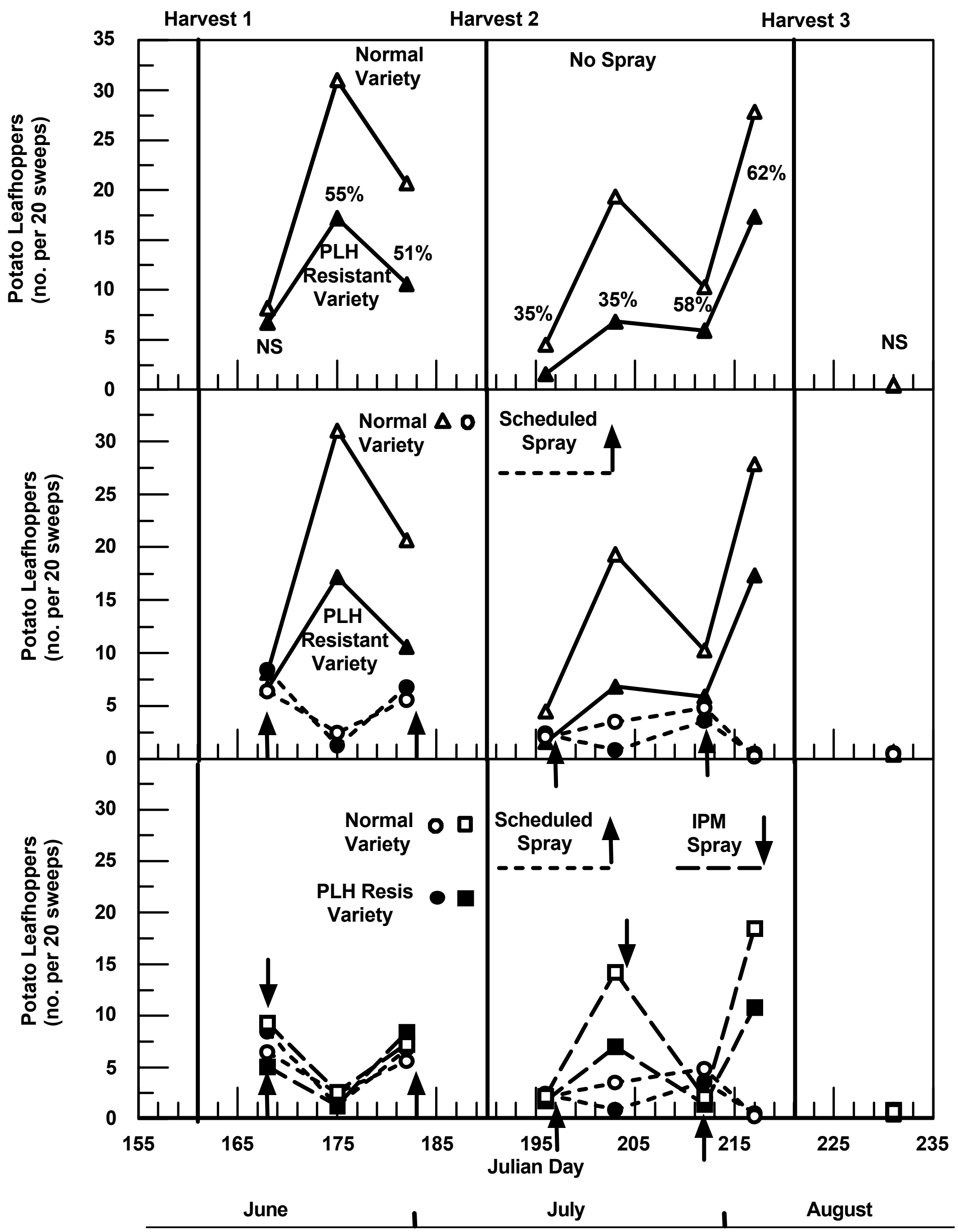


Figure 5. Top panel shows populations of potato leafhopper between harvest dates in the no-spray treatment (control). The top panel also gives the percentage control provided by the PLH-resistant variety compared with the normal variety. Middle panel shows the populations in the no-spray treatment (same as top panel) compared to those in the scheduled spray treatment (arrows pointing up). Note the excellent control. The lower panel shows the populations in the scheduled spray treatment (same as middle panel) compared to the IPM treatment (arrows pointing down). No leafhoppers were found previous to the first harvest and only a few in the early regrowth of the fourth harvest.

Objectives for year 2 (2003):

Our objectives are to continue the experiment as proposed. It is anticipated the K effect will be expressed in 2003 if leafhopper populations are high, so we will monitor alfalfa weevil and especially potato leafhopper throughout the growing season. We will use the sod cutter to help count alfalfa plants in both spring and fall. Forage yield will be measured. Stems per plant will be counted after the first and fourth cuttings to monitor development and spread of the crowns.

For good persistence data we need to maintain the experiment for at least three years (2002, 2003, and 2004). First year funds were used to cover the research costs of the experiment in 2002. Other funds were used in 2001 to reestablish the stands. The year 2003 will be year 2.

Proposed budget for year 2 and 3, (2003 and 2004):

	2002	**2003**	2004	Total
Salaries[1]	$2000	**2000**	2000	$6000
Operating[2]	3000	**3000**	4000	10000
Equipment[3]				0
Other (travel)[4]	1700	**2250**	2250	6750
Total	$6700	**7250**	8250	$22750

[1]Part-time labor ($2,000) for sampling and counting insects at the FSRC. Originally, we were going to count the insects in Columbia, but staff members at FSRC have been trained to do both the sampling and counting of the insects. Staff at FSRC will also help with the harvests and plant counts.

[2]Fertilizer, pesticides, maintenance of spreader, sprayer, and harvester, and general supplies. Rental of sod cutter ($300/year). Standard soil tests will be done on all plots in the fall of 2004 to calculate removal and residual P and K. Includes regular trips by PIs to FSRC to do regular duties of the project.

[3]No special equipment needed.

[4]Travel is to professional meetings ($750 each PI/year). In addition, PIs on the project are associated with two multi-state projects (NC-225, Forage-Beef systems; and NC-226, Alfalfa Persistence) which both have an annual meeting to discuss research findings.

Cotton Response to Midseason Potassium Applications and Bronze Wilt

Bobby Phipps, Gene Stevens, David Dunn, and Allen Wrather
University of Missouri-Delta Center
Portageville, MO

Objectives

(1) Determine effects of foliar midseason potassium (K) applications on lint yields of modern cotton varieties.
(2) Determine effects of midseason potassium applications on incidence and severity of bronze wilt in cotton.

Introduction

Cotton is an important crop in Southeast Missouri and the relatively short growing season encourages producers to plant cotton varieties that mature quickly. These varieties achieve maximum yields by setting relatively greater number of bolls in a shorter time. This increased boll load per day requires that nutrients be available to the plant in greater rates per day. Potassium is an essential nutrient for cotton production because it is involved in maintaining plant water status, cell turgor pressure, and controlling the opening and closing of stomata. The opening of the stomata controls the availability of CO_2 and potassium has an indirect control over photosynthetic activity. Potassium is also involved in cellulose synthesis. Eighty-five percent of K movement in the soil is by diffusion. Since diffusion is a relatively slow process, K fertilization is required to maintain high levels of exchangeable K. Rapid plant growth and uptake may deplete K around the root surfaces. During peak flowering a cotton crop may require 3 to 4 lbs. of K per day and this may be larger than Southeast Missouri soils are capable of supplying.

Cotton bronze wilt was first observed in Missouri, Louisiana, and Mississippi in late July to early August of 1995. No cases were reported in Missouri during 1996, but it did develop in 1998-2000. Leaves, stems, and petioles of affected plants turn red and the plants grow poorly and may produce no bolls. This discoloration is also characteristic of potassium deficiency. Yield losses have been up to 80% in some fields. Research has shown that some cotton varieties are more susceptible to bronze wilt than other varieties. However, no one has been able to identify a pathogen that causes bronze wilt. Field observations at the Delta Center have shown that bronze wilt is sometimes induced by water stress and subsides after irrigation. This suggests that the problem may not be a disease but a gene that is turned on and off by the environment. Because potassium is important in plant water relations, we hypothesize that foliar K applications may help reduce bronze wilt in cotton.

Methods and Materials

A cotton study was conducted on a field at the University of Missouri-Delta Center Lee Farm (36^{o}N, 89^{o}W) in Pemiscot County, Missouri in 2001 and 2002. The eight varieties of cotton were planted on a Tiptonville silt-loam series soil on May 13, 2002. Soil samples of the study area were collected from the 0 to 15-cm depth before planting. The soil test recommendation for K for this area was for a maintenance fertilization of 25 lbs./a of K_2O. Forty-two lbs./acre of KCl was applied on April 23, 2002 to plots scheduled for pre-plant K. The nitrogen recommendation was 100 lbs. N/a. Urea-Ammonium nitrate 32% liquid fertilizer was applied in a ¼ at planting and the remainder applied at first-square (June 18). Other than potassium fertilization the standard practices for cultivating dry land cotton in Southeast Missouri were employed.

The experimental design was a split plot with potassium treatment as main plot with variety as the sub-plot. The main plot K treatments are listed in Table 1. These applications were made using a Schwiess 4 row self-propelled high clearance sprayer on July 20 And July 31, 2002. The cotton varieties were STV 373, DP 1218BR, FM 958, FM 819, DP 436RR, PSC 355, STV 474, and BXN 47.

Table 1. Potassium treatments and application dates for 2002.

Treatment #	Pre-plant K April 23, 2001	Peak bloom K August 1, 2002	Peak bloom +10 K August 13, 2002
1	0	0	0
2	0	5	0
3	0	5	5
4	25	0	0
5	25	5	0
6	25	5	5

Each plot was rated for incidence and severity of bronze wilt four times during the growing season on 7-19, 7-27, 8-3, and 8-17-2002. Plant height was measured three times during the growing season, 7-19, and 8-16-2002. A boll count was conducted on 10-8-2002. Cotton petiole samples were collected from the fourth fully expanded leaf down. These samples were collected following each potassium application. The petioles were dried, ground, digested using H_2SO_4 and H_2O_2, and analyzed by atomic absorption.

On October 24, 2002 the two middle rows of each strip were mechanically harvested and the seed cotton weighed and recorded. The seed cotton was ginned using a 20-saw Continental gin stand preceded by an inclined cleaner and feeder extractor. The gin stand was followed by one stage of lint cleaning. Lint samples from each plot were sent to the International Textile Research Center for fiber quality analysis using a high volume instrument.

Statistical analyses of the data were preformed with SAS (1990) using General Linear Modeling procedures. Fisher's Protected Least Significant Difference (LSD) was calculated at the 0.05 probability level for making treatment mean comparisons.

Project Accomplishments 2002

Data collected during 2001and 2002 is presented as Tables 2-11. In 2002 plant growth measurements were significantly effected by K treatment and cotton variety. Levels of potassium were significantly effected both K treatment and variety for the first sampling date. For the second sampling date levels of tissue K were affected by K treatment but not by variety. Cotton yield and lint quality parameters were significantly affected by cotton variety and K treatment. There was also a variety by treatment interaction for yield and fiber properties in 2002. Yields were erratic among the K treatments. The fiber property micronaire was affected by K treatment generally increasing as applied K increased. This indicates a delay in maturity with increasing K rates. Trash content was increased with increasing K rate. As with micronaire a significant difference was observed with the application of pre-plant K. Average trash contents were generally equivalent for all foliar K treatments that received the same pre-plant K. Trash content was significantly greater for treatments receiving 25 lbs/acre pre-plant K. This also indicates a delay in maturity with increasing K rates. Fiber strength was generally decreased by increasing K rates. Bronze Wilt was not encountered in any plot during 2002.

This data will be presented to cotton producers and researchers as an oral presentation at the 2003 Belt-Wide Cotton Conferences. This conference is being held in Memphis, TN and is attended by over 1,500 participants.

Table 2. Average plant growth parameters as affected by K treatments averaged across all varieties.

Treatment #	Plant Height (peak bloom)			Plant Height (cut out)		
	2001	2002	2-year average	2001	2002	2-year average
1	20.2	24.5	22.3	30.4	33.6	33
2	19.8	24.4	22.1	28.8	33.8	31.3
3	20.6	24.5	22.5	29.1	34.3	31.7
4	20.6	25.1	22.9	30.1	34.3	32.2
5	22.0	25.1	23.5	31.1	34.2	22.7
6	21.7	25.1	23.4	29.8	32.3	31
LSD=0.05	1.2	NS		1.5	1.1	

Table 3. Average plant growth parameters as affected by varieties averaged across all K treatments.

Variety	Plant height (peak bloom)			Plant height (cut out)		
	2001	2002	2-year average	2001	2002	2-year average
STV 373	21.0	26.0	23.5	30.9	34.3	32.6
DP 1218BR	22.0	26.8	24.4	31.5	35.3	33.4
FM 958	19.2	22.1	21.7	27.2	32.	29.6
FM 819	21.0	24.1	22.5	29.6	31.5	30.6
DP 436RR	19.6	22.9	22.2	26.9	31.6	29.2
PSC 355	20.4	26.2	23.3	29.1	35.4	32.2
STV 474	21.0	24.8	22.9	31.6	34.9	33.2
BXN 47	22.2	25.3	23.7	32.5	35.0	33.7
LSD=0.05	1.3	1.1		1.7	1.3	

Table 4. Average petiole K % as affected by K treatments averaged across all varieties.

Treatment #	Petiole K% (peak bloom)			Petiole K% (peak bloom + 10 days)		
	2001	2002	2-year average	2001	2002	2-year average
1	4.94	5.51	5.23	4.89	1.50	3.20
2	4.79	5.50	5.15	4.97	1.81	3.39
3	4.79	5.80	5.30	5.41	2.07	3.74
4	5.04	7.76	6.40	6.01	2.05	4.03
5	5.23	5.45	5.34	5.19	2.30	3.75
6	5.23	6.23	5.73	4.99	2.35	3.67
LSD=0.05	0.44	0.56		NS	0.24	

Table 5. Average petiole K % as affected by varieties averaged across all K treatments.

Variety	Petiole K% (peak bloom)			Petiole K% (peak bloom + 10 days)		
	2001	2002	2-year average	2001	2002	2-year average
STV 373	5.38	6.21	5.79	5.46	2.30	3.88
DP 1218BR	4.57	5.31	4.94	4.70	1.86	3.28
FM 958	4.73	5.66	5.20	5.37	1.91	3.64
FM 819	5.81	5.61	5.71	5.08	2.03	3.55
DP 436RR	4.56	5.59	5.08	6.15	1.88	4.02
PSC 355	4.24	5.34	4.79	4.32	1.93	3.13
STV 474	5.52	6.07	5.79	5.64	2.12	3.88
BXN 47	4.16	5.87	5.02	5.27	2.10	3.64
LSD=0.05	0.51	0.65		NS	0.28	

Table 6. Average cotton lint yield parameters as affected by K treatments averaged across all varieties.

Treatment #	Boll #			Seed Cotton Weight			Lint Yields lbs/acre			Gin turnout		
	2001	2002	2-year average	2001	2002	2-year average	2001	2002	2-year average	2001	2002	2-year average
1	7.52	8.85	8.16	11.40	12.28	11.84	1018	1005	1012	.401	.37	.38
2	8.39	9.40	8.90	10.99	12.40	11.69	982	1015	999	.401	.37	.38
3	7.99	9.10	8.54	11.15	12.66	11.91	1006	1044	1025	.406	.37	.39
4	8.84	9.05	8.94	11.34	12.62	11.98	1022	1034	1028	.404	.37	.38
5	7.72	8.85	8.29	11.70	12.22	11.96	1043	1009	1026	.400	.37	.38
6	8.69	8.54	8.61	11.43	12.17	11.80	1023	996	1009	.402	.37	.38
LSD=0.05	NS	NS		NS	0.51		NS	43		NS	NS	

Table 7. Average cotton lint yield parameters as affected by varieties averaged across all K treatments.

Variety	Boll #			Seed Cotton Weight			Lint Yields lbs/acre			Gin turnout		
	2001	2002	2-year average	2001	2002	2-year average	2001	2002	2-year average	2001	2002	2-year average
STV 373	9.38	9.20	9.29	10.72	11.95	11.34	977	996	987	.409	.38	.40
DP 1218BR	7.93	9.35	8.64	11.61	11.67	11.64	1070	968	1019	.413	.37	.39
FM 958	7.02	7.95	7.49	11.41	13.42	12.42	1015	1015	1015	.400	.37	.38
FM 819	6.60	8.50	7.55	11.16	11.28	11.22	990	990	990	.398	.37	.38
DP 436RR	7.76	8.75	8.25	11.52	12.73	12.13	976	975	976	.380	.34	.36
PSC 355	8.66	8.25	8.45	11.64	13.24	12.44	1010	1074	1042	.390	.36	.38
STV 474	9.38	9.55	9.47	11.62	13.11	12.37	1083	1109	1096	.418	.38	.40
BXN 47	8.82	10.56	9.69	11.00	11.58	11.29	1005	969	987	.410	.37	.39
LSD=0.05	1.33	1.16		0.64	0.61		64	49		0.01	0.01	

Table 8a. Average fiber quality parameters as affected by K treatments averaged across all varieties.

Treatment #	Micronaire			Length			Strength		
	2001	2002	2-year Average	2001	2002	2-year Average	2001	2002	2-year Average
1	4.78	4.46	4.62	1.143	1.139	1.141	31.39	32.23	31.81
2	4.79	4.49	4.64	1.145	1.138	1.142	31.62	31.86	3.174
3	4.82	4.46	4.64	1.142	1.143	1.143	31.39	32.19	31.79
4	4.81	4.56	4.68	1.140	1.141	1.140	31.42	31.88	31.6
5	4.82	4.57	4.64	1.148	1.144	1.146	31.33	31.53	31.43
6	4.79	4.61	4.70	1.145	1.129	1.136	31.50	31.98	31.74
LSD=0.05	NS	0.07		NS	0.008		NS	0.54	

Table 9a. Average fiber quality parameters as affected by varieties averaged across all K treatments.

Variety	Micronaire			Length			Strength		
	2001	2002	2-year Average	2001	2002	2-year Average	2001	2002	2-year Average
STV 373	4.61	4.22	4.42	1.146	1.162	11.54	29.76	30.41	30.09
DP 1218BR	5.12	4.69	4.91	1.100	1.101	11.00	29.70	29.68	29.19
FM 958	4.77	4.53	4.65	1.161	1.162	11.61	33.91	34.94	34.43
FM 819	4.54	4.31	4.42	1.179	1.177	11.78	34.24	34.75	34.59
DP 436RR	4.80	4.52	4.66	1.157	1.146	11.51	30.31	30.60	30.46
PSC 355	4.99	4.94	4.96	1.137	1.121	11.29	32.28	32.62	32.45
STV 474	4.85	4.56	4.70	1.130	1.112	11.22	30.48	30.94	30.71
BXN 47	4.73	4.38	4.55	1.141	1.135	11.38	30.85	31.21	31.03
LSD=0.05	0.07	0.08		0.009	0.009		0.38	0.62	

Table 8b. Average fiber quality parameters as affected by K treatments averaged across all varieties.

Treatment #	Elongation			Uniformity			Trash			+b		
	2001	2002	2-year Average	2001	2002	2-year Average	2001	2002	2-year Average	2001	2002	2-year Average
1	5.73	5.11	5.42	84.03	83.08	83.55	2.2	2.4	2.3	8.31	8.65	8.48
2	5.72	5.13	5.43	83.87	82.79	83.33	2.1	2.4	2.3	8.28	8.84	8.57
3	5.82	5.15	5.48	83.85	82.84	83.34	1.9	2.7	2.3	8.21	8.77	8.49
4	5.74	5.06	5.40	83.87	83.09	83.48	2.2	2.6	2.4	8.22	8.77	8.49
5	5.76	5.12	5.44	84.20	82.97	83.58	2.3	2.5	2.4	8.24	8.86	8.55
6	5.74	5.31	5.53	83.98	83.23	83.61	2.2	2.9	2.6	8.22	8.77	8.49
LSD=0.05	NS	0.13		NS	0.22		NS	0.2		NS	0.16	

Table 9b. Average fiber quality parameters as affected by varieties averaged across all K treatments.

Variety	Elongation			Uniformity			Trash			+b		
	2001	2002	2-year Average	2001	2002	2-year Average	2001	2002	2-year Average	2001	2002	2-year Average
STV 373	5.70	4.98	5.32	83.48	82.64	83.04	2.2	2.4	2.3	8.57	8.98	8.78
DP 1218BR	6.15	5.54	5.85	83.90	82.65	83.28	1.5	2.1	1.8	8.50	9.13	8.82
FM 958	4.40	3.76	4.08	83.93	83.04	83.49	2.0	2.5	2.3	7.89	8.25	8.07
FM 819	4.59	4.24	4.42	84.26	83.20	83.73	2.6	3.2	2.9	7.31	8.04	7.68
DP 436RR	6.35	5.68	6.02	84.27	82.98	83.63	1.7	2.3	2.0	7.94	8.65	8.30
PSC 355	6.90	6.30	6.60	84.70	83.53	83.46	2.8	2.9	2.9	8.36	8.92	8.64
STV 474	6.07	5.46	5.76	83.63	82.92	83.28	2.3	2.4	2.4	8.67	9.21	8.94
BXN 47	5.86	5.19	5.53	83.56	82.95	83.26	2.0	2.7	2.4	8.72	9.15	8.93
LSD=0.05	0.14	0.17		0.36	0.26		0.4	0.3		0.14	0.18	

Table 10. Average incidence and severity of Bronze Wilt as affected by K treatments averaged across all varieties.

Treatment #	Bronze Wilt rating 7-19-2002	Bronze Wilt rating 7-27-2002	Bronze Wilt rating 8-3-2002	Bronze Wilt rating 8-17-2002
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
LSD=0.05	NS	NS	NS	NS

Table 11. Average incidence and severity of Bronze Wilt as affected by K treatments averaged across all K treatments.

Variety	Bronze Wilt rating 7-19-2002	Bronze Wilt rating 7-27-2002	Bronze Wilt rating 8-3-2002	Bronze Wilt rating 8-17-2002
STV 373	0	0	0	0
DP 1218BR	0	0	0	0
FM 958	0	0	0	0
FM 819	0	0	0	0
DP 436RR	0	0	0	0
PSC 355	0	0	0	0
STV 474	0	0	0	0
BXN 47	0	0	0	0
LSD=0.05	NS	NS	NS	NS

Budget for 2003

Expenses	Year		
	2001	2002	**2003**
Res. Specialist salary (0.25)	6,750	6,953	**7,162**
Fringe benefits	1,688	1,739	**1,791**
Student Labor (.125)	2,000	2,060	**2,122**
Fringe benefits	160	165	**170**
Supplies	2,000	2,060	**2,122**
Plant and soil analysis	2,600	2,678	**2,758**
Travel	1,200	1,236	**1,273**
Total	$16,398	$16,891	**$17,398**

Multiple Nutrient Studies

Refining Soil Test Recommendations for Corn

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Objectives:

1. Test the performance of current University of Missouri soil test recommendations for predicting corn response to P and K in a statewide network of experiments.
2. Explore the possibility that subsoil test values, soil type, or soil region could be used to improve our fertilizer recommendations and make them more site-specific.
3. Evaluate corn response to S, Zn, and B in Missouri, and evaluate factors (including soil test values) that might help predict where responses to these nutrients are likely.

Methods:

- Experiments were carried out alongside an existing statewide network of corn hybrid performance trials conducted by the University of Missouri in 2001 and again in 2002. Variety testing personnel planted and harvested the experiments, as well as controlling weeds.
- Thirteen experiments were conducted in 2001 and twelve in 2002, however two experiments were not harvested each year due to problems including Roundup drift, missed N applications due to miscommunication, and stand problems. Over the two-year period a total of 21 experiments were conducted, harvested, and analyzed. Experiments were distributed across the corn-growing areas of Missouri (Figure 1).
- Fields used in 2002 were different than fields used in 2001, though mostly on the same farms.
- P, K, S, Zn, and B fertilizers were hand-applied to separate plots at rates of 100 lb P_2O_5, 100 lb K_2O, 20 lb S, 10 lb Zn, and 1 lb B/acre. These rates should be high enough to produce full yield response.
- Two unfertilized check plots were used in each replication.
- Five replications were used.
- Soil samples were taken at depths of 0 to 6, 6 to 12, 12 to 24, and 24 to 36 inches in each experiment and analyzed for pH, P, K, S, Zn, and B.
- One well-adapted hybrid was used at each location (Tables 1 and 2).
- Due to promising results with zinc in the 2001 experiments, zinc treatments were also added to 13 fall N experiments around Missouri in 2002. Zinc treatments were hand-applied, and these plots were hand-harvested and shelled.

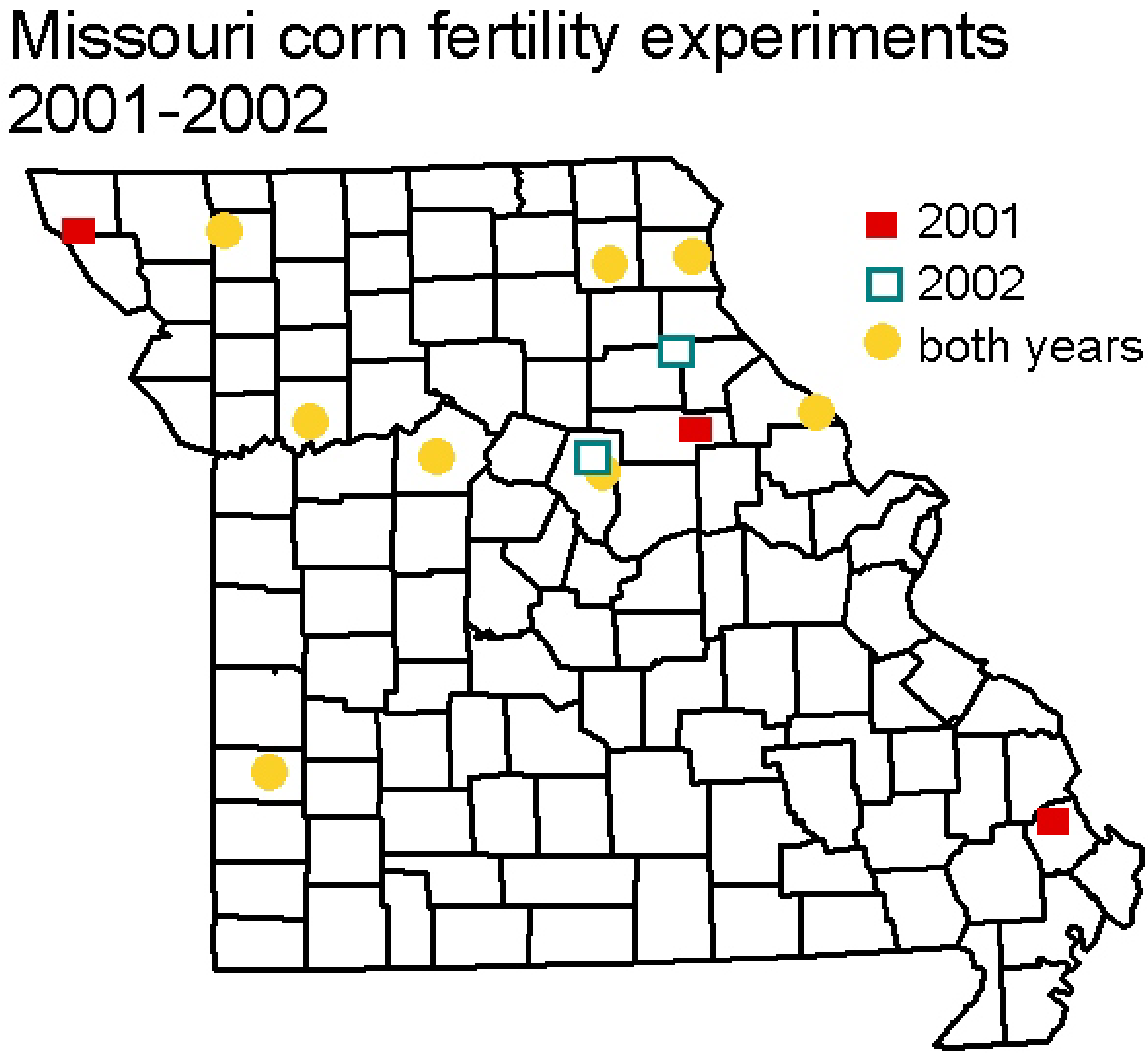

Figure 1. Locations of corn fertility experiments in 2001 and 2002. Only experiments that were harvested and analyzed are shown.

Table 1. 2001 EXPERIMENTAL LOCATIONS FOR CORN FERTILITY TRIALS

LOCATION	COUNTY	SOIL SERIES	HYBRID
Osborn	DeKalb	Grundy Silt Loam	Pioneer 33P67
Novelty	Knox	Putnam Silt Loam	Burrus 56
Annada	Pike	Tice Silt Loam	Novartis N7070
Truxton	Montgomery	Mexico Silt Loam	Mycogen 2833
Marshall	Saline	Joy Silt Loam	Mycogen 2833
Henrietta	Ray	Aholt Clay	Golden Harvest 9533B
Laddonia	Audrain	Putnam Silt Loam	Mycogen 2833
Oran	Scott	Commerce Silty Clay Loam	Mycogen 7821 BT
Lamar	Barton	Barden Silt Loam	Mycogen 7821 BT
Corning	Atchison	Salix Silty Clay Loam	
Albany	Gentry	Grundy Silt Loam	NK N67-H17
La Grange	Lewis	Westerville Silt Loam	Golden Harvest 922
Columbia	Boone	Mexico Silt Loam	Novartis 67-T4

Table 2. 2002 EXPERIMENTAL LOCATIONS FOR CORN FERTILITY TRIALS

LOCATION	COUNTY	SOIL SERIES	HYBRID
Novelty	Knox	Kilwinning Silt Loam	Asgrow 730YG
Annada	Pike	Tice Silt Loam	Mycogen 2833
Truxton	Montgomery	Mexico Silt Loam	Asgrow 730YG
Marshall	Saline	Joy Silt Loam	Pioneer 33P67
Henrietta	Ray	Haynie Silt Loam	Asgrow 730YG
Lamar	Barton	Parsons Silt Loam	Dekalb 65-26
Albany	Gentry	Grundy Silt Loam	Asgrow 730YG
La Grange	Lewis	Westerville Silt Loam	Mycogen 2833
Coumbia 1*	Boone	Mexico Silt Loam	Dekalb 65-26
Columbia 2	Boone	Mexico Silt Loam	Dekalb 65-26

*Columbia 1 is non-irrigated, Columbia 2 is irrigated.

Results:

- Average yield across all locations was 179 bu/acre in 2001, 147 bu/acre in 2002. Drought stress limited yields at several locations in 2002. Overall, yield levels were representative of good production practices and conditions for Missouri.
- Soil test levels were also representative of good production practices.
  - Soil test P was medium in 7 fields and high in 14 fields according to MU soil test interpretations (of the 21 experiments harvested).
  - Soil test K was low in 1 field, medium in 10 fields, and high in 10 fields.
  - The target soil test level for MU fertilizer recommendations is at the border between medium and high, so equal numbers of fields testing medium and high is considered ideal.
- Only one of eleven locations harvested in 2001 had statistically significant (90% confidence) yield response to fertilizer treatments (Table 3). This was at the Pike County site, where responses to both potassium (16 bu/acre) and boron (15 bu/acre) were observed. Soybean yield also responded to boron in a nearby field. Soil test potassium was medium at this location, and soil test boron was higher than at most other locations. Interpretations are not well-established for the boron soil test and it is generally not considered very reliable.
- Three of 10 locations harvested in 2002 had statistically significant (90% confidence) yield response to fertilizer treatments (Table 4), including responses to K, S, and B.
- All results that follow come from analyzing 19 experiments together. The Columbia 2001 and Henrietta 2002 experiments were excluded from these analyses because yield variability was extremely high.

<u>Response to P</u>

- Averaged over all 19 locations, there was no yield response to P.

- No statistically significant responses (90% confidence) to P were seen at any of the individual locations. However, there was a 9 bu/acre response to P at Columbia (dryland) in 2002 with 83% confidence (Table 4).
- Soil test P was not a significant predictor of the yield difference between check plots and P-fertilized plots.
  - Two-thirds of the experimental locations tested high for P according to University of Missouri soil test interpretations. If the interpretations are correct, we would expect no response to P at these locations, and possibly one or two responses to P in the locations that tested medium.
  - This definitely shows that current University of Missouri recommendations for P are high enough to support good corn yields.
  - We did not find any regions of the state or soil types where P recommendations might need to be higher.
  - These experiments can’t answer the question of whether current University of Missouri recommendations for P are higher than is economically optimum for corn production.

Table 3. Yields From Corn Fertilizer Trials 2001

LOCATION	COUNTY	YIELD WITH FERTILIZER TREATMENT:					
		UNFERTILIZED CHECK	P	K	S	ZN	B
Albany	Gentry	82	87	73	77	88	82
Annada	Pike	181	184	197*	182	188	196*
Columbia	Boone	146	135	154	139	123	121
Corning	Atchison/Holt	125	116	124	114	127	130
Henrietta	Ray	210	204	210	212	221	220
Laddonia	Audrain	238	246	236	227	227	225
LaGrange	Lewis	177	177	183	180	177	179
Lamar	Barton	189	175	172	194	193	172
Marshall	Saline	190	189	193	196	205	193
Novelty	Knox	176	183	177	175	178	171
Oran	Scott	265	258	246	239	261	255

*This yield is greater than the yield of the unfertilized check with greater than 95% confidence.

Table 4. Yields From Corn Fertilizer Trials 2002

LOCATION	COUNTY	YIELD WITH FERTILIZER TREATMENT:					
		UNFERTILIZED CHECK	P	K	S	ZN	B
Albany	Gentry	77	73	62	81	84	72
Annada	Pike	187	193	197†	196†	189	188
Columbia-Dry	Boone	112	121§	125*	119	116	107
Columbia-Irr	Boone	208	215	209	217	211	210
Henrietta	Ray	174	177	156	139	177	168
LaGrange	Lewis	170	167	‡	179§	169	180†
Lamar	Barton	93	99	100	98	97	95
Marshall	Saline	209	215	207	201	208	204
Novelty	Knox	161	162	153	152	161	159
Truxton	Montgomery	77	76	82	83	82	82

*This yield is greater than the yield of the unfertilized check with greater than 95% confidence.

†This yield is greater than the yield of the unfertilized check with 90 to 95% confidence.

§This yield is greater than the yield of the unfertilized check with 80 to 90% confidence.

‡ K treatments were not applied at the LaGrange location due to an accidental broadcast K application to the experimental area.

Response to K

- Averaged over all 19 locations, there was no yield response to K.
- Statistically significant responses (90% confidence) to K were seen at three locations out of 19. Corn yield responded to K at the Annada location in both years (16 bu/acre in 2001, 10 bu/acre in 2002), and at the Columbia dryland location in 2002 (13 bu/acre).
- We saw weak evidence that soil test K was related to yield response.
- For the two locations with soil test potassium < 200 lb/acre, the average yield difference between check plots and K-fertilized plots was 9 bu/acre. Because there were only two locations in this category, no statistical test can be run.
- When soil test potassium was above 200 lb/acre, no yield response was seen.

- This definitely shows that current University of Missouri recommendations for K are high enough to support good corn yields. The MU target value for soil test K depends on soil cation exchange capacity, but is around 300 lb/acre for most Missouri soils.
- These experiments can't answer the question of whether current University of Missouri recommendations for K are higher than is economically optimum for corn production.
- Yield response to K may also be related to soil pH. The average yield difference between check plots and K-fertilized plots was 10 bu/acre for the three locations with the lowest pH values. However, this may be a coincidence since two of the three locations with the lowest pH values were the two Annada fields.
- Recent research at Iowa State has found quite a few yield responses when soil test K is high. Low soil test K in the subsoil is one factor that helps them to predict when high-testing soils will give yield responses. Our results did not follow this pattern. We did not see many yield responses when soil test K was high, and subsoil fertility was not helpful in predicting where we saw yield responses.

<u>Response to S</u>

- Averaged over all 19 locations, there was no yield response to S.
- One of the 19 locations (Annada 2002) had a significant (90% confidence) 9 bu/acre yield response to S, while another was near significance (Lagrange 2002, 9 bu/acre with 87% confidence). Both of these fields are located in the flood plain of the Mississippi River. However, neither location responded to S in 2001.
- We were not able to identify any factors that helped to predict the yield difference between check plots and S-fertilized plots.

<u>Response to Zn</u>

- Averaged over all 19 locations, there was a 3 bu/acre response to Zn (97% confidence). This suggests a slight yield limitation due to zinc deficiency occurring in many fields.
- However, there is also evidence that this is not the case. Due to promising results with zinc in the 2001 experiments, zinc treatments were also added to 13 fall N experiments around Missouri in 2002 in order to test zinc response over a larger range of fields. Yield response to zinc was not seen in these fields, and averaged over 32 total locations there was no response. The results from the additional 13 experiments are not as reliable because only three replications were used, compared with five replications in the 19 original experiments.
- When analyzed individually, none

of the experiments showed a significant (90% confidence) yield response to Zn.

- We were not able to identify any factors that helped to predict the yield difference between check plots and Zn-fertilized plots.

Response to B

- Averaged over all 19 locations, there was no yield response to B.
- Statistically significant responses (90% confidence) to B were seen at two locations out of 19. Corn yield responded to B at the Annada location in 2001 (15 bu/acre) and the Lagrange location in 2002 (10 bu/acre). In similar experiments with soybeans, yield responses to B were seen at Annada and at Novelty in 2001. All of these locations are in the northeastern part of Missouri, and three of the four are in the Mississippi River floodplain, possibly indicating greater potential for response to B in these areas.
- Soil test values were not useful in predicting response to B.

Summary and Conclusions:

- Overall our results indicate that MU current soil test target levels are high enough so that when they are maintained, as in most of these fields, response to P and K fertilizer additions is minimal. This is the intent of the recommendations, which are built on a philosophy of long-term management. Even at the very high yield levels in some of these fields, and in a wide range of soil types, the P- and K-supplying capacity of these well-maintained soils was adequate to supply crop needs.
- Averaged over all locations, yield responses to S, Zn, and B were not seen. Statistically significant yield responses to S and B were seen at two locations each, but these responses could not be predicted from soil test values (either shallow or deep samples). Responses to B were all in northeastern Missouri for both corn and soybean (soybean response to B was measured in a separate set of experiments).

Acknowledgements

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Refining Soil Test Recommendations for Soybean

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Objectives:

1. Test the performance of current University of Missouri soil test recommendations for predicting soybean response to P and K in a statewide network of experiments.
2. Explore the possibility that subsoil test values, soil type, or soil region could be used to improve our fertilizer recommendations and make them more site-specific.
3. Evaluate soybean response to S and B in Missouri, and evaluate factors that might help predict where responses to S or B are likely (including soil test S and B).
4. Test soybean response to N at planting or at early pod fill in a statewide network of experiments.

Methods:

- Experiments were added to an existing statewide network of 20 soybean variety trials conducted by the University of Missouri in 2000 and again in 2001. Variety testing personnel planted and harvested the experiments, as well as controlling weeds.
- Five experiments were located in northern Missouri, 5 in central Missouri, 5 in southwest Missouri, and 5 in southeast Missouri each year (Figure 1).
- Fields used in 2001 were different than fields used in 2000, though mostly on the same farms.
- N, P, K, S, and B fertilizers were hand-applied to separate plots at rates of 25 lb N, 80 lb P_2O_5, 120 lb K_2O, 20 lb S, and 1 lb B/acre. These rates should be high enough to produce full yield response. Two separate N timings were applied: at planting and at early pod fill.
- Two unfertilized check plots were used in each replication.
- Five replications were used.
- Soil samples were taken at depths of 0 to 6, 6 to 12, 12 to 24, and 24 to 36 inches in each experiment and analyzed for pH, NO_3^-, NH_4^+, P, K, S, and B.
- One well-adapted variety was used at each location (Tables 1 and 2).
- All experiments followed a previous crop of corn.
- 2001 experiments are in different fields than 2000 experiments.
- Eight experiments with N applications to soybean that were conducted by Bill Wiebold at the Bradford Research Center near Columbia are also included in analyzing the effects of N applications on soybean yield.

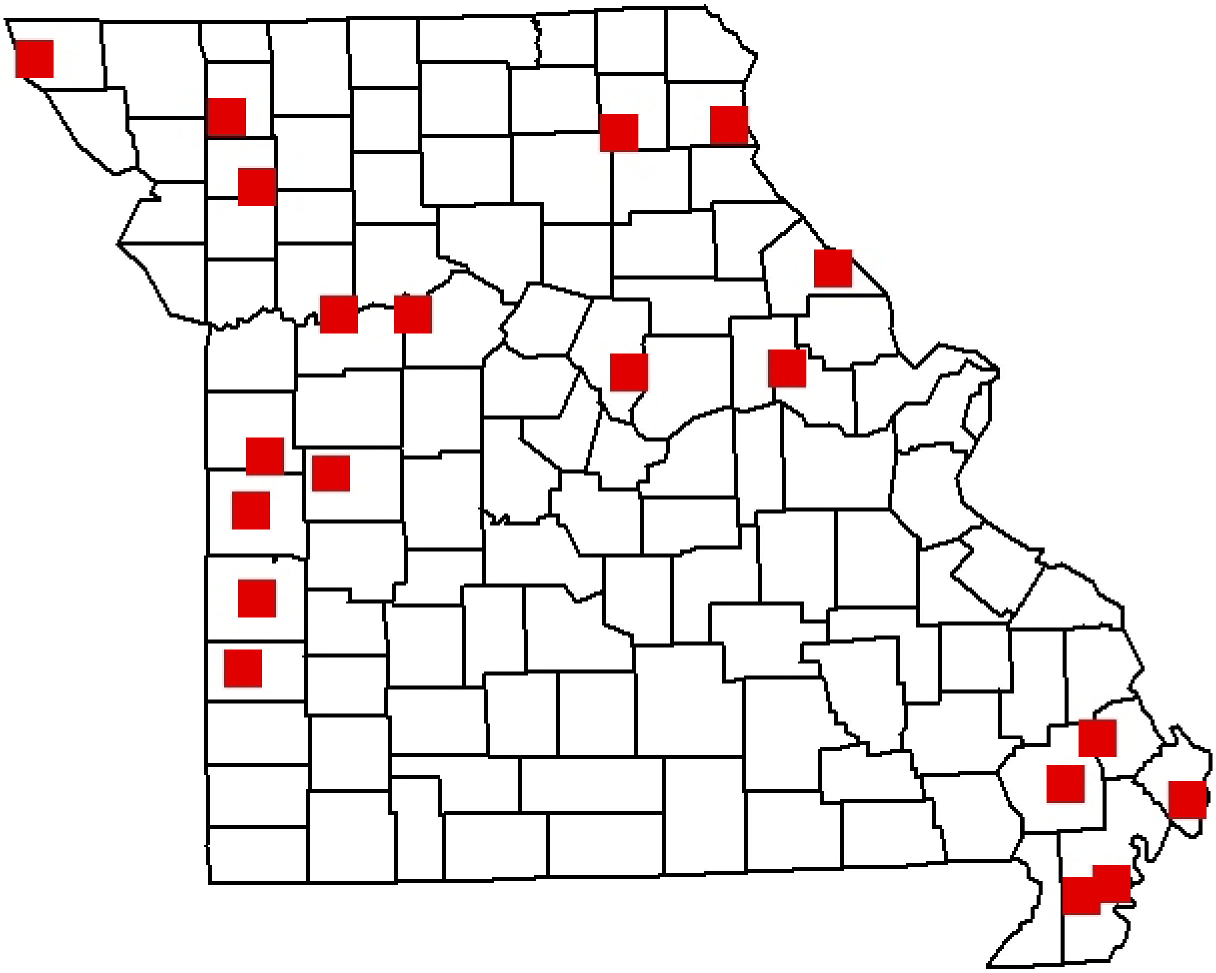

Figure 1. Locations of soybean fertility experiments in 2000. Locations in 2001 were approximately the same.

Table 1. 2000 EXPERIMENTAL SITES

LOCATION	COUNTY	SOIL SERIES	VARIETY
Corning	Atchison/Holt	Salix Silty Clay Loam	Asgrow 3302
Albany	Gentry	Grundy Silt Loam	Pioneer 93B82
Osborn	DeKalb	Grundy Silt Loam	Pioneer 93B82
Novelty	Knox	Putnam Silt Loam	Asgrow 3701
LaGrange	Lewis	Westerville Silt Loam	Pioneer 93B82
Henrietta	Ray	Aholt Clay	Asgrow 3701
Grand Pass	Saline	Haynie Silt Loam	Pioneer 93B82
Columbia	Boone	Mexico Silt Loam	Asgrow 3701
Truxton	Montgomery	Mexico Silt Loam	Asgrow 3701
Annada	Pike	Tice Silt Loam	Pioneer 93B82
Garden City	Cass	Haig Silt Loam	Pioneer 93B82
Butler	Bates	Kenoma Silt Loam	Asgrow 4301
Urich	Henry	Hartwell Silt Loam	Asgrow 4403
Nevada	Vernon	Barden Silt Loam	Novartis S46-W8
Lamar	Barton	Parsons Silt Loam	Novartis S46-W8
Oran	Scott	Commerce Silt Loam	Stine 4790
Wyatt	Mississippi	Commerce Silt Loam	Pioneer 9492
Morehouse	Stoddard	Sharkey Clay	Pioneer 9594
Portageville	Pemiscott	Portageville Clay	Asgrow 4602
Portageville	Pemiscott	Dundee Silt Loam	Pioneer 9594

Table 2. 2001 EXPERIMENTAL SITES

LOCATION	COUNTY	SOILSERIES	VARIETY
Grand Pass	Saline	Haynie Silt Loam	Pioneer 94B01
Truxton	Montgomery	Mexico Silt Loam	Kruger K-369RR/SCN
Corning	Atchison	Salix Silty Clay Loam	Asgrow 3302
Albany	Gentry	Grundy Silt Loam	Asgrow 3302
Henrietta	Ray	Haynie Silt Loam	Pioneer 94B01
LaGrange	Lewis	Westerville Silt Loam	Asgrow 3302
Annada	Pike	Tice Silt Loam	Asgrow AG3701
Novelty	Knox	Putnam Silt Loam	US Seeds 3701
Oran	Scott	Sharkey Silty Clay	Garst D484
Lamar	Barton	Barden Silt Loam	Delta King 4868
Garden City	Cass	Haig Silt Loam	MFA 4478SCN
Urich	Henry	Hartwell Silt Loam	Pioneer 94B53
Butler	Bates	Kenoma Silt Loam	Asgrow AG4301
Osborn	DeKalb	Grundy Silt Loam	Croplan RC3838
Nevada	Vernon	Parsons Silt Loam	Asgrow AG4403
Morehouse	New Madrid	Sharkey Clay	Asgrow 5501
Columbia	Boone	Mexico Silt Loam	Dekalb 36-51
Portageville	Pemiscot	Portageville Clay	MFA 4809
Portageville	Pemiscot	Tipton Silt Loam	Asgrow AG4902
Wyatt	Mississippi	Commerce Silty Clay Loam	MPV 457NRR

Results:

- Average yield across all 20 locations was 45 bu/acre in 2000, 50 bu/acre in 2001. Drought stress caused yields in the southwest experiments to be low in 2000. Overall, yield levels were representative of good production practices and conditions for Missouri.
- Soil test levels were also representative of good production practices.
  - Soil test P was low in 1 field, medium in 18 fields, and high in 21 fields according to MU soil test interpretations.
  - Soil test K was medium in 21 fields and high in 19 fields.
  - The target soil test level for MU fertilizer recommendations is at the border between medium and high, so equal numbers of fields testing medium and high is considered ideal.
- Only two of 20 locations had statistically significant (90% confidence) yield response to fertilizer treatments in 2000 (Table 3). Both responses were to potassium. Early-season drought stress led to numerous reports of K deficiency in Missouri soybeans, reduced K availability to crops, and probably contributed to the yield responses.
- Seven of 20 locations had statistically significant (90% confidence) yield response to fertilizer treatments in 2001 (Table 4), including responses to P, K, N at planting, N at early pod, S, and B.
- All results that follow come from analyzing all 40 experiments together.

Response to P

- Averaged over all 40 locations, there was no yield response to P.

- Statistically significant responses (90% confidence) to P were seen at three locations out of 40; one responsive location tested low, one tested medium, and one tested high for P.
- Soil test P was not a significant predictor of response to P.
  - For the five locations with soil test P < 30 lb/acre, plots receiving P averaged 1.2 bu/acre more than the check plots, but this was not statistically significant (partly because of the small number of locations with P test this low).
  - This is not surprising, since most locations were either in the high range for soil test P, or at the high end of the medium range. Yield responses are expected to be small and infrequent at these soil test levels.
  - This definitely shows that current University of Missouri recommendations for P are high enough to support good soybean yields.
  - These experiments can't answer the question of whether current University of Missouri recommendations for P are higher than is economically optimum for soybean production.
- For the sixteen locations with soil salt pH < 6.0, average yield response to P was 1.4 bu/acre (99% confidence).

- At lower pH, solubility of iron and aluminum is increased, both of which tend to react with P to make it unavailable.
- This result agrees with Kansas State research, which has found that much of the yield response that can be obtained by applying lime to low pH soils can also be obtained by making a small band application of P.

Response to K

- Averaged over all 40 locations, there was no yield response to K.
- Statistically significant responses (90% confidence) to K were seen at four locations out of 40.
- Soil test K was related to yield response.
  - For the seven locations with soil test potassium < 200 lb/acre, average yield response to K was 1.4 bu/acre (94% confidence).
  - When soil test potassium was above 200 lb/acre, no yield response was seen.
  - This definitely shows that current University of Missouri recommendations for K are high enough to support good soybean yields.
  - These experiments can't answer the question of whether current University of Missouri recommendations for K are higher than is economically optimum for soybean production.
- Recent research at Iowa State has found quite a few yield responses when soil test K is high. Low soil test K in the subsoil is one factor that helps them to predict when high-testing soils will give yield responses. Our results did not follow this pattern. We did not see many yield responses when soil test K was high, and subsoil fertility was not helpful in predicting where we saw yield responses.

Response to N applied at planting

- Averaged over all 48 locations (including 8 experiments with N treatments only at Columbia), yield response to N applied at planting was 0.5 bu/acre (90% confidence).
- Several factors helped to predict yield response to N applied at planting:
  - For the sixteen locations with salt pH less than 6.0, average yield response to N applied at planting was 0.9 bu/acre (95% confidence). At low soil pH, survival of soil *Rhizobia* is not as good, and availability of soil molybdenum is low. Both *Rhizobia* and molybdenum are required to establish effective N-fixing nodules on soybean roots.
  - When soil nitrate to two feet was less than 50 lb/acre (this was true at eight locations), average yield response to N at planting was 1.0 bu/acre (89% confidence). Previous research in Minnesota has also shown that yield response is higher when soil nitrate is lower, but their yield responses were much larger, between 5 and 10 bu/acre.
  - For the five locations with

check yield above 60 bu/acre, average yield response to N at planting was 1.6 bu/acre (80% confidence). Ray Lamond at Kansas State thinks that the N fixation system of soybeans can't keep up to supply all the N needed to produce yields above 60 bu/acre. Our results give a small amount of support to this theory.

Response to N applied at early pod stage

- Averaged over all 44 locations (including 5 experiments with N treatments only at Columbia; we missed making early pod N applications at one of the 40 experiments paired with the variety tests), there was no yield response to N applied at early pod.
- We were not able to identify any factors that helped to predict yield response to N applied at early pod.

Response to S

- Averaged over all 40 locations, there was no yield response to S.
- Only one of the 40 locations had a significant (90% confidence) yield response to S. Sulfur was the only nutrient for which we saw less than two locations with statistically significant response.
- We were not able to identify any factors that helped to predict yield response to S.
- It does not appear that there are any particular regions or growing conditions in Missouri that require S additions to optimize soybean yields.

Response to B

- Averaged over all 40 locations, there was no yield response to B.
- For the sixteen locations with soil salt pH < 6.0, average yield response to B was 1.0 bu/acre (99% confidence).
    - At lower pH, solubility of aluminum is increased, and can be toxic to roots. B is known to help increase root tolerance to aluminum.

Table 3. Yields From Soybean Fertilizer Trials 2000

LOCATION	COUNTY	YIELD WITH FERTILIZER TREATMENT:						
		unfertilized check	B	K	N-1	N-2	P	S
Albany	Gentry	46	47	46	43	45	44	45
Annada	Pike	52	53	51	54	52	55	50
Butler	Bates	26	26	27§	26	27	27	26
Columbia	Boone	58	53	55	53	52	53	59
Corning	Atchison/Holt	50	47	49	50	46	48	49
DRC-Clay	Pemiscott	55	57	56	56	52	56	55
DRC-Loam	Pemiscott	49	50	48	50	50	48	48
Garden City	Cass	26	26	26	26	26	27	25
Grand Pass	Saline	51	47	52	52	49	51	51
Henrietta	Ray	39	40	42	40	41	39	39
LaGrange	Lewis	55	56	56	58§	55	56	54
Lamar	Barton	25	25	24	24	23	23	24
Morehouse	Stoddard	64	64	68†	68§	66	66	66
Nevada	Vernon	32	32	32	33	32	33	33
Novelty	Knox	61	60	63	62	62	61	60
Oran	Scott	44	43	47§	43	---	44	45
Osborn	DeKalb	50	50	51	50	48	49	49
Truxton	Montgomery	51	51	52	49	52	51	49
Urich	Henry	30	29	32†	31	29	31	32§
Wyatt	Mississippi	35	34	34	36	33	32	35

*This yield is greater than the yield of the unfertilized check with greater than 95% confidence

†This yield is greater than the yield of the unfertilized check with 90 to 95% confidence

§This yield is greater than the yield of the unfertilized check with 80 to 90% confidence
The N-1 treatment is N applied at planting, N-2 is N applied at early pod development (both are 25 lb N/ac)

Table 4. Yields From Soybean Fertilizer Trials 2001

LOCATION	COUNTY	YIELD WITH FERTILIZER TREATMENT: unfertilized check	B	K	N-1	N-2	P	S
Albany	Gentry	48	50	47	51§	50	50	48
Annada	Pike	60	63†	57	60	62	60	59
Butler	Bates	41	43	41	40	40	43	40
Columbia	Boone	34	35	35	33	30	34	33
Corning	Atchison	50	48	45	50	49	50	49
DRC-Clay	Pemiscott	34	36	31	36	35	35	34
DRC-Loam	Pemiscott	46	46	44	48	48	47	45
Garden City	Cass	49	47	47	48	49	48	49
Grand Pass	Saline	62	63	60	62	60	66*	63
Henrietta	Ray	59	57	54	58	62†	61§	58
LaGrange	Lewis	61	62	59	60	62	63	62
Lamar	Barton	43	46†	46†	43	45	46†	43
Morehouse	Stoddard	57	52	56	57	59	56	59
Nevada	Vernon	62	64§	66†	66†	61	67*	66*
Novelty	Knox	45	47*	44	47*	47†	46	45
Oran	Scott	57	54	55	55	56	54	50
Osborn	DeKalb	53	46	48	50	53	51	53
Truxton	Montgomery	55	55	54	55	54	56	54
Urich	Henry	55	52	53	56	52	51	54
Wyatt	Mississippi	41	40	39	39	47†	43	43

*This yield is greater than the yield of the unfertilized check with greater than 95% confidence

†This yield is greater than the yield of the unfertilized check with 90 to 95% confidence

§This yield is greater than the yield of the unfertilized check with 80 to 90% confidence

The N-1 treatment is N applied at planting, N-2 is N applied at early pod development (both are 25 lb N/ac)

Summary and Conclusions:

- Averaged over all experiments, the only treatment that gave a yield response was N applied at planting, and that response was very small. We conclude that there is no need to increase applications of any of these nutrients across the board (i.e. on all fields in the state).
- Current University of Missouri soil test based recommendations for P and K ensure that enough P and K is available to maximize yields. We did not find any regions or soil types that need to have higher recommendations.
- These experiments can't answer the question of whether current University of Missouri recommendations for P and K are higher than is economically optimum for soybean production. Soil test P and K levels were generally well-maintained in these fields, so we didn't expect much yield response to P and K.
- At low soil pH (salt pH < 6.0), small yield responses were seen to P, B, and N at planting. This points out the importance of a good liming program.
- There was a small yield response to K when soil test K was below 200 lb/acre.
- There was a small yield response to N applied at planting when soil pH was low, when soil nitrate was low, or when yield levels were high.
- Subsoil nutrient concentrations did not help to predict yield response to any of the nutrients.

Acknowledgements

We gratefully acknowledge the Missouri Fertilizer & Ag Lime Council for providing funding for this project. Thanks are also due to Larry Mueller, Howard Mason, Del Knerr, Richard Hasty, Travis Fritts, and Dennis Wambuguh for their help in making this project happen.

Refining Soil Test Recommendations for Wheat

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Objectives:

1. Test the performance of current University of Missouri soil test recommendations for predicting wheat response to P and K in a statewide network of experiments.
2. Explore the possibility that subsoil test values, soil type, or soil region could be used to improve our fertilizer recommendations and make them more site-specific.
3. Evaluate wheat response to S in Missouri, and evaluate factors (including soil test values) that might help predict where responses to S are likely.

Methods:

- Experiments were carried out alongside an existing statewide network of wheat variety trials conducted by the University of Missouri in 2000-2001 and again in 2001-2002. Variety testing personnel planted and harvested the experiments.
- Five experiments were conducted each year, however two of the experiments were not harvested in 2001–one was abandoned in early spring due to poor stand, and a second location was abandoned at harvest due to poor stand. Planting dates were slightly late for the 2000 experiments (Oct. 20 to Nov. 1), and with a very early and cold fall in 2000, the wheat had very little fall growth and in some cases did not emerge until late winter.
- Experiments were distributed across the wheat-growing areas of Missouri (Figure 1).
- Fields used in 2002 were different than fields used in 2001, but were on the same farms.
- P, K, and S fertilizers were hand-applied to separate plots at rates of 80 lb P_2O_5, 80 lb K_2O, and 20 lb S/acre. These rates should be high enough to produce full yield response.
- Two unfertilized check plots were used in each replication.
- Five replications were used.
- Soil samples were taken at depths of 0 to 6, 6 to 12, 12 to 24, and 24 to 36 inches in each experiment and analyzed for pH, P, K, and S.

- Roane wheat was used at all locations.
- Soil series for the Bradford location was Mexico silt loam; for the Trenton location was Grundy silt loam; for the Novelty location was Kilwinning silt loam; for the Mount Vernon location was Gerald silt loam in 2000-2001, and Creldon silt loam in 2001-2002; and for the Portageville location was Tiptonville silt loam in 2000-2001 and Dubbs silt loam in 2001-2002.

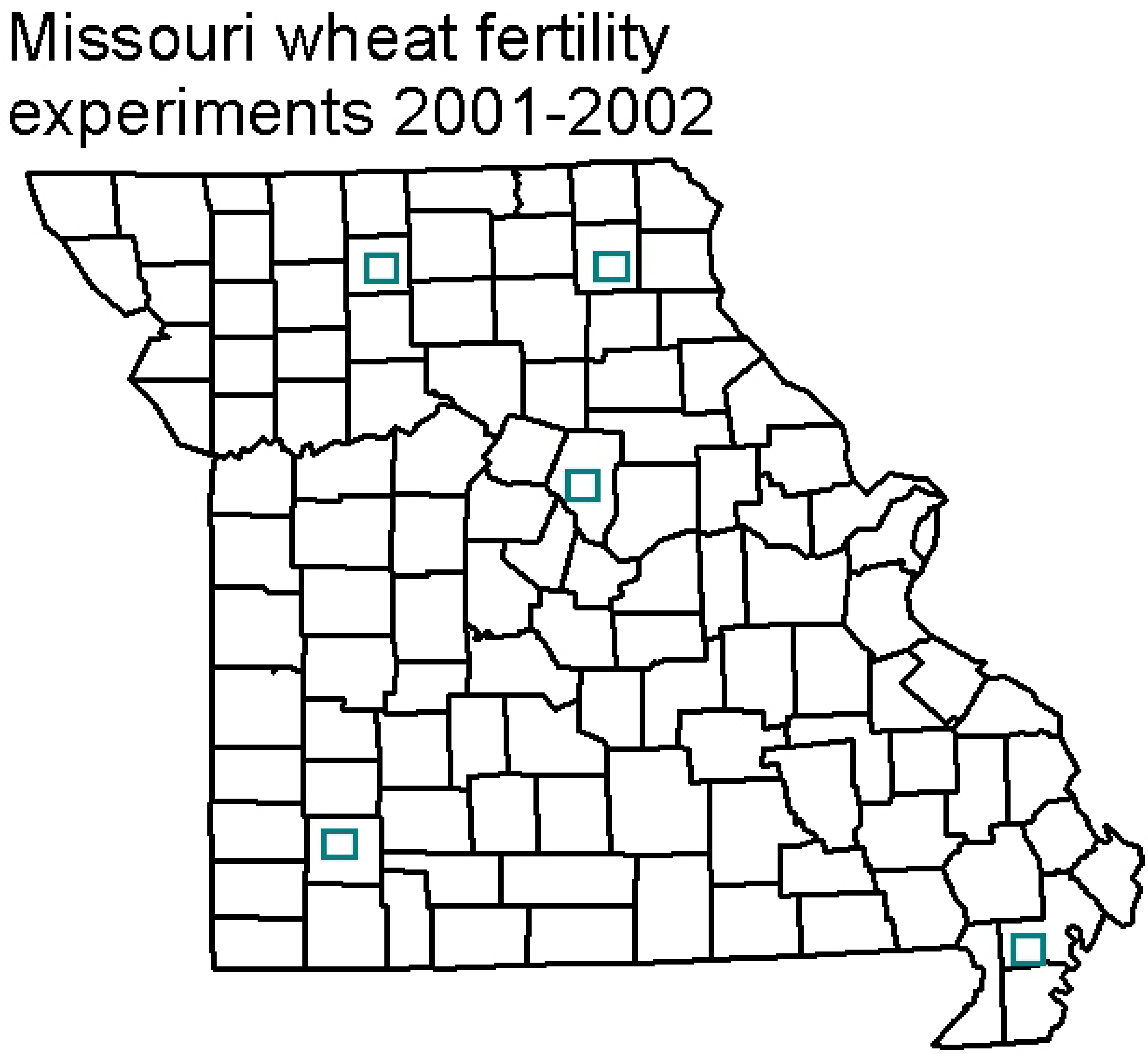

Figure 1. Locations of wheat fertility experiments in 2000-2001 and 2001-2002. All five locations had experiments both years, but the Columbia and Novelty locations were not harvested in 2001 due to poor stands.

Results:

- Average yield across all locations was 42 bu/acre in 2001, and 58 bu/acre in 2002. There were several experiments with outstanding yields, and several with disappointing yields. Overall, these yield levels are about the same as the state average over the past five years.
- Soil test levels were well-maintained for P and adequately maintained for K.
    - Of the eight experiments that were harvested, soil test P was medium in 2 fields and high in 6 fields according to MU soil test interpretations.
    - Soil test K was low in 1 field, medium in 6 fields, and high in 1 field.
    - These soil test levels would suggest minimal chance for yield response to P, but some chance for yield response to K if MU soil test interpretations are accurate for the soils in these experiments.
- Only one of three locations harvested in 2001 had statistically significant (90% confidence) yield response to fertilizer treatments (Table 1). This was at the Mt. Vernon site, where responses to both K (4 bu/acre) and S (5 bu/acre) were observed.
- Of the five experimental locations harvested in 2002, yield responses to fertilizer were seen at Portageville (K and S), at Bradford (K), and possibly at Novelty (P).

<u>Response to P</u>

- Averaged over all eight locations, there was no yield response to P.
- Only one of eight locations showed any evidence of a positive yield response to P. The P treatment increased yield by 3 bu/acre at the Novelty 2002 experiment with 82% confidence. Soil test P (Bray 1) was 40 lb/acre in this experiment, which is at the high end of the medium range, but the second-lowest P value out of the eight sites.
- Lack of response to P was not surprising, since six of the eight locations had soil test P in the high category, and the other two locations were in the medium category.
- At Mt. Vernon, 2002 yields were significantly reduced in the plots receiving P. This is probably because the plots that received P were farther along in flower development when hard freezes hit in late April of 2002.
- Soil test P was not a significant predictor of the yield difference between check plots and P-fertilized plots. This was true for both Bray 1 and Bray 2 soil P tests, and for both normal and deep samples. It appears that current University of Missouri recommendations for P are high enough to support good wheat yields (at the sites where good yields were obtained). Wheat is thought to require higher phosphorus levels than other grain crops (to support good fall growth).
- These experiments can't answer the question of whether current University of Missouri recommendations for P are higher than is economically optimum for wheat production.

Response to K

- Averaged over all eight locations, there was a 1.5 bu/acre yield response to K (91% confidence). This makes sense, since 7 of 8 locations tested low or medium for K.
- Statistically significant responses (>90% confidence) to K were seen at three locations out of eight :
  - Bradford 2002, 4 bu/acre response, soil test was low (138 lb K/acre)
  - Portageville 2002, 3 bu/acre response, soil test was medium (222 lb K/acre)
  - Mt. Vernon 2001, 4 bu/acre response, soil test was medium (216 lb K/acre)
  - These were the three locations with the lowest values for soil test K
- Soil test K was related to yield response.
  - It was a significant (95% confidence) predictor of the yield difference between check plots and K-fertilized plots. When soil test was low, K response was higher. For the three locations with soil test potassium < 230 lb/acre, average yield response to K was 3.5 bu/acre.
  - When soil test potassium was above 230 lb/acre, little or no yield response was seen.
  - This definitely shows that current University of Missouri recommendations for K are high enough to support good wheat yields.
  - These experiments can't answer the question of whether current University of Missouri recommendations for K are higher than is economically optimum for soybean production.
- Soil test K from deep samples was no better at predicting yield response to K than normal samples.

Response to S

- Averaged over all eight locations, there may have been a 2 bu/acre yield response to S (84% confidence).
- The largest and clearest response to S was at Portageville in the 2001-2002 season, when S treatment increased yield by 8 bu/acre with 99.9% confidence. This experiment had the lowest value for soil test S among all the experiments. The soil test from the Portageville 2000-2001 experiment also showed low S levels, but no yield response to S was seen that year; however, yields were very low, so not much S would have been required.
- A statistically significant response (97% confidence) to S was also seen at the Mt. Vernon location in the 2000-2001 season. However, the high soil test value for S and the high subsoil S at this location suggest that the yield response to S might not be real.
- There was weak evidence that soil test S was useful for identifying where yield response would occur, but only for deep samples. Soil test S to a 24"

depth was a weak predictor of the yield difference between check plots and S-fertilized plots (77% probability). The two locations with the largest yield differences (Portageville 2002 and Trenton 2001) also had low soil test S in the top two feet. For the three locations with soil test S less than 30 lb/acre in the top two feet, plots receiving S had average yields that were 4 bu/acre higher than check plots.

Table 1. Yields From Wheat Fertilizer Trials 2001-2002.

LOCATION	COUNTY	YEAR	YIELD WITH FERTILIZER TREATMENT:			
			UNFERTILIZED CHECK	K	P	S
Bradford	Boone	2002	27	31*	27	26
Trenton	Grundy	2002	94	95	96	95
Novelty	Knox	2002	73	74	76§	74
Mount Vernon	Lawrence	2002	53	50	37	52
Portageville	New Madrid	2002	40	43*	42	48***
Trenton	Grundy	2001	45	46	46	51
Mount Vernon	Lawrence	2001	48	52†	49	53*
Portageville	New Madrid	2001	29	28	28	27

*** This yield is greater than the yield of the unfertilized check with greater than 99.9% confidence.

* This yield is greater than the yield of the unfertilized check with greater than 95% confidence.

† This yield is greater than the yield of the unfertilized check with 90 to 95% confidence.

§ This yield is greater than the yield of the unfertilized check with 80 to 90% confidence.

Summary and Conclusions:

- Averaged over all experiments, it appears that wheat yield responded to potassium applications (1.5 bu/acre with 91% confidence) and possibly to S as well (2.1 bu/acre with 84% confidence).
- Current University of Missouri soil test based recommendations for P and K ensure that enough P and K is available to maximize yields. We did not find any regions or soil types that need to have higher recommendations.
- These experiments can't answer the question of whether current University of Missouri recommendations for P and K are higher than is economically optimum for wheat production.
- There was a 3.5 bu/acre yield response to K when soil test K was below 230 lb/acre.
- There was weak evidence that low soil test S can indicate a location that is likely to respond to S fertilizer.
- Subsoil nutrient concentrations did not help to predict yield response to any of the nutrients.

Acknowledgements

We gratefully acknowledge the Missouri Fertilizer & Ag Lime Council for providing funding for this project. Thanks are also due to Larry Mueller and Ray Wright for their help in making this project happen.

Magnesium, phosphorus, potassium and calcium concentrations in stockpiled tall fescue leaves following phosphorus and boron fertilization

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Missouri is number one in tall fescue production among states in the USA, and is number two in cattle numbers and feeder calf production (Missouri Farm Facts, 2002). The beef cattle industry is based on the 10 million acres of tall fescue pasture in the state. Missouri is also the leading state in tall fescue hay production, however many people are suggesting that it would be better economically for cattle producers to stockpile some tall fescue for winter grazing rather than investing in the harvesting and storage of hay. We have found that phosphorus fertilization of tall fescue pastures in southern Missouri is an effective way to increase tall fescue productivity, and increase the magnesium concentration of leaves during the early spring (Reinbott and Blevins, 1997). Based upon our work on grass tetany, we have become concerned about the forage quality of tall fescue pastures and hay, in terms of the magnesium, calcium and phosphorus in the forage. A search of the literature revealed only one publication on the nutrient concentration of stockpiled tall fescue leaves (Collins & Balasko, 1981). In addition, our work on alfalfa and squash has shown that boron nutrition also has a major impact on uptake of magnesium by roots (Stone, 2000; Waters, 1996; Blevins, unpublished). Therefore the objective of this study was to determine if fertilization with both phosphorus and boron would increase leaf magnesium, phosphorus, potassium and calcium concentrations of stockpiled tall fescue leaves.

Materials and Methods

A tall fescue plot area was selected on August 9, 2001 at the University of Missouri Southwest Center near Mt. Vernon (Creldon silt loam soil; Fine, mixed, mesic Mollic Fragiudalfs) and this site had the following soil test results: pH 5.4; N.A. 3.0 meq/100g; O.M. 2.9%; Bray I P 7 lbs/acre; Ca 2687 lbs/acre; Mg 247 lbs/acre; K 667 lbs/acre and B 0.26 lbs/acre. Please note two important problems with this soil, P level is very low and should be around 40 lbs/acre, and B level is low and should be 1.0 lb/acre for tall fescue pastures. These problems are typical of tall fescue pastures in this part of SW Missouri. On August 23, tall fescue on the selected site was cut with a forage chopper and the forage was removed. Then 10' x 25' plots with 5' alleys were prepared and treated with the various quantities of P and B. Each treatment was replicated six times. Phosphorus was applied at rates of 12.5 or 25 lbs P/acre, as triple super phosphate, and boron was added at 0.5 and 1.0 lb B/acre as boric acid. On August 27, nitrogen was applied as topdress 100-0-0. After forage removal in late August, the first leaf samples were harvested on October 23. For this sampling, 20 of the most recently collared leaf blades were harvested from each plot. Other leaf harvests were made in late November

2001, early January 2002, and each month thereafter until the May hay harvest. Leaf samples were dried, ground, and digested with nitric/perchloric acids. These samples were used for flame ionization, atomic absorption analyses of K, Mg and Ca. Phosphorus concentrations in the samples were determined colorimetrically. In late May 2002, forage was harvested for total yield and samples analyzed for macronutrient concentrations.

Results

Leaf magnesium concentrations in the stockpiled tall fescue were higher throughout fall, winter and spring with the phosphorus fertilization treatments (Fig. 1). However, leaf magnesium concentrations of plants from all treatments dropped during late fall and into winter. The magnesium concentrations of leaves from all treatments dropped by mid-winter to levels below those recommended for diets of lactating beef cows (National Research Council, 2000). The highest phosphorus fertilization treatment produced the highest leaf magnesium concentrations and plants in this treatment maintained magnesium concentrations near the required levels for lactating beef cows. Leaf phosphorus concentrations also were higher with phosphorus fertilization treatments at each sampling date, except November (Fig 1). In November, the month when remobilization of nutrients in tall fescue apparently begins, plants with the highest phosphorus fertilization remobilized phosphorus earlier than plants in the other treatments. By January and until April, leaf phosphorus concentrations of all treatments fell far below the levels required for lactating beef cows.

Calcium levels in tall fescue leaves were highest with phosphorus fertilization treatments, and remained higher during winter and spring than those in leaves of untreated plants (Fig. 2). It is important to note that calcium levels did not drop during late fall and early winter. This is consistent with the fact that calcium is an immobile element in plants and is not remobilized like most other elements. Potassium levels in leaves were slightly higher in plants treated with phosphorus in October and November, but there was no effect of phosphorus treatment on leaf potassium concentrations during winter and early spring (Fig. 2). It is obvious that potassium, a very mobile element in plants, was remobilized as leaf concentrations dropped in plants from all treatments as winter approached, however leaf concentrations of potassium remained far above those required for lactating beef cows throughout winter and spring.

Hay was harvested in late May and the hay production showed a strong response to phosphorus fertilization (Fig. 3). The 25 lbs P/acre increased hay yield by 1000 lbs/acre. Interestingly, with the 0 and 12.5 lbs P/acre treatments, there was a response to boron, with the 1.0 lb B/acre treatment increasing hay yield by ~300 lbs/acre. When hay yields in May were added to the hay yield in August, total hay yield was increased by 1600 lbs/acre with the high phosphorus applications compared to the control treatment (Fig. 4). This increase in hay yield should be worth about $40. Analysis of the May hay samples revealed that both magnesium and calcium concentrations in the hay treated with 0 and 12.5 lbs P/acre were highest with the 0.5 lbs B/acre (Figs 5 & 6). This boron effect was eliminated with the high phosphorus treatment. This boron/phosphorus interaction on magnesium and calcium concentrations in hay has not been reported previously, to my knowledge.

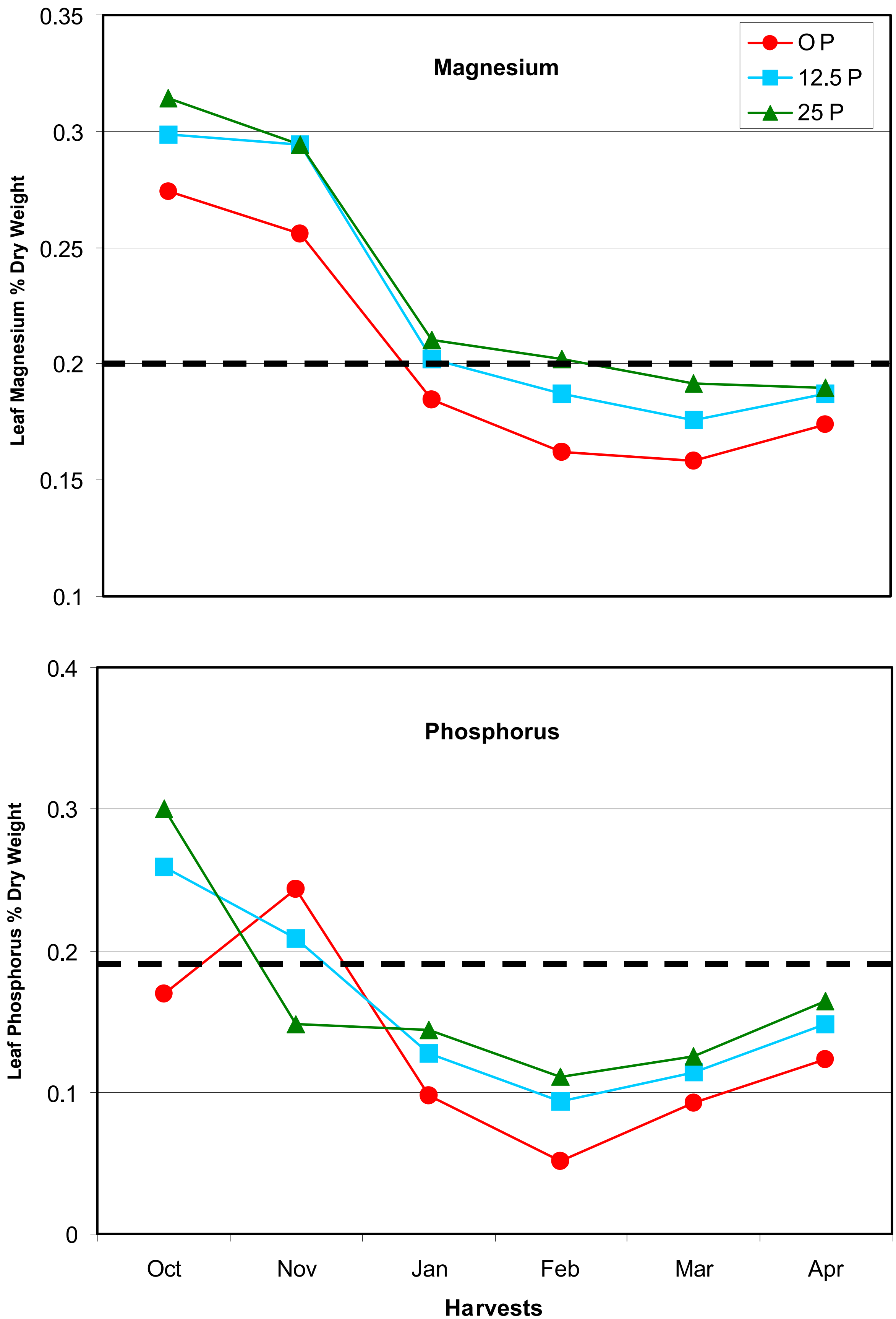

Figure 1. The magnesium and phosphate concentrations of stockpiled tall fescue during fall, winter and spring of 2001-2002 following fertilization with phosphorus. Dashed lines indicate the percentage of macronutrient required in the diet of a lactating beef cow.

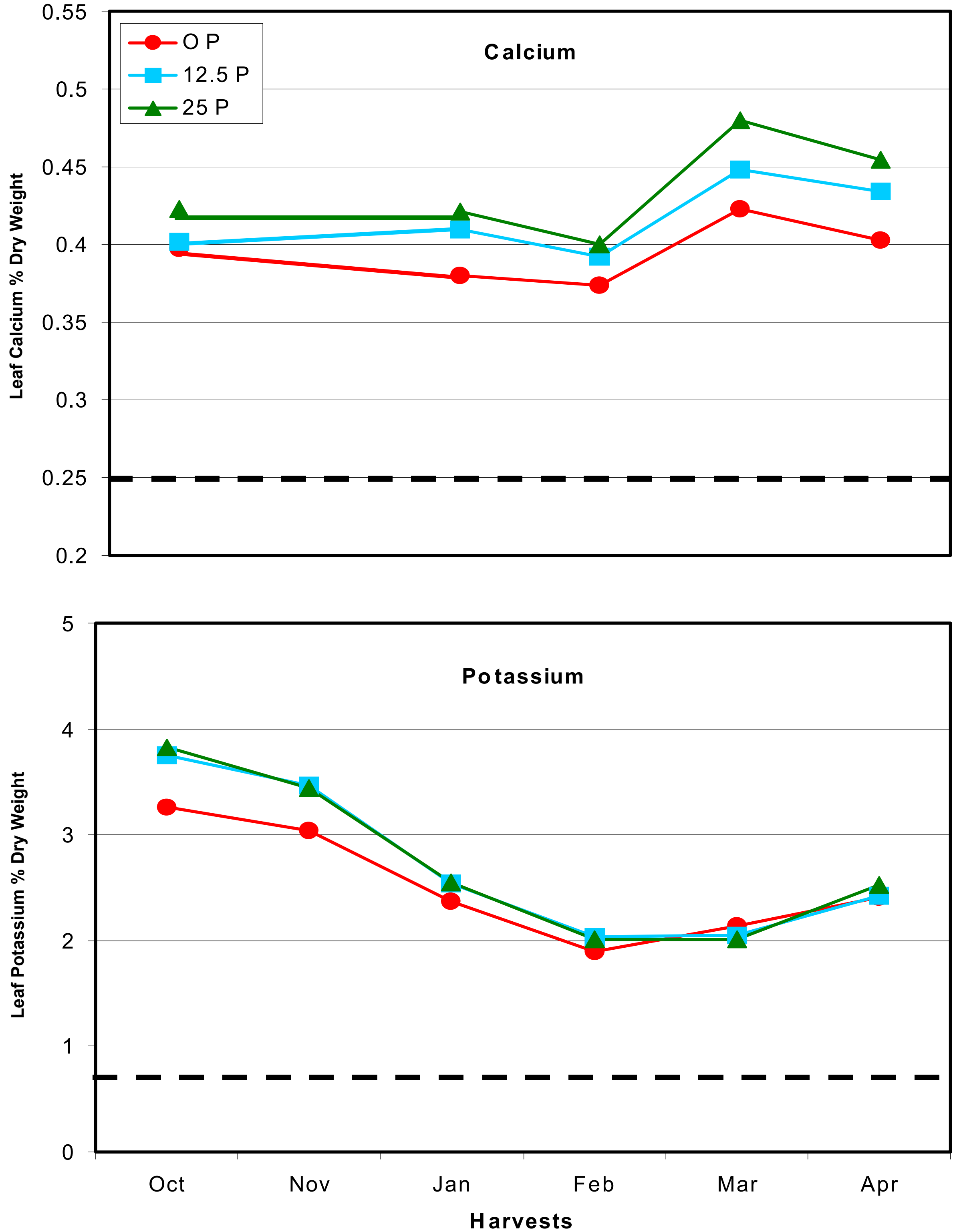

Figure 2. The calcium and potassium concentrations of stockpiled tall fescue leaves during fall, winter and spring of 2001-2002. Dashed lines indicate the percentage of macronutrient required in the diet of a lactating beef cow.

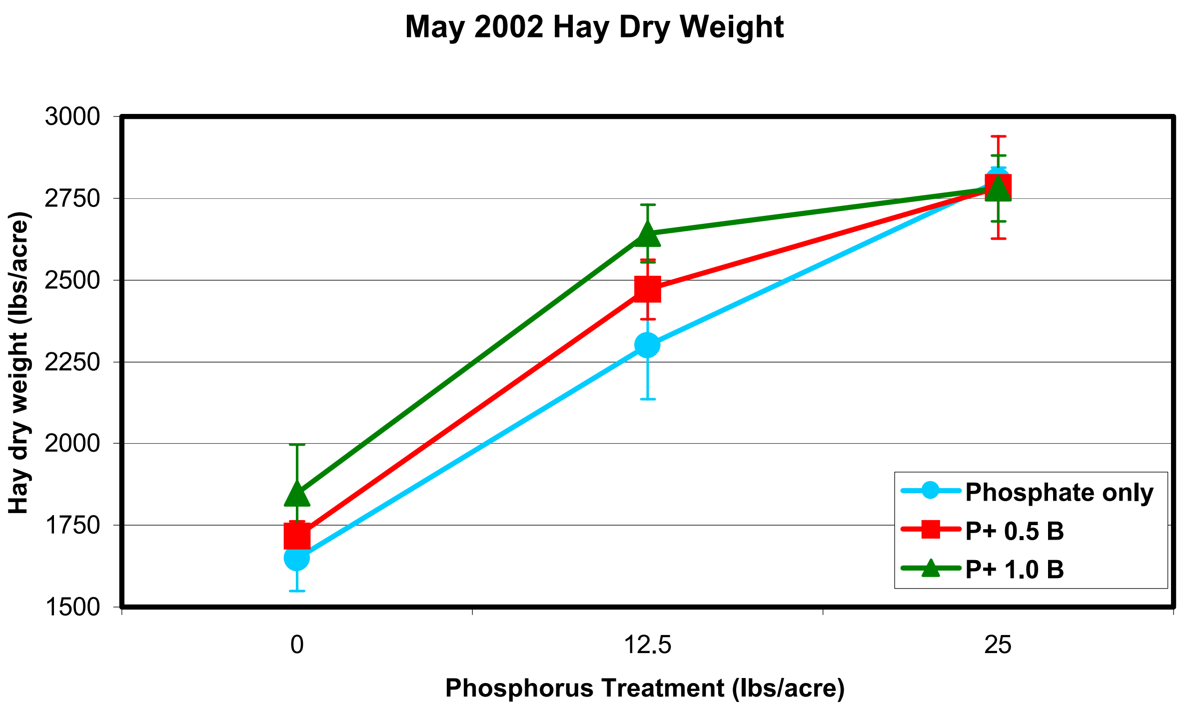

Figure 3. May 2002 hay yield of tall fescue treated with phosphorus and boron in late August 2001.

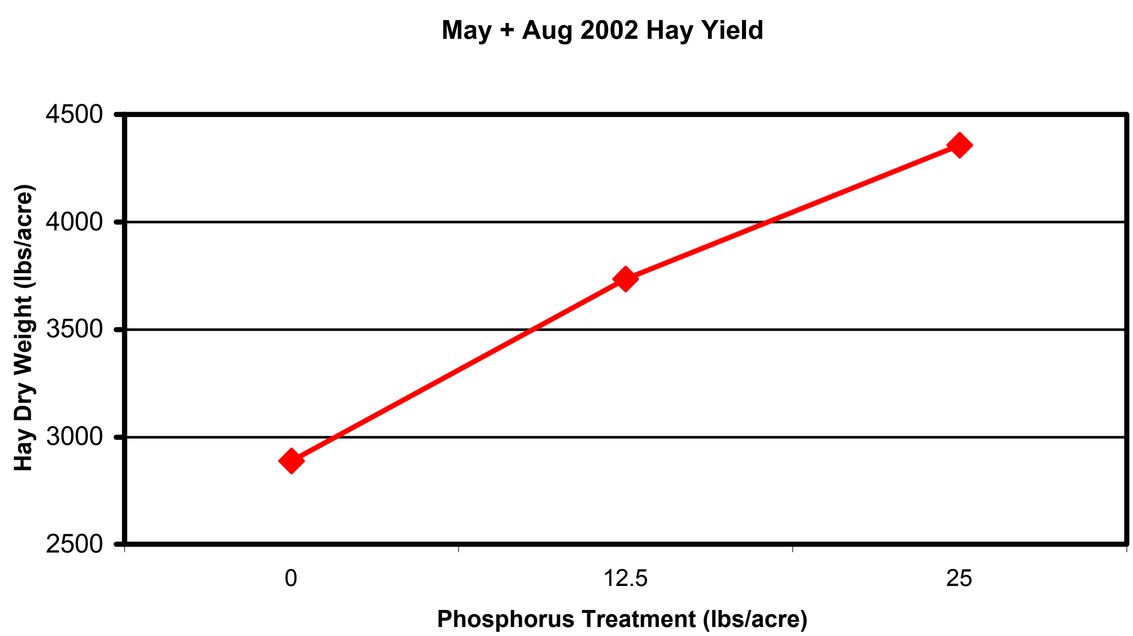

Figure 4. Combined tall fescue hay yield from May and June 2002 after phosphorus fertilization treatment in August 2001.

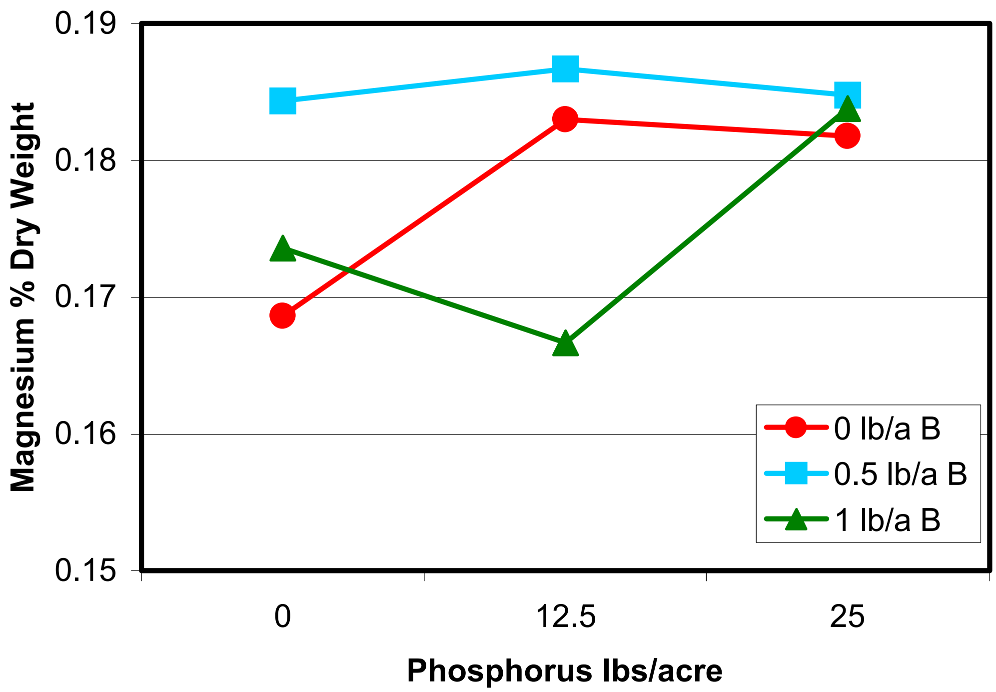

Figure 5. The impact of August 2001 phosphorus and boron fertilization on the magnesium concentration of tall fescue hay harvested in late May 2002.

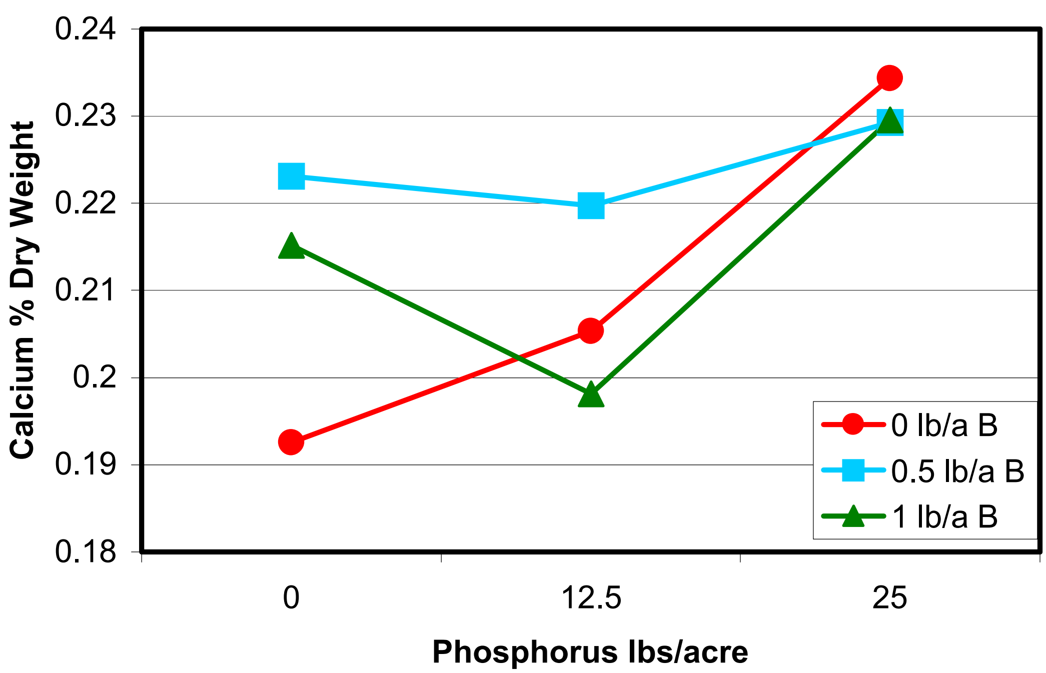

Figure 6. The calcium concentration of tall fescue hay harvested in late May 2002 following fertilization in late October 2001 with phosphorus and boron.

Discussion

Phosphorus fertilization of tall fescue increased the macronutrient concentrations of leaves in the stockpiled grass during late fall and winter. Mobile macronutrient concentrations during winter, consistent with its lack of remobilization in plants.

Hay yields in May and August were dramatically increased by the phosphorus fertilization treatments, with the increase totally 1600 lbs/acre with the 25 lbs P/acre treatment. The hay yield in May responded to boron treatments at the 0 and 12.5 lbs P/acre rates. In other words, when phosphorus levels in the soil were high enough, boron additions provided no yield response, but when soil phosphorus levels were low, boron was important for increasing yield. Interestingly, analysis of the hay samples indicated that both magnesium and calcium concentrations increased with the 0.5 lbs B/acre at the 0 and 12.5 lbs P/acre treatments.

These results are consistent with data presented 20 years ago on stockpile tall fescue in West Virginia (Collins and Balasko, 1981). In that study, both magnesium and phosphorus levels of the forage dropped below levels recommended for lactating beef cows. The question now becomes, can we modify the natural process of nutrient remobilization in the perennial grass, tall fescue, to maintain enough magnesium and phosphorus in leaves for grazing

concentrations, magnesium, phosphorus and potassium, dropped dramatically in the late fall, early winter, indicating that these nutrients were remobilized during winter. Calcium, an immobile element in plants, showed no drop in leaf

beef cows during winter and early spring?

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P and K Fixation by Missouri Soils

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Accomplishments for 2001:

- Last year we reported that we had completed collection of forty-two Missouri soils for this study, representing many major agricultural soil types (see map and table).
- The laboratory incubation part of this project is now complete. Each soil received three treatments:
  - P fertilizer added
  - K fertilizer added
  - no fertilizer added

  All soils were incubated moist (water was added periodically to maintain soil moisture at field capacity) in the laboratory for three months, then they were sampled and dried.
- All soils have been analyzed for K. Analysis for P is in progress and twenty soils have been completed.
- Clay fractions have been isolated from all soils. Preparation of slides for clay mineral analysis using X-ray diffraction is in progress.

<u>Results for potassium</u>

- K was added to the soils at a rate equivalent to 300 lb K_2O/acre. This K rate resulted in increases in soil test K values ranging from 100 to 240 lb K/acre (see table). This range matches well with the current University of Missouri equation, which predicts that 300 lb K_2O/acre will raise soil test K values by about 100 lb/acre on low-testing soils and 200 lb K/acre on very high-testing soils. However, when used by itself, the initial soil test K value was a very poor predictor of how much soil test K would increase. Only when combined with the region that the soil came from and the amount of clay in the soil were predictions fairly accurate.
- Soil test K increased less in soils with higher clay content. The clay component of the soil is responsible for the process of K fixation (tie-up in forms not available to crops). We may need to recommend more K for soils with higher clay contents. This is partly accounted for by current University of Missouri recommendations, which recommend higher soil test K target levels for soils with higher CEC (cation exchange capacity) values, which are closely related to clay content. The end result is that more K is recommended on soils with more clay.
- The most clearly distinguishable regional effect is that soil test K increased more for Ozark soils than for other Missouri soils. Lower K rates may be appropriate in the Ozarks than in other regions. We expected this result based on expected lower concentrations of 2:1 type clays (K-fixing) in Ozark soils.
- In general, soils test K increased less for soils from the claypan and bootheel regions than for soils from other regions. There were a few soils in these regions with large increases in soil test K, mainly sandy soils in the bootheel.
- By combining initial soil test K, clay content, and soil region, we are able to explain 58% of the variability in how

much soil test K increased. This is much lower than for P. The type of clay is probably more important for K fixation than for P fixation. We are in the process of analyzing the types of clays found in each soil.

Results for phosphorus

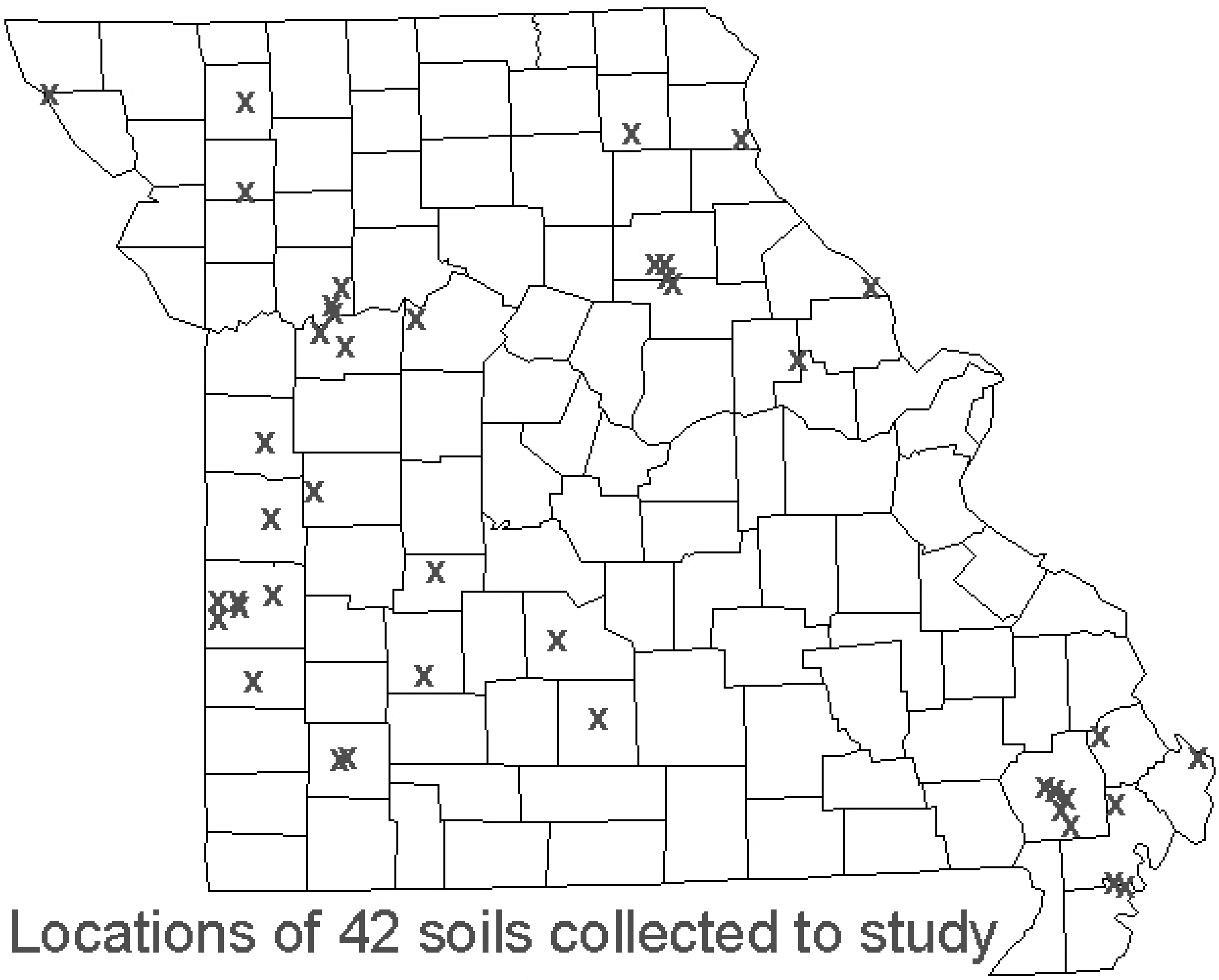
- Results presented for phosphorus are preliminary since only about half of the soils have been analyzed for P following the lab incubation. Some conclusions could change as the remaining analyses are completed.
- P was added to the soils at a rate equivalent to 215 lb P_2O_5/acre. This P rate resulted in increases in soil test P values ranging from 21 to 64 lb P/acre (see table). This range is higher than the current University of Missouri equation, which predicts that 215 lb P_2O_5/acre will raise soil test P values by about 15 lb/acre on low-testing soils and 45 lb P/acre on very high-testing soils.
- The concept that more fertilizer P is needed on low-testing soils to raise soil P by a certain amount appears to be valid. When used by itself, the initial soil test P value explained 25% of the variation in the size of the increase in soil test P. The interpretation of this observation is tricky, since it seems to contradict the result from the project "Soil-Specific Phosphorus Rates" showing that for an individual soil, each increase in the amount of P added gives the same increase in soil test P.
- The combination of initial soil test P value, the region that the soil came from, and the amount of clay in the soil explained 94% of the variation in the size of the increase in soil test P.
- As with K, soil test P increased less in soils with higher clay content. The clay component of the soil is responsible for the process of P fixation, which is tie-up in forms not available to crops. We may need to recommend more P for soils with higher clay contents. Currently we do not have a system in place to account for differences in soil clay content in our P recommendations.
- The most clearly distinguishable regional effect is that soil test P increased less for claypan region soils than for other Missouri soils. This is true even after correcting for clay contents of all soils, indicating that there is some property of claypan soils in addition to high clay content that results in lower soil test P increases. Higher P rates may be appropriate for claypan soils than for other soils.
- As we started this experiment, we thought that it might take more P fertilizer to raise soil test P for Ozark soils due to the highly-weathered clay minerals in these soils. This does not appear to be true. Soil test P increases as much or more in Ozark soils as in other Missouri soils when fertilizer P is added. We also thought that Osage Plain soils might need more P for the same reason. It appears that this might be true. We will evaluate this possibility more closely as the rest of the soil P analyses are completed.

Objectives for 2002:

- Finish soil P analyses and statistical analysis of what factors control increases in soil test P.
- Finish clay mineral analyses with the soil clay fractions that we have isolated, and analyze the effect of clay mineral types on P and K fixation.
- Measure extractable aluminum in these soils to see if it can help to predict differences in soil test increases between soils. This would

be much easier to measure than soil clay content and might be more practical to implement as a lab procedure that would improve the quality of fertilizer recommendations.

- Use results to plan appropriate greenhouse or field experiments that would lead to improved P and K



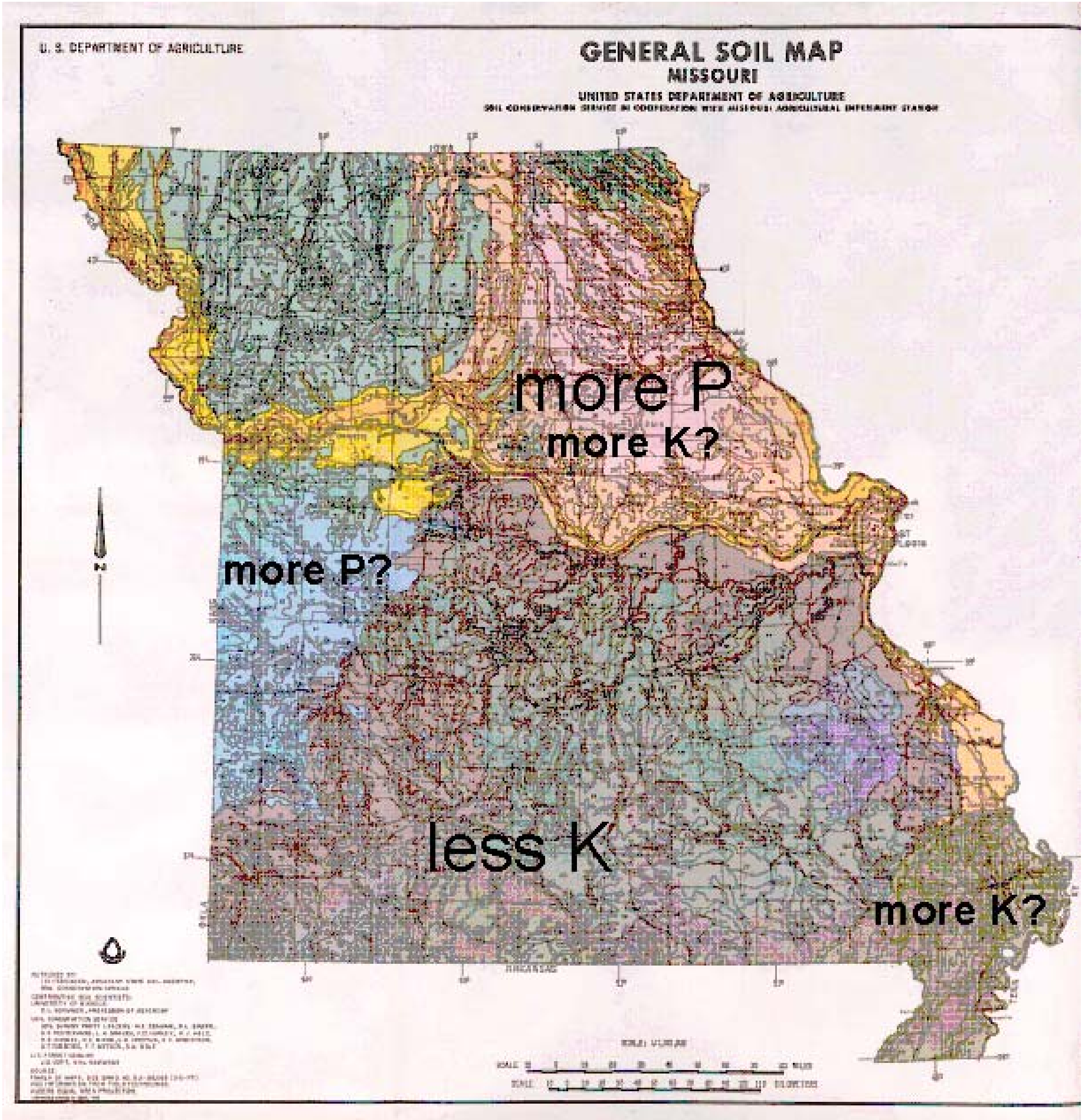
Locations of 42 soils collected to study P and K fixation by Missouri soils

Table 1. Increase in soil test K for 42 Missouri soils with K added at a rate of 300 lb K_2O/acre.

Region	Soil Type	Increase in soil test K lbs/acre
Bootheel	Commerce Silty Clay Loam	98
Claypan	Mexico Silt Loam (#1)	105
Loess and Drift	Lagonda Silt Loam	107
Bootheel	Portageville Clay	111
Loess and Drift	Marshall Silt Loam	115
Claypan	Putnam Silt Loam (#1)	117
Loess and Drift	Grundy Silt Loam (#1)	120
Osage	Barden Silt Loam (#1)	125
Osage	Barco Loam (#1)	126
Bootheel	Sharkey Silty Clay Loam	127
Osage	Kenoma Silt Loam (#1)	131
Bootheel	Sharkey Clay	132
Bootheel	Loring Silt Loam (#1)	132
Bootheel	Commerce Silty Clay Loam (#1)	133
Claypan	Mexico Silt Loam (#2)	134
Claypan	Mexico Silt Loam (#3)	136
Osage	Barden Silt Loam (#2)	139
Claypan	Putnam Silt Loam (#2)	140
Osage	Barden Silt Loam (#3)	140
Bootheel	Loring Silt Loam (#2)	141
Claypan	Mexico Silt Loam (#4)	142
Ozarks	Cedargap Cherty Silty Loam	142
River Bottom	Haynie Silt Loam	147
Osage	Barco Loam (#2)	148
River Bottom	Westerville Silt Loam	150
Loess and Drift	Sharpsburg Silt Loam	152
Loess and Drift	Grundy Silt Loam (#2)	152
Ozarks	Huntington Silt Loam	153
River Bottom	Leta Silty Clay	154
Osage	Hartwell Silt Loam	158
Bootheel	Lilbourn Sandy Loam	163
Loess and Drift	Higginsville Silt Loam	164
Osage	Osage Clay	165
Ozarks	Viraton Silt Loam	167
Osage	Parsons Silt Loam	173
Bootheel	Lilbourn Fine Sandy Loam	177
Ozarks	Goss Gravelly Silt Loam	179
Ozarks	Keeno Cherty Silt Loam	179
Ozarks	Creldon Silt Loam	198
Ozarks	Clarksville Very Cherty Silt Loam	198
Loess and Drift	Haig Silt Loam	221
Claypan	Putnam Silt Loam (#3)	240

Table 2. Increase in soil test P for 20 Missouri soils with P added at a rate of 215 lb P_2O_5/acre.

Region	Soil Type	Increase in soil test P lbs/acre
Bootheel	Sharkey Clay	21
Bootheel	Loring Silt Loam	28
Loess and Drift	Lagonda Silt Loam	28
Claypan	Putnam Silt Loam	29
Osage	Barco Loam	32
Claypan	Mexico Silt Loam	33
Claypan	Putnam Silt Loam	34
Osage	Barden Silt Loam	37
Osage	Osage Clay	38
Ozarks	Viraton Silt Loam	43
Loess and Drift	Sharpsburg Silt Loam	49
River bottom	Haynie Silt Loam	49
Ozarks	Creldon Silt Loam	50
Ozarks	Clarksville Silt Loam	51
Osage	Barden Silt Loam	51
Bootheel	Commerce Silty Clay Loam	56
Loess and Drift	Grundy Silt Loam	60
Ozarks	Goss Gravelly Silt Loam	61
Bootheel	Lilbourn Sandy Loam	63
Loess and Drift	Higginsville Silt Loam	64



Map of Missouri soil regions with regional differences in fertilizer needs as suggested by this research. These suggestions are based only on differences in the amount of fertilizer needed to increase soil test values to target levels. Whether different regions should have different target levels is an important unanswered question. Experiments with plant response to fertilizer in different soil types would be needed to answer this question.

recommendations; these might be region-specific, or based on an additional lab test such as extractable aluminum. We have learned about how soil properties affect a soil's reaction with fertilizer. The next step is to understand how soil properties affect the plant's reaction with fertilizer.

Budget requested for 2002:

No additional funds are requested for this project for 2002. The project will be completed with funds allocated in 2000. However, we do anticipate submitting a proposal for a greenhouse project in 2003 based on the results of this study and the study "Soil-specific phosphorus rates" funded by the Fertilizer and Lime Board. We were able to screen a lot of soils in the lab and learn about how soil test values respond to fertilizer additions for different soils.

Even more important is how soil properties affect plant uptake in response to fertilizer additions. The studies that we have done so far tell us how to do a better job of hitting our target soil test levels for different soils. What they don't tell us is whether target soil test levels should be different for different soils. This depends on how soil properties affect nutrient availability to plants at a given soil test level. We look forward to taking the next step with this study.

On-Farm Starter Fertilizer Response in No-till Corn

Peter Scharf, MU Agronomy Extension

Background

Early research on starter fertilizer showed that it usually increased early season crop growth, but in Missouri and adjacent states this only occasionally translated into a yield advantage. With widespread changes in tillage practices over the past twenty years, this conclusion appears to be changing. Recent starter fertilizer trials from other states are giving results that make the use of starter fertilizer look like an economically sound practice in no-till systems. Dave Mengel at Purdue University found a yield response to starter in 8 of 11 no-till site-years, but only in 1 of 11 moldboard-plowed site-years. These experiments were paired so the weather and soils were the same for both tillage systems. This yield response was primarily to the N component of the starter. Indiana is now recommending starter in no-till situations, but not when tillage is used.

Bob Hoeft and associates at the University of Illinois often found substantial yield responses to starter in both no-till systems (1993 to 1996) and in reduced-till systems (1997). Their research broke the starter down into component nutrients, and they found that the main yield response was definitely to the N in the starter. They may have had a response to P in starter as well.

No-till corn and sorghum in Kansas have frequently responded to starter fertilizer in experiments conducted by Barney Gordon and David Whitney. One of their experiments tried N-only, P-only, and combinations, and found clear responses to both the N and the P; also, 30 lb N/acre out-yielded 10 lb N/acre in starter. Their research has also established that some hybrids of both corn and sorghum consistently respond to starter fertilizer, while other hybrids do not. They have found a trend for later-maturing hybrids to respond more.

Missouri experiments

These favorable results with starter for no-till corn in states adjacent to Missouri prompted the research reported here. Based on the Illinois and Kansas experiments, it was possible to focus in on a few specific treatments of interest and evaluate them in on-farm replicated strip trials. The core treatments are:

1) No starter
2) Typical low-N, high-P_2O_5 starter
3) Medium-N, medium-P_2O_5 starter
4) N-only starter

Experiments were planted in cooperation with producers who currently use starter fertilizer for no-till corn production. Details from each experiment are given in Table 1. Previous crop was no-till soybean at all locations except for Elliott 1998, which was in a field newly formed from two smaller fields, one in no-till corn and the other in no-till soybean the year before the experiment. The producers' equipment was used to plant and to apply the various starter fertilizer treatments, which are described in Table 2. All experiments used the basic four starter types listed above; several producers had additional treatments that they were interested in looking at. All treatments at a location were replicated three or four times using a randomized complete-block design. Starter fertilizer materials were weighed before and after planting to determine the actual rates applied. Plots were 12 to 30 feet wide and 375 to 1290 feet long, measured with a field wheel. Two of the cooperating producers used dry starter fertilizer and two used liquid. All starter materials were placed approximately 2-3" to the side of and 2" below the seed furrow. Plots were harvested using the producers' combines and grain was weighed in a weigh wagon.

Table 1. Details of on-farm starter fertilizer experiments.

Year	Cooperating producer	County	Soil type	Planting date	Hybrid	Seeding rate	Dimensions of one plot	Soil test P	Nitrogen management: Rate	Source	Timing
						Seeds/acre		lb Bray-1 P	lb N/acre		
1996	Earl Borgman	Lafayette	Marshall silt loam	23 April	Cargill 7997	22,000	12' x 375'	17	140	NH_3	sidedress
1997	Earl Borgman	Lafayette	Marshall silt loam	5 May	Burruss BX80	22,000	12' x 450'	43	148	NH_3	sidedress
1997	Richard & Jim Elliott	Morgan	Friendly & Glensted silt loam	6 May	Burruss 720	23,500	30' x 1425'	47	108	NH_3	sidedress
1998	Earl Borgman	Lafayette	Marshall silt loam	15 May	Cargill 7770	22,000	12' x 375'	22	136	NH_3	sidedress
1998	Richard & Jim Elliott	Morgan	Glensted silt loam	24 April	Burruss 720	23,500	30' x 1290'	136	100†	NH_3	sidedress
1998	Eddie & John Hoff	Cooper	Crestmeade silt loam	23 April	Pioneer 33G26	22,400	30' x 990'	51	80	NH_3	sidedress
1998	Jim & Jerry Klasing	Saline	Marshall silt loam	16 May	Pioneer 33A14 & 33V08*	28,500	30' x 1010'	20	105‡	UAN-knife	sidedress

*The planter was split between these two hybrids, six rows of each
†The plots with no starter received 106 lb N sidedressed
‡The plots with no starter received 135 lb N sidedressed

Table 2. Starter fertilizer treatments. All starter materials were placed 2" to the side and 2" below the seed furrow except as noted.

			--------------analysis applied for treatment category:----------------				
Year	Cooperating producer	fertilizer form	low N /high P_2O_5	med N/ med P_2O_5	N only	other #1	other #2
			---------------------------------lb N-P_2O_5-K_2O/acre---				
1996	Borgman	dry	11-44-44	24-24-24	40-0-0		
1997	Borgman	dry	10-42-42	26-26-26	30-0-0		
1997	Elliott	dry	22-57-57	28-28-28	36-0-0	22-57-57 + in-furrow*	22-57-57 + starch**
1998	Borgman	dry	12-47-47	25-25-25	32-0-0		
1998	Elliott	dry	15-39-39	33-33-33	40-0-0	15-39-39 + in-furrow*	
1998	Hoff	solution	13-43-0	22-22-0	34-0-0	19.8-15.5-0-2.9S-0.4Zn	17.6-13.8-0-5.8S-0.4Zn
1998	Klasing	solution	12-42-0	30-30-0-	44-0-0		
				1Zn-0.5B			

*5 gallons/acre of 10-34-0 in-furrow = 5.5-18-0

**starch was mixed in with dry starter fertilizer

<u>Results</u>

In-field observations and measurements by me and by the producers consistently found increased growth and earlier tasseling due to applications of starter fertilizer. This was also visible in aerial photos of the experiments. In general, differences between plots with starter and plots with none were clear, but differences between plots with different types of starter were small or undetectable. The N-only starter plots appeared to have less growth than the N + P starter plots in an early-season aerial photo from the Borgman 1998 experiment (the N-only starter also yielded lower at this experiment).

Significant yield increases to starter fertilizer were found in six of the seven experiments, generally with no difference in yield between the different starters (see Table 3). A yield increase of at least 9 and up to 26 bu/acre was seen in each of these six experiments. Yield increases were smaller in 1998 than in 1996 or 1997. I don't know why response to starter fertilizer is bigger some years than others, and I haven't heard anyone else with a good explanation either.

Table 3. Yield results for on-farm starter fertilizer experiments in no-till corn.

Year	Cooperating producer	no starter	low N/ high P_2O_5	med N/ med P_2O_5	N only	other #1*	other #2*	LSD**
		yield with starter treatment category:						
		bu/acre						
1996	Borgman	170	190	189	184			6
1997	Borgman	137	150	154	155			12
1997	Elliott	106	132	127	132	130 †	128 ‡	13
1998	Borgman	130	140	139	134			9
1998	Elliott	141	138	149	150	143 †		5
1998	Hoff	130	140	138	137	140 §	139 ¶	6
1998	Klasing	166 ***	148	151	156			8
Average over 1st 6 sites		136	148	149	149			3

*all starter treatments listed as "other" had medium N & P_2O_5, plus additions as noted below (and in Table 2):
**least significant difference, statistically, at the 95% confidence level
† placed starter + 10-34-0 in-furrow
‡ starch mixed with starter fertilizer
§ plus about 3 lb S/acre
¶ plus about 6 lb S/acre
***yield loss to starter appears to be associated with late application of Basis Gold (see text)

In the seventh experiment, at the Klasings', plots with starter fertilizer yielded significantly **less** than plots with no starter by an average of about 15 bu/acre. This was probably due to a late application of Basis Gold. Basis Gold has a label restriction of 12" corn height because it can damage the embryonic ear which begins to form shortly after the corn passes 12" height. Basis Gold was applied in this field when the corn was about knee-high (18" to 20"); because the plants were larger in the starter fertilizer plots, developing ears were probably damaged more in these plots. This idea was confirmed by ear size measurements at harvest, which showed that ears were significantly larger in the plots that had not received starter fertilizer. The yields from this location were not used in calculating average treatment effect across all locations.

The only experiments in which N + P starter appeared to out-yield N-only starter were the Borgman 1996 and 1998 locations. These experiments were on rented ground that tested low in P. Using starter P may be worthwhile in this situation, but when soil test P was medium or higher there was no benefit to adding P. Overall, the N-only starter appears to be the most cost-effective alternative.

Averaged over six experiments, the N-only starter increased yield by 13 bu/acre. An average value for this yield increase might be 13 bu/acre x $2.50/bu = $32/acre. By comparison, the material cost for the N averaged about $9/acre at the rates used, and equipment cost for the starter attachments is about $3/acre if used at least 5 years over at least 300 acres. This gives an average net return to material and equipment of $32 - 9 - 3 = $20/acre for these six experiments. Slower planting is another cost associated with using starter fertilizer, but is very difficult to put a number on. On average, using starter slows the planting operation by about ten to fifteen percent. The value of this lost time depends on the individual farming operation.

There did not appear to be any yield benefit to using in-furrow starter in addition to placed starter, nor to the addition of starch, S, Zn, or B in the experiments where those materials were used. The starch treatment was tried because researchers in Idaho have reported yield gains from using row-placed starch for wheat.

Table 4. Yield response of no-till corn to starter fertilizer in small-plot experiments.

Year	Researcher	Location	Yield Response
			Bu/ac
1996	Wiebold	Columbia	-2
1996	Blevins	Columbia	17
1996	Stecker	Columbia	4
1996	Stecker	Novelty	12
1996	Stecker	Corning	5
1997	Wiebold	Columbia	10
1997	Blevins	Columbia	0
1998	Wiebold	Columbia	15
Average			8

Other recent experiments in Missouri

I know of eight other starter fertilizer experiments for no-till corn that have been conducted in Missouri over the past three years. These have all been small-plot experiments, mostly at Bradford Research Farm near Columbia. Results are shown in Table 4. Average yield response to starter over these eight experiments was 8 bu/acre. This is not as large as the 12 or 13 bu/acre in the strip-plot experiments, but confirms that substantial yield responses to starter are often observed in Missouri conditions.

Summary

- Seven on-farm starter fertilizer experiments in no-till corn were conducted from 1996 to 1998 using large strip plots.
- The main treatments were no starter, low-N/high-P_2O_5 starter, medium-N/medium-P_2O_5 starter, and N-only starter.
- Averaged over six of these experiments (the seventh was omitted due to probable herbicide damage), all starter treatments gave statistically significant yield increases relative to the no starter treatment of 12 or 13 bu/acre.
- The N-only starter was best economically due to lower material cost. Average return to fertilizer and equipment for this treatment was $20/acre.
- The cost of slower planting when starter fertilizer is used is difficult to put a number on, but should be subtracted from the $20/acre figure above to figure true return to starter.
- Eight small-plot experiments in Missouri over the last three years have shown an average yield response to starter of 8 bu/acre for no-till corn.
- Starter fertilizer for no-till corn in Missouri appears to be a profitable practice on average.

Acknowledgements

I would like to thank Earl Borgman, Richard & Jim Elliott, Eddie & John Hoff, and Jim & Jerry Klasing for their interest and cooperation, not to mention the time that they invested in this research. Thanks also to Tom Anderson, Pieter Los, and Dave Hoehne for an excellent job of helping me with this research. Finally, I would like to acknowledge support for this research from the Missouri Agricultural Experiment Station.

Site-Specific Fertility

Spectral radiometer to control variable-rate N applications for corn

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Objectives and relevance:

- We have already done four years of research showing that corn color measured with a spectral radiometer can do a good job of predicting how much N is needed at sidedress time or for mid-season rescue applications.
- Our ultimate objective is to mount the radiometer on a variable-rate applicator to make real-time variable-rate N applications based on corn color.
- This technology can potentially be extended to variable-rate N applications for other crops as well.
- The radiometer senses and corrects for variations in incoming sunlight due to time of day and clouds, but it appears that these corrections need improvement for the radiometer to be practical in the field.
- Our objective for this project is to improve the radiometer's corrections for variations in incoming sunlight so that it will give the same color reading (and same recommendation) for the same plants regardless of time of day or cloud conditions.

Procedures:

- Spectral radiometers will be mounted in a stationary position about ten inches above the canopy.
- Readings will be taken from morning until night over several days with a range of sky conditions (sunny, overcast, partly cloudy).
- Experiments will be done on corn ranging from knee-high to just before tasseling.
- Mathematical functions will be developed to compensate for the effects of changing sun angle and cloud conditions.
- A computer programmer will incorporate these functions into programs for translating radiometer readings into variable-rate N recommendations.
- These programs will ultimately be used in developing real-time control of variable-rate N applicators based on corn color measured with a spectral radiometer.
- We will also continue separately-funded experiments in which we collect GPS (global positioning system)-referenced radiometer readings in field-scale on-farm N rate experiments (three experiments in Missouri and three in Iowa)

Current status and importance of research area:

- Field-scale research has shown that corn N need often varies by 100 lb N/acre or more within a field (Malzer et al., 1996; Blackmer and White, 1998).
- Nitrogen-deficient corn is lighter in color than nitrogen-sufficient corn, and color measurements can be used to predict N need (Piekielek and Fox, 1992).
- Color has been mainly measured with a hand-held instrument in the past, which has limited its usefulness for N

management in production fields; measurement on the go with an instrument on board a variable-rate applicator would make this idea much more practical.

- A German company, Hydro, has already introduced a variable-rate N applicator for wheat based on this concept. However, reports from Kentucky, where one has been imported, are not favorable, nor is this applicator suited for use on corn.
- Our research group appears to be in the lead nationally in terms of hard data that can be used to translate radiometer measurements into N rate recommendations.
- Ten on-farm experiments in Missouri showed that corn color measured with a radiometer was related to optimum sidedress N rate (Figure 1).
- A radiometer could also be used to direct high-clearance rescue N applications when substantial N is lost during a wet May/June, as happened in northeast Missouri in 1998 (Figure 2).
- This technology could become very important for maintaining productivity if N fertilizer comes under regulation, because it allows precise application according to crop needs.

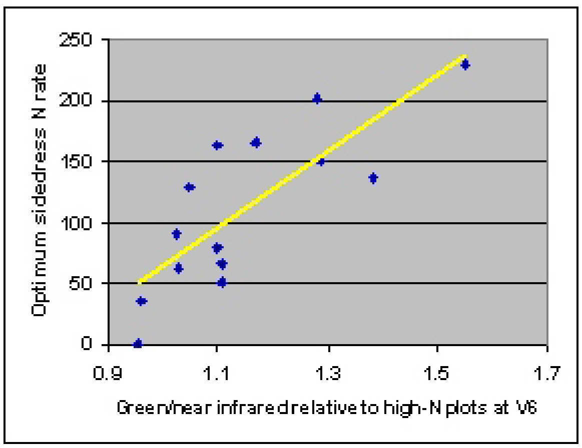

Figure 1. Corn color measured with a spectral radiometer can predict optimum sidedress N rate for on-farm experiments in Missouri.

Figure 2. Nitrogen deficiency was widespread over northeast Missouri in 1998 due to wet soil conditions in June leading to denitrification.

Timetable for proposed research:
April-June 2001Plant corn at Bradford Farm near Columbia over a wide range of planting dates, so that we will have corn at a variety of stages at any given time.
June-August 2001Take radiometer readings on corn from morning till night with a variety of sky conditions and corn growth stages.
Sept.-Nov. 2001Analyze data and develop mathematical functions to correct for sun angle and sky/cloud conditions.
December 2001Incorporate correction functions into a computer program that translates radiometer readings into N rate recommendations.

Strategy for application of knowledge:

We hope to partner with, or otherwise make the information that we generate, available to industry so that this technology can be commercialized in a way that will result in consistent and reliable N rate recommendations and applications. We are in contact with three companies with an interest in developing this technology for market: AGCO, Patchen, a former John Deere subsidiary based in California that manufactures weed vision/spraying systems, and Crop Circle, a startup manufacturer of spectral radiometers for agricultural use. We have had several discussions with Dave Murray of AGCO about the possibility of high-clearance variable-rate radiometer-directed N applications.

References:

Blackmer, A.M. and S.E. White. 1998. Using precision farming technologies to improve management of soil and fertilizer nitrogen. Aust. J. Agric. Res. 49:555-564.

Malzer, G.L., P.J. Copeland, J.G. Davis, J.A. Lamb, P.C. Robert, and T.W. Bruulsema. 1996. Spatial variability of profitability in site-specific N management. p. 967-975. In P.C. Robert et al. (ed.) Precision Agriculture, Proceedings of the Third International Conference. American Society of Agronomy, Madison, WI.

Piekielek, W.P. and R.H. Fox. 1992. Use of a chlorophyll meter to predict sidedress nitrogen requirements for maize. Agron. J. 84:59-65.

Budget:

- The budget will be primarily for the salary of Eduardo Souza, a visiting professor of Agricultural Engineering from Brazil, who will conduct the experiments.
- Eduardo has been a visiting scientist at the University of Missouri since the summer of 2000.
  - He has done considerable background research on the problems of sun angle and cloud cover effects on reflectance values measured by a spectral radiometer.
  - His support from his home institution runs out in June 2001. In order to keep him here through the field season to bring this project to completion, we propose six months' salary at \$3500/month for a total of \$21,000.
- We also propose four weeks of computer programmer time at \$25/hour, for a total of (4 weeks) x (40 hours/week) x (\$25/hour) = \$4,000.
- We have most of the equipment that we will need for the experiments (two different models of spectral radiometer, laptop computers, cables) but propose a budget of \$1000 to be used for miscellaneous additional equipment needs such as fabrication of radiometer stands, replacement filters for radiometers, etc.

Budget summary:

Salary, visiting scientist	
100% time for 6 months	\$21,000
Programmer contract time	4,000
Miscellaneous equipment	1,000
Total	**\$26,000**

Appendix- Additional Report

Liming in Missouri
in the 20th Century

J.R. Brown and John Stecker

Agricultural Experiment Station
College of Agriculture, Food and Natural Resources
University of Missouri-Columbia

Special Report 548

February 2003

Liming in Missouri in the 20th Century

J. R. Brown and John Stecker

Preface

Soil acidity research conducted in Missouri was last summarized in 1969 (Fisher, 1969). More than thirty years have passed, which suggested that another summary may be in order. Therefore, a formal proposal was made to review the research conducted since the mid-1960s and publish a summary for distribution to interested parties. The Fertilizer and Liming Materials Advisory Councils established by the Missouri Fertilizer and the Missouri Agricultural Liming Materials Laws (Missouri Revised Statutes, sections 266.336 and 266.543) oversee the implementation of the laws. The Director of the Missouri Agricultural Experiment Station manages the fees collected under the inspection programs for fertilizer and liming materials with the advice of the advisory councils. The councils recommended funding of the proposal in early 2000 and this document is the result.

Research done at the Missouri Agricultural Experiment Station since the mid-1960s included both field projects and graduate student research problems focused mainly in the laboratory. As we started the review, historical questions concerning the derivation of the Missouri liming program arose. Thus, the document expanded over that which may be expected from the statement of objectives in the original request for funding and includes both state of the liming program in Missouri as well as a condensed history.

The authors considered the following target audiences might benefit from material in this paper:

1. Farmers and consultants.
2. University of Missouri research and extension soil scientists and agronomists.
3. Agricultural faculty and students at the universities and colleges of the state.
4. Regional and national soil testing and nutrient management specialists.
5. Missouri Limestone Producers Association and MO-AG Industries Council members.

Acknowledgements

This paper could not have been written without the work done by many research scientists and extension specialists. We have cited much of this work, but likely we have missed some that should have been cited. For those unintentional omissions we apologize.

The Missouri liming program is especially indebted to Dr. Ted R. Fisher, who devoted much of his short career as a MU faculty member to liming issues. Dr. Manjula Nathan, Director of the Columbia-based Soil Testing Laboratory, Associate Dean Michael Chippendale, and Joe Slater, Manager of Missouri Fertilizer/Agricultural Lime Control Services, were particularly helpful by providing access to the soil test files, for support of our proposal, and for procedural information, respectively.

The Director of the Missouri Agricultural Experiment Station provided funding for this paper with the advice of the Advisory Council as established by the Missouri Agricultural Liming Materials Law. The Executive Director of the Missouri Limestone Producers Association, Steve Rudloff, was supportive in getting this paper published.

Matthew Herring, agronomy specialist, University Outreach and Extension, reviewed the manuscript.

Contents

Introduction

A thorough review of liming in Missouri has not been conducted since Dr. Ted Fisher summarized research through 1967 (Fisher, 1969). The Fisher summary provided the data supporting changes in the liming recommendations. More than 30 years have now passed, and it seems appropriate to review the recommendations and utilize research on liming conducted since 1970, which may suggest modifications in the recommendations.

This publication reviews the status of liming and soil acidity at the end of the Twentieth Century. There are several issues involved, which are overlapping, causing organizational problems in putting this publication in readable form. Following a broad overview of soil acidity, there is a condensed discussion of the evolution of liming practices since the formation of the Missouri Agricultural Experiment Station with the addition of research results of liming studies conducted since 1970. A discussion of current laboratory methods, a reevaluation of the current recommendations, and suggestions for changes and further research follow the discussion of the evolution of liming activity in Missouri.

The following are the objectives of this publication.

Objectives

- Provide a condensed history of liming research and practices in Missouri.
- Summarize the methods in use at the end of the Twentieth Century to estimate the need for liming material.
- Summarize research on liming conducted by the Missouri Agricultural Experiment Station between 1967 and 1999 and related issues.
- Recommend improvements in the recommendation program for agricultural liming materials in Missouri.

Soil Acidity

Liming of acid soils is considered by many soil scientists as the first step toward balanced nutrition of cultivated plants. Barber (1984), in a condensed review of the history of liming of agricultural soils, cited references as far back as 200 BC that extol the virtues of lime. Remnant pits from which marl was mined for spreading on crop fields are still present on fields at the Rothamsted Station in the United Kingdom. The first experiments were started at Rothamsted in 1843, so spreading of marl must have started in the previous century or before. In the Western Hemisphere Ruffin (1821) is given credit for drawing attention to the benefits of “calcareous manures.”

Acid soils in humid regions have developed through removal of basic cations by leaching with rainfall charged with carbon dioxide. Additionally, crop removal and acidifying fertilizers, especially ammoniacal nitrogen and sulfur containing materials, have increased soil acidity. Removal of produce from agricultural land is also inherently acidifying (Albrecht and Smith, 1952).

Soil acidity adversely affects most arable crops in several ways. Albrecht (1941), for example, showed that acid soils were infertile because of inadequate calcium (Ca). Foy (1984) summarized the physiological effects of hydrogen (H), aluminum (Al) and manganese (Mn) toxicities on plants in acid soils. Deficiencies of calcium, magnesium (Mg) and molybdenum (Mo) resulting from soil acidification significantly decrease plant biomass production (Clark, 1984). In addition to toxicities and deficiencies associated with soil acidity, availability of almost all essential nutrients and activity and species distribution of microbes are influenced by the relative acidity of a soil (VPI, 1953; Coyne, 1999).

Field studies to determine the benefits to plants of reducing soil acidity have been conducted at least since the early 19th Century. Attempts were made to determine the nature of soil acidity and to explain soil acidification. Jenny (1961) likened the course of these studies to a merry-go-round. Illustrating the analogy were alternating emphases of the causal agents responsible for the negative effects of soil acidity on plant growth. The impact of aluminum on plants and its role in soil acidity was of great interest in the early 20th Century (Hartwell and Pembee, 1918). As methods of measuring proton activity in soils improved, the focus shifted to the study of hydrogen in soil acidity. Then in the early 1950s attention was redirected toward aluminum (see, for example, Coleman and Harward, 1953). The role of aluminum in soil acidity has become better understood, however, there are unanswered questions concerning the nature of the interacting factors that affect soil acidity and its impact upon plant growth. One excellent review of soil acidity concepts was written by Bloom (2000).

Magdoff and Bartlett (1985) showed variable buffering of soil to lime additions. They titrated soil samples that had been incubated with calcium carbonate ($CaCO_3$) with strong acid. The pH in the resulting titration curves changed exponentially with applied acid. When these titrations were conducted in 0.01 M $CaCl_2$ (calcium chloride), the plot of pH against quantity of acid was linear between pH 4.5 and 6.5. The soils were highly buffered above and below pH 6.5 and 4.5, respectively. Buffering increased with an increase in cation exchange capacity (CEC).

Soils contain both permanent and variable cation exchange capacities. When the acidity in an acid soil is progressively eliminated by liming, the CEC tends to increase as the impact of the variable charges comes into play (Thomas and Hargrove, 1984). Soil organic matter (SOM) contributes much of the variable CEC in soils through ionization of carboxyl (-COOH) and aromatic hydroxyl (AR-OH) groups. The ionization of these two organic groups is not complete until pH 8 and 11 are reached, respectively. The ionization process contributes to the buffering of both soil pH and active aluminum. In acid soils many –COOH sites are satisfied with Al^{+3} not exchangeable to potassium chloride (KCl) (Bloom et al., 1979, Bertsch and Bloom, 1996).

Hargrove and Thomas (1982) reported that Al-SOM buffers at a higher pH than H-SOM. In general as the soil solution pH rises above 5, the Al-SOM ionizes and the aluminum activity is controlled by the solubility of $Al(OH)_3$. The aluminum in SOM combinations slowly becomes active and is precipitated as gibbsite. In the process as many as three protons may be released by the reaction of active aluminum and water at soil pHs below 7.0 (McLean, 1976). Barium chloride ($BaCl_2$) and triethanolamine (TEA) have been used to determine total titratable acidity (Mehlich, 1948, Thomas, 1982). This procedure measures the total acidity to pH 8.2. It may, however, be more useful to have an estimate of total acidity based at pH 7.0, because most arable crops do best when soils are slightly on the acid side of neutral. The increase in soil pH from 7.0 to 8.0 is slow as suggested, for example, by the work reported by Magdoff and Bartlett (1985). In order to neutralize soil acidity to a target pH, one must account for the slowly released acidity that is non-exchangeable to 1 M KCl. This acidity, variably termed residual, labile, or pH dependent acidity, can be calculated by subtracting the quantity of KCl extractable acidity from the total acidity determined by $BaCl_2$-TEA @ pH 8.2 or a method that measures total acidity at pH 7.0.

It is this residual acidity that is estimated by the various buffer methods used to determine lime requirements by soil testing laboratories. These buffer methods include the original Woodruff method (Woodruff, 1948), the revised Woodruff (Cisco and Brown, 1984), and the SMP method (Shoemaker, McLean, and Pratt, 1961; Watson and Brown, 1998). All these soil test methods are quick test methods, which permit only a short contact time between the buffer solution and the soil sample. It is unlikely that all the residual acidity, as defined in the previous paragraph, can be estimated by quick test methodology. Therein lies the need for calibration (Sims, 1996).

Liming soils with agricultural limestone or other liming materials neutralizes the hydrogen and aluminum ions held on the soil exchange sites to form either neutral (H_2O) or insoluble products

($Al(OH)_2$). This neutralization causes the soil pH to approach 7.0. Excess lime raises the pH above 7.0 often with adverse effects on plant nutrition.

Attempts to calibrate plant response to measures of acidity (pH, KCl extractable, total acidity, $CaCO_3$ incubation titration, percentage base saturation, etc.) have given erratic results (Farina and Channon, 1991 and Blosser and Jenny, 1971 as examples). This failure is especially true with attempts to extrapolate laboratory and greenhouse results to the field and emphasizes the need for field calibration of any quick soil test.

Adding liming materials to acid soil benefits many species of plants, but plants thrive at different ranges of soil acidity, so the target of liming is to provide the proper soil acidity for the plant or plants to be grown (Havlin et al., 1999). Liming an acid soil usually increases the soil content of the essential nutrients calcium and magnesium. Adding calcium and magnesium to acid soil replaces acidity from the exchange complex, which subsequently is neutralized by the basic component of the liming material. Lowering the intensity of soil acidity enhances microbial activity, which tends to increase the availability of nutrients, especially N, P, and S. Alteration of the proton activity in soil solution affects the solubility of most micronutrients. A more complete discussion of soil acidity can be found in soil science texts such as Hassett and Banwart (1992).

History of Liming in Missouri

Liming experiments had been conducted in Midwestern United States by 1903 (McLean and Brown, 1984). A review of Agricultural Experiment Station publications of humid region states from the first decade of the Twentieth Century makes numerous references to research that included liming treatments (Duley and Miller, 1926). Most early field studies were designed in a very systematic manner without replication to determine the factors most limiting crop production. Nitrogen fertilizers were not readily available, so reliance was placed on manure and legume crops as sources of N. Bonemeal was an early P source with acidulated phosphate (ordinary superphosphate) and ground rock phosphate also used. Potassium was applied as “potash” which likely was muriate of potash (KCl). The focus of liming treatments in these early field studies seemed directed toward demonstration of the value of liming rather than the determination of rates of application.

Selected citations of the earlier work on liming in Missouri have been included in chronological order. The 40 years from 1888 through 1927 included numerous demonstration studies scattered across the state. The sophistication of liming research intensified from 1928 through 1946. Research focused on soil chemistry because the Soils Department faculty and graduate students included people such as C. E. Marshall, Hans Jenny, L. D. Baver, and Ellis Graham. In addition, World War II affected both the approach to the science of soil and the management of cropland. Starting in 1947 the increasing availability of manufactured fertilizers changed agriculture forever. Intensive research funded by the fertilizer industry and state and federal governments resulted in hundreds of fertilizer and lime studies including soil test calibration.

Soil testing laboratories were located in almost all Missouri counties by 1950. Extension programs on crop production were generated by interest in fertilizer. However, by 1969 methodology had changed such that the accuracy and precision of the county soil testing labs was questioned. This led to the centralization of soil testing at Portageville and Columbia, where the soil sample volume could support precise analytical tools. From 1970 to the end of the century interest in soil fertility including liming continued. Yield levels increased with improved varieties and the development of hybrids. Also greater precision was desired in recommendations and management of nutrients.

1888–1927

Soil acidity and liming did not seem to be of much concern prior to 1900. In fact, historic Sanborn Field, which was started in 1888, did not have a liming treatment until 1928 (Smith, 1942). Field experiments were started in many of the soil regions of the state in the first decade of the century (Miller and Hutchison, 1910). The experimental sites were located near local train stations, as trains and horses were the common means of transportation at the time.

In most cases, the set of treatments in these early experiments consisted of manure, P, P + K, P + K + manure, and P + K + manure + lime or some variation of these combinations (Miller et al., 1915; Krusekopf, 1938). These treatments were similar to those used in other states such as Illinois (Bauer et al., 1945). Lime was rarely applied in excess of 4,000 pounds per acre. There were no early rate studies with lime due to limitations of material and labor. These early field studies, while unacceptable by late 20th Century research standards, provided information that was the basis for liming and fertility practices recommended to farmers into the middle of the 20th Century.

Early Missouri liming studies were reviewed by Miller (1909) for the American Society of Agronomy. Some yield depressions attributed to lime were observed but with no explanation. Duley and Miller (1926) summarized studies on 14 different fields and stated that “on fields where the combination of all three (phosphate, lime, and manure) of the above materials [were all applied], the yields have usually been outstandingly high.”

The lack of a reliable measurement of intensity of acidity in soils was an early limitation to scientific study of soil acidity problems. One early measurement technique was the litmus paper test. Barlow (1916) described in detail how to use litmus paper to estimate the intensity of soil acidity. The litmus paper test, however, was very subjective, and, according to Barlow, the interpretation of the test differed between practitioners.

The Bureau of Chemistry in the United States Department of Agriculture was a major player in developing methodology for estimating acidity in agriculture. For example, the Vietch test for acidity was formulated and was used extensively in some state laboratories (Vietch, 1902). By 1920 there were several methods to estimate the intensity of acidity. These included the use of litmus paper, the Truog test, and the Vietch test (Miller and Krusekopf, 1920).

Although by the 1920s soil testing materials to estimate lime needs were made directly available to farmers, calibration studies that linked liming material to be applied with the results of these soil tests were limited. Miller and Krusekopf (1920) thoroughly covered agricultural liming practices in a Missouri Agricultural Experiment Station bulletin.

Availability of liming material during this period gradually increased, as the need became more apparent. By 1920 commercial limestone quarries were in operation. Also, Missouri extension personnel were providing individuals and groups of farmers with information about the purchase and use of small limestone crushers (Miller and Krusekopf, 1920).

Lime recommendations were based on material such that the majority passed a 10-mesh screen. While it was recognized that some fields needed 5 or more tons of ground limestone, the dominant recommendation for the period was 1 to 2.5 tons per acre. An application of 1 to 1.5 tons per acre every 4 to 6 years was suggested as a reasonable practice (Miller and Krusekopf, 1920). Miller (1924) suggested limestone rates of 1 to 2.5 tons per acre in his soil management textbook.

Thus by 1927 there was widespread knowledge about liming acid soils to benefit the contemporary corn-forage legume based crop rotations. Acceptance of soil testing to estimate lime needs was increasing, yet calibration data for the tests regarding the amount of liming material needed were still lacking.

1928-1946

During this time period, the Soils Department developed expertise in clay mineralogy and ionic chemistry, which led to better understanding of the behavior of soil additives. Concurrently the liming program improved quantitative estimation of lime needs and increased the emphasis on quality of agricultural liming materials.

According to Trotter and Coleman, "Recommendations are uniformly made in terms of limestone ground finely enough so it will all pass through a 10-mesh screen and have a calcium carbonate equivalent of 95% or more." When lime was coarser than 10-mesh, their suggestion was "The recommendation gives the minimum amount to apply. If in doubt apply more" (Trotter and Coleman, 1928). The authors republished their circular with only minor modifications in 1935 (Trotter and Coleman, 1935).

Miller (1936) published guides for quantities of limestone based upon the Comber soil test for acidity, the fertility rating of the soil and the kind of legume crop. The Comber test used an alcoholic solution of potassium thiocyanate (KSCN) (Comber, 1920). The KSCN reacted with soluble iron (Fe^{2+}) forming a red colored complex. Increasing intensity of red color in the filtrate indicated increasing soil acidity. Color charts were available for conversion of color intensity into pounds of limestone per acre.

Although not specifically stated by Miller (1936) and other authors of the period, it was implied that since crop rotations included legumes to supply N for grain crops, lime needed by the legume would automatically satisfy the lime needs of the non-legume crops. The amount of N added to soil by legumes would sustain yields on low fertility land of 25 bushels corn per acre, while medium and high fertility land would produce 35 and 50 bushels per acre, respectively. The Miller recommendations for limestone called for a calcium carbonate equivalent (CCE) of 95% with nearly all material passing a 10-mesh screen. Miller (1936) stated "…the percentage of material which passes a 40-mesh screen represents the percentage of limestone which is active in the soil the first year." Miller's comments were similar to those made by Trotter and Coleman (1935).

Baver and Bruner (1939), in their comprehensive soil testing methods bulletin, included a modification of the Comber approach for estimating lime requirement. They retained the Comber test, but instead of a fertility rating they used 3 categories of exchangeable calcium as determined by an oxalate turbidimetric test using an acid extractant. The quantities of limestone recommended for each Comber-calcium category differed from those used by Miller (1936). No mention was made of limestone quality. Because of the apparent absence of published material, it is assumed that the bulletin by Baver and Bruner served as a basis of lime recommendations up through the end of World War II.

The primary achievement of soil liming research during the period 1928 to 1946 was the improved estimation of the amount of lime to apply. Several extension publications on liming were published up through 1941. As World War II ended in 1945, faculty returned to campus to resume a departmental research program, and an influx of veterans financed by the GI bill provided a sizeable pool of graduate students. Going into 1947, the stage was set for rapid advancement of soil science knowledge and an explosion in agricultural production.

1947-1970

Significant changes occurred in agriculture in general and in the soil fertility programs of the Missouri College of Agriculture from 1947 to 1970. Manufactured fertilizer became readily available after World War II as a result of advancements made in the munitions industry during the war. Cheap nitrogen fertilizer for the first time became readily available. Use of ammonium nitrate and anhydrous ammonia increased almost exponentially after 1947. Both of these nitrogen fertilizers increase soil acidity, which increased the importance for a soil acidity monitoring program. The research and extension faculty of the Soils Department did an excellent job of providing an information stream for Missouri farmers, which resulted in increases in crop production and the use of fertilizers and liming materials.

During World War II, C.M. Woodruff served as an electronics scientist with the War Department. Upon his return to the University of Missouri after the war, he used his experience to construct a simple pH meter, which he called a limemeter. Potentiometers with a glass electrode and a calomel electrode were more accurate and precise in measuring active acidity than the Comber test or other indirect measurements. At the time the potentiometers used to measure soil acidity were fragile and expensive in part because of reliance upon tube electronics. Woodruff used his experience with the electronics of ruggedly built military radar instrumentation to make a rugged and cheap pH meter.

To supplement the limemeter, Woodruff formulated a buffer to estimate the lime requirement of soils. His initial publication reported that the buffer was formulated to have a pH of 7.0 (Woodruff, 1947). When mixed in the correct proportion with acid soil, the calcium and magnesium in the buffer mixture replaced exchangeable acidity from the soil exchange complex, which Woodruff called exchangeable hydrogen. In turn, this exchangeable acidity depressed the pH of the soil/buffer mixture. Woodruff stated that each 0.1 pH unit depression from 7.0 "corresponds to a requirement of 1000 pounds of 10-mesh mill run limestone per acre-plow-depth of soil" (Woodruff, 1947). The following year Woodruff published a refinement, which showed that each 0.1 unit of pH depression of the soil/buffer mix below 7.0 was equivalent to 1 me H per 100 grams of soil (Woodruff, 1948).

During the later part of the 1940s, Ellis Graham developed a set of simple soil tests that enabled each county to have a soil testing lab. Graham (1950) incorporated the Woodruff methodology of estimating the lime requirement of Missouri soils in his circular entitled "Testing Missouri Soils." This circular and the succeeding bulletin used the concept of ionic saturation of the colloidal complex, which subsequently was expanded into the Balanced Soil Saturation method of evaluating the cation balance in soils. Graham made no statements about limestone quantity or quality in his circular.

Later Graham (1959) expanded upon his concept of the balance of cations and salt pH. In theory if the balanced soil saturation concept was followed, a lime requirement could be calculated from the quantity of calcium needed to achieve 75% calcium saturation of the calculated CEC of the soil. Graham included a table to determine the effective calcium per ton of limestone using the CCE and percentage of particles that passed a 40-mesh screen with "proportionate amounts" through 8 and 100-mesh screens. The maximum effective calcium per ton allowed was 400 pounds per ton (Note that if a liming material has 100% CCE there should be 800 pounds of calcium per ton with the effectiveness reduced by particles larger than 100- or 60-mesh). Graham's publications served as resource material for the county lab soil testing program.

The county soil testing laboratories served the county agents (later many became area agronomists) in promoting increased crop yields through balanced fertility programs. The Soils Department provided the county labs with supplies and equipment at cost. Research faculty in the Soils Department developed a statewide program of soil fertility research, including liming studies to calibrate the soil tests for improved interpretation. George Smith, C.M. Woodruff, C.E. Marshall, Ellis Graham, Ted Fisher, and Earl Kroth all contributed to a strong soil fertility research program. Arnold Klemme, Marshall Christy, Alva Preston, and John Falloon (state extension soil fertility specialists) provided interpretive material and technical support during the years when the county labs were most active. The interpretive material enabled the county extension agents and later area agronomists to make recommendations for lime and fertility based upon soil tests run in the local soil testing lab.

Another addition to the soil evaluation program of the Soils Department in 1957 was the introduction of the salt pH measurement (pH_s or pH in a 1:1 soil and 0.01 M $CaCl_2$ suspension). This pH measurement was based on work by Schofield and Taylor (1955). It provided the grower with an estimate of the active acidity in the soil following application of the recommended amount of chemical fertilizer. The application of fertilizers, which are salts, tends to lower the pH of the soil. Both the Woodruff buffer and salt pH remain routine soil tests in the Missouri soil testing program.

Graham (1959) included an interpretive scale for soil pH measured in 0.01 M $CaCl_2$ suspension. This scale is reproduced as follows:

pH_s	**Interpretation**
>7.5	Alkali soil
7.5	Free lime
7.0	!00% base saturation
6.5-7.0	Ideal for alfalfa, satisfactory for most crops
6.0-6.5	Ideal for most crops, satisfactory for alfalfa
5.5-6.0	Satisfactory for grasses, small grains and corn
5.0-5.5	Deficient in calcium, should be limed
4.5-5.0	Very deficient in Ca; unsatisfactory for almost all crops

Graham (1959) included the concept of balanced soil saturation in his revised bulletin. Simply stated, addition of liming material and potassium was needed to provide 75% saturation of the CEC with calcium, 10% with magnesium, 2.5 to 5% with potassium and the remaining 10 to 12.5% with acidity. This concept was included in Missouri lime and fertilizer recommendations in part as a teaching tool. Emphasis on the balanced soil saturation concept became minimal after 1968 for two reasons. Research demonstrated that considerable fluctuation in the percentages was possible without affecting crop performance. Further, the concept was expanded into areas of calcareous soils where soluble calcium inflated the CEC, resulting in unneeded recommendations of potassium.

Interpretation guidelines by Christy (1965, 1968) provided information on making lime recommendations for the period from 1961 through 1977. The Woodruff buffer procedure was used to estimate “exchangeable hydrogen” in a soil sample (Graham, 1959). Through 1965 the exchangeable hydrogen amount expressed in milliequivalents (Me or me per 100g) was multiplied by 400 to get an “acidity index.” An acidity index of 400 represents the pounds of effective calcium per acre furrow slice of soil (2,000,000 pounds) equivalent to 1 me of exchangeable hydrogen per 100 grams of soil. The lime recommendation was given in pounds of effective calcium needed to neutralize the estimated acidity with 100 added to give a range in the recommended amount of lime. The grower calculated his actual agricultural lime need by dividing the acidity index on the soil test report form by the “effective Calcium Index” of the limestone to be used to get tons of limestone to apply per acre.

During this period recommendations included statements concerning the adequacy of calcium and magnesium as measured by soil tests based on the balanced soil saturation tables. Dolomitic limestone was always recommended when the percentage of magnesium saturation was below 10%. Soluble magnesium was recommended only when the magnesium saturation was below 5% of the CEC.

Significant changes in the soil testing program were started in 1968, which indirectly impacted both soil testing and the interpretation of those tests. The Missouri Cooperative Extension Service decided to start phasing out the county soil testing program and developed a computer program to interpret the soil test results. A regional soil testing lab was installed at the University of Missouri Delta Center in 1968. In 1976 a second regional soil testing lab started operation in Columbia. By 1977 there were only 26 county labs still operating, and these were gradually phased out.

In September 1968 the lime recommendation terminology and calculations were changed (Christy, 1968). The term "neutralizable acidity" was introduced to replace reference to "exchangeable hydrogen." Christy stated "1 ton per acre of standard agricultural limestone is required to supply enough carbonate to offset 1 Me of neutralizable acidity. The value 400 is used below because that figure represents 1 ton of "standard agricultural limestone" in the acidity index tables. Further, lime requirement guidelines for the first time considered pH_s. An attachment to a letter by Alva Preston, Extension Agronomist (Soils), dated August 2, 1968 is summarized below and was incorporated in Christy's material (Christy, 1968).

"1. For pH less than 6.0, multiply neutralizable acidity (Me) by 400."

The value 400 was the effective calcium content in 1 ton of "standard agricultural limestone." The Woodruff buffer had been formulated so that when used with the soil test procedure in theory each 1 Me acidity/100g of soil would depress the buffer pH 0.1 unit.

"2. For pH 6.0 to 6.5, enter 0 except for the following:"

For southern and southwestern soils where forage legumes were to be grown, use the effective calcium (ENM) representing 2 tons of limestone. For other conditions and locations, a maintenance application equivalent to 2 tons of limestone per acre was to be suggested.

"3. For pH 6.5 and above, enter 0."

Note that up to this point, several abbreviations for milliequivalents have been used including Me, me, and meq because of the direct quotations. The current preferred abbreviation is meq (Soil Sci. Soc. Am., 1997).

At this point it seems appropriate to insert some comment on limestone quality, although more detail will be provided in a later section. Prior to World War II, the standard for making lime recommendations was a limestone having nearly 100% passing a 10-mesh screen with a CCE of at least 95% (Trotter and Coleman, 1935). In the 1950s new lime and fertility recommendations adopted a standard limestone that had at least 50% passing a 40-mesh screen and "proportionate amounts through 8 and 100 mesh" and a CCE of 100% (Falloon, 1965). Limestone meeting these qualifications was given an Acidity Index of 400. Falloon (1965) included a table in his publication giving acidity indices for limestones with <100% CCE and/or <50% passing a 40-mesh screen.

The consolidation of the Soils Department and the Field Crops Department into an Agronomy Department under a new chair resulted in, among other activities, a total review of the soil fertility program in Missouri. From about 1968 through 1972 there was considerable activity that makes the time break we have made at 1970 somewhat arbitrary. The 1946-1970 period saw rapid development of the Missouri soil fertility and liming programs. The introduction of calibrated soil tests, the limemeter, increased availability of manufactured fertilizer and the Woodruff buffer all impacted the practice of liming acid soils during the 1947 through 1970 period. Fisher's summary of the liming experiments provided the substance behind the move toward the new liming programs introduced shortly after 1970 (Fisher, 1969).

1971-2000

At the start of the 1971 to 2000 period, the fertility recommendation programs were under review. The introduction of the computer and computer compatible laboratory instrumentation changed the way soil tests were done and interpreted.

Soil testing and recommendations

A gradual change occurred in soil extension activities, which in part might be attributed to the combination of the Soils Department and the Field Crops Department into the Agronomy Department. The state soil extension people were moved to Waters Hall leaving the soil research/teaching faculty in Mumford Hall. A formal Soil Testing and Soil Fertility Committee in the Agronomy Department was charged with the review of all soil fertility programs. This departmental committee continued a high level of activity through the initial tenure of Department Chair R.L. Mitchell and of E.C.A. Runge who followed Dr. Mitchell.

The Fisher (1969) summarization of the results of field lime studies conducted between 1956 and 1963 provided up-to-date calibration data for the Woodruff buffer and salt pH. Fisher summarized the data graphically using relative crop yield within a given site-year as the dependent variable and soil pH_s as the independent variable. Variable soil acidity levels were attained at the initiation of the experiments with the addition of agricultural limestone. Data were analyzed to determine the soil pH_s above which no additional yield increase would be expected. This provided a target pH_s to be attained by application of a "lime requirement" as agricultural limestone.

The review of soil testing and fertilizer and lime recommendations starting in 1969 led to computerization of recommendations. This computerization was finally accomplished in 1971 under the guidance of Dr. Roger Hanson and Marshall Christy.

Prior to the late 1940s, it was assumed that the soil should be near neutral for optimum crop growth. This assumption, in hindsight, likely came from the reliance on crop rotations containing legumes to provide a significant amount of nitrogen for the grain crops to follow. It was understood that one should lime to the needs of the least acid tolerant crop in the crop rotation. By mid-century the use of legumes as the major source of N had declined.

A Missouri liming materials law was passed in 1976 that set standards for agricultural liming materials and included some unique terminology. A discussion of liming material terminology will be included later in this publication. Effective neutralizing material (ENM) was introduced in the new law as the liming material quality designator.

By 1976 the definition of a standard limestone had changed to 50% or more passing a 40-mesh screen with all passing through an 8 and 25% through a 100 mesh screen (Christy, 1976). This change in definition of the standard limestone had been presented earlier by Coleman (1955), but it seemed to take nearly 20 years for it to be used. There are two reasons for pointing out these subtle changes. First, no data based verification for the changes in wording were found, and secondly, it was possible that some limestones were undervalued.

Recommendations were programmed into the University mainframe computer in 1977, and a hard copy was published for use manually (Hanson and Brown, 1977). These recommendations also incorporated the use of Effective Neutralizing Material (ENM) as the liming material quality factor dictated by the state liming law passed in 1976. Calculation of the ENM value of liming materials included an adjustment of the calcium carbonate equivalent (CCE), based upon the fineness assumptions given in the preceding paragraph. In 1985 the liming materials law was modified to include a new fineness factor for calculating the ENM of liming materials. The lime inspection program administered by the provisions of the law started using 8-mesh and 60-mesh screens in addition to the 40-mesh. Weighting was assigned to each particle size based on a review of literature that reported on effectiveness of different particle sizes of liming materials.

The computer program used for converting soil test results to recommendations was rewritten in 1980, particularly to condense the program from a table based interpretation to interpretations based on equations and to base the fertility recommendations, especially P and K, upon research reported by Fisher (1974) (Brown, et al., 1980). A few minor changes have been made in the recommendation program since 1980 (Buchholz, 1992).

The major events affecting the liming program during the 1970-1999 period was the passage of the Missouri liming materials law, especially a data-based-fineness evaluation, and the complete revision of the liming and fertility programs with the appropriate software written for interpretation of soil test results by computers.

Published research

Several field research projects started after the Fisher summary did not have liming as a primary objective, yet liming treatments within the studies provided insight to liming issues. For example, while studying fertility management of forages, Dr. Earl Kroth found that red clover could be successfully grown in established cool season grass fields with acid soils if 2 tons per acre of agricultural limestone were top dressed prior to seeding. Similar results were found by J.R. Brown in his studies on utilization of lime stabilized sludge from milk processing plants in southern Missouri (Brown et al., 1993).

In three studies in the early 1970s, Jim Roth and T.E. (Jake) Fisher evaluated cotton response to lime on three soils that are widespread in the Missouri Bootheel. As the soils varied in texture, CEC, pH_s, lime requirement, and exchangeable magnesium, Roth and Fisher using three distinctly different limestones were able to evaluate several aspects of the current lime recommendations. Table 1 shows the limestone treatments for the different studies (identified by soil series). Because the current limestone recommendations were not in use at the time of study initiation, treatments are given in tons/acre rather than lb ENM/acre.

Table 1. Limestone quantities applied by Roth and Fisher to three sites using cotton as a test crop.

Limestone Source*	Tiptonville	Portageville	Beulah**
	---------------------------- tons/acre ----------------------------		
Jonesboro, IL	0,2,4,8,12	0,2,4,8,12,24	none
Ste. Genevieve, MO (fine)	1,2,4	0.5 banded	2,4,8
Piedmont, MO (dolomitic)	none	none	0,2,4,8,12

*The Jonesboro and Ste. Genevieve limestones were calcitic. The Ste. Genevieve stone was more finely ground than the other two stones.
**Low soil magnesium (62 lb/acre ≈ 3.9% of the CEC).

Jonesboro limestone caused a slight non-significant cotton yield response on the Tiptonville loam soil with 2 tons/acre applied. The lime requirement of this soil (684 lb ENM/acre) with the Jonesboro lime (522 lb ENM/ton) was 1.3 tons per acre. Beginning with a pH_s of 5.3, the Jonesboro limestone increased pH_s linearly with the incremental rates to pH 7.0. Alternatively, the finely ground Ste. Genevieve limestone resulted in the pH_s plateauing at 5.8 with 2 and 4 tons/acre (Roth and Fisher, 1972a). This is consistent with earlier work.

Maximum seed cotton yield (through 8 years) was obtained on the Portageville clay soil with the 4 tons/acre treatment, significantly greater than the 2 ton/acre treatment. This soil with an initial pH_s of 5.8 and CEC of 23 meq/100g had a lime requirement of 748 lb ENM/acre, which translates to 1.4 tons/acre of the Jonesboro lime. So in this case the calculated lime requirement was less than the actual amount of lime that resulted in maximum yield. Maximum pH_s levels on the limestone treated soil occurred 5 to 6 years following application. Previous assumptions suggested that the full effect of lime on soil acidity maximized 4 years following application. Annual banding of the fine Ste. Genevieve limestone (at 500 lb/acre) had no effect on cotton seed yields (Roth and Fisher, 1972b).

Roth and Fisher recognized the low magnesium of the Beulah fine sandy loam (3.9% of the CEC — a minimum of 5% is recommended for row crops and 10% for forages) as an opportunity to evaluate dolomitic limestone relative to cacitic limestone. From the initial soil tests, the estimated lime requirement was 1.4 ton/acre for the Ste. Genevieve limestone (ENM of 788 lb/ton) and 1.7 tons/acre for the dolomitic limestone (ENM of 632 lb/acre). Only the first increment of both applied limestones (2 tons/acre) resulted in significant cotton yield increases. Thus the lime requirement seemed to be validated from the perspective of crop response. However based on a plot of pH_s versus ENM applied, an estimated 8 tons/acre (4728 lb ENM/ acre) of the St. Genevieve limestone would have been required to raise the pH_s to 5.9. Alternatively, 7000 lb ENM/acre of the dolomitic limestone would have been required to reach the same pH_s. Also observed, the finer calcitic limestone increased soil pH_s faster than the dolomitic limestone.

Roth and Fisher's results corroborated some of the limestone recommendations, but also indicated potential inconsistencies or needed refinements in others. On high CEC soils, the calculated lime requirement appeared to be underestimating actual needs. On low CEC soils, the estimated amount of limestone required to reach the target pH_s exceeded the actual amount to which cotton was responsive. There seemed to be no advantage to banding limestone.

During the 1970s and 80s, Dr. Earl Kroth included liming treatments (primarily placement and rate) in several forage studies that also investigated N, P, and K management. In one study there was no crop response to dolomitic limestone on a pH_s 4.0 soil (Kroth and Mattas, 1974). Red clover was successfully seeded into established cool season grass fields that had acid soils provided 2 tons of limestone were top-dressed per acre prior to seeding. Similar results were observed in studies of surface applied lime-stabilized sludge in southern Missouri (Brown et al. 1993).

In an extensive study at the Southwest Missouri Research Center, Kroth and Mattas (1981) used five N-P-K topdressing treatments and four liming treatments (unlimed, 8 ton lime/acre plowed down, and top dressing treatments of 3 and 6 ton/acre). This study investigated the interactive effects of the acidifying effect of nitrogen fertilizer with limestone application on crop yields and soil pH and the effect of lime-stone placement (Table 2). The lime treatments were applied in 1972 (plowdown) and 1973 (topdressing), and forage yields were measured from 1974 through 1978. Specifications on the limestone used were not provided, however soil test results indicate that a dolomitic limestone was used. The only quarry in the vicinity of the Southwest Center that would supply such limestone was at Chesapeake, MO. Assuming no change with time of the limestone from the quarry, a 1997 analysis of this limestone (Missouri Agricultural Liming Materials Report, July 1 to December 31, 1997; Missouri Agricultural Experiment Station, 1998) indicated an ENM value of 432 lb/ton and an magnesium content of 2.5%.

Table 2. Lime placement treatments of a study at the Southwest Missouri Research Center.

Treatment	Applied ENM	Applied Mg	Yield*
Tons/acre	------------------lb/acre	--------------------	
None	0	0	5,800b
3 top-dress	1296	150	5,820b
6 top-dress	2592	300	6,080b
8 plowed	3456	400	6,620a

*Values followed by the same letter are not significantly different.

Kroth and Mattas (1974) concluded, "Three T/A calcium limestone topdressed on tall-fescue is adequate to provide high quality forage free of weedy plants and grasses that are tolerant of acid soil." The only reference to sward composition was given on page 9 in their bulletin in which the zero lime plots were stated to have large quantities of "blackberry vines, sour dock and weedy grasses." One could challenge Kroth and Mattas' conclusion that 3 tons/acre top-dressed is an adequate lime treatment. The plow-down treatment of the study significantly increased hay yields over the topdress treatments. The long-term economics need to be calculated to determine if the extra expense of treating the plow layer with lime at establishment is justified.

Perhaps a more valuable component of this study was the soil data (Kroth and Mattas, 1981). At the conclusion of the study, they sampled every plot by one-inch increments to a total depth of 6 inches and tested each 1-inch increment. Initial soil test results made on samples randomly collected to a 7 inch depth over the entire study area were as follows:

> OM, 2.6%; pH_s, 4.7; neutralizable acidity, 6.1 meq/100g; Ca, 2025; Mg, 151; and K, 154 lb/acre; and CEC, 12.0 meq/100g.

During the seven-year period of the study, the 160 pounds of N applied each year as ammonium nitrate to all plots would have generated the equivalent of 3.4 me of acidity per 100 grams of soil (Kroth and Mattas, 1981)—each pound of N as ammonium nitrate theoretically will result in formation of acidity equal to 3.6 pounds of $CaCO_3$ (Havlin et al., 1999). This quantity of acidity attributable to the nitrogen was equivalent to over half the quantity of acidity in the soil initially. The 3 tons/acre treatment supplied

Table 3. Effects of limestone treatments on soil properties by 1 inch depth increments 7 years after treatment (Kroth and Mattas, 1981).

	Lime treatment[*]			
Soil Depth	None	3 T/a TD	6 T/a TD	8 T/a PD
inch		pH_s		
1	4.1	6.4	6.7	5.0
2	4.1	5.9	6.5	5.9
3	4.4	5.8	6.2	6.7
4	4.8	5.7	6.0	6.8
5	4.9	5.7	5.9	6.8
6	5.0	5.5	5.1	6.7
		Mg lb/acre		
1	135	227	202	259
2	75	120	99	203
3	93	98	80	166
4	96	85	80	128
5	91	83	76	107
6	94	83	86	98
		Ca lb/acre		
1	690	3540	4492	1810
2	567	2608	3177	2950
3	1184	2529	2814	3435
4	1654	2507	2721	3555
5	1932	2546	2658	3661
6	2049	2344	2479	3568

[*]TD = top-dressed; PD = 50% plowed down and 50% applied after plowing and disked in.

sufficient liming material (6 meq/100g) to neutralize the acidity initially in the soil. The pH_s results in Table 3 show that the soil treated with 3 tons/acre still reflected the neutralizing ability of the applied limestone seven years after application. The unlimed plots received the same quantity of N as the limed ones, but the pH_s in the upper three inches of soil dropped well below the initial pH_s of 4.7 (Table 3).

Limestone placement had marked effects on the distribution of the soil acidity neutralization. Despite no mixing with the soil, top-dressed treatments showed neutralization through the full 6 inches sampled. Where the limestone had been mixed with the soil (8 ton/acre plowed down), soil acidity appeared to be neutralized deeper than with the top-dressed treatments, but the acidifying N effect was marked in the upper 2 inches compared to the lower 4 inches of soil. The calcium data in Table 3 further demonstrate the effects of lime placement and N application over time. As Kroth and Mattas pointed out, the top-dressing effects on hay production were marked. This effect was in part due to the movement of calcium downward. Earlier in this paper reference was made to Albrecht's emphasis of the value of calcium added to acid soils as a benefit separate from but complementary to acidity neutralization (Albrecht, 1941).

The Kroth and Mattas work focused on semi-permanent forage production systems. The nature of permanent forage programs dictate that soil amendments such as limestone and fertilizer are surface applied once the forage is established. The use of the moldboard plow declined during last three decades of the 20th Century, and row crop producers shifted to reduced tillage or no-till culture. Therefore lessons learned from forage research may also be applicable to no-till culture.

Alkaline by-products such as kiln dust, lime stabilized sludges (biosolids), lime from clarifiers in sugar plants, and water treatment sludges have become available for land application in some areas. The increased number of potential combinations of liming materials and crop management practices raised several issues.

- How may the alkaline by-products substitute for agricultural limestone?
- Under what conditions can lime suspensions, pelletized lime, and by-products be used to correct soil acidity problems?
- How should no-till and reduced tillage fields be sampled to provide accurate guides to liming material application?
- How may variable rate application of liming materials be done on individual fields?

In addition to these concerns, there remain questions about longevity of lime treatments, ionic ratios (especially calcium and magnesium), impact of lime placement on the soil surface on sub-surface soil over time, and liming for forage establishment. A recent concern is the failure to reach the target pH_s after application of recommended quantities of limestone.

Recent sparse budgets have prevented addressing these questions that were deemed of lower priority than other agricultural production problems. Attempts were made to "bootleg" lime studies in other projects. However, the limited scope of the studies resulted in mixed successes. For example, Brown et al. (1993) found that lime stabilized biosolids were useful as lime sources in forage systems. Application rates based upon percent solids and ENM of the dried solids worked well.

Limited work showed that fluid lime, pelletized lime, and kiln dust products that the Missouri ENM measurement on dry basis worked well. An analysis of each product for other components is highly suggested. For example some kiln dusts have been found to contain sufficient boron to be toxic to sensitive plants. Most of these finely ground or suspended by-products will quickly lower soil acidity but do not maintain a higher pH as does quarry-run limestone which has a range in particle sizes.

Long-term research results on liming in no-till and reduced tillage cropping systems are scarce. The Kroth work demonstrated movement of the liming effect from the soil surface downward as much as 6 inches into the soil. Also Kroth and Mattas showed that when lime had been mixed to plow depth, application of acidifying N fertilizer to the soil surface over several years lowered the pH_s at least 2 inches below the surface. These observations, while on permanent forage fields, suggest that a soil-sampling regimen for pastures, hay fields, no-till fields and fields in other reduced tillage systems should be revised. A monitoring sampling program should consist of two samples from each field or sampling area of a field — a 2 to 3 inch sample and a 6 to 7 inch sample. There remains a need for lime-soil sampling calibration work on non-moldboard plow cropping systems.

Another concern is that of variable rate or precision farming. The authors have not seen sufficient research reports to properly address this concern. There is a limited amount of on-going research, but conclusive recommendations are not available. It is logical that where field variability is anticipated some form of systematic sampling be conducted. Application of lime can then be focused on the portion of the field that requires neutralization of acidity.

Liming recommendations of the 1950 to 1970 period in Missouri were based upon the balanced soil saturation concept incorrectly attributed to Dr. W. A. Albrecht. The concept, useful as a teaching tool in extension, originated in New Jersey. It was unfortunate that the concept useful for humid region soils was used on semi-arid soils. It resulted in applications of fertilizers to balance the ratios resulting from dissolution of calcium from calcareous soils, which inflated the CEC of the soil. This problem was deemed sufficiently important by members of North Central Region Soil Testing and Soil Amendments committees for them to develop a policy statement (Rehm, 1994). Fertility programs should be based on calibrated crop response to target soil test levels, rather than a particular balance between calcium, magnesium, and potassium. The Ca/Mg ratio idea has hung on far too long, as numerous studies have shown that the Ca/Mg ratio in soils can vary widely without detrimental effects upon crop performance. Deficiencies of either magnesium or calcium must be corrected. Toxicities of magnesium have not been documented in field studies, but allusions to poisonous levels of magnesium in soil still persist. Adverse effects of magnesium on rainfall infiltration into the soil profile have been suggested. As with the nutrient aspects of calcium and magnesium, any effect of magnesium on infiltration may well be due to lack of calcium to promote soil aggregation.

Concern about high pH_s levels in limed cropland soils surfaced especially in the 1990s. These conditions arose, in part, because in the early days of liming in Missouri, the quality of applied limestone was not appropriately accounted for in the recommendation procedures. Therefore, at times twice as much limestone was applied as needed for at least two reasons. First, was the mistaken idea that all soils should be limed to near pH 7.0. Second, limestone was evaluated only on the basis of CCE and percentage passing through a 40-mesh screen, and a maximum of 400 lb of effective calcium equivalent (ECE or ENM) per ton was allotted (Falloon, 1966). The consequence of use of a single screen size to estimate effectiveness and allowing at best-half credit for the CCE of the limestone was failure to properly account for the larger particle sizes, which slowly dissolve with time. The result was pH_s values on well-limed fields that exceeded 7.0. Consequently herbicide carryover has adversely affected succeeding crops. The changes in liming material recommendations brought about in the 1970s should avoid excessive increases in pH_s value. By fully crediting the effective calcium equivalent in liming material, the "cushion" of liming material has been removed. Close monitoring of soil acidity will be important with the removal of the "cushion."

Recent technology developments have focused attention, among other things, on patterns of soil acidity. Spacial variability of soil acidity is not new; the effects of dust from lime rock roads has been observed for most of the 20th Century. However, the means are available now to consider the inherent and manmade variability of the soil resource over the field on nutrient availability, herbicide effectiveness, and over-all crop vigor.

The research related to liming since 1970 has been limited. The work directed by Earl Kroth provided data to better account for placement of limestone and should be referred to when studies are designed to calibrate liming of unplowed fields with soil tests. Liming effects persist beyond four years meaning that long-term liming research is needed to provide justification for recommendations. The high CEC soils of the Missouri Bootheel seem to require additional calibration work based on the Roth and Fisher results.

Summaries of graduate student research

Between 1970 and 1999 several soil science graduate students conducted research on liming and soil pH problems. The students' theses are available for loan from Ellis Library on the University of Missouri campus. Short summaries of each student's thesis or dissertation are included in this section. A more comprehensive condensation of each has been included in Appendix D for the reader wishing more detail.

Measurement of soil CEC contains some uncertainty, especially considering its variable nature. Permanent CEC arises from the mineralogy of the clay sized particles, while pH-dependent CEC results from the chemical reactivity of many soil components, especially aluminum compounds and organic matter. In acid soils the measured CEC will usually increase as liming neutralizes the acidity. It is of value in the management of soil fertility to have an idea of the magnitude of the CEC of soil both before and after liming. Thus the estimation of the CEC is of value especially at the pH desired for crop production.

The estimation of a soil's CEC is useful for other purposes. For example, the USDA taxonomic classification of soils requires measurement of the percentage base saturation of selected diagnostic horizons (Soil Survey Staff, 1975). A relatively quick and precise method of CEC measurement is desirable for both plant nutrition and soil classification purposes.

Kenneth Benham — Estimation of exchangeable acidity

Kenneth Benham (1970), for his MS research problem, evaluated techniques to measure exchangeable acidity with reasonable accuracy. It was easier to titrate an acid soil to neutrality with $Ca(OH)_2/CaCl_2$ (standardized @ 0.01 M) solution than it was with the Mehlich $BaCl_2$/triethanolamine procedure (Soil Survey Staff, 1972). Many of the graduate students who followed Benham conducted research on liming related problems and used the $Ca(OH)_2/CaCl_2$ titration as the basic estimation of exchangeable acidity.

James Cisco — Buffer estimation of neutralizable acidity

James Cisco (1981) evaluated three buffer methods for estimation of neutralizable acidity for quick soil testing purposes. These methods were the old Woodruff buffer (Woodruff, 1947), the SMP buffer (Shoemaker et al., 1961) and a modified Woodruff buffer. The modified Woodruff buffer had been developed to replace the older formulation (Brown and Cisco, 1984).

Cisco used the $Ca(OH)_2/CaCl_2$ titration as the reference procedure for the estimation of neutralizable acidity. He used incremental rates of laboratory grade $CaCO_3$ added to acid soil in a greenhouse-pot study with soybean and in a closed-system incubation. Cisco's results supported the adaptation of the modified Woodruff buffer as a basis for estimating neutralizable acidity in farmer soil samples submitted for soil testing.

With the demonstration of a $Ca(OH)_2/CaCl_2$ titration as a useful reference procedure for measuring exchangeable acidity and the Woodruff buffer as the best available estimate of reserve acidity, succeeding graduate students focused on other problems and questions related to liming acid soils. One problem was the often reported failure of lime recommendations to raise the soil pH_s to the target range, especially in southern Missouri. Concurrently, some growers observed stand and germination problems with alfalfa seeded on recently limed fields

A.A. Yusef — Aluminum and lime requirements of southern Missouri soils

Many of the fields where questions about liming arose in southern Missouri were dominated by highly weathered soils developed from bedrock. These soils, mapped as Ultisols and some as Alfisols, have measurable amounts of exchangeable aluminum. Much of the field calibration work on liming practices prior to 1970 had been done on Mollisols and associated Alfisols in northern Missouri. These northern soils have higher amounts of soil organic matter and little exchangeable aluminum relative to the soils of southern Missouri. These facts led A.A. Yusef (1986) to study aluminum chemistry in these soils for his Ph.D. dissertation. His objectives were to characterize the nature of soil acidity and to evaluate alternatives to buffer procedures for estimating neutralizable acidity in southern Missouri soils containing significant quantities of exchangeable aluminum. He conducted pot studies with incremental rates of $CaCO_3$ using alfalfa and soybean as test crops. Like Cisco he incubated soils in a closed system to evaluate acidity changes resulting from incremental lime additions.

Yusef used several methods to estimate acidity. These included the New Woodruff and the SMP buffers to estimate neutralizable acidity. Exchangeable aluminum was extracted with 1 M KCl, 0.5 M $CuCl_2$, and 1 M NH_4Acetate @ pH 4.0. “Total acidity” was estimated using the Benham procedure, ($Ca(OH)_2/CaCl_2$). Yusef concluded that KCl exchangeable acidity may have merit as a basis for calculating lime requirements if the measured quantity of acidity was doubled and KCl extraction is restricted to soils with pH_s <4.8. This conclusion needs field verification. The KCl extraction step would increase a soil testing lab’s workload, as the pH_s would have to be determined and then a separate KCl extraction would be required if the pH_s<4.8.

Maximum yields of both soybean and alfalfa were obtained in Yusef’s greenhouse studies at pH_s values below the target levels used in the statewide liming program. The quantity of lime calculated to reach the pH_s range of 6.5 to 7.0 instead raised the pH_s only to the 6.0 to 6.5 range. Yusef noted that the soil pH_s increase to added lime was nearly linear from the mid 4s to nearly 6.5, which supported the published work by Magdoff and Bartlett (1985). Based upon the currently used formulas for calculating lime requirements using the Woodruff buffer, Yusef calculated that 16% of the lime requirement was needed to increase pH_s from 5.5 to 6.0, 20% from 6.0 to 6.5, and 29% from 6.5 to 7.0. Therein may lie the explanation for the failure of recommended lime requirement to reach target pH_s range because of the increased quantity of liming material needed to effect a pH change at higher pH values.

David Bennett — Liming forage legumes

Cisco and Yusef pointed out problems in calibration of acidity measures and liming material recommendations using greenhouse and incubation studies. Therefore, David Bennett, for his MS research, studied the adequacy of liming material recommendations for alfalfa, red clover, and lespedeza in a southern Missouri field study. This work was needed to help answer the questions about the failure of recommendations to reach the target acidity ranges. His project included a limestone particle size incubation.

The selected field sites were located in southwestern Gasconade County (Wilson site) and in Phelps County, southeast of Rolla (McWhorter site). Both sites were on Typic Paleudults. The soil used for Bennett's greenhouse and incubation studies was surface soil of a Typic Paleudult from a cleared site in the Mark Twain National Forest southwest of Rolla. The acidity-related measurements made on 0-6 inch soil samples from the three sites are recorded in Table 4.

Table 4. Acidic properties of soils used in the Bennett limestone studies.

Site	pH_s	Neutralizable Acidity	Exchangeable Al
		meq/100g	ppm
Greenhouse	4.8	4.0	24
McWhorter	4.7	4.5	14
Wilson	4.5	7.0	76

Bagged calcitic limestone (Columbia, IL) was used for the major part of the field studies. One treatment was a dolomitic limestone from a stockpile at a Beck quarry near Rolla. One greenhouse treatment was <60 mesh material from the bagged Columbia limestone. Inadequate bagged Columbia limestone was available for the Wilson site when the treatments were applied, so a limestone from Alton, IL (Mississippi limestone) was used instead on the lespedeza block. The limestone characteristics are given in Table 5.

Table 5. Characteristics of limestone used in the Bennett studies.

Limestone	ENM	Ca	Mg
	lb/ton	--------------%--------------	
Columbia	427	38.4	0.4
Columbia <60	782	38.4	0.4
Beck	342	18.8	8.9
Mississippi	448	35.0	0.1

Lime treatments were applied and plowed under in late summer 1988. The treatment quantities were based upon the lime requirement for alfalfa, red clover, and lespedeza for each location using soil test results (Table DB-1, Appendix D; Buchholz, 1983). The target pH_s range was 6.6 to 7.0 for alfalfa and 6.1 to 6.5 for red clover and lespedeza. The spreader could not be calibrated to deliver precise fractional increments of the lime requirements as planned, so the actual fractional application for each treatment was calculated from the amount of liming material spread (Table 6).

Soil samples taken in fall 1989 to a 6 inch depth showed that the treatments failed to reach the target pH_s range and did not show the incremental declines in acidity expected from the quantities of ENM applied (Table DB-7, Appendix D). The 1991 sampling showed the major limestone effects on soil acidity were in the 3-6 and 6-9 inch layers, suggesting that plow depth was nearer 9 inches than 6.67 inches as planned. Table 6, in addition to the fractional increments of the lime requirement calculated after treatment application, contains recalculated incremental treatments adjusted for a plow depth of 9 inches.

Seeding of the forages was completed in spring 1989. Yields only for 1989 were reported in Bennett's thesis, but the study was continued into 1991. Combined and individual yield results were not significantly affected by treatment. Summer moisture stress in 1989 and 1991 caused quite low yields (see Table DB-9 in Appendix D).

The average 1991 pH_s results were plotted against the recalculated fractional lime requirements applied. From this plot the pH_s for each quarter increment was estimated for each of the two sites giving the results in Table 7 (Appendix D, Table DB-7).

These results were surprising since the actual quantity of liming material applied for a given fractional treatment was greater for the more acid Wilson site. The Wilson site originally had 76 ppm KCl extractable aluminum and the McWhorter site had 14 ppm. These results suggest that as time passes after incorporation of lime into soils containing significant exchangeable aluminum, the lime is neutralized faster than would be expected based upon old calibration data. These results also support grower observations that the target pH_s ranges are not reached when recommended lime requirements have been applied. The real puzzle in the Bennett results is why there were no significant yield responses to lime, especially at the Wilson site.

Table 6. Fractional limestone treatments used in Bennett's field studies on liming.

Treatment Number*	Limestone Source	McWhorter Alfalfa	McWhorter Red Clover	McWhorter Lespedeza	Wilson Alfalfa	Wilson Red Clover	Wilson Lespedeza**
		Original fraction of lime requirement***					
1	None	0	0	0	0	0	0
2	Columbia	0.42	0.49	0.49	0.26	0.30	0.48[2]
3	Columbia	0.83	0.98	0.98	0.52	0.60	0.96
4	Columbia	1.25	1.47	1.47	0.79	0.92	1.43
5	Columbia	1.67	1.96	1.96	1.04	1.20	1.91
6	Beck	1.09	1.28	1.28	0.70	0.81	1.27
		Recalculated fraction of lime requirement					
1	None	0	0	0	0	0	0
2	Columbia	0.28	0.33	0.33	0.17	0.20	0.32
3	Columbia	0.55	0.66	0.66	0.35	0.40	0.64
4	Columbia	0.82	0.98	0.98	0.52	0.61	0.95
5	Columbia	1.10	1.30	1.30	0.69	0.80	1.27
6	Beck	0.73	0.83	0.83	0.54	0.54	0.85

*The original quantities of limestone were determined assuming a 6-inch plow depth and quantity of limestone applied. The recalculated fractional applications were based on a 9-inch plow depth.

**The Mississippi limestone was used only on the lespedeza block at the Wilson site.

***The LRs were to increase pH_s to 6.6-7.0 for alfalfa and 6.1-6.5 for red clover and lespedeza.

Table 7. Estimated pH_s for fractions of lime requirements from plots of measured pH_s and applied limestone adjusted to 9-inch plow depth.

Site	Species	Fractional Lime Requirement 0	0.25	0.5	0.75	1.00
McWhorter	Alfalfa	5.2	5.8	6.15	6.4	6.55
	Red clover	5.4	5.8	6.1	6.3	6.5
	Lespedeza	5.7	6.05	6.3	6.5	6.7
Wilson	Alfalfa	4.6	5.1	5.6	6.0	*
	Red clover	4.5	4.95	5.3	5.55	*
	Lespedeza**	5.1	5.4	5.65	5.8	5.9

*Based upon calculations the full lime requirement for 9 inches was not applied.
**Columbia limestone used for all except lespedeza at the Wilson site.

Maximum yields of the forage legumes in Bennett's greenhouse study were reached at 0.67 to 1.00 times the calculated lime requirements, which were at a higher fractional lime requirement than obtained by Yusef. The effect on soil pH_s in both studies was similar in that the lime requirement that was to bring the soil to a particular range actually resulted in a pH_s the next range lower (6.0 to 6.5 rather than 6.5 to 7.0). This might be explained by a shorter contact time of the lime treatments with soil in the greenhouse than in the field study. A different soil was used, so the field and greenhouse results should not be directly compared.

In an incubation study Bennett evaluated the relative effectiveness of particle sizes in changing soil acidity. The Beck limestone was sieved into separates using the screen sizes used to estimate of fineness by the Missouri Fertilizer and Lime Control Laboratory (>8, 8-40, 40-60, and <60 mesh). Lime requirements were calculated for each particle size including the bulk quarry run sample. Fractional quantities of the lime requirement were applied to soil in plastic bags. The soil/limestone mixture was then wetted to field capacity and incubated in the dark for 9 months. In 3-month intervals the incubated soil/lime mixture were sampled and pH in water and 0.01 M $CaCl_2$ were measured.

Table 8. The effects of quantities of different limestone particle sizes on pH_s of soils incubated for 9 months.

Material	Fraction of LR*	Incubation time-months 3**	6	9
None		4.5j	4.3h	4.2k
Bulk	0.33	5.8efg	5.4k	5.3h
	0.66	6.0def	5.9hi	5.9f
	1.00	6.2bc	6.5def	6.4de
	1.33	6.5a	6.6cde	6.6cd
	1.66	6.4ab	6.7bcde	6.6bcd
>8 mesh	0.33	4.5j	4.3n	4.2k
	0.66	4.8j	4.6m	4.5j
	1.00	4.6j	4.6m	4.5j
	1.33	5.1I	4.9l	4.9i
	1.66	5.1I	4.9l	4.8i
8-40 mesh	0.33	5.0i	5.0l	4.9i
	0.66	5.5h	5.6jk	5.5h
	1.00	5.7gh	6.0h	5.9f
	1.33	5.9rfg	6.3fg	6.2e
	1.66	6.0cde	6.3fg	6.3e
40-60 mesh	0.33	5.7fgh	5.4k	5.5h
	0.66	6.1cd	6.5efg	6.4de
	1.00	6.4ab	6.7abcd	6.7bc
	1.33	6.6a	6.8ab	6.7bc
	1.66	6.5a	6.7bcde	6.7bc
<60 mesh	0.33	5.9defg	5.7b	5.7g
	0.66	6.4ab	6.8a	6.7abc
	1.00	6.5a	6.8a	6.8ab
	1.33	6.6a	6.9a	6.9a
	1.66	6.6a	6.8a	6.9a

*Particle size range and fraction of total lime requirement for alfalfa.
**pH_s values within a column followed by the same letter were not significantly different at the 5% level.

The pH_s of the untreated control samples declined over the 9 month incubation from an initial 4.8 (Table 8). This increase in acidity might have resulted from CO_2 generated by microbial activity. The greatest effect from the >8 mesh material was to maintain the acidity near the initial pH_s 4.8. The data in Table 8 supports the practice of not allowing effectiveness credit for particles >8 mesh. All particle size fractions, except the 8 mesh material, significantly lowered the amount of acidity in the soil (Table 8). The two finer particle size groups (40-60 and <60 mesh) raised the pH_s near the target pH_s (6.6-7.0) within 3 months and reached mid-range by 6 months. The 8-40 mesh material failed to reach the target range even when 1.66 times the lime requirement was applied.

The Bennett studies did not provide useful field yield-response data, due in large part because of severe moisture stress in 2 of the 3 summers of the field study. The McWhorter site would have reached the target pH_s range had the lime requirement been calculated for the actual depth of plowing. The Wilson site had significantly more aluminum (76 vs. 14 ppm) and less organic matter (2.0 vs. 2.3%) than the McWhorter site. The Wilson site when plowed supported a stand of stunted ragweed, while a vigorous stand of tall fescue was plowed under on the McWhorter site. The failure of any treatment on the Wilson site to exceed pH_s 6.0 concurs with farmer observations and likely was due to aluminum reacting with the liming material (Table 7). Unfortunately the site was sold and the project was terminated at the new owner's request.

The particle size results tended to support the weightings used for estimating the effectiveness of the different particle size groups.

Lime particle size serves as a rough index of surface area exposed by a given quantity of liming material. The finer the size of particles the greater is the surface area exposed to soil particles and moisture. That is, both quantity of material applied and particle size determine the reactivity of liming material (Table 8).

Jeffrey Stevens — Dissolution of limestone particles

In a moist acid soil that has been mixed with crushed limestone, soil moisture bathes both the soil and limestone particles. Acidity in soil solution attacks the limestone surface and is neutralized with calcium released from the particle into soil solution. In the past it was not possible to measure the rate and magnitude of these reactions. However the development of microelectrodes has permitted the measurement of the rate of limestone-soil solution interactions with time at selected distances from limestone particles into the soil surrounding the particles.

Jeffrey Stevens conducted an MS study on dissolution of limestone particles in a soil collected from Tucker Prairie that had an initial pH_s of 4.5. Microelectrodes were used to measure acidity changes at selected distances from individual limestone particles. Stevens found that dissolution occurred within 15 minutes, but the effect extended only 1.0 mm from the particles. The pH was always greater at a given distance from a calcitic limestone particle than a dolomitic limestone particle. Small leaching cells were used to simulate up to 4 years of leaching under Missouri rainfall conditions. Stevens observed no significant directional differences due to leaching. He presented a discussion of the possible reasons for this lack of significant difference, focusing upon the tortuocity of soil pores and the relative sizes of pores and limestone particles.

Stevens' work has significance for soil testing operations. In the North Central Region pH measurements include a 1:1 (w:v) soil:suspending-medium mixture and a 30 minute wait before the pH measurements are taken (Brown, 1998). Stevens' data showed that dissolution of limestone occurs within 15 minutes of wetting the soil. If in a soil sample undissolved limestone particles are present, it is likely that the measured pH of the soil suspension would be greater than in the field because of the nature of particle dissolution in suspension. At the plant root level, a growing root in a limed soil will be exposed to a range of active acidity.

The preceding studies made it clear that the chemistry of the acid southern Missouri soils is complex. Proper lime application seems to be highly dependent upon the behavior of soil aluminum and its reactions with liming material. It is also clear from the Yusef and Bennett studies that neutralization of acidity in high aluminum soils requires time in terms of months.

Syed Omar Syed Rastan — Soil aluminum behavior as it affects estimates of lime requirements

With an MS degree from the University of Georgia and with research experience in his native Malaysia on plant responses on soils high in active aluminum, Syed Omar Syed Rastan came to the University of Missouri to study. The objectives of his graduate research were to document changes in soil solution chemistry when highly acid soils are limed, evaluate methods to improve estimates of lime requirements of acid soils, and to conduct a pilot study on the influence of organic soil amendments upon active aluminum.

The surface soils of two southern Missouri Typic Fragiudalts (Captina and Hobson series) were collected as soil material for greenhouse and laboratory studies. Some chemical characteristics of the surface soil samples are given below in Table 9.

Table 9. Chemical characteristics of the surface soil samples for Syed Omar's studies.

	Exchangeable		Cation Exchange Capacity		
Soil	Al	NA*	Effective	NH_4Acetate	pH_s
	-------------------------------- meq/100g	----------------------------			
Captina	3.3	9.0	4.2	9.9	4.0
Hobson	2.8	9.5	3.6	10.3	3.9

*Neutralizable acidity by the Woodruff buffer

A greenhouse study was conducted with alfalfa as a test crop through five harvests. Liming treatments included 0, 0.25, 0.5, 1.0, and 2.0 times the equivalent of the 1 M KCl exchangeable aluminum in each soil and another treatment that was the lime requirement for alfalfa based upon the Woodruff buffer estimate of neutralizable acidity. Note that Yusef (1986) suggested 2 times the 1 M KCl extractable aluminum as an alternative to the Woodruff buffer for estimation of lime requirement for high aluminum soils. The liming material (calcium and magnesium in a 6:1 ratio) and the soil were incubated in a closed system. Soil chemical parameters were measured at 1, 2, 5, and 10 months.

A second greenhouse study used 5 rates of lime as fractions of the KCl exchangeable aluminum (0, 0.5, 1.0, and 2.0 x) with a low C:N residue (alfalfa) and a high C:N residue (wheat straw). Alfalfa, the test crop, was grown through 4 harvests.

In the initial greenhouse study, the two soils were sufficiently acid that alfalfa did not grow without added lime. Alfalfa plants were not productive when grown on soil with lime applied at the 0.25 and 0.5 limed fractions of exchangeable aluminum. Maximum yields were obtained with the Woodruff-buffer-based lime requirement, which were 2.96 and 3.38 times the exchangeable aluminum equivalent for the Captina and Hobson soils, respectively.

Soil analyses made after the second and fourth harvests showed that, in spite of adding lime equivalent to the initial exchangeable aluminum, the active acidity produced a $pH_s < 4.9$ in both soils, but KCl ex-changeable aluminum was significantly lowered (Table 10). The lime requirement based upon the Woodruff buffer decreased the active acidity into the target pH_s range for alfalfa (6.5-7.0).

Table 10. Soil chemical parameters measured after the second and fourth harvests in greenhouse study 1.

Soil	Initial Al	Treatment*	Post Harvest 2		Post Harvest 4	
			Al	pH_s	Al	pH_s
			meq/100g		meq/100g	
Captina	3.3	0	1.9	4.1	2.0	4.1
		0.25	1.5	4.2	1.6	4.2
		0.5	1.2	4.4	1.2	4.2
		1.0	0.4	4.6	0.6	4.6
		2.0	0	6.1	0	5.8
		2.96**	0	6.9	0	6.2
Hobson	2.8	0	1.5	4.1	1.5	4.1
		0.25	1.1	4.2	1.2	4.2
		0.5	0.8	4.3	0.5	4.3
		1.0	0.3	4.8	0.4	4.7
		2.0	0	5.9	0	5.6
		3.38**	0	7.2	0	6.8

*Lime equivalent to the fraction of initial KCl exchangeable aluminum.
**Lime equivalent to the Woodruff buffer estimate of neutralizable acidity.

Syed's results do not agree with those of Yusef, Cisco, and Bennett. They found the Woodruff-based lime requirement raised soil pH_s only into the 6.0 to 6.5 range, but top yields of forage legumes were obtained at pH_s <6.5. Syed's results suggest that at higher lime rates aluminum may be slowly released from a form unextractable by KCl, based upon the decline of the active acidity even at 2.0 times the exchangeable aluminum and the Woodruff-buffer-based lime requirement.

Assuming that there is some level of non-exchangeable but labile aluminum in acid soils, as has been demonstrated in many studies, there remains the problem of estimating that labile aluminum so a more accurate lime requirement estimate may be made. Syed's evaluation of several extractants suggested that 0.33 M $LaCl_2$ merited further study, as he obtained maximum yields with the Woodruff buffer based lime requirement and $LaCl_2$ extracted no aluminum with that treatment (Table 11). The KCl extraction did not measure labile aluminum, while 0.5 M $CuCl_2$ and KCl plus ammonium citrate over-estimated labile aluminum. Oates and Kamprath (1983) also concluded that $LaCl_2$ was a better extractant than $CuCl_2$, because the $CuCl_2$ tended to over-estimate the organically bound aluminum in soils.

In Syed's second study, alfalfa grew without added lime with the low C:N plant residue on both soils. However, after the second harvest yields declined. Alfalfa could not be established without added lime when the high C:N residue was used. Yields of the greenhouse grown alfalfa continued to increase through 4 harvests only when lime was applied at twice the equivalent KCl exchangeable aluminum (see Appendix D, Table SO-7). The effect of the low C:N residue was temporary. However, further research may be merited to evaluate addition of such residues or organic waste materials with lime to enhance legume establishment when it is not convenient to apply the lime requirement a year ahead of legume establishment.

Syed's incubation which included extraction of soil solution indicated as expected that the concentration of calcium increased with lime, but it also suggested that the calcium activity may become sufficiently large that it would interfere with uptake or soil solution activity of other cations. However his study did not conclusively support the inference that a high concentration of active calcium may explain why some growers in southern Missouri have observed off-color early seedling growth of alfalfa.

Table 11. Extractable aluminum in two differentially limed soils as measured by extraction with four different extractants after 2 alfalfa harvests.

Soil	Lime*	pH_s	Extractant*** NA**	KCl	$LaCl_2$	$CuCl_2$	KCl + NH_4Citrate
			---------- meq/100g ----------				
Captina	0	4.1	6.37	1.92	2.27	3.50	3.64
	0.25	4.2	6.00	1.52	1.92	3.07	3.26
	0.50	4.4	5.50	1.19	1.58	2.68	2,93
	1.00	4.8	4.12	0.42	0.89	2.0	2.29
	2.00	6.1	1.75	0.00	0.22	1.43	2.00
	2.96	6.9	0.00	0.00	0.00	1.31	1.93
Hobson	0	4.1	6.75	1.47	1.85	2.59	2.82
	0.25	4.2	6.00	1.09	1.64	2.17	2.64
	0.50	4.3	5.50	0.80	1.28	2.00	2.56
	1.00	4.8	4.12	0.28	0.81	1.58	2.17
	2.00	5.9	1.75	0.00	0.25	1.18	1.90
	3.38	7.2	0.00	0.00	0.00	1.00	1.89

*Fractional equivalent of the initial KCl extractable aluminum.
**Neutralizable acidity using the New Woodruff buffer.
***1 M, 0.33 M, 0.5 M, and 1 M + 0.5 M, respectively.

Current Laboratory Methods and Interpretations

At the end of the 20th Century, two regional laboratories conducted soil testing for the Missouri Extension and Outreach programs at Portageville and Columbia. The two labs operated independently but are coordinated so that the same tests, recommendation program, and billing systems are used.

The methods used by the two regional soil testing labs for estimation of lime requirements were first published in 1977 (Brown et al., 1977; Brown and Rodriguez, 1983). The methods used to measure acidity and estimate liming material needs are unique to the Missouri program and differ from those used in the rest of the North Central Region (Brown, 1998).

Measurement of active acidity

Active soil acidity is estimated using a 1:1 soil/0.01 M $CaCl_2$ (wt/v) suspension. If pH in distilled water is desired (the North Central method) a 1:1 suspension is used with distilled water as the suspending liquid. Evaluation of pH_s is made by a rating system modified from that of Graham (1959).

Rating	Alfalfa	All other Crops
	-------- pH_s range --------	
Very low	<5.0	<4.5
Low	5.0-5.8	4.5-5.3
Medium	5.8-6.5	5.3-6.0
High	6.5-7.5	6.0-7.5
Very High	>7.5	>7.5

The interpretation of these ratings, quoted from Buchholz (1983, page 27), is "Soils with a pH_s rating of very low or low have a definite need for limestone. These soils may be limiting yield potential due to severe soil acidity. A medium pH_s indicates a need for limestone very soon, but soil acidity is likely not so severe at this time to be causing yield reductions. Soils rated high have a soil pH_s optimum for crop growth and limestone is not needed at this time."

Neutralizable acidity

Neutralizable acidity is estimated with 10 g soil, 10 ml 0.01 M $CaCl_2$, and 10 ml of the *New* Woodruff buffer (Brown and Rodriguez, 1983). C.M. Woodruff changed the recipe for the buffer named for him around 1963. The new recipe increased the quantitative estimate of acidity by including an estimate of reactive aluminum. Unfortunately, Dr. Woodruff did not publish the new recipe. Brown and Cisco (1984) compared the old and New Woodruff buffers and the SMP buffer.

Hanson and Brown first published in 1977 the currently used interpretations of soil test results to provide quantitative lime requirements. As responsibility for the soil fertility extension program passed from Roger Hanson to Daryl Buchholz the format changed but not the substance.

The actual quantity of limestone recommended to a grower is based on the test of his soil. The target pH_s range is primarily fixed by the crop, but also in part, by the soil region. Soils for which alfalfa is planned should be limed to pH_s 6.6-7.0 in the Ozarks, Ozark Borders, and Cherokee Prairies of southern Missouri (soil regions 5, 6, 7, 8) and to pH_s 6.1-6.5 in all other soil regions. The target pH_s for all other forage legumes in regions 5, 6, 7, and 8 is 6.1-6.5. The target pH_s range for forage grasses throughout the state is 5.6-6.0. The reason for the higher pH_s for alfalfa and forage legumes in southern Missouri is to assure sufficient liming material to cause some leaching of calcium over time into the very acid, high exchangeable aluminum subsoils. The data of Kroth and Mattas (1981) showed that downward movement of the liming effect does take place given time. The target pH_s for all row crops throughout the state is 6.1-6.5.

Fisher derived the formulae used for calculating the lime requirement in ENM per acre for the Agronomy Department Soil Test Committee. Three target pH_s ranges are used in the program and the appropriate equations are reproduced below. Note that a multiplier of 400 is found in each equation. The value 400 represents the pounds of equivalent calcium per acre furrow slice (2,000,000 pounds of soil) needed to replace or neutralize 1 me of neutralizable acidity per 100 grams of soil.

pH_s Range 6.6-7.0

$$\text{LR ENM lb/acre} = 400 \times \text{NA}$$

pH_s Range 6.1-6.5

$$\text{LR ENM lb/acre} = 400\ \{\text{NA} - [(\text{NA}) \div (41.425 - 10.307\ pH_s + 0.629\ (pH_s)^2)]$$

pH_s Range 6.1-6.5

$$\text{LR ENM lb/acre} = 400\ \{\text{NA} - [(\text{NA}) \div (19.109 - 4.802\ pH_s + 0.297\ (pH_s)^2)]$$

Ratings of soil test magnesium and effective nutrient requirements to correct soil magnesium limitations are used when soil test magnesium falls below certain values (Buchholz, 1992).

Neutralizing value of liming material

Any grower requiring lime would take soil test results and recommendations to a liming-material dealer who by law must provide the lb ENM and lb EMg per ton of his agricultural limestone or other liming material. The tonnage of liming material required can be calculated with the following formula:

Tons/acre = lb ENM required per acre ÷ lb ENM per ton of liming material.

Two important measures of the acid neutralizing value of liming material are calcium carbonate equivalent (CCE) and the distribution of particle sizes or fineness of grind. Earlier in this paper it was pointed out that Missouri research demonstrated the value of finer limestone particles. Early evaluation of crushed limestone indicated that to be effective all liming material should pass a 10-mesh screen. As late as the mid-1960s, reference was made to ground limestone recommendations based upon the "percent passing 40 mesh screen (with proportionate amounts through 8 and 100 mesh)" (Falloon, 1966). In 1976 the Missouri legislature passed a Missouri Agricultural Liming Materials Law (Missouri Revised Statutes, 1976). All vendors of liming material sold in Missouri are required by law to provide the buyer quality information based upon CCE and fineness of grind.

The 1976 law raised many questions about the rules written to implement the law. In response to the criticism from vendors and others, J.R. Brown and Daryl Buchholz, MU Agronomy Faculty members and members of the Agronomy Department soil test committee, were asked to respond to the criticism by providing the "agronomic basis" for the various rules. This was done in a report submitted to the Director of the Missouri Agricultural Experiment Station and members of the Liming Materials Advisory Council established by RSMo 266.543 (Brown and Buchholz, 1981). This report was based on a review of published literature in which liming material purity (CCE) and/or particle size were studied.

The calculation of the Effective Neutralizing Material (ENM) for liming material was defined by the 1976 version of the lime law rules by the following formula:

ENM = %CCE/100 x [66.67 + (6.67 x % passing U.S. No. 40 sieve)]

The 1976 version of the rules for implementing the law stated that liming materials should have a minimum CCE of 70% and have a fineness range of 35% to 65% passing a 40-mesh screen. Brown and Buchholz could find no agronomic justification for the minimum CCE of 70% although the intent was to protect the buyer from the sale of impure liming material. The right-hand term of the preceding equation [66.67 + (6.67 + % passing U. S. 40 sieve)] had no sound agronomic basis either. The formula was devised around the maximum and minimum percentages passing a 40-mesh screen as written in the rules used to implement the law. If a liming material had 100% CCE and 65% passing a 40-mesh screen the ENM value would be 500 lb. per ton. The rules were worded so that any material passing the 40-mesh screen beyond 65% could not be used in calculation of ENM.

In the review by Brown and Buchholz the following conclusions were reached which parallels those of W.W. Hinish (1981) in Pennsylvania.

1. Limestone particles coarser than 20-mesh give some effect, but anything coarser than 8-mesh is of no value for agronomic liming material.

2. Maximum crop yields in fineness studies occurred when the liming material was finer than 60-mesh.

3. There was little advantage of grinding finer than 100-mesh.

4. Dolomitic limestone needs to be more finely ground than calcitic stone for equal effectiveness.

5. Thorough incorporation into the soil is needed for most effective neutralization.

Brown and Buchholz presented material that showed that the ENM calculation formula was incorrect, because it did not adequately address the relative effectiveness of different particle sizes. In fact, the formula implies an interaction between CCE and fineness that was not supported by any research-based literature. Finally, no justification for using any maximum ENM for liming material could be found. If a liming material is pure $CaCO_3$ (CCE = 100%), then it, in fact, contains 800 lb ENM per ton not 400. Therefore Brown and Buchholz concluded that the rules that implement the lime law should be changed to consider the relative effectiveness of different particle sizes of liming material in neutralization of soil acidity in a 2 to 4 year time frame.

In 1985 the Missouri Agricultural Liming Materials Law rules were modified. The revised rules specified a minimum CCE of 65% (6 CSR 250.10.020(2)). Fineness of grind was changed to require a minimum of 90% to pass an 8-mesh sieve [RSMo 266.505 (1)]. Much of the field research done in calibrating limestone applications to plant growth indicated that limestone particles larger than 8-mesh have relatively little effect in changing soil acidity in a 3 to 4 year period (Barber, 1984).

Particle size and solubility determine the rate of reaction of liming materials placed in acid soil. Small particle sizes are most effective in neutralizing soil acidity, because the finer particles expose more surface area per weight of material. For example, if one has a 1' x 1' x 1' solid cube of liming material it would have 864 sq. in. of surface area (6 sides times 144 sq. in. per side). Cut that cube into eight solid cubes each 0.5' x 0.5' x 0.5' doubles the exposed surface area of the material. Stevens (1990) showed the dissolution products of limestone move only a short distance, thus the more limestone surface exposed the more effective the material will be in neutralizing soil acidity.

The particle size distribution of liming material in the 1985 and the 1999 versions of the rules is determined by screening a sample through sieve sizes of 8-, 40-, and 60-mesh. After shaking a nest of the sieves, the material held on each is weighed and expressed as a percentage of the weight of the entire sample. These percentages as decimals are multiplied by an effectiveness factor for each particle size group shown below. The cumulative total of these values makes up the term Fineness Factor (73.9% in the example).

	Effectiveness	Example	
Screen size	Factor	Quantity	Weighting
Held on the 8-mesh sieve	0%	2%	0
Passed the 8-mesh, held on the 40-mesh 25%	25%	14%	3.5%
Passed the 40-mesh, held on the 60-mesh	60%	34%	20.4%
Passed the 60-mesh	100%	50%	50.0%
Total		100%	73.9%

The weightings placed on the particle size groups were based upon published research reports and extension publications, principally from the North Central States of the United States. The particle size weightings were selected to estimate of the effect of particle size on the neutralizing ability of limestone over a 3 to 4 year period after incorporation into the upper 6 inches of soil in crop production fields. A review by Barber (1984) provided much of the availability information and would be a good reference to understand the complexity of providing a broad-based estimate of the neutralizing ability of agricultural limestones.

Many small particles in a volume of soil will be more effective than a few larger particles, but there are some negatives to very finely ground materials. First, the additional grinding to produce very fine particles adds to the cost of the limestone. Also, care must be taken in transporting and spreading dry fine material because wind easily moves finely ground solids, which may result in unequal spreading over the field. Larger particles will help maintain a given pH_s for a longer period of time than the finest particles.

One of the earliest guides to proper liming of acid soils was to mix the liming materials with the soil months ahead of planting an acid intolerant crop to allow acid neutralization to occur. The finer portion of the liming material (<60-mesh) would be expected to fully dissolve in a few weeks when mixed with acid soil. The larger particle sizes would provide staying power; that is, they would continue to dissolve over time to maintain the target level of acidity for 3 to 4 years. Now that minimum tillage is widely used, limestone rates likely need to be reduced and the frequency of application increased. This would be especially true if fertilizers are surface applied and not incorporated to plow depth (6 to 8 inches).

Use of liming materials that completely pass a 60-mesh sieve requires more frequent testing for soil acidity buildup, because there are no large particles of liming material to counteract acidity build up from acidic precipitation, crop removal and fertilization. Increasing the soil pH above 7.0 is undesirable, as nutrient availability and herbicide effectiveness may be adversely affected.

In making recommendations that specify limestone particle sizes, agronomists should recognize that for quarry operator there may be little interest in providing specific sized materials, as aggregate is the product of commercial interest and agricultural limestone is, at best, a sideline and, at worst, a waste product. However, because crop production is an acidifying activity that accelerates the natural tendency of soils to become more acid in humid regions, good liming practices should be based upon proper weighting of both fine (<60-mesh) and coarser (8 to 60-mesh) agricultural limestone particles.

Definitions

We have included in this section definitions that apply to liming acid soils. Some terms may have different meaning when used for other applications. Also, some terms have evolved to a meaning that varies from scientific usage. Refer to any soil fertility text, such as Havlin et al. (1999) and to the Soil Science Society of America glossary (SSSA, 1997) for detailed explanations of terms used in liming and soil acidity modification.

Acid soil — A soil with a pH <7.0

Active acidity — The activity of hydrogen ions in the soil solution. Active acidity is estimated by the pH soil test and is an extremely small quantity compared to exchangeable, reserve (residual) and total acidity in a soil.

Cation exchange capacity (CEC) — The capacity of soil particles to hold cations (positively charged ions). The sum of exchangeable bases and total acidity determined at a specified pH which is 7.0 in Missouri.

Effective neutralizing material (ENM) — The quantity of effective calcium equivalent in a liming material. It is determined by measuring the purity of the liming material, expressed as calcium carbonate equivalent (CCE), and multiplying the CCE by a fineness factor, determined by screening a sample of the liming material. The resulting product is multiplied as a decimal times 800 lb to get pounds of ENM per ton of liming material. The 800 lb is the quantity of calcium per ton in pure $CaCO_3$. Thus, ENM is numerically equivalent to effective calcium equivalent.

Exchangeable acidity — Acidity that is replaced from soil particles by an unbuffered salt solution.

Fineness factor — A calculated numerical value that estimates the effectiveness of a liming material based upon particle size distribution. In Missouri the factor is determined by screening a sample through sieve sizes of 8-, 40-, and 60-mesh. The decimal fraction held on each sieve is multiplied by the effectiveness factor to obtain a fineness value for the sieve size group. The cumulative total of these fineness values makes up the term Fineness Factor. An example is given below.

Screen size	Effectiveness Factor	Quantity Held	Fineness Value
Held on the 8-mesh sieve	0%	0	0
Passed the 8-mesh, held on the 40-mesh	25%	10	2.5
Passed the 40-mesh, held on the 60-mesh	60%	10	6.0
Passed the 60-mesh	100%	80	80.0
Total (Fineness Factor)			88.5

Lime requirement (LR) — the quantity of liming material needed to raise the pH of a volume of soil to some specified value expressed in pounds of effective neutralizing material (ENM) per acre.

Neutralizable acidity (NA) — the quantity of soil acidity estimated by the Woodruff buffer soil test.

Reserve acidity — Acidity held on clays and organic matter that can be neutralized by liming to pH 7.0 or some other target pH (also called residual acidity).

Total acidity — The sum of reserve and exchangeable. For soil testing purposes in Missouri total acidity is estimated by the Woodruff buffer procedure.

Salt pH — The pH measured in a soil-0.01 M $CaCl_2$ suspension (pH_s).

Water pH — The pH of a soil-distilled water suspension (pH_w).

Reevaluation of Missouri Limestone Recommendations Incorporating Recent (1993–1999) Soil Test Results

The current recommendations for correction of adverse soil acidity have been in use for about 30 years. The basis for these recommendations is the empirical relationship between two indices of soil acidity: pH_s and neutralizable acidity as measured by the Woodruff Buffer. The relationship was established from a soil test database of samples analyzed in the early 1970s. A larger more current soil test database is now available from which to examine soil-lime interactions.

Computing advancements since 1970 have vastly improved the ability to include more complex factors in recommendation calculations. Our improved understanding of soil-plant interrelationships as pertaining to liming and changes in cropping practices may also effect a need for revised recommendations. As a review of the basis of lime recommendations used by the Soil Testing Laboratory, this section has three objectives: 1) review the development of current recommendations, 2) compare the relationship between NA and pH_s as used in the current recommendations to that of a current data-base, and 3) consider potential changes that could update or improve lime recommendations. Questions to be evaluated include: 1) Should lime recommendations be based on percentage base saturation rather than pH_s and NA? 2) Should the "needed ENM" calculation be a function of pH_s, NA, and CEC? 3) Should Soil Regions continue to be included in the lime recommendation? 4) May a measure of extractable aluminum as it relates to NA improve recommendations for low pH_s soils (for example $pH_s < 4.8$)?

Development of current lime recommendations

The current algorithm of lime recommendations by the University of Missouri Soil Testing Lab was developed by T. R. Fisher in 1972. The *Soil Test Interpretations and Recommendations Handbook* (Buchholz, 1992) shows the algorithm as presently used. Fisher did not publish a detailed description of the development of his equations. However, in a letter to the Agronomy Department Soil Testing Committee dated July 20, 1972, he provided a brief description of three equations (Equations 1, 2, 3) that relate NA to pHs for the purpose of making lime recommendations. Each of equations 1, 2, and 3 assumes a different relationship between NA and pH_s. Fisher's letter and a description of his methods were published by J. R. Brown in Agronomy Miscellaneous Publication 84-03 (Brown, 1984). Included were tables that compared lime requirements calculated from the different equations at various pH_s and NA values. As a basis for his recommendation equations, Fisher used a database of about 30,000 soil samples analyzed by extension soil testing laboratories during 1970 and 1971.

Equation 1 was based on a linear relationship between pH_s and NA even though the actual relationship was curvilinear. Equation 1 consistently underestimated lime requirements on low pH_s soils.

$$ENM = 400 * \left(NA - \frac{NA}{14 - 2 * pH_s} \right) \qquad \text{Equation 1}$$

Equation 2 was based on the assumption that on average NA occupied 6% of the soil's CEC with a pH_s of 6.5 (Equation 2a) and 13.5% with a pH_s of 6.0 (Equation 2b). The assumptions were not accurate across all CEC groups (see Figure 1), and as a result some soils would not be given a lime requirement despite having a pH_s value less than optimum for plant growth.

$$ENM = 400 * \left[NA - (0.06 * CEC) \right] \qquad \text{Equation 2a}$$

$$ENM = 400 * \left[NA - (0.13 * CEC) \right] \qquad \text{Equation 2b}$$

Equation 3 is similar to Equation 1, but it was based on a quadratic relationship between NA and pH_s. Fisher's database (Figure 2A) and that of the 1990's database (Figure 2B) show this to be an accurate assumption. The constants a, b, and c in Equation 3 are obtained from the quadratic equations fitted to the curves in Figure 2A. The presently used lime recommendation equations are variations of Equation 3.

$$ENM = 400 * \left[NA - \frac{NA}{a - b * (pH_s) + c * (pH_s)^2} \right] \qquad \text{Equation 3}$$

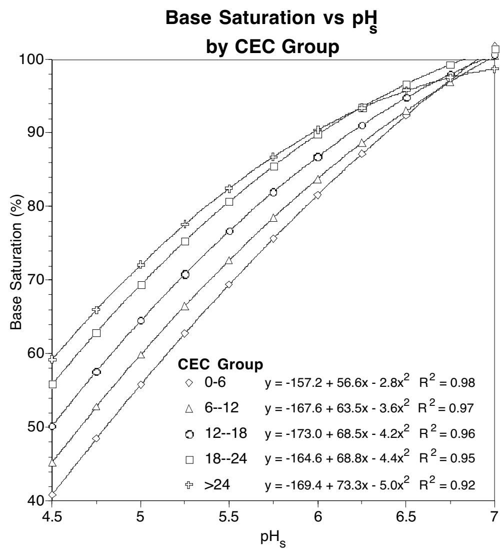

Figure 1. Percent soil base saturation versus pH_s

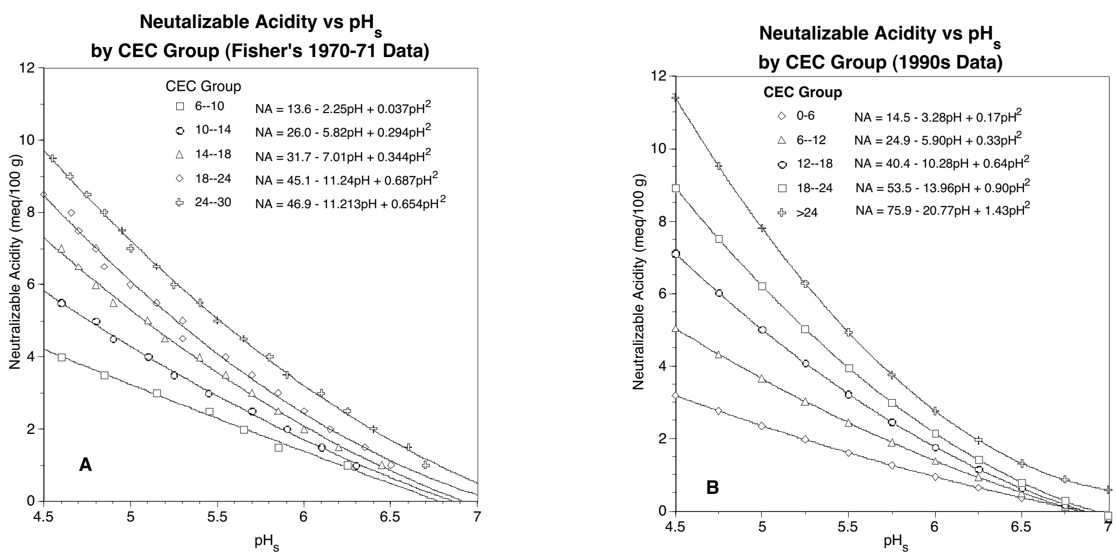

Figure 2. NA versus pH_s as varied by CEC group for A) 1970-1971 and B) 1993-1999 data sets.

Fisher's development of Equation 3 began with a mathematical description of a portion of the NA versus pH_s curve (Equation 4). A graphical example is given in Figure 3. The objective was to describe the portion of the curve (an amount of NA) from NA_o (NA observed) to NA_d (NA desired) and from the observed pH (pH_o) to the desired pH (pH_d). If NA = 0 then $pH_d = pH_v = pH_s$ 7.0.

$$\frac{dNA_o}{dpH_o} = C\left(pH_v - pH_o\right) \qquad \text{Equation 4}$$

where C is a constant

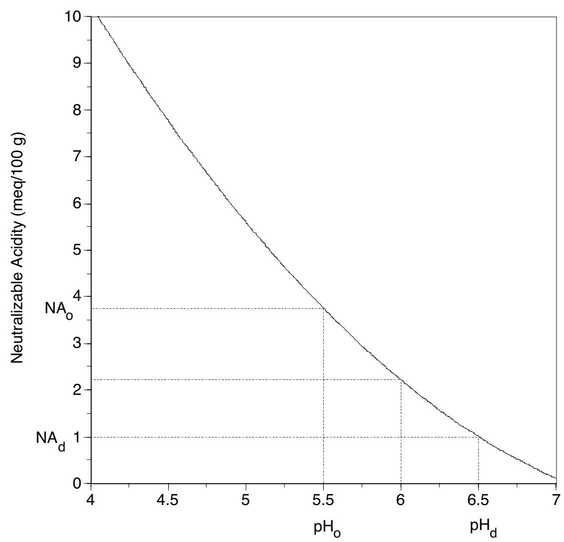

Figure 3. Graphical representation of the calculation of lime requirement (NA) from a NA versus pH_s curve. NA_o is the observed NA, NA_d is the NA at the desired pH_s, pH_o is the observed pH_s and pH_d is the desired pH_s.

Following integration, substitution and rearrangement, Equation 5 is obtained (see Brown, 1984 or Appendix A of this document for a complete description). The denominator in Equation 5 is a quadratic equation, which describes the NA versus pH_s curve. Fisher then could substitute coefficients from NA versus pH_s curves obtained from soil test data into Equation 5 (coefficients l, m, and n).

$$NA_d = \frac{NA_o}{l - m * pH_o + n * pH_o^2} \qquad \text{Equation 5}$$

The amount of NA to neutralize (NA_l) is represented in Equation 6.

$$NA_l = NA_o - NA_d \qquad \text{Equation 6}$$

The final step was to convert the equation into units of effective neutralizing material (ENM), which resulted in Equation 3. In the final algorithm, there were three variations of Equation 3 (Equations 7, 8 and 9), each of which was based on a different target pH_s (6.0, 6.5, and >6.5). With a target pH_s greater than 6.5, the quadratic part of Equation 3 drops out resulting in Equation 7.

$$ENM = (400) * (NA) \qquad \text{Equation 7—for a target } pH_s > 6.5$$

$$ENM = 400 * \left[NA - \frac{NA}{41.425 - 10.307 * (pH_s) + 0.629 * (pH_s)^2} \right]$$ Equation 8—for a target pH_s of 6.5

$$ENM = 400 * \left[NA - \frac{NA}{19.109 - 4.802 * (pH_s) + 0.297 * (pH_s)^2} \right]$$ Equation 9—for a target pH_s of 6.0

The precise dataset used by Fisher is now unavailable, so we are unable to recalculate precisely the coefficients in his recommendation equations (Equations 1, 2 and 3). Yet among the family of CEC group curves in Figure 2A, the coefficients from the 18-24 CEC group essentially match those in Equation 8. The 12-18 CEC group of the 1990's data set resulted in similar coefficients. For a target pH_s of 6.0 (Equation 9), integration of a smaller area of the NA vs pH_s curve results in smaller coefficients.

Evaluation of prospective changes to lime recommendation algorithm

Following the preceding review of data and the methods used to develop the current lime requirement recommendations, it is appropriate to review potential changes that would update or improve recommendations. Some considerations are issues that were originally considered by Fisher, but perhaps were not implemented because of limited computing capabilities. It is not our intent to promote one method over another; rather we want to review the legitimate alternatives to the presently used algorithm.

Use of Percent Base Saturation

Fisher originally explored the possibility of using average percent saturation of the soil exchange complex with NA as a means of making lime recommendations (see Equation 2). His objection to this approach was that occasionally no lime recommendation would be given for samples with pH_s values less than 5.6 or 6.1. As evident in Figure 1, there is a good relationship between base saturation and pH_s. At a target pH_s of 6.5, there is a small range (about 5%) in the percent base saturation across CEC groups. For the 12 to 18 CEC group, the percent base saturation is 95%. Similarly, there is a good relationship between NA and percent base saturation (R^2 between 0.93 to 0.98 across CEC groups). Thus it would be feasible to substitute a measure of base saturation for NA and use the current algorithm to calculate lime requirement. As Fisher noted, there would still be the problem of some soils not receiving a lime recommendation despite the observed pH_s being less than the target pH_s.

Varying Recommendations by CEC Group

The relationship between NA and pH_s is not the same across all soils as shown in Figure 2. As cation exchange capacity increases, it tends to buffer the release of protons from the exchange complex of the soil. The CEC groupings used in Figure 2 illustrate the differences in NA as related to CEC groups, which suggests that CEC may be included in equations used to calculate lime requirements.

In trying to follow Fisher's development of equations 8 and 9, he apparently used coefficients from the 18-24 meq/100 g curve to represent an average of the NA vs pH_s relationship. Using both the 1970's (Table 12) and 1990's databases (Table 13), we attempted to contrast lime requirements that result from Fisher's equations as varied by CEC group. Although the NA groups do not perfectly overlap between the two datasets, this exercise provides an opportunity to analyze the contribution that grouping soils by CEC would make toward improving lime recommendations.

In Tables 12 and 13, lime recommendations were calculated by substituting coefficients generated from curves in Figure 2 into Equation 8. Table 12 was generated from Fisher's 1970 and 1971 dataset (see Figure 2A), and Table 13 from the 1993 to 1999 data set (see Figure 2B). Each pH_s range reflects an appropriate range in NA for the CEC group. For each CEC group, the Curve Coefficient column was generated using coefficients taken from the quadratic equations that describe the curves (in Figure 2). The second column was generated using Equation 8, which remember represents an average CEC (18-24 meq/100g). In Table 12 there is no 18-24 CEC group for comparison, because this is the CEC group on which it is assumed that Fisher based Equation 8. The coefficients are essentially identical.

Table 12. Lime recommendations using coefficients from curves generated by 1970-1971 data set CEC groups that were substituted into Equation 8.

CEC Groups												
	6-10			10-14			14-18			24-30		
NA	pHs	Curve Coeff†	Avg Coeff‡	pHs	pHs	Curve Coeff	pHs	Curve Coeff	Avg Coeff	pHs	Curve Coeff	Avg Coeff
		lb ENM/acre			lb ENM/acre			lb ENM/acre			lb ENM/acre	
1.0	6.25	0	146	6.30	13	125	6.45	0	41	6.70	0	0
1.5	5.85	245	374	6.10	191	293	6.20	195	247	6.60	166	0
2.0	5.65	411	555	5.90	385	481	6.00	408	441	6.40	384	146
2.5	5.45	588	746	5.70	584	679	5.85	597	623	6.25	577	366
3.0	5.15	798	961	5.45	805	895	5.70	791	814	6.10	777	587
3.5	4.85	1005	1175	5.25	1008	1099	5.55	989	1011	5.90	1001	842
4.0	4.60	1202	1381	5.10	1199	1293	5.40	1189	1211	5.80	1186	1029
4.5	4.30	1409	1594	4.90	1406	1501	5.20	1406	1428	5.65	1393	1249
5.0	4.10	1599	1795	4.80	1589	1690	5.10	1593	1617	5.50	1601	1469
5.5				4.60	1798	1900	4.90	1809	1835	5.40	1794	1665
6.0				4.45	1996	2101	4.80	1999	2028	5.25	2004	1884
6.5				4.25	2206	2311	4.70	2192	2222	5.15	2200	2083
7.0				4.15	2396	2505	4.60	2385	2418	5.00	2410	2301
7.5							4.45	2591	2626	4.95	2596	2484
8.0							4.30	2796	2834	4.85	2795	2686
8.5							4.20	2992	3032	4.75	2995	2889
9.0							4.00	3208	3249	4.65	3196	3093
9.5										4.55	3397	3297
10.0										4.45	3598	3501
Average Difference#			163			100			31			-131

†Curve coefficients used from curves shown in Figure 2A and substituted into Equation 8.
‡Average coefficients used by Fisher in Equation 8—approximately that of the CEC group 18-24.
#Average ENM difference between the Curve Coefficients and the Average Coefficients (Fisher's 18-24 CEC Group) across all pH_s values.

Because of the similarity of curve slopes, there is little difference in ENM recommendations between CEC groups. For CEC groups with values less than the presumed 18-24 meq/100 g in Fisher's Equation 8, lime requirements (Curve Coefficient column) are slightly less than recommended by Equation 8 (Avg. Coefficient column). At greater CEC values, lime requirements of the CEC groups are slightly greater than that of the average. The greatest discrepancies between CEC group recommendations and the average CEC recommendation are with the low CEC groups. The curve of the 6-10 CEC group deviates from the other CEC groups by being more linear (small value for the squared term). However, because of the relatively small NA values that are associated with the low CEC soils, ENM recommendations differ only slightly. A direct comparison of CEC-group curves between the two datasets is not possible, because the data were not identically grouped. However there appears to have been little change. An exception is the largest CEC group. The curve for the >24 group (1990s data set) is more strongly curvilinear than the 24-30 group (1970s data set). This may be due to improved precision of lab techniques. The 1970s' dataset consisted of significant numbers of samples that were run in county labs, while

Table 13. Lime recommendations using coefficients from curves generated by the 1993-1999 dataset CEC groups that were substituted into Equation 8.

	CEC Groups														
	0-6			6-12			12-18			18-24			>24		
NA	pH_s	Curve Coeff[†]	Avg Coeff[‡]	pH_s	Curve Coeff	Avg Coeff	pH_s	Curve Coeff	Avg Coeff	pH_s	Curve Coeff	Avg Coeff	pH_s	Curve Coeff	Avg Coeff
		lb ENM/acre			lb ENM/acre			lb ENM/acre			lb ENM/acre			lb ENM/acre	
1.0	6.25	0	146	6.30	0	125	6.45	0	41	6.50	0	2	6.70	0	0
1.5	5.85	69	374	6.10	96	293	6.20	126	247	6.35	76	152	6.60	59	0
2.0	5.65	226	555	5.90	293	481	6.00	345	441	6.15	326	362	6.40	282	146
2.5	5.45	402	746	5.70	498	679	5.85	538	623	6.00	533	551	6.25	486	366
3.0	5.15	633	961	5.45	729	895	5.70	738	814	5.85	744	748	6.10	703	587
3.5	4.85	860	1175	5.25	937	1099	5.55	942	1011	5.70	958	950	5.90	953	842
4.0	4.60	1068	1381	5.10	1128	1293	5.40	1149	1211	5.55	1173	1155	5.80	1148	1029
4.5	4.30	1291	1594	4.90	1340	1501	5.20	1376	1428	5.40	1387	1362	5.65	1371	1249
5.0	4.10	1488	1795	4.80	1522	1690	5.10	1567	1617	5.20	1619	1587	5.50	1594	1469
5.5				4.60	1736	1900	4.90	1792	1835	5.10	1815	1779	5.40	1796	1665
6.0				4.45	1937	2101	4.80	1986	2028	4.90	2042	2002	5.25	2017	1884
6.5				4.25	2151	2311	4.70	2182	2222	4.80	2240	2196	5.15	2221	2083
7.0				4.15	2341	2505	4.60	2379	2418	4.70	2440	2393	5.00	2441	2301
7.5							4.45	2591	2626	4.60	2640	2590	4.95	2631	2484
8.0							4.30	2801	2834	4.45	2852	2801	4.85	2836	2686
8.5							4.20	3001	3032	4.30	3064	3011	4.75	3042	2889
9.0							4.00	3222	3249	4.20	3265	3210	4.65	3248	3093
9.5													4.55	3455	3297
10.0													4.45	3661	3501
Average Difference[#]			299			167			55			-19			-125

[†]Curve coefficients used from curves shown in Figure 2A and substituted into Equation 8.
[‡]Average coefficients used by Fisher in Equation 8—approximately that of the CEC group 18-24.
[#]Average ENM difference between the Curve Coefficients and the Average Coefficients (Fisher's 18-24 CEC Group) across all pH_s values.

the 1990s data came from only two labs (Columbia and Portageville). With the elimination of the county labs, potentially more NA would have been measured on low pH_s soils. Subsequently, a greater curvilinearity resulted in the 1990's dataset curves. Nevertheless, lime recommendations generated from the 1970s' and 1990s' datasets were relatively similar. The small differences due to CEC are not large enough to justify the inclusion of CEC groups in the algorithm.

Varying Recommendations by Soil Region

Soils across Missouri vary considerably with respect to weathering and parent material (see Appendix B), and these differences affect the nature of reserve acidity. In general, weathering of soils in the state increases to the south and east from the northwest corner of the state. Soil regions were established in the recommendation algorithm in order to provide region-specific lime recommendations. Present recommendations vary only by the target pH_s for forage legumes in the Cherokee Prairie, Ozark and Ozark Border regions (Soil Regions 6, 7, and 8).

Each NA versus pH_s curve for any CEC group shown in Figure 2 could be considered an average, comprising a group of curves that result from individual soil regions. An example of a family of curves by soil region for two CEC groups is shown in Figure 4. At lower pH_s values and the larger CEC groups, the NA values of some soil regions diverge from the "pack" of curves of other soil regions. In particular, curves of Soil Regions 6 and 7 lie above those of other soil regions. For Soil Regions 6 (Ozarks) and 7 (Ozark Border), the greater NA per pH_s may be a consequence of increased activity of soil aluminum. As was observed with the different CEC groups, the similarity of curve slopes as varied by soil region would result in little difference in ENM recommendations.

Is There a Need for a Measure of Extractable Aluminum?

The activity of soil aluminum increases appreciably at pH_s values of 4.5 or lower. At such low pH_s values, aluminum activity in soil solution becomes toxic to plant growth. In Missouri the problem of low pH_s and toxic aluminum is mostly isolated to the highly weathered Ozark soils. Even when the surface soil acidity is reduced by application of liming materials, the subsoils remain highly acidic. The present lime recommendations account for the acid subsoils by increasing the amount of lime recommended for legumes. The increase in lime requirement results from an increase in the desired pH_s. The hoped-for-effect is that the greater amount of lime will neutralize some of the subsoil acidity. The effectiveness and efficiency of such an increased lime application toward alleviating aluminum toxicity can not be quantified, but Kroth and Mattas (1981) showed that the liming effect will move downward given time.

It must be remembered that the NA measurement is an index of reserve acidity, and may not accurately represent acidity that results from soil aluminum. A measurement of extractable aluminum may indicate the potential for additional reserve acidity. Yusef (1986) and Syed Rastan (1995) both showed that neither KCl extractable aluminum nor two times that amount of aluminum was a satisfactory estimate of lime requirement. Syed Rastan (1995) had promising results from aluminum extracted with 0.33 M $LaCl_2$. As with any index such as the laboratory measurement of NA, field calibration is necessary to determine the actual effectiveness of the limestone amount recommended by the NA measurement.

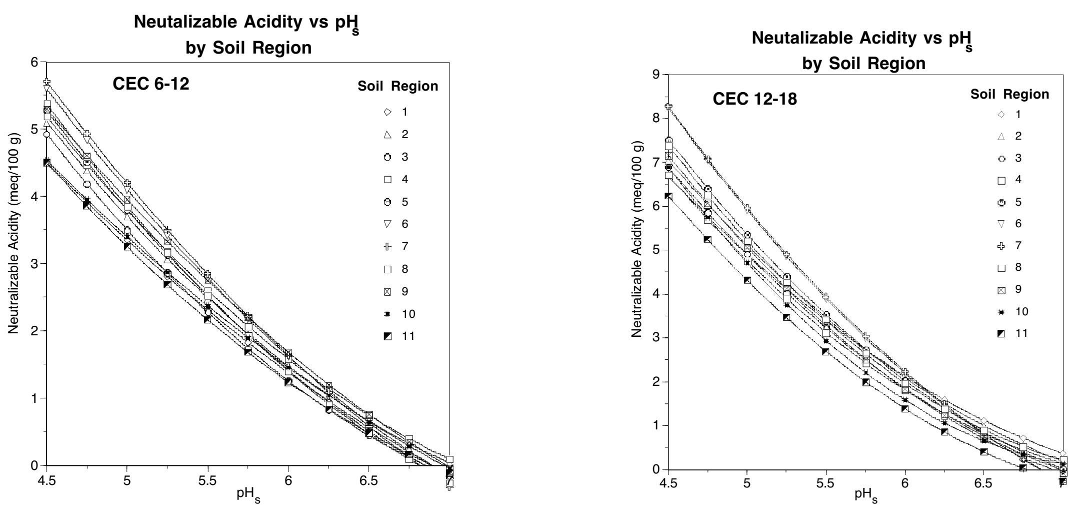

Figure 4. Soil Region effect on NA vs pH_s curves for a) 6-12 CEC and b) 12-18 CEC. 1993 to 1999 data set.

Summary and recommendations

The current lime recommendation algorithm used by the University of Missouri Soil Testing Laboratory has not changed in 30 years since implementation. The essence of the algorithm is that NA and pH_s are measured in the laboratory, and then an empirical relationship between the two is used as the basis for determining the amount of limestone to apply. The algorithm is not varied by soil CEC. Soil test results collected from 1993 to 1999 indicated that the relationship between NA and pH_s is essentially unchanged relative to the data set used in 1972 when the current algorithm was developed. The algorithm was developed such that differences in the NA versus pH_s relationship due to CEC or Soil Region do not dramatically affect limestone recommendations. Thus we do not propose the inclusion of CEC in a new algorithm. We feel that the work by Kroth and Mattas (1981) justify retaining the separate recommendation for legumes grown in Soil Regions 6, 7, and 8.

With each curve of NA versus pH_s examined, there was a considerable scatter of data points around the fitted curve. Identifying the sources of such scatter may lead to modifications in the algorithm that improve recommendations. Some soils may be more buffered against limestone applications. That is, the NA versus pH curve for some soils may have a greater slope or greater curvilinearity than expressed by the recommendation equations. Similarly, different liming materials may vary in their neutralization of soil acidity to a target pH. For example some liming materials may be somewhat self-buffered through reduced dissolution. Some soils may also have large amounts of extractable aluminum, and the NA measurement may not accurately express all of the reserve acidity.

This review of the basis of liming recommendations and its historical background provide the necessary information to answer the questions posed at the start of this section of the paper.

1. Should lime recommendations be based on percentage base saturation rather than pH_s and NA?

   No. Percentage base saturation is calculated from the sum of the milliequivalents of basic cations divided by the CEC. The estimate of basic cations in the soil comes from the soil tests for potassium, calcium, and magnesium, all extracted with 1 M ammonium acetate. The estimate of NA, which is obtained using the Woodruff buffer, is necessary to get the CEC. Thus, no test would be eliminated by using the percentage base saturation method for making recommendations. As yet, there is no quick test method to substitute for the Woodruff buffer as a measure of NA unless there was a significant increase in turn-around time for soil testing.

2. Should the "needed ENM" calculation include CEC in addition to pH_s and NA?

   Probably not. The review using the 1993-1999 data set showed minimal ENM differences (fractional ton of limestone) in recommendations when CEC was included in the algorithm between the current algorithm and the algorithm including CEC. If however, improved precision in calculated quantities is desired, then computing capabilities make this a simple change.

3. Should soil regions continue to be included in lime recommendations?

   A qualified yes. The review using the 1993-1999 dataset suggests using the soil regions added little to the value of the lime recommendations. However, the ultisols of the highly weathered Ozark region have profound effects on rooting depths due to high levels of aluminum. For this reason it seems desirable to continue to use a separate algorithm for soil regions 6 and 7. The curves in Figure 4 showed that Region 7 was somewhat different from the other regions. Historical data have been presented that showed downward movement of the liming effect with time on highly acid soils.

4. May a measure of extractable aluminum as it relates to NA improve recommendations for low pH_s soils?

   Not at this time. Research by Yusef and Syed presented in this paper is not adequate to support inclusion of an extractable aluminum soil test on low pH_s soils. There were no field data on which to base recommendations, even though both former students showed that such a test is feasible. Syed's work suggested that 0.33 M $LaCl_2$ had potential for a test, but requires field calibration; greenhouse results are inadequate for calibration. Addition of an aluminum test to the soil testing program would increase the turn-around time for results and require some laboratory improvements to be able to analyze for aluminum.

No-tillage culture of crops was virtually unknown when the present limestone recommendations were developed. The assumption of the present recommendations is that all liming material is evenly distributed throughout the depth of tillage. Thus a target pH should be achieved uniformly in the tillage depth. As all row crops have a target pH_s of 6.1 to 6.5, application of lime only to the soil surface will likely violate the assumption of reaching a target pH_s with the recommended amount of lime. The NA versus pH_s curves show soil, particularly high CEC soils, to be more buffered at pH_s near or above 6.5. So it seems likely that no-till lime recommendations would require modification.

The average relationship between NA versus pH_s (across all soils) seems to be well defined and provides a good basis for making limestone recommendations. Future directions for liming research should evaluate the impact of extractable aluminum, examine the effects of different liming materials and the response of different soils to effect changes in pH_s. The principles of recommending lime based on laboratory measurement of NA and pH_s seem well based. However, further field calibration of these indices remains ever necessary.

Evaluation of Existing Laboratory Procedures and Suggestions for Improvements in the Limestone Recommendation Programs

As the authors compiled this document, several concerns arose about the management of acid agricultural soils. Mankind has recognized the benefits of liming for centuries as was pointed out in the section on history of liming. Yet today it seems that agricultural producers and researchers have relegated liming to a lessor status than other aspects of crop management.

In this era of precision in agriculture, improving the precision of liming has been difficult. Recommendations for lime based upon quick soil tests often do not lower the soil acidity to the desired levels. Further, liming does not always increase crop yields. There are several reasons for these inconsistencies. First, the quasi-quantitative estimation of the need for liming material seems to under-estimate the amount of soil acidity needing neutralization. Second, assumptions about the ideal soil acidity levels for each crop species (and perhaps variety) may over generalize the actual situation. Third, it is incorrect to assume the ENM measure of reactivity of individual liming materials can be uniformly applied regardless of the physical and chemical properties of individual liming materials. Fourth, recommendations need to be recalibrated for reduced tillage systems, because liming material often is not mixed with the "plow layer" of soil but is placed on the soil surface and mixed only superficially.

The recommendations for liming material in Missouri are based upon the estimate of neutralizable acidity using the Woodruff buffer and an estimate of active acidity in a suspension of soil and 0.01 M $CaCl_2$. Both measurements are made after about 30 minutes of soil/solution contract. While this may be adequate for the measurement of active acidity, the contact time may be insufficient to get a true measure of the labile acidity needing neutralization for optimum growing conditions. The graduate student research summarized herein was inconsistent in finding an optimum measurement of the need for liming material, although 0.33 M $LaCl_2$ extraction of aluminum has possibilities. Any quick test that appears to be improved over existing procedures must be calibrated to field response of crops under field conditions over a period of time. Based upon the experience with the studies reported in this paper, that time period should be a minimum of 10 years. Our experience suggests that no source of funding is available that will support the needed fieldwork for extended time periods. The 1993-1999 data base showed that Soil Regions 6 and 7 have many acres of very acid soil, yet because of the dominant grass-forage-based agriculture of those regions, profit margins are so narrow that financial support of liming research is not considered cost effective.

Research may improve the laboratory portion of the program. The assumption that 1 milliequivalent of acidity per 100 grams of soil will depress the Woodruff buffer pH by 0.1 unit needs to be reevaluated using very acid soils and aluminum solutions. Further, it might be helpful to manipulate the standing time for the soil-buffer mixture in an attempt to better estimate the reserve or labile acidity due to slow release of bound aluminum.

In addition to questions concerning exactly what the Woodruff buffer does and does not measure, Missouri research suggests that the three target pH_s ranges may be too high. Likely these ranges have a built in "cushion" based on the assumption that growers will not monitor soil acidity sufficiently to detect a gradual drop in pH_s. In addition, these targets may need reevaluation for specific crops. The research upon which the targets are based is, in most cases, older than 25 years. Field work reported by Fisher (1969), Roth and Fisher (1972a, 1972b, 1973) and Bennett (1990) indicated that optimum response to liming treatments in the field is not as predictable as theory suggests.

Our summary of research also suggests that liming materials differ in their reactivity in acid soil. The liming materials used for agriculture lime come from different geologic strata. Geologists characterize the different limestone strata by crystalline structure and physical properties, which in part, would explain differences in dissolution rates and reactivity. We were unable to find any Missouri work that had been designed to determine if dissolution differences affected crop response to lime. Stevens (1990) showed that dolomitic limestone was less effective in neutralizing soil acidity than calcitic stone. Further, some unreported work suggested that certain dolomitic stones will raise the pH only to the mid 6.0s. As we pointed out earlier in the paper, the effectiveness of the different particle size groups needs to be reevaluated, as the 8-40 and 40-60 mesh sizes may be undervalued.

The acceptance of reduced tillage practices makes the lime calibration work done with moldboard plow primary tillage questionable for use in making liming material applications. Unincorporated lime applied to the soil surface results in a greater concentration of the liming material than if thoroughly mixed with the "plow layer." Thus the lime requirement perhaps should be less. Stevens showed that the impact of dissolution of limestone extends only a short distance from the particle and occurs in a very short time. Kroth and Mattas found that surface application of limestone in relatively small quantities was adequate for establishment of clover stands in fescue sod. The timing of lime application affects seedling establishment. Unless time is allowed for reaction of the limestone dissolution products with acid soil, local build up of calcium may adversely affect seedlings, especially alfalfa (Syed, 1995).

The recent emphasis on precision farming for row crops, while focusing on the major nutrients (N, P, K), also considers banding of lime, variable rate application over the field, and frequent application of finely ground or pelletized liming material. Over application of liming material, especially finely ground material, may excessively increase pH_s and interfere with the reactivity of pesticides. There is a limited amount of ongoing research on these later topics, which is not ready to be reported. It is likely that the studies should be expanded, especially to measure the long-term effects of precision and variable rate production practices.

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Appendix A

Development of the Lime Requirement Equations by T. R. Fisher

In 1972 Dr. T.R. Fisher developed a system to interpret the Woodruff Buffer pH to calculate recommended amounts of limestone that would alleviate deleterious soil acidity to crops. A basic assumption was that soil acidity should be reduced to a level that resulted in an optimum pH. Related to this is the fact that a soil's pH_s is related to its base saturation, or conversely its base unsaturation. The Woodruff Buffer pH estimates a soil's base unsaturation, which is reported as neutralizable acidity (NA). As a soil's CEC increases so must the quantity of neutralizable acidity to maintain a given pH_s. Thus for any given CEC, the pH_s and NA are related and can be expressed mathematically. In the following discussion several subscripts will be used with the pH symbol. All subsequent references to pH infer a pH measured in 0.01 M $CaCl_2$—the standard method of pH measurement used by the University of Missouri Soil Testing Laboratory.

The quantity of NA to be neutralized is the difference between NA in the soil initially (NA_o at an initial pH, pH_o) and the NA in the soil at the target pH (NA_d). A target pH is defined as specific desired pH less than or equal to 7.0.

For a curve that describes NA versus pH, the change in NA relative to a change in pH is described as

$$\frac{dNA_o}{dpH_o} = C(pH_v - pH_o)$$

where NA_o is the observed NA, pH_o is the observed pH, and pH_v is the pH where NA = 0. The integral of this expression is

$$\int dNA_o = C\int (pH_v - pH_o)dpH_o$$

Upon integration ($0 < NA < NA_o$ and $pH_v < pH < pH_o$)

$$NA_o = \frac{c}{2}(pH_v - pH_o)^2 + Ci$$

when $pH_o = pH_v$, NA = 0, therefore the integration constant Ci = 0 and

$$NA_o = \frac{c}{2}(pH_v - pH_o)^2$$

If we define a target pH as pH_d (desired pH), then when $pH_o = pH_d$, $NA_o = NA_d$. Thus

$$NA_d = \frac{c}{2}(pH_v - pH_d)^2$$

Upon rearrangement

$$\frac{c}{2} = \frac{NA_d}{(pH_v - pH_d)^2} \qquad \text{and}$$

$$NA_o = NA_d \frac{(pH_v - pH_o)^2}{(pH_v - pH_d)^2} \quad \text{or}$$

$$NA_d = NA_o \frac{(pH_v - pH_d)^2}{(pH_v - pH_o)^2}$$

Upon inversion the expression becomes

$$\frac{1}{NA_d} = \frac{1}{NA_o}\frac{(pH_v - pH_o)^2}{(pH_v - pH_d)^2}$$

Expansion of the numerator gives

$$\frac{1}{NA_d} = \frac{1}{NA_o} * \frac{pH_v{}^2}{(pH_v - pH_d)^2} - \frac{1}{NA_o} * \frac{2pH_v pH_o}{(pH_v - pH_d)^2} + \frac{1}{NA_o} * \frac{pH_o{}^2}{(pH_v - pH_d)^2}$$

If we define coefficients l, m, and n as

$$l = \frac{pH_v{}^2}{(pH_v - pH_d)^2}\ ,\ m = \frac{2pH_v}{(pH_v - pH_d)^2}\ \text{, and}\ n = \frac{1}{(pH_v - pH_d)^2}$$

then

$$\frac{1}{NA_d} = l * \frac{1}{NA_o} - m * pH_o \frac{1}{NA_o} + n * pH_o{}^2 \frac{1}{NA_o}$$

which results in

$$NA_d = \frac{NA_o}{l - m * pH_o + n * pH_o{}^2}$$

In this form pH is related to NA as a second-degree polynomial, and coefficients from empirically derived curves can be substituted for the coefficients l, m, and n.

NA_d was defined as the amount of NA to remain in the soil at the target pH. The amount of NA to be neutralized (NA_l) by liming is

$$NA_l = NA_o - NA_d$$

Substitution results in

$$NA_l = NA_o - \frac{NA_o}{l - m * pH_o + n * pH_o{}^2}$$

To report NA_l in units of lime the conversion factor of 400 pounds of ENM per unit of NA is used. The equation then becomes

$$lb\ ENM\ /\ acre = 400\left(NA_o - \frac{NA_o}{l - m * pH_o + n * pH_o{}^2} \right)$$

If the target pH is greater than 6.5 then NA_d is effectively equal to zero. The quadratic portion of the curve drops out, which results in

$$lb\ ENM\ /\ acre = 400 * NA_o$$

This equation is one of the three that Fisher developed. Substitution of coefficients from curves resulted in the other two curves for different target pH ranges.

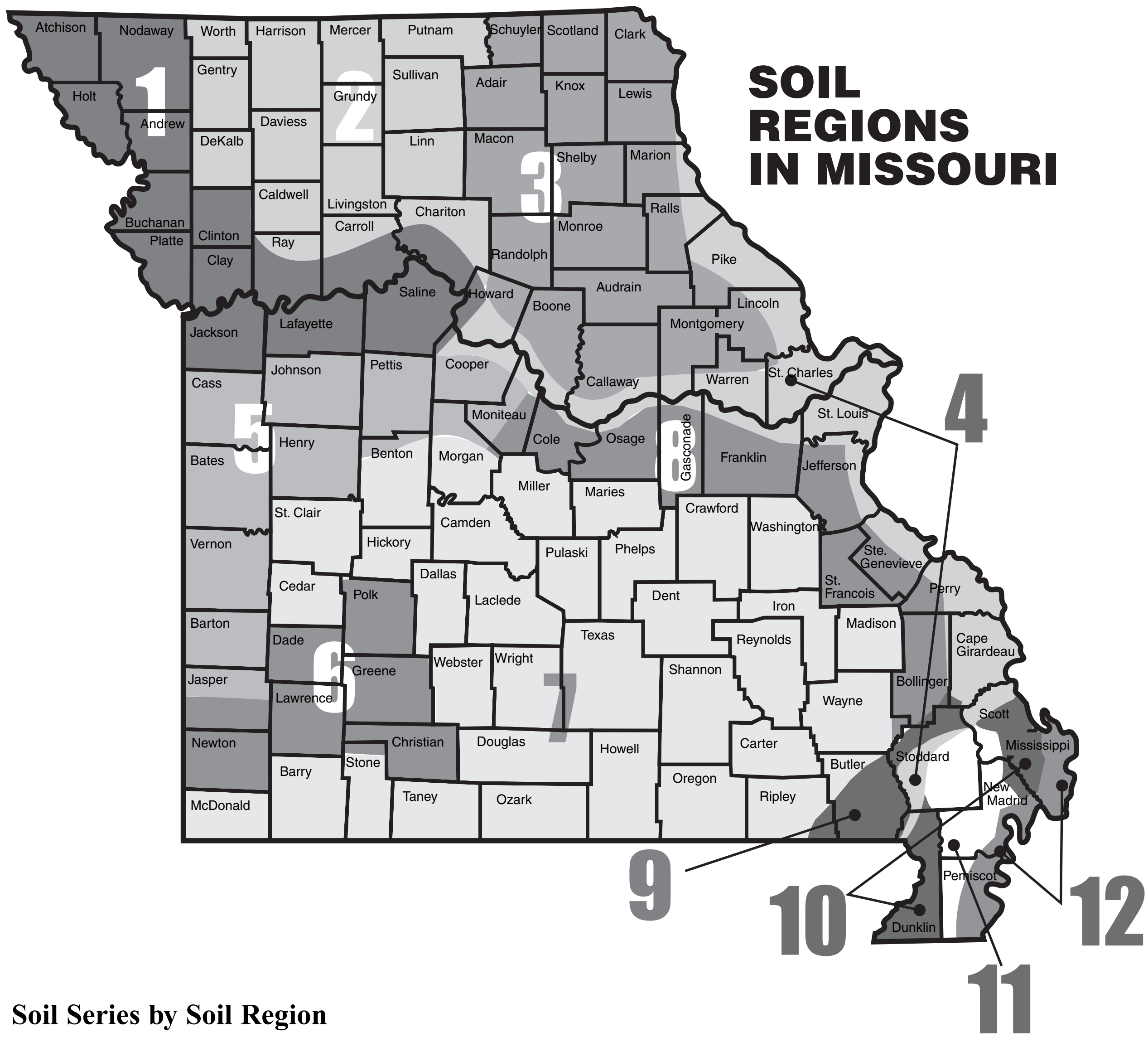
For a target pH = 5.5 to 6.0

$$lb\ ENM\ /\ acre = 400\left(NA_o - \frac{NA_o}{19.109 - 4.802 * pH_o + 0.297 * pH_o{}^2} \right)$$

For a target pH = 6.0 to 6.5

$$lb\ ENM\ /\ acre = 400\left(NA_o - \frac{NA_o}{41.425 - 10.307 * pH_o + 0.629 * pH_o{}^2} \right)$$

Appendix B
Map of Soil Regions in the State



Soil Series by Soil Region

Region 1:	Knox, Marshall (Mollic Hapludalf, Typic Hapludoll)
Region 2:	Grundy, Shelby (Aquertic Argiudoll, Typic Argiudoll)
Region 3:	Putnam, Mexico, Lindley (Vertic Albaqualf, Vertic Epiaqualf, Typic Hapludalf)
Region 4:	Menfro, Winfield (Typic Hapludalf, Oxyaquic Hapludalf)
Region 5:	Parsons, Cherokee, Bates (Mollic Albaqualf, Typic Albaqualf, Typic Argiudoll)
Region 6:	Baxter, Craig (Typic Paleudalf, Mollic Paleudalf)
Region 7:	Clarksville, Lebanon (Typic Paleudult, Typic Fragiudult)
Region 8:	Union (Oxyaquic Fragiudalf)
Region 9:	Waverly (Typic Fluvaqent)
Region 10:	Dexter (Ultic Hapludalf)
Region 11:	Sharkey (Chromic Eqiaquert)
Region 12:	Sarpy (Typic Udipsamment)

Appendix C

Notes from early Twentieth Century Missouri research and extension reports

Albrecht, W.A. 1941. Drilling limestone for legumes. Missouri Agricultural Experiment Station Bulletin 429.

Comment: Emphasizes the value of calcium in quantities smaller than that needed to eliminate soil acidity.

Barlow, J.T. 1916. Soil acidity and the litmus paper method for its determination. Jour. Amer. Soc. Agronomy 8:23-30.

Comment: Theory assumed that soil acidity was the result of organic acids, although leaching studies did not support that concept. This was the theory of Hopkins, Petit, Knox, etc.

RCOOH + KNO3 -> RCOOK + HNO3

Place 25 g soil in a dish. Add distilled water to give a thick paste. Lay 2 strips of blue litmus paper on a clean square glass plate 4 to 5 inches on each side. Place the "mud" on the litmus paper and force down with the palm of the hand. Turn the plate over and observe the color change of the paper to a standard color. The results differ between people.

Baver, L.D. and F.H. Bruner. 1939. Rapid soil tests for estimating the fertility needs of Missouri soils. Missouri Agricultural Experiment Station Bulletin 404.

Comment: Lime requirements were calculated from tables based upon the Comber test and the amount of 0.3 N HCl soluble calcium. calcium described as low, medium and high with the numerical ranges low ≤3000, medium = 3000 to 6000, high = 6000 to 7000, and very high ≥7000 pounds per acre. Detailed methodology of other soil tests.

Coleman, O.T. 1936 Home grinding limestone. Missouri Agricultural Extension Circular 352

Comment: General discussion of on-farm limestone crushing.

Coleman, O.T. 1955. Lime your soil for better crops. Missouri Agricultural Extension Circular 651.

Comment: A general liming promotion circular.

Duley, F.L. and M.F. Miller.1926. The soils experiment fields of Missouri. Missouri Agricultural Experiment Station Bulletin 238.

Comment: Summary of work on outlying fields, some of which were started in 1905 following the pattern used in Illinois with modifications. That is, the same treatments were used at nearly all locations. "Lime has been of great value on certain soil types in growing the clovers and alfalfa." Rock phosphate did not give the results like bonemeal and acid phosphate. Manure was of such benefit that the recommendation was to use crop rotations and have a livestock enterprise. So most of the grain was fed on the farm.

Hartwell, B.L. and F.R. Pembee. 1918. Aluminum as a factor influencing the effect of acid soils on different crops. Jour. Amer. Soc. Agronomy 10:45-47.

Comment: Barley was more sensitive to soil acidity in a Delaware location than rye. The effect was attributed to aluminum.

Kroth, E.M. and R. Mattas. 1981. Effect of top-dressed limestone, nitrogen, phosphorus and potassium of yield and mineral content of tall fescue forage and soil test values. Missouri Agricultural Experiment Station Research Bulletin 1040.

Comment: Three top-dressed rates of lime and 1 rate (recommended) mixed with the top 7 inches of soil. Soil test data 3 and 7 years after application.

Krusekopf, H.H. 1938. Soil fertility investigations on Brown limestone land of southwestern Missouri. Missouri Missouri Agricultural Experiment Station. Bulletin 395.

Comment: 1921-1931 results from the Newtonia Field (northeast Newton Co.) Treatments: none, P, P+lime, P+lime+potash, N+P+K+lime, Manure, manure+P, manure+P+lime, Manure+lime+rockP. C_SB_Wh_Cl rotation. Manure+lime+superP gave the greatest yields of all crops over the 11 year period. N at only 40 lb to corn and wheat.

Miller, M.F. 1909. Some results with lime on Missouri soils. Jour. of the Amer. Soc. Agronomy. 1:228-233.

Comment: A report on the early liming results of the outlying experiments. Yield depressions were observed, but there was no obvious explanation.

Miller, M.F. 1936. Testing soils for acidity by the modified Comber method. Missouri Agricultural Extension Circular 339.

Comment: Interpretation of the colors from the Comber test. No recipe.

Miller, M.F. and F.L. Duley.1917. Soil experiments on the Ozark upland. Missouri Agricultural Experiment Station Bulletin 148.

Comment: Location 1 mile west of St. James. Introduction refers to soil analysis but does not elaborate. N, P, K, lime need in top 7 inches=2340, 1320, 21480 and 4800 ("rich soil"=6000, 2000, 30000 and 0) Treatments: manure, manure+rock P, legumes+lime+bonemeal+potash, none, legumes+lime+ bonemeal, legumes+lime, legumes. 1911-1916 1000 lb rock P, 2 tons lime, 8 tons manure. Lime paid especially well for legume establishment.

Miller, M.F. and R.R. Hudelson. 1914. Soil investigations- Jasper County Experiment Field. Missouri Agricultural Experiment Station Bulletin 119.

Comment: Site 2.5 miles south of Carthage. Data 1909 to 1913. The acid soil required "2400 pounds of ground limestone to sweeten the surface seven inches of an acre." Treatments: cowpeas (CP), CP+Lime, CP+Lime+Bonemeal (B), CP+Lime+B+K, None, Manure, manure+rock phosphate, manure+rock phosphate+Lime. Manure increased corn yield 10 Bu/a but did not affect wheat yields. Lime and P most beneficial. Soil "so low in organic matter that grain crops should never be continuously grown upon it."

Miller, M.F. and C.B. Hutchison. 1910. Soil experiments on the prairie silt loam of Southwest Missouri. Missouri Agricultural Experiment Station Bulletin 84.

Work done on a farm southeast of Lamar. Treatments: N+P, None, N+K, P+K, N+P+K, N+P+K in hill, N+P+K+Lime. There were other treatments in other experiments, but these were the basic treatments. After the first year, cowpeas were added to the rotation to provide for N. Blood meal (50 lb/acre) was the N source the first year. P = 150 lb fine bone meal, K = 50 lb muriate of potash, Lime = 2000 lb/acre ground limestone before corn each rotation cycle. Experiments suggest the order of deficiency = N>P>lime>K.

Miller, M.F. and C.B. Hutchison. 1910. Soil experiments on the rolling limestone upland of southwest Missouri. Missouri Agricultural Experiment Station. Bulletin 86.

Location selected in 1905 was on a farm 3.5 miles south of Billings. Cowpeas used as a catch crop. Treatments: None, cowpeas (CP), CP+lime, CP+lime+P, CP+lime+P+K. Summary gave recommendations for owned and rented land treatments. 2,000 to 4,000 lb of ground limestone per acre once in a 4 to 5 year rotation. (Area of coverage includes what is now recognized as a low magnesium limestone area.).

Miller, M.F., C.B. Hutchison, and R.R. Hudelson. 1915. Soil experiments on the Gray Prairie soils of southwest Missouri. Missouri Agricultural Experiment Station Bull. 130.

Comment: A complete coverage of the subject including soil tests and lime quality over the state.

Miller, M.F., C.B. Hutchinson, and R.R. Hudelson. 1915. Soil experiments on the level prairies of northeast Missouri. Missouri Agricultural Experiment Station Bull. 126.

Comment: Putnam silt loam. 3 locations: 2.5 miles northeast of Monroe City 1905-1908; 0.25 mile north of the High Hill railroad station 1907-; 1 mile southwest of Bowling Green. 1907. Treatments: cowpeas (CP), CP+Lime, CP+Lime+Bonemeal (B), CP+Lime+B+K, None, Manure, manure+rock phosphate, manure+rock phosphate+Lime. Cowpeas worked only at High Hill. Rock phosphate a long-term treatment. Manure should be carefully returned to the land. Bone meal is productive.

Miller, M.F., C.B. Hutchinson, and R.R. Hudelson. 1915. Soil experiments on the rolling glacial land of north Missouri. Missouri Agricultural Experiment Station Bull. 128.

Comment: Site was 1 mile north of Laclede, classified as Shelby loam. Treatments: Legume, Legume+bonemeal, Legume+bonemeal+lime, Legume+bonemeal+lime+potash, None, Manure, manure+rock phosphate, manure+rock phosphate+legume. Order of response: available P>potash>lime.

Miller, M.F. and H.H. Krusekopf. 1920. Agricultural lime. Missouri Agricultural Experiment Station Bulletin 171.

Trotter, I.P. and O.T. Coleman. 1928. How to use agricultural limestone. Missouri Agricultural Extension Circular 208.

Comment: General use is described based on soil test. The test use is not stated. Directions include the statement “use at least as much lime as the test calls for.” Recommendation is based upon 10-mesh grind.

Appendix D

Details from graduate student theses and dissertations

Appendix D contains extended summaries of several thesis and dissertations submitted by soil science graduate students as partial completion of an advanced degree. Several of these theses were not published beyond the requirements for a bound thesis. Therefore, the authors of this document on Liming in Missouri decided to include the following summaries.

Exchangeable Acidity, Salt pH, and Base Saturation of Some Missouri Soils

K.E. Benham, MS Thesis-1970
C.L. Scrivner, advisor

Benham (1970) tested methods for estimating exchangeable acidity to use in calculating percentage base saturation as an aid to classification of upland soils. In his literature review, he cited several references for measuring cation exchange capacity and acidity in soils going back to the early 1900s. One of Benham's objectives was to determine the pH at which the CEC should be determined for use in classification.

Benham selected a group of soil series differing in parent material and native vegetation including 4 Mollisols and 12 Alfisols. With some duplication of series he had a total of 23 different sites. The solum of the soil at each site was sampled by diagnostic horizon. Exchangeable acidity was measured by titration with a standardized solution of $CaOH_2$ and $CaCl_2$ (0.04 N in base and 0.02 N in Cl), the New Woodruff buffer (Brown and Rodriguez, 1983) and the $BaCl_2$/TEA method of Mehlich as outlined by Peech (1965).

Titration curves of samples from diagnostic surface soil horizons differed from those of the subsurface horizons. Benham suggested that the differences might be due to eluviation-illuviation of clay during soil formation and/or to organic matter in the surface soil. No organic matter data were provided.

Benham stated "… the $Ca(OH)_2$/$CaCl_2$ method provides a reliable and accurate way to measure exchangeable acidity in all horizons of mineral soils." The results compared favorably with measures of exchangeable acidity by the $BaCl_2$–TEA method.

Benham did not succeed in his attempt to develop a family of curves for the set of soils that would relate pH in 0.01 M $CaCl_2$ to percentage base saturation as an aid in soil classification. The amount of scatter was too large for reasonable predictability. Since pH is an intensity value and percentage base saturation is a capacity factor that integrates amounts of three or more cations, such a negative result is not surprising.

Benham also estimated acidity using the New Woodruff buffer and compared those results with the $Ca(OH)_2$/$CaCl_2$ determinations of acidity. He reported the following results of that comparison:

Samples	Number of Samples	r^2	Slope
A horizons	44	0.690	0.893
B & C horizons	101	0.811	1.400
Combined	145	0.800	1.419

These results indicate the New Woodruff buffer underestimated acidity measured by the titration method. This inconsistency raises the question of validity of using the neutralizable acidity measured by the New Woodruff buffer with the soil test estimates of exchangeable calcium, magnesium, and potassium to calculate a cation exchange capacity (CEC) (Brown and Rodriguez, 1983). However, the quick test measures have been calibrated in field studies to arrive at recommendations of liming material and fertilizer. These relationships emphasize that soil test results are estimates in contrast to the results from analytical procedures used to more accurately measure soil components.

In conclusion, Benham's results showed that the $Ca(OH)_2/CaCl_2$ titration measurement of soil acidity was reasonably accurate when compared to the $BaCl_2$/TEA method of Mehlich. Further, he showed that salt pH was a poor indicator of percentage base saturation.

Estimating the Lime Requirements of Missouri Soils

J.R. Cisco MS Thesis-1981
J.R. Brown, Advisor

J.R. Cisco (1981) evaluated different buffer methods for estimating total (neutralizable) acidity in acid Missouri soils for his thesis problem. Woodruff (1948) developed a buffer solution for estimating lime requirements that was put into practice in the Missouri soil testing program and was adopted by other states. Shoemaker, et al. (1961) proposed a new buffer to use in the North Central states, because research had shown that the Woodruff buffer did not properly account for acidity that arose from exchangeable aluminum. This buffer, termed the SMP, was adapted by the soil testing programs in most of the North Central states. Woodruff reformulated his original buffer, which replaced the original Woodruff buffer in the Missouri soil testing program in 1963. Woodruff never formally published the recipe for his revised buffer, which caused confusion among soil testing professionals.

Cisco obtained 75 samples of acid soil submitted to the two laboratories in the Missouri soil testing program. These samples were from 34 of the 114 counties in the state. The neutralizable acidity in these samples was estimated using the 3 buffers to obtain some idea of anomalies that might arise from soils of different histories. Cisco more extensively studied bulk samples collected from sites in Harrison, Marion, Callaway, Henry, Crawford, and Dent counties. The 14 samples of about 40 kg each were air dried, and crushed to pass a 4-mesh screen. Subsamples for laboratory work were processed through a 10-mesh screen.

Neutralizable acidity was measured using the three soil testing buffer procedures (Graham, 1959; Brown et al., 1977; Shoemaker et al., 1961) and titrated with a mixed solution of $Ca(OH)_2$ and $CaCl_2$ (Benham, 1970). In addition, 2.5 kg quantities of each soil were treated with different rates of laboratory grade $CaCO_3$. After two cycles of wetting to field capacity and drying, the treated samples were potted and soybeans grown for 45 days. Following the first crop soil in each pot was air dried, crushed and then repotted for a second soybean crop. Soil samples (100 grams) for analysis (see table below) were taken prior to planting the first crop and after each of the two crops.

Measurement	Method	Reference
Exchangeable Al	1 M KCl	McLean (1965)
Exchangeable Al	Ammonium Acetate @ pH 4.8	McLean (1968)
pH	0.01 M $CaCl_2$	Brown et al. (1977)
Acidity	$Ca(OH)_2/CaCl_2$	Benham (1970)

Based on Benham's work (Benham, 1970), the $Ca(OH)_2/CaCl_2$ titration was considered as the reference measurement of neutralizable acidity, as it most nearly estimated true neutralizable acidity in each soil. While the differences between the means of SMP, New Woodruff, and $Ca(OH)_2/CaCl_2$ were not statistically significantly different, a trend was indicated (Table C-1). The old Woodruff buffer underestimated neutralizable acidity, as suggested by Shoemaker et al. (1961). The results of the New Woodruff procedure best paralleled the results of the $Ca(OH)_2/CaCl_2$ titration. The intercept in the SMP regression equation showed the SMP method overestimates neutralizable acidity in slightly acid soils.

The other portion of Cisco's work focused on the growth response to lime of two crops of soybean grown in the greenhouse on the 14 acid soils. These soils ranged in pH in 0.01 M $CaCl_2$ from 3.85 to 5.60 (pH 4.37 to 6.00 in distilled water). Only three of the soils had more than 0.5 cmol/100g of aluminum extractable in 1 M KCl.

Table C-1. Comparisons of estimates of lime requirements of 75 farmer samples regressed against the lime requirement calculated using $Ca(OH)_2/CaCl_2$ determinations of neutralizable acidity.

Method	Mean* NA cmol/kg	Regression equation**	R^2
SMP	6.67a	y = 1.67x – 3.23	0.91
New Woodruff	6.25a	y = 1.16x – 0.63	0.94
$CaCO_3$	5.94a	y = 0.95x – 0.87	0.91
Old Woodruff	3.86b	y = 0.65x – 0.02	0.95

*Means of NA (Neutralizable Acidity) followed by the same letter are not significantly different at the 5% level.
**y = buffer method and x = $Ca(OH)_2/CaCl_2$.

Based in part upon Fisher's summary of liming in Missouri (Fisher, 1969), a lime requirement target of pH_s = 6.5 was selected to evaluate the results. Estimates of lime requirements of each of the 3 buffers were plotted against the incremental amounts of pure $CaCO_3$ added to the soil, which was then incubated and sampled after 2 crops of soybean with soil mixing between crops.

Table C-2. Comparisons of estimates of $CaCO_3$ lime requirements of greenhouse soils and requirements calculated using different determinations of neutralizable acidity.

Method	Regression equation*	R^2
SMP	y =1.99x – 7.12	0.83
New Woodruff	y = 1.16x – 1.72	0.88
$Ca(OH)_2/CaCl_2$	y = 0.95x – 0.87	0.91
Old Woodruff	y = 0.75x – 1.35	0.87

*Each method regressed against the $CaCO_3$ incubation where y = buffer results and x = $CaCO_3$ incubation results.

The plot between lime requirements estimated by the SMP buffer and the $CaCO_3$ incubation had a much different slope and the smallest R^2 relative to the other buffers. Since the basic calibration of the SMP was based upon a 17 month incubation with $CaCO_3$ and pH was measured in distilled water, one would expect the SMP to be different (Shoemaker, et al., 1961). The New Woodruff buffer was the better predictor of lime requirement in Missouri (Brown and Cisco, 1984).

Soil aluminum was measured after each harvest to determine the treatments' effect on plant growth. Yield results were inconclusive in determining the nature of the soybean response to lime. The 3 soils with measurable initial aluminum were the only soils that resulted in 25% or more yield increase to the first increment of $CaCO_3$. There were insufficient data to define a target pH_s from the study. On most of the soils, vegetative growth declined on pots treated with sufficient $CaCO_3$ to raise the pH_s above 7.0. In fact, Cisco fitted a parabola to a plot of yield results from pots that responded to liming, which maximized at pH_s 5.88. Work reported later in this document by Syed-Rastan (1995) suggested that in closed systems, such as greenhouse pots, liming may raise the soil solution calcium activity above saturation and cause a condition that might be called calcium toxicity, which restricted vegetative production.

Liming had no effect on plant aluminum (Table C-3). This result was not surprising based upon several references cited by Cisco and the fact that only 1 soil had a large amount of KCl extractable aluminum (7.1 cmol/100g). Even on that soil the large lime treatments did not consistently reduce plant aluminum concentrations, although plants grown on that soil without any lime had more that twice the aluminum concentrations than plants grown on the other untreated soils.

Table C-3. Mean Al, Fe, and Mn concentrations in soybean averaged across 14 soils.

$CaCO_3$	Al*	Fe*	Mn*
Tons/acre	--------------------ppm-----------------		
0	93a	81a	236a
2.23	91a	85a	111b
4.46	90a	80a	78c
6.70	93a	73a	72c
8.93	99a	77a	77c
11.16	99a	77a	77c

*Concentrations in a given column followed by the same letter are not significantly different.

There were no significant main effects (lime rate or soil) nor interactions on Fe concentration in soybean vegetative material (Table C-3). In contrast, both main effects and their interaction significantly affected the manganese concentrations. Manganese concentrations were much less on all soils with the lowest two rates of lime. The lime by soil interaction was significant at the 5% level, because the manganese concentrations did not decline with lime rates beyond the first two on all soils. Ozarks soils resulted in the greatest soybean-tissue manganese concentrations as shown below:

Soil Region†	Mn††
	ppm
Ozarks	213a
Central Claypan Area	94b
Cherokee Prairies	67b
Deep Loess and Drift	46b

†Based upon Allgood and Persinger (1979).
††Means across all soils and rates of lime within each region.
Concentrations followed by the same letter are not significantly different at the 5% level.

Cisco titrated both Woodruff buffers and the SMP buffer with incremental additions of 0.05 M HCl and 0.05 M acetic acid. Both Woodruff buffers were formulated with an initial pH of 7.0. In theory when the designed soil:0.01 M $CaCl_2$:New Woodruff buffer ratio of 10 g:10 ml:10 ml was used, each depression in the buffer pH-soil mixture of 0.1 unit represented 1 cmol acidity/kg (Note the appropriate ratio of the old Woodruff buffer was 5 g:5 ml:10 ml). The appropriate buffer/diluent mixture was titrated with standard HCl and the resulting pH measured to evaluate the response of the buffers to acidity. This titration assumed that once the exchangeable acidity was in solution, the activity of the acidity is at equilibrium with any remaining reserve acidity held by the soil particles.

Cisco also used a titration procedure in which increments of all 14 acid soils were added to 30 ml of each buffer and the decline in buffer pH was measured. The total acidity of each increment of soil was based upon the estimation of total acidity using the 7 month incubation of soil and increments of $CaCO_3$ conducted in the greenhouse.

Direct titration of the buffers with 0.05 M HCl caused a faster decline in buffer pH than did titration with acid soil. About 0.3 me of strong acid caused the same decline as 1.0 me of estimated total acidity in soil. The point of this work was that the buffer decline due to a given amount of acidity can not be estimated using only strong acid. The interaction of acid soil and the buffer to cause a decline in the buffer pH is unique to soil systems. Therefore the use of buffers to estimate neutralizable acidity requires calibration to the soils of a given region. Sims (1996) stated "…the suitability of a lime requirement test must be verified by comprehensive *calibration* studies that reflect the intended use of the soil and the variation in soil properties expected in the geographic area where the test will be used."

In summary, Cisco's thesis work supported the use of the New Woodruff buffer for estimation of lime requirements of Missouri soils. The Missouri soil testing procedures (Brown and Cisco, 1984 and Brown and Rodriguez, 1983) should be followed, because the New Woodruff buffer estimation of neutralizable acidity has been calibrated to the range of Missouri soils while the SMP has not. In addition, Cisco showed that SMP tends to be more inaccurate for soils with both low and quite high amounts of neutralizable acidity. Cisco's data showed that if the buffer pH drops below 6.0, the quantity of soil should be reduced as directed by Brown and Rodriguez (1983).

Estimation of Lime Requirements of Selected Missouri Soils

A.A. Yusef Ph.D. Dissertation-1986
J.R. Brown, Advisor

When Abdugiali Ali Yusef's arrived from Libya to work towards a Ph.D., there was some discussion regarding the validity of using the New Woodruff buffer procedure for estimating lime requirements for the Alfisols and Ultisols of southern Missouri. The concern was that the buffer estimate was not correctly accounting for acidity arising from active aluminum in the very acid soils. Yusef's dissertation study attempted to address these concerns. The objectives of Yusef's dissertation were "…to (i) characterize the nature of the acidity in selected Missouri soils and (ii) develop an improved method of estimating lime requirement of these acid soils" (Yusef, 1984).

In cooperation with extension agronomists in southern Missouri and with USDA/NRCS personnel, surface soils from six locations were selected. At each location bulk soil was taken from the A_1 or the A_p horizon. The surface organic layer was removed from the forested sites before sample collection. Two of the locations were farmer fields; three were forested in the area studied by Gamble and Mausbach (1982); and one was a forested portion of the University of Missouri's Wurdack Farm near Cook Station, MO. Location information is given in Table Y-1.

Table Y-1. Location information about the six soils used in the Yusef study.

Location*	County	Vegetation	Classification*
Alton	Oregon	Pasture	Clarksville series
Howell	Howell	Fallow	undetermined
003	Laclede	Hardwood forest	SND**, Loamy-skeletal over clayey siliceous, mesic Typic Paleudalf
005	Laclede	Hardwood forest	Doniphan series, Clayey, mixed, mesic Typic Paleudult
006	Laclede	Open conifer forest	Wilderness series, Loamy-skeletal, siliceous, mesic Typic Fragiudalf
Wurdack	Crawford	Hardwood forest	SND, site appeared to be a Coulstone Clarksville integrade

*The numbered locations were from the NRCS(SCS) study sites (Gamble and Mausbach, 1982).
**SND = series not defined. The Howell location was similar to the 003 and 005 locations, except it had been cleared.

The air-dried soils were crushed to pass a 0.5-mm screen and mixed. A random subsample was taken to obtain quick-test information as a guide to developing a lime treatment plan (Table Y-2). Greenhouse studies were conducted on variably limed soil using both alfalfa (*Medicago sativa* L.) and soybean (*Glycine max* L) as test crops on all six soils. All soils were brought to the recommended levels of P and K in bulk (Buchholz, 1983). The bulk samples of the soils were thoroughly mixed after the appropriate treatments were added and were divided into 2.5 kg quantities. Each 2.5 kg of soil was treated with one of the selected incremental quantities of $CaCO_3$, mixed, and placed in a plastic lined No. 10 metal can. A watering tube was placed vertically in each pot to facilitate watering.

The incremental liming rates were calculated as equivalent fractions of the neutralizable acidity (NA) estimated by the New Woodruff buffer quick test method (Brown and Rodriguez, 1983). The rates were 0, 0.125, 0.25, 0.5, 1.0, 1.5, and 2.0 times the cmol(+) of NA per kilogram of soil. Laboratory grade

$CaCO_3$ was used. It was assumed that CCE and fineness of grind were not factors with laboratory grade $CaCO_3$, and that if all the NA in each soil was neutralized (1.0 x NA) the resulting pH would be 7.0.

Table Y-2. Chemical parameters of the six soils used in the Yusef study.

				P		Exchangeable					NH_4Ac
Location	pH_w	pH_s	OM	P1	P2	NA	Ca	Mg	K	CEC	CEC
			%	mg/g		---------------------- cmol(+)/kg ----------------------					
Alton	5.2	4.5	2.4	8.5	2.3	7.00	1.8	0.3	0.2	9.1	7.8
Howell	5.4	4.8	1.7	5.5	1.4	4.00	2.0	0.4	0.2	6.6	5.8
003	5.4	4.7	2.8	5.0	1.3	4.66	2.5	0.6	0.3	8.1	8.1
005	4.9	4.4	3.0	4.5	8.5	5.43	1.4	0.4	0.2	7.3	7.3
006	5.0	4.2	2.3	3.5	6.5	6.12	1.4	0.7	0.2	8.4	8.6
Wurdack	4.8	4.1	2.4	-	7.0	7.20	0.8	0.3	0.3	8.6	7.4

Methods: Brown and Rodriguez (1983); P extracted by Bray and Kurtz extractants: P1 = 0.025 M HCl with 0.03 M NH_4F; P2 = 0.1 M HCl with 0.03 M NH_4F; NA = neutralizable acidity by the New Woodruff buffer. The "exchangeable CEC" is a summation of the exchangeable cations determined in the soil testing process. The NH_4Acetate CEC was determined by distillation of NH_3 following leaching with 1 M NH_4Acetate @ pH 7.0 and methanol with magnesium from MgO as the replacing cation.

The potted soil was brought to field capacity; plastic bag liners were closed; and the pots were incubated for 2 weeks. After this preliminary incubation, the bags were opened and the surface soil allowed to dry. Alfalfa and soybean seeds were planted, the soil moistened, and the stands thinned after germination. Two cuttings of alfalfa were taken, one 60 days after seeding and another 25 days after the first. A soybean vegetative harvest was taken 55 days after seeding. From the time of initial watering, the soils used for alfalfa remained moist for 99 days and the soils for soybeans 69 days. After the last harvests pots were allowed to air dry, after which the soil was removed, mixed, and sampled from each pot.

Table Y-3. Methods applied to subsamples of the initial soils and to soils used in the greenhouse and incubation portions of the studies on lime relationships.

		Soil		
Method	Measurement	Initial	Greenhouse	Incubation
pH_w	Active Acidity	√	√	√
pH_s	Active Acidity	√	√	√
Woodruff buffer	Total acidity	√	√	√
SMP buffer	Total acidity	√	√	√
KCl	Al	√	√	√
$CuCl_2$	Al	√	√	√
1 M NH_4Acetate, pH 4.0	Al	√		
$CaOH_2/CaCl_2$	Total acidity	√		
1 M CaAcetate, pH 4.0	Total acidity	√		
1 M NH_4Acetate, pH 7.0	CEC, Ca, Mg, K	√		

A laboratory incubation study on all six soils was conducted using incremental rates of $CaCO_3$. After treatments were applied, the soil was brought to field capacity, placed into closed plastic bags, and incubated for successive 30-day increments. At the end of each 30-day period, the bags were opened and allowed to air dry. After mixing each bag was subsampled, the soil brought to field capacity, and incubated for another 30 days. At the end of the incubation experiment, the subsamples were tested for pH_w, pH_s, neutralizable acidity (Woodruff buffer), and SMP lime requirement. Several different extractants and measurements were used to characterize the effects of treatments and are summarized in Table Y-3.

Maximum dry matter yields were achieved at different fractional lime requirements for the different soils, suggesting different target pH_s (Table Y-4). Also yields were depressed at the higher rates of $CaCO_3$. However, the very low alfalfa yields make these data questionable. The lsd is not the most appropriate means test to use on the data, but no other is now available, since Yusef did not leave an accessible set of results other than the limited summary data in his dissertation. Assuming that the lsd calculated for the soybean yields in response to lime has some validity, Yusef's data would suggest that half the lime requirement was nearly adequate for the soils used in the soybean study. This result has been observed in other greenhouse studies with lime (Cisco, 1981; Syed Rastan, 1995).

Table Y-4. Average yield of soybean and alfalfa in response to $CaCO_3$ added to six different soils (3 replications).

		Fraction of lime recommendation (LR)				
Crop	Soil	0	0.25	0.5	1.0	2.0
		------------- grams per pot				-------------
Soybean	Alton	4.6	4.7	6.1	3.5	3.3
	Howell	5.8	6.1	6.6	6.8	5.8
	003	6.4	6.5	7.5	6.6	5.4
	005	5.9	6.9	7.2	6.5	4.6
	006	4.7	6.4	5.7	4.8	3.0
	Wurdack	3.1	5.4	4.8	3.8	3.7
	Mean	5.1	6.0	6.3	5.3	4.3
	$Lsd_{0.05}$ LR = 0.75g; soil = 0.82; LR x soil = 1.83					
Alfalfa	Alton	0.23	1.60	0.50	0.44	0.22
	Howell	1.34	1.69	2.02	1.80	1.60
	003	1.95	3.86	2.72	1.66	1.69
	005	1.44	3.68	2.96	1.36	1.15
	006	0.32	1.27	0.58	0	0
	Wurdack	0.22	2.49	1.94	1.15	1.1
	Mean	0.92	2.49	1.77	1.07	0.98
	$Lsd_{0.05}$ LR = NS; soil = NS; LR x soil = 0.72g					

Yields were less at the full lime requirement than at lower rates, which was puzzling at the time Yusef completed his work. Since then, we think that the negative effect on yield may be due to excess calcium in the soil solution that could be obtained under certain circumstances, especially closed systems such as greenhouse pots and incubation bags.

Regression equations were fitted to each data set which included estimates of neutralizable acidity using the initial soil analyses and the New Woodruff and SMP buffers. Using the initial soil tests Yusef calculated the percentage base saturation on each soil and then calculated the percentage base saturation at pH_s 6.5 and pH_s 6.0. He assumed stoichiometric reactions from adding $CaCO_3$ to the acid soils and that no neutralizable acidity would remain at pH_s 7.0 (100% saturated). Yusef also estimated lime requirement at pH 6.5 using acidity extractable by molar calcium acetate at pH 7.0 and $CuCl_2$ extractable acidity. In addition to these different estimates of neutralizable acidity at different target pH levels, he used data generated by titrating each incrementally-limed acid soil with $Ca(OH)_2$ solution and measuring pH_s following the growth of soybeans and alfalfa. The data were compared by calculating the lime requirement to raise each soil from the initial pH_s to target pH levels of 6.0, 6.5, and 7.0. These specific pH_s values are at the upper end of the recommended target ranges for crops in Missouri (6.6 to 7.0. 6.1 to 6.5, and 5.6 to 6.0) (Buchholz, 1983).

Examples of Yusef's evaluation of the methods to estimate lime requirements are given in Table Y-5. The most striking observation is that lime requirements estimated from the post cropping measures based upon the incremental carbonate treatments show nearly 3 cmol(+)/kg greater lime requirements than those based upon the calcium hydroxide titration. All the estimates given in the table other than the carbonate are based upon the uncropped soils. It is probable that carbon dioxide from the roots in the soil as a normal result of respiration was responsible for development of acidity. Excretion of protons from active roots may have occurred due to biological nitrogen fixation in the nodules of soybean and alfalfa.

Table Y-5. Estimated lime requirements (LR) to reach alternative target pH values for three acid soils using different estimation methods given in cmol(+)/kg.

Soil	Alton		005		Wurdack	
Target pH_s	LR	Method*	LR	Method*	LR	Method*
	cmol(+)/kg		cmol(+)/kg		cmol(+)/kg	
7.0	8.87	CO	8.85	CO	9.78	CO
	7.87	SMP	5.79	OH	7.70	SMP
	7.00	W	5.69	SMP	7.20	W
	6.50	OH	5.43	W	7.04	OH
6.5	6.68	SMP	6.01	CO	7.29	CO
	6.23	CO	6.00	BS	6.58	SMP
	6.12	W	5.18	Acetate	6.46	W
	5.60	Acetate	4.85	W	6.30	BS
	5.40	BS	4.78	SMP	5.65	Acetate
	4.50	OH	4.18	OH	5.40	OH
6.0	5.49	SMP	4.60	BS	5.57	W
	5.00	W	4.20	CO	5.45	CO
	4.97	CO	4.13	W	5.33	SMP
	4.58	Cu	4.10	Cu	5.10	BS
	4.30	BS	3.92	SMP	4.56	Cu
	3.35	OH	2.98	OH	4.10	OH

*CO = $CaCO_3$ incubation, W = New Woodruff buffer, SMP= Shoemaker-McLean-Pratt buffer, OH = titration with $Ca(OH)_2/CaCl_2$ solution, BS = percentage base saturation, Acetate = Acidity estimated with calcium acetate at pH 7.0, Cu = acidity extracted with $CuCl_2$.

The $Ca(OH)_2$ titration data and the pH_s measurements made after incubation with $CaCO_3$ were fitted to a quadratic expression with pH_s the dependent variable and quantity of base as the independent variable. Regression statistics showed a very good fit, however, examination of the data suggested that the fit was linear from pH_s in the mid 4s to nearly 6.5. Above that pH it then became exponential, as observed by Magdoff and Bartlett (1985) (data not shown). Yusef calculated the percentage of the total lime requirement needed to reach target pH_s 7.0 from starting pH_s values of 5.5 (target pH_s range of 5.5-6.0), 6.0 (target pH_s range of 6.0-6.5), and 6.5 (target pH_s range of 6.5-7.0). For the six soils the average percentage lime requirement for each 0.5 pH_s increment was 16%, 20%, and 29%, respectively. This observation may explain field observations that lime requirements based upon quick test methods do not meet target pH levels in the field. Quick tests are unable to accurately measure the slowly released acidity (pH dependent acidity) encountered in the pH 6.0 to 7.0 range (Sims, 1996). Black (1967) attributed the characterstic acidity in the linear range—noted later by Magdoff and Bartlett (1985)—to weak and very weak acid components of the soil. In the vicinity of pH 6.5, the source of pH dependent acidity is very, very weak acids, characterized by organic phenolic groups and hydroxy aluminum polymers. Because the ionization rate of these two soil components is slow, this acidity is not measured by the quick test methods used in lime requirement determinations.

One of Yusef's objectives was to develop an alternative method of estimation of lime requirement that is more useful for low organic matter, highly weathered soils of the Ozark region of Missouri. Extractants proposed for areas dominated by Ultisols and Oxisols were selected. These aluminum extractants were 1 M KCl (Coleman et al., 1959), 0.5 M $CuCl_2$ (Juo and Kamprath, 1979) and 1 M NH_4Acetate @ pH 4.8 (McLean et al, 1958) (Table Y-6).

Soil aluminum extracted with 1 M KCl is considered exchangeable. According to Kamprath (1984) the resulting acidity is dominantly due to Al^{3+}. However, a multiplier is often used in addition to the factor to convert exchangeable aluminum into equivalent amounts of limestone or $CaCO_3$ per unit area. The need for the multiplier is a result of pH dependent acidity, which likely becomes active with time as the added lime neutralizes more active acidity.

The uncertainty implied by the use of a factor caused Thomas and Hargrove (1984) to state, "However, salt-exchangeable Al^{3+} is scarce in surface soils, even acid ones, and too much reliance should not be put on an ion exchange treatment that may have limited applicability." Yet these authors went on to suggest that since lime application to field soils is not exact, the use of KCl extractable aluminum as a basis for lime requirements might be useful. The use of some measure of soil aluminum for lime requirement estimation will be expanded upon later in this summary.

Yusef suggested in his dissertation that the KCl extractable aluminum might be a useful estimate of lime requirements if multiplied by 2. This calculation has been included in Table Y-6. The resulting average lime requirement is about 1.5 cmol(+)/kg less than the lime requirement of the Woodruff buffer estimate. As an alternative to the Woodruff buffer estimate of lime requirement on acid low organic matter soils of the Ozark portion of Missouri (soil regions 6 and 7; Buchholz, 1983), it is suggested that KCl extractable aluminum be used only on soils with pH_s <4.8.

Table Y-6. Measurements of soil aluminum by different extractants.

Soil	Exchangeable* Al	Extractable Al by CuCl$_2$	NH$_4$Acetate	NA**	Exchangeable Al x 2
	----------	----------	cmol(+)/kg	----------	----------
Alton	2.20	4.58	3.10	7.0	4.4
Howell	1.70	3.36	1.95	4.0	3.4
003	1.67	3.50	2.60	4.7	3.3
005	2.25	4.10	2.55	5.4	4.5
006	2.50	4.70	3.55	6.1	5.0
Wurdack	2.40	4.56	4.20	7.2	4.8

*Exchanging reagent = M KCl. **NA = neutralizable acidity by the New Woodruff buffer.

It seems logical that the impact of exchangeable aluminum and/or acidity upon the pH measurement depends not only on quantity but upon the nature of the exchange complex. Cation exchange capacity along with the quantity of exchangeable bases held on the soil exchange complex will affect the relationship between active acidity (pH) and total acidity. Yusef measured the CEC of the six soils using different techniques suggested by others.

Effective CEC is that exchange capacity measured with an unbuffered salt (1 M KCl) at near the pH of the unammended soil (Coleman et al., 1959). In his calculations Yusef used the exchangeable bases measured in the 1 M NH_4 acetate @ pH 7.0 extract of unammended soils (except in those instances where he made calculations using the incrementally limed soils). The NH_4 acetate CEC was that measured by saturation with ammonium from NH_4 acetate @ pH 7.0m followed by distillation of the retained ammonium with magnesium as the replacing cation (Brown, 1981).

Yusef also measured the acidity replaced by M calcium acetate @ pH 7.0. He used this quantity of acidity plus the NH_4 acetate exchangeable bases to calculate an estimate of CEC. In a questionable practice, he also plotted the pH of the soils used in the greenhouse studies as a function of added $CaCO_3$ to estimate a quantity at pH 7.0 that he called total acidity. This quantity of acidity was added to NH_4 acetate exchangeable bases to obtain an estimated CEC. As pointed out elsewhere, acidity may have been generated while the soybean and alfalfa plants were growing, which would have inflated the CEC over that of unammended soil. The values obtained from these measures of CEC are given in Table Y-7 except for the CEC values calculated on the limed soils at the end of the greenhouse studies .

Table Y-7. Estimated cation exchange capacities of soils used in the Yusef studies.

	CEC Measurement*				
Soil	Effective	NH_4 Acetate	Ca Acetate	WB	pH dep.
	-- cmol(+)/kg	--			
Alton	4.3	7.8	7.7	9.1	3.5
Howell	4.3	5.8	5.9	6.6	1.5
003	5.0	8.1	8.0	8.0	3.1
005	4.3	7.3	7.1	7.5	3.0
006	4.7	8.6	7.9	8.3	3.9
Wurdack	3.7	7.4	6.9	8.5	3.0

*Methods –see text. WB = New Woodruff buffer, pH dep. = pH dependent.

The Missouri Soil Testing laboratories calculate an estimated CEC by summing extractable bases and acidity estimated by the New Woodruff buffer procedure (WB-CEC in Table Y-7). Compared to other measurements of CEC of the soils used in this study, the WB-CEC seems elevated (Table Y-7). This higher value using the Woodruff buffer might explain, at least in part, the yield maxima observed at pH values less than 7.0.

In Yusef's pot studies, among the soils the pH_s varied some at which yield was maximized (5.4 to 6.5 for alfalfa and 4.8 to 6.0 for soybean). Yusef gave several citations of greenhouse pot studies that gave maximum yields in the same pH ranges. These kinds of results suggest that when the plant roots develop in uniform soil material that has been supplied with adequate fertility and water, growth will maximize at a lower level of active acidity than in the field where conditions are more variable. It may be that Albrecht's theory that calcium supply to the root is the key to good growth. In humid region fields calcium, activity especially below the surface soil (A_p horizon) may limit root growth which would not be the case in pot studies.

This latter point about making comparisons should also apply to comparisons of results from incubation and field responses to liming of acid soil and should be considered when evaluating Yusef's conclusions. For example, Yusef stated (p. 113), "The lime requirement estimated by quick test methods to a target pH_s 7.0 were in agreement with the lime requirement estimated by $CaCO_3$ incubation to pH 6.5." The lime requirements estimated using the Woodruff buffer that are used in the current recommendation program were verified using the Fisher (1969) summaries of field-liming studies conducted through 1967 by workers of the Missouri Agricultural Experiment Station. In the Yusef's incubations, he did not account for either the oxidation of ammonium and sulfur compounds released by mineralization or the effect of microbial respiration during incubation, all of which are acidifying. Further, the quick test method is based upon a short 30 minute soil/buffer contact time, which would fail to estimate slowly available acidity that a longer incubation time would measure. Lack of sufficient contact time between the soil sample and the quick test buffer may explain why lime requirements have not been observed to lower soil acidity to the desired target pH. Another explanation, of course, is that the grower may sample the soil the year following application of liming material and find the target pH was not reached. In this case, the grower expected results that would not be possible based upon the findings of J.J. Stevens (see the following section).

Limestone Dissolution and pH Gradients in Soil

J.J. Stevens MS Thesis-1990
R.W. Blanchar, Advisor

The rate of dissolution of individual limestone particles when mixed with acid soil and the resulting affected soil volume determines the effectiveness of the liming material in lowering the quantity of total acidity. Over the years many attempts have been made to quantify both the rate and pattern of dissolution, but the precision of early work was limited by equipment. The development of reliable microelectrodes has improved the accuracy and precision of measurements of soil pH surrounding limestone particles. Jeffrey Stevens utilized microelectrodes in his MS thesis research to study the rate and pattern of limestone particle dissolution (Stevens, 1990).

Stevens' research had three phases. He characterized 7 calcitic (0% Mg) and 6 dolomitic limestones (10.3 to 12.6% Mg) selected from samples submitted between January and June 1988 to the Missouri Fertilizer and Liming Materials Control Service. The second part of the study measured those soil characteristics that might affect the dissolution pattern of limestone particles. Third, the reactivity of one calcitic and one dolomitic limestone was studied after they were mixed with acid soil.

Stevens did not identify the limestones that he used other than by laboratory number and the town nearest the location sampled by the Control Service inspectors. Those towns were Savannah, Kahoka, Hannibal, Kingdom City, Sedalia, Rolla, Mt. Vernon, Springfield, Marshfield, Hollister, Piedmont, and Patterson. The calcitic stone selected for intensive study was from Kahoka and the dolomitic stone was from Patterson. The geologic stratum that each stone represented was not identified. There were no limestones included that contained between 0 and 10% magnesium.

There were few differences in particle size distribution of the limestones with the exception of the dolomitic stones from Piedmont and Patterson, MO. These two limestones had much lower percentages of material in the 8- to 40-mesh size range and much greater percentages of material in the 40- to 60-mesh size range than all other samples. This size distribution caused these two stones to have greater ENM per ton that the other stones. The CCEs of the <60-mesh material in the two stones Stevens used for detailed study were slightly lower than the CCEs of the coarser size fractions, but not by much.

Stevens used a surface soil from Tucker Prairie, west of Kingdom City in Callaway County for his studies. The soil would be mapped as Mexico (fine, smectitic, mesic, Aeric Vertic Epiaqualf). The site had never been plowed, and cover was native prairie vegetation. The surface soil was silt loam and X-ray diffraction patterns indicated the presence of kaolinite and illitic-type clays in addition to smectite. The soil had a pH in water of 5.0 and in 0.01 M $CaCl_2$ of 4.5. The CEC was 21.1 cmol(+)/kg using the $BaCl_2$ measure of acidity (Thomas, 1982) and 17.3 cmol(+)/kg using 1 M NH_4Acetate @ pH 7—used by the Missouri Soil Characterization Laboratory. The organic carbon percentage was 3.02%.

Stevens studied dissolution of three different sizes of limestone particles (2>x>1 mm, 1>x>0.5 mm, and 0.5>x>0.25 mm) under both a static system and a leaching system. Soil was placed in Plexiglas cylinders (internal dimensions were 3 cm high and 5 cm in diameter) and packed to a bulk density of 1.2 Mg/m^3. A single limestone particle was placed on the soil surface in the center of each cylinder and pushed below the surface with a fine tipped weighing spatula. The soil was wetted to field capacity and pH was measured with a calibrated microelectrode at distances of 0, 0.1, 0.2, 0.4, 0.8, and 1.6 mm at 15 and 30 minutes and 1, 2, and 4 hours. Measurements at 2 and 4 days were made at distances of 0. 0.5, 1.0, 1.5, 2.0, 2.5 and 3.0 mm from the individual limestone particles.

In the static system, changes in pH of the soil surrounding the individual limestone particles occurred within 15 minutes of wetting the soil, and the effect extended to 1.0 mm from the limestone particle surface. There was little change either in the magnitude of pH change or the distance of pH change over 4 days of measurements. There was little difference between calcitic and dolomitic limestones, except the pH attained near the particle surface was slightly less with the dolomitic material.

Leaching studies were conducted in Tempe cells. These cells were modified for entry of a leaching solution of 0.005 M $CaCl_2$.and removal of leachate under slight pressure. The internal cylinder of the cells holding the treated soil was 3 cm high and 5 cm in diameter. An amount of limestone to bring the soil in each Tempe cell cylinder to pH 7.0 was determined based upon CCE of the limestone and the $Ca(OH)_2$ titration curve of the soil. The appropriate amount of limestone was mixed with the soil in each cylinder. Three sets of leaching were done as follows:

Leaching Number	Mesh	Limestone Dimensions	Leaching Conditions	Estimated Field Time
1	60	0.5 mm ≥ x ≥ 0.25 mm	Continuous	1 year
		0.5 mm ≥ x ≥ 0.25 mm	Discontinuous	1 year
2	18	2 mm ≥ x ≥ 1 mm	Continuous	4 years
3	35	1 mm ≥ x ≥ 0.5 mm	Continuous	4 years
4	60	0.5 mm ≥ x ≥ 0.25 mm	Continuous	1, 4, 8 years

The amount of solution to be leached through each cell was calculated using a formula—developed by Scrivner et al. (1973) for Missouri soils—which estimates the amount of percolation that would pass a given soil depth based on annual precipitation data. A 9 to 12 cm depth was chosen to calculate the amount of leaching solution. The flow rate was 0.7 ml per minute. Both limestones were used in the leaching studies. When the results of leaching number 1 was studied, there was little difference between the continuous and discontinuous leaching, so all other leachings were done continuously.

Unreacted carbonate following leaching in studies 1, 2, and 3 was measured by reacting the cell contents with strong acid and collecting the evolved carbon dioxide. In addition to measuring unreacted carbonate following the leaching periods in study 4, pH gradients were measured above, below, and to the side of the limestone particles with microelectrodes.

The reactivity of the different particle sizes of limestone in a simulated 4 year leaching increased as particle size decreased and was significantly different between the calcitic and dolomitic limestones. The appropriate equations from Stevens' thesis are:

Calcitic $\quad$ % reacted = $10.33 - 53.44\ (\log_{10}(d))$ $\quad$ $R = 0.986$

Dolomitic $\quad$ % reacted = $3.765 - 58\ (\log_{10}(d))$ $\quad$ $R = 0.998$.

d = mean diameter

Measurement of pH gradients after various leaching regimes failed to demonstrate differences in pH at a given distance above and below the limestone particles and perpendicular to the assumed direction of solution flow. In trying to rationalize this finding, Stevens discussed the complexity of measuring small differences in a complex system like soil. Figure 5 in his thesis is the basis of his arguments about measuring soil pH with microelectrodes. Spatially, a particle of limestone passing a 35-mesh sieve (d = 0.50 mm) and held on a 60-mesh sieve (d = 0.25 mm) approximates the size of micro-aggregates of soil material that has passed a 2 mm sieve. A 2 mm sieve (10-mesh) is used in most soil testing labs to prepare soil samples for testing. The matrix of soil with a limestone particle fills a volume that has about 50% pore space and 50% solid. The pore spaces may be capillary in size but are tortuous in nature, which affects the movement of reaction products, following dissolution, from the limestone particle surface and counteracts the tendency, in Stevens' study, for leaching. (Note that flow rates used by Stevens were less that 1 ml per minute.) Couple this observation with the fact that there were many limestone particles in the leaching cylinders. Stevens calculated the number of calcitic limestone particles added to each Tempe cell in the leaching study. The cell volume was 67.5 cm^3 and 350 mg of calcitic stone was mixed with the soil. The resulting ideal distribution of particles was calculated for 3 particle sizes with the following results:

Particle Size	Number of Particles	Distance between Particles
mesh		mm
18	87	11.4
35	700	5.69
60	5600	2.85.

Most of the data showed that, at most, the effect of dissolution extended 1 mm from the particle surface. Even though Stevens' calculations only approximate actual field results, one can not help but recognize that when the pH of a limed soil is determined by usual soil testing methods (1:1 soil:solution) with separate glass and calomel electrodes or combination electrodes, the electrode surfaces may contact the dissolution fields of more than one limestone particle. Stevens showed that dissolution from the surface of a limestone particle occurs in less than 15 minutes. The mixing of the soil and suspending solution during the 30 minutes recommended in most soil testing labs for pH measurements allows time for considerable dissolution as limestone particles in a limed soil move around in the suspension. There is good reason for requesting the liming history on any soil sample submitted for testing to aid in evaluating the soil test results.

Since Stevens' data showed that dissolution from a limestone particle affected the pH no more than about 1 mm distance from the particle surface, one should be able to visualize the variability in acidity over short distances. With time however, the bulk soil pH rises, as measured in soil testing programs.

Stevens' results can be extrapolated to common techniques of calibration work in short term studies. Examples are the studies by Yusef (1988), Cisco (1981), and Syed-Omar (1995). Given the nature of quick test estimates of lime requirements, it is important to relate the estimates to target pH values as discussed above. Such field calibration takes many years, which graduate students do not have. Reliance is placed upon calibration in the greenhouse. In those studies reagent grade carbonates are thoroughly mixed with the soil. The carbonates are <100 mesh in size, which given the 1 mm dissolution distance found by Stevens, suggests that the entire soil mass in a pot study would be under the influence of dissolution of the added carbonates. In the field, however, this would not be the case. Thus calibration in the field is required to properly develop lime recommendation algorithms.

Finally, the Stevens data showed that within 1.6 mm of limestone particle surfaces, the pH was always higher with calcitic stone than with dolomitic stone.

The Stevens studies on the whole reinforced several concepts about liming acid soils. Calcitic stone dissolves quicker than dolomitic and tends to raise the bulk soil pH to a higher level than dolomitic stone given equivalent effectiveness estimates (CCE and fineness). Stevens did show that initial effects of dissolution near particle surfaces occur within 15 minutes, but the soil volume affected is limited (1 to 1.6 mm from the lime particle surface). The results support the contention that an effective liming material for agronomic applications must include fines (<60-mesh) and coarser material (between 8- and 40-mesh) for quick immediate action and maintenance of a desirable pH_s for several years.

Agronomic Response of Three Forage Legumes to Agricultural Limestones

D.R. Bennett, MS Thesis-1990
J.R. Brown and J.C. Henning, Advisors

Field verification of the greenhouse observations made by Cisco (1981) and Yusef (1986) was considered a knowledge gap. David Bennett (Bennett, 1990) conducted a three-phase study from 1988 through 1990 to start to fill this knowledge gap. He conducted trials at two southern Missouri sites using alfalfa, red clover, and lespedeza with 6 liming material treatments, which were fractions of the calculated LR.

The Bennett sites were identified as the McWhorter and the Wilson sites, named for the owners of the properties at the initiation of the studies. The McWhorter site, southeast of Rolla in Phelps County, was in a mixed cool-season grass sward harvested for hay, and the Wilson site in southern Gasconade County, was an overgrazed pasture dominated by ragweed with very little evidence of desirable forage species. Deep core samples and observable properties would suggest that both sites were Typic Pale-udults. The owners did not provide any past management history. A third soil used in the incubation and greenhouse phases was from the surface horizon of a site in permanent pasture in the Mark Twain National Forest near Rolla, MO. The site had been mapped as a loamy-skeletal, siliceous, mesic Typic Paleudult in the Hudson-Coulstone-Clarksville association.

The field sites were laid out in three blocks one for each of 3 forage legume species. Each block was subdivided into 24 plots (each 8' x 21'), which were sampled to a 6" depth for prior to plowing in late summer of 1988. The soil for the greenhouse and incubation studies was collected in plastic lined metal garbage cans. The bulk soil material was air dried, and screened through a 0.25 inch mesh screen. The screened soil was subsampled for testing (Table DB-1).

Table DB-1. Initial soil test results for soils used in the forage legume study*.

Soil	pH_s	NA	OM	P	Ca	Mg	K	CEC	Al
		meq/100g	%	----------------	ppm	-------------		meq/100g	ppm
Greenhouse	4.8	4.0	2.2	10	410	78	131	7.0	24
McWhorter	4.7	4.5	2.3	1	480	218	66	8.9	13
Wilson	4.5	7.0	2.0	1	700	237	76	12.7	76

*Missouri soil test procedures according to Brown and Rodriguez (1983). P = Bray-Kurtz P1. Al = extractable aluminum by 1 M KCl.

In all cases the bulk soil and the soil at the two field sites were given corrective build-up P and K treatments based on soil tests (Table DB-1) and Missouri fertilizer recommendations (Buchholz, 1983). The soil and corrective fertilizers for the greenhouse and incubation studies were mixed thoroughly before subdivision for the addition of individual limestone treatments. Fertilizer materials for the field study were 0-46-0 and 0-0-60. The nutrient carriers for the greenhouse and incubation studies were laboratory grade monocalcium phosphate, potassium sulfate and magnesium chloride (15 ppm magnesium added).

The limestone carriers differed between studies. The sources of the limestones were the Beck Quarries near Rolla, MO and bagged limestone from Columbia, IL. Insufficient "Columbia" limestone was available for the entire Wilson site so a bagged limestone with the trade name "Mississippi", which originated near Alton, IL, was used for the lespedeza block. Only the Beck limestone was used in the incubation study. All limestone treatments were made using an effective neutralizing material value

(ENM) of the limestone determined in the MU soil fertility research laboratory (ENM = ECE (effective calcium equivalent))(Table DB-2).

Table DB-2. Characteristics of the limestones used in the Bennett studies.

Limestone	Fineness	CCE	ENM	Ca	Mg	Use
	-------- % --------		lb/ton	-------- % --------		
Beck	51.86	82.6	342	18.8	8.9	All
Columbia	54.65	97.7	427	38.4	0.4	Field, GH*
Columbia <60 mesh	100.0	97.7	782	38.4	0.4	Field, GH*
Mississippi	58.47	95.7	448	35.0	0.1	Wilson

*GH = greenhouse.

In the incubation study, samples of the Beck limestone were screened through 8-, 40-, and 60-mesh screens, as used in the Missouri Agricultural Experiment Station Laboratory to determine the fineness grades. Including the unscreened bulk limestone, there were 5 particle size treatments. Bennett selected treatments that were fractions of the calculated lime requirement using the estimate for alfalfa lime requirements in southern Missouri (Buchholz, 1983) and the ENM for the bulk Beck limestone. The estimated lime requirement was 1,600 lb ENM/acre. Table DB-3 gives the actual quantities of ENM applied for the fractional applications. The calculated ENM data for each fraction are also provided in Table DB-3 with the >8-mesh material having no ENM value. The soil-treatment mixtures were incubated in plastic bags at field capacity for 9 months. Samples for measurement of soil acidity were taken each 3 months.

Table DB-3. Equivalent quantities of Beck limestone applied as different particle size fractions based upon a lime requirement of 1,600 lb ENM/acre.

Particle Size	ENM of Particle Size	Fraction of Beck Lime Requirement				
		0.33	0.66	1.00	1.33	1.66
Mesh	lb/ton	----------------------- tons ENM/acre -----------------------				
Beck	342	1.54	3.08	4.68	6.22	7.76
>8	0	0	0	0	0	0
8-40	165	0.74	1.48	2.25	3.00	3.74
40-60	396	1.78	3.57	5.41	7.20	8.98
<60	661	2.98	5.95	9.02	12.02	15.00

Plastic lined pots containing 3 kg of treated soil and a subsurface watering tube were used in the greenhouse study. Pre-germinated Pioneer 532 alfalfa, Redland II red clover, and Korean lespedeza plants were transplanted into pots. Alfalfa and red clover were harvested 3 times at monthly intervals. Lespedeza, which grew more slowly than the other species, was harvested twice.

The target pH_s for red clover and lespedeza is 5.6 to 6.0 in the Missouri program for northern Missouri. The fractional lime increment of 1.00 reached that range (Table DB-4). However, the target for southern Missouri is pH_s 6.1 to 6.5, which was not reached. A similar result was obtained for alfalfa in that the pH_s achieved with the fractional application of 1.00 was in the target range for northern Missouri (pH_s 6.1 to 6.5) not that for southern Missouri (pH_s 6.6 to 7.0). This is not the first time these kinds of results have been observed, as has been pointed out elsewhere in this paper.

The yields for all species approached a maximum at either 0.67 or 1.00 fraction of the calculated "lime requirement." This suggests, based upon the effect of the treatments on soil acidity, that the target pH_s ranges for southern Missouri may not need to be greater than those for northern Missouri. The southern Missouri recommendations being used in the last quarter century were purposely made higher than those for northern Missouri to account for the very acid subsoils found in southern Missouri. For example, the pH_s in the subsoil of the Wilson site used in Bennett's field study was 4.3 in the 8 to 12 inch depth increment and dropped to 4.1 for the next 12 to 16" depth. Active aluminum in the soil solution reaches levels toxic to plant roots at these pH_s levels. Rarely is subsoil acidity in northern Missouri soils sufficient to result in appreciable active aluminum.

Table DB-4. Results from a greenhouse study of incremental quantities of limestone using 3 legume forage species*.

Species	Treatment	Limestone	Fractional LR	Total Yield	pH_s	Extractable Aluminum
	Number			grams/pot		ppm
Alfalfa	1	Columbia	0	5.2d	4.5f	46a
	2	Columbia	0.33	9.1c	5.1e	6b
	3	Columbia	0.67	15.2a	5.6d	0c
	4	Columbia	1.00	13.8b	6.1b	1bc
	5	Col.<60 mesh	1.22	15.2a	6.3a	2bc
	6	Beck	0.88	13.5b	5.9c	2bc
Red Clover	1	Columbia	0	6.1d	4.4e	38a
	2	Columbia	0.34	9.3c	4.8d	11b
	3	Columbia	0.67	12.8b	5.3c	3c
	4	Columbia	1.00	17.3a	5.7b	3c
	5	Col.<60 mesh	1.22	18.2a	5.9a	2c
	6	Beck	0.89	16.2a	5.4c	2c
Lespedeza	1	Columbia	0	5.0b	4.4f	50a
	2	Columbia	0.34	10.5a	5.0e	7b
	3	Columbia	0.67	11.9a	5.6d	3c
	4	Columbia	1.00	11.5a	5.9b	2b
	5	Col.<60 mesh	1.22	11.1a	6.1a	2b
	6	Beck	0.89	11.8a	5.8c	2b

*Comparisons within columns by species with Fisher's Protected LSD test at alpha = 0.5 (Snedecor and Cochran, 1980).

The initial pH_s of the greenhouse soil was 4.8 with some extractable aluminum, but the first increment of limestone dropped the aluminum to quite low levels. Bennett's thesis contains the plant analysis results of his plants. There were mixed effects from the liming treatments on plant aluminum. In 5 out of the 9 species-harvest combinations, the first increment of limestone significantly decreased aluminum concentration in the harvested material. The data were erratic, and there was no evidence to explain the departure from the usual finding, that plant aluminum also declines as extractable soil aluminum and acidity in soil decline due to liming.

The pH_s data after 6 months of incubation are given in Table DB-5 as representative results. Incubation lowered pH_s from the initial 4.8 to 4.3. In the fineness factor calculation, the >8 mesh particle size is given a value of 0, but that particle size did at least offset the acidification that occurred during incubation. The bulk treatment (quarry-run limestone) raised the pH_s to the upper limit of the alfalfa target range for northern Missouri, as it did in the greenhouse. The data in Table DB-5 suggest that the neutralizing value of the 8-40 and 40-60 mesh fractions are underestimated in the current fineness factor evaluation, at 25% and 60%, respectively. Under the conditions of the Bennett incubation, these values would be closer to 40% and 80%, respectively. However, incubation results in a closed system should not be extrapolated to the field without repeating the study under field conditions.

Soil samples from the field study sites taken in 1988 were only 0-6” samples and the soil test results were used to determine the corrective treatments for P, K and limestone (see Table DB-1 for test results).

Table DB-5. The effects of limestone particle size fractions applied at increments of the calculated lime requirement on the active acidity of an acid soil after 6 months of incubation.

Particle Size	Fraction of Lime Requirement					
	0	0.33	0.66	1.00	1.33	1.66
Mesh				pH_s		
Bulk	4.3n	5.4k	5.9hi	6.5efg	6.6cde	6.7bcde
>8	4.3n	4.3n	4.6m	4.6m	4.9l	4.9l
8-40	4.3n	5.0l	5.6jk	6.0h	6.3fg	6.3fg
40-60	4.3n	5.4k	6.5efg	6.7bcde	6.8a	6.7bcde
<60	4.3n	5.7j	6.8a	6.8a	6.9a	6.8a

Bennett used fractional increments of the calculated lime requirement similar to those used in the greenhouse and incubation studies. Due to on-site calibration problems of the limestone spreader, some deviation from intentions resulted (Table DB-6). The treatments were applied prior to plowing in the fall of 1988. Seedbed preparation and seeding at both sites was done in spring 1989.

Table DB-6. Limestone treatments used in liming field studies.

Site	Treatment Number	Limestone Source	Species: Alfalfa	Red Clover	Lespedeza
				Fraction of LR*	
McWhorter	1	none	0	0	0
	2	Columbia	0.42	0.49	0.49
	3	Columbia	0.83	0.98	0.98
	4	Columbia	1.25	1.47	1.47
	5	Columbia	1.67	1.96	1.96
	6	Beck	1.09	1.28	1.28
Wilson	1	none	0	0	0
	2	Columbia	0.26	0.30	0.48**
	3	Columbia	0.52	0.60	0.96
	4	Columbia	0.79	0.92	1.43
	5	Columbia	1.04	1.20	1.91
	6	Beck	0.70	0.81	1.27

*The LRs were to increase pH_s to 6.6-70 for alfalfa and 6.1-6.5 for red clover and lespedeza.
**The Mississippi limestone was used only on the lespedeza block at the Wilson site.

Bennett’s field study was cut short due to the time constraint of his appointment so only the data from the establishment year were included in his thesis. The study was, however, continued through 1991. Yields from 1989, the establishment year, and 1989 soil acidity test results are summarized in Table DB-7. The limestone treatments did not have any statistically significant effects upon forage yields. Dry weather was partly responsible for the low yields and likely for limited response to treatments.

Fall 1989 soil samples taken to a 6 inch depth showed only very modest increases in pH_s and decreases in neutralizable acidity attributable to treatment (Table 14 in Bennett’s thesis). There are at least 2 reasons for the apparent lack of response to lime. Logistics in getting the study started in time to have data for Bennett's thesis resulted in the decision to apply all the treatments on the unplowed soil and then plow them under with no mixing with soil before plowing. As a result placement of the treatments was a result of how the plow turned over the soil. As will be shown later, plowing was deeper than 6 inches and the 6" sampling did not probe into the full treated layer of soil.

The pH_s results showed that acidity was lowered by liming but not in the amount expected. Liming did significantly lower the extractable aluminum in the soil at the McWhorter site. However, this was not the case at the Wilson site. The Wilson site initially had 5 to 6 times more extractable aluminum than the McWhorter site (Table DB-1). Liming significantly lowered aluminum on 2 blocks at the Wilson site but did not on the lespedeza block. This block received a different kind of limestone than the alfalfa and red clover blocks. There is no explanation for the different effects on aluminum, as both limestones had nearly the same ENM values.

Table DB-7. Soil acidity measures and forage yields as affected by limestone treatments in the stand establishment year (1989)*.

Species	Treatment	Site					
		McWhorter			Wilson		
		pH_s	Al*	Yield	pH_s	Al[1]	Yield
			ppm	tons/acre		ppm	tons/acre
Alfalfa	1	4.9c	13a	1.51	4.6c	113a	0.98
	2	5.0bc	8b	1.57	4.7c	73ab	0.79
	3	5.4a	5b	1.56	5.3ab	34b	1.02
	4	5.5a	2b	1.78	5.3ab	24b	1.07
	5	5.3ab	5b	1.59	5.4a	23b	1.00
	6	5.3ab	4b	1.83	5.0bc	54b	1.17
Red Clover	1	4.9b	15a	1.92	4.3b	178a	1.01
	2	5.2ab	6b	2.21	4.7a	86b	0.98
	3	5.3ab	6b	2.15	4.7a	97b	1.24
	4	5.4a	4b	2.31	4.7a	98b	1.00
	5	5.5a	5b	2.28	4.9a	85b	1.08
	6	5.2ab	6b	2.06	4.6ab	95b	1.15
Lespedeza	1	5.1c	11a	1.83	5.0c	37	1.24
	2	5.2ab	6b	2.21	5.5b	18	1.08
	3	5.5ab	5b	1.59	5.6b	9	1.10
	4	5.7a	0b	1.98	5.6b	17	1.11
	5	5.6ab	2b	1.97	5.9a	12	1.07
	6	5.3bc	3b	1.78	5.2c	44	1.15

*Comparisons within cells with Fisher's protected LSD test at alpha = 0.5. Yields are means of two harvests, except only one harvest was taken of lespedeza at the Wilson site.

In Fall 1991 all plots at both sites were sampled by 3 inch increments down to 12 inches to document the placement of limestone from plowing prior to forage establishment. This sampling pointed out that the lime treatments based upon a lime requirement which had been calculated for alfalfa in southern Missouri (target pH_s range = 6.6 to 7.0) and a plow depth of 6.67 inches affected the soil to a depth of 9 inches (Table DB-8). Thus if pH_s has any value in detecting the effects of treatments, the fractional lime requirement treatments as set up by Bennett (Table DB-6) need to be adjusted for depth of treatment. This was done by multiplying each of the values in Table DB-6 by 0.75 (rounded 6.67"/9").

Table DB-8. Effects of limestone applied in 1989 upon soil pH_s in samples taken in Fall 1991.

			Treatment*					
Site	Block	Depth	1	2	3	4	5	6
		inches						
McWhorter	Alfalfa	0-3	5.2	5.6	5.7	6.0	6.6	5.7
		3-6	5.3	6.2	6.3	6.6	6.7	6.1
		6-9	5.2	6.4	6.5	6.4	6.6	6.0
		9-12	4.7	4.8	5.2	4.8	4.8	4.6
	Red Clover	0-3	5.3	5.7	5.6	6.1	6.2	6.3
		3-6	5.5	6.1	6.2	6.7	6.8	6.4
		6-9	5.5	6.0	6.2	6.7	6.6	6.1
		9-12	4.6	4.8	4.6	5.0	4.9	4.8
	Lespedeza	0-3	5.8	6.1	6.4	6.4	6.6	6.1
		3-6	6.0	6.7	6.6	6.9	7.0	6.6
		6-9	5.4	5.8	6.2	6.5	7.0	6.3
		9-12	4.7	4.7	4.8	4.8	5.0	4.8
Wilson	Alfalfa	0-3	4.7	4.7	5.0	5.6	5.2	5.0
		3-6	4.8	5.2	5.7	6.2	6.3	5.9
		6-9	4.2	4.4	4.5	5.0	5.0	4.6
		9-12	4.0	4.0	4.1	4.2	4.2	4.1
	Red clover	0-3	4.5	4.6	5.2	4.8	5.3	4.8
		3-6	4.6	5.4	5.7	5.6	6.3	5.5
		6-9	4.3	4.5	4.8	4.5	4.5	4.4
		9-12	4.0	4.0	4.0	4.1	4.2	4.0
	Lespedeza	0-3	5.3	5.5	5.8	5.6	6.0	5.4
		3-6	5.4	6.2	6.1	6.3	6.6	6.1
		6-9	4.6	4.8	5.0	4.8	5.5	4.9
		9-12	4.1	4.2	4.2	4.2	4.2	4.2

*See Table DB-6 for more detail on the treatments.

The recalculation of the fraction of the lime requirement applied compared to the mean of the pH_s of the 0 to 9 inch layer of each of the cells in Table DB-8 shows the following:

1. At the McWhorter site slightly more than the full lime requirement was needed to get the mean soil pH_s into the target range 30 months after application.

2. At the Wilson site none of the treatments was at full lime requirement after adjustment for depth, and this was reflected by the pH_s values on the alfalfa and red clover blocks, which received the same limestone as the McWhorter site.

3. The Beck limestone at both sites and the Mississippi limestone on the Wilson lespedeza block did not affect the soil as did the Columbia limestone. The neutralizing value of the Beck limestone was slightly over estimated and that of the Mississippi limestone under estimated.

Based upon the soil data after recalculation of the treatments, it appears that the lime requirement was underestimated. Further the soil data suggest that there were distinct differences between the three limestones in their effects on neutralization of soil acidity. These differences may have been due to their mineralogical characteristics, making them differ in reactivity to soil acidity. Stephens' results, however, suggested that in the lab there was no difference between calcitic and dolomitic limestones. In the Bennett study the Beck dolomitic limestone did not react as would be expected from the ENM value. Thus, a single calculation method for limestone needed to correct a soil acidity problem should be expected to have variable effects on soil acidity due to differences in stone and soil parameters. However, due to differences in the reactivity with soil acidity between various liming materials, the recommendation system in place at the start of 2000 may be as good as can be obtained.

The analysis of the yield data from 1990 and 1991 would suggest that there were factors other than calculated lime requirement and the ENM values of the limestones affecting the outcome of the study. Dry weather adversely affected the yields. The region of the study consists of soils with limited rooting depths due to strongly acidic subsurface horizons preventing access of roots to stored soil moisture. Table DB-9 shows a significant but inconsistent response to liming especially at the more acidic Wilson site. Lespedeza failed and attempts to reseed also failed. The 1991 red clover yields were affected by the biennial nature of the species. Reseeding in 1991 was only partially effective. The Wilson site was terminated in mid-1991 at the new land owner's request, and the McWhorter site was terminated at the end of 1991.

Table DB-9. The effects of lime treatments upon annual forage legume yields — 1990 and 1991.

a. Yields

Site	Year	Species	Treatment 1	2	3	4	5	6	Statistics*
			tons/acre						
McWhorter	1990	Alfalfa	4.4	4.6	4.8	4.9	5.2	4.8	NS
	1991		2.6	2.8	2.9	3.1	2.8	2.9	NS
Wilson	1990	Alfalfa	2.1	3.0	3.0	3.5	3.3	3.2	$lsd_{0.05} = 0.18$
	1991		1.4	1,4	1.8	1.7	1.6	1.7	NS
McWhorter	1990	Red Clover	5.0	5.2	5.1	4.9	5.2	5.1	NS
	1991		2.6	2.4	2.3	2.4	2.4	2.4	NS
Wilson	1990	Red Clover	4.4	4.7	4.6	4.7	4.5	4.5	NS
	1991					lost			

*Results of general analysis of variance. Analysis of data by fitting to linear and quadratic expressions by regression gave the following significant results (T = treatments as fraction of LR).

b. Model: Yield = f(lime treatments x T)

Site	Year	Species	Model	Equation	Significance
McWhorter	1990	Alfalfa	Linear	Total $Y = 4.23 + 0.18075T$	10%
Wilson	1990	Alfalfa	Linear	Total $Y = 2.13 + 0.294T$	<1%
Wilson	1991	Alfalfa	Linear	Total $Y = 1.36 + 0.079T$	<10%
Wilson	1990	Alfalfa	Quadratic	Total $Y = 1.2815 + 1.0204T + 0.121T^2$	<5%
Wilson	1990	Red Clover	Quadratic	Total $Y = 4.118 + 0.362T + 0.0585T^2$	<10%

The harvested forages in 1990 were analyzed for N, P, K, Ca, and Mg. The Beck limestone treatment consistently increased magnesium in both alfalfa and red clover, but the absence of significant yield response suggests that magnesium was not limiting on the calcitic limestone treatments.

Based upon the Bennett work, the methods of estimating lime requirements in place since the 1970s are still effective. Changes in the forage recommendations would require several field calibration sites; the expense of these studies likely could not be justified.

Application of Lime and Crop Residues to Ameliorate Phytotoxic Aluminum in two Acid Missouri Soils

Syed Omar Syed Rastan, Ph.D. Dissertation1995
J.R. Brown and R.J. Miles, Advisors

In spite of the work done by the students reported in preceding sections of this paper, there remained several uncertainties about the chemistry of limestone amendments to acid soils. Syed Omar Syed Rastan contacted us concerning a Ph.D. program with emphasis on the chemistry of acid soils. He had experience in Malaysia and in Georgia (USA) with highly acid soils containing toxic levels of active aluminum.

Syed conducted four different studies designed to reach the following objectives:

- Evaluate the merits of the Woodruff buffer and several different extractants of extractable aluminum for estimating lime requirements for highly acid soils.
- Measure the changes in soil solution chemistry in lime amended highly acid soils,
- Document the effects of organic soil amendments upon toxicity of soil aluminum to alfalfa.

Yusef (1986) suggested that extractable aluminum in highly acid soils may be useful as a basis for the estimation of lime requirement of such soils. Syed Omar (1995) tested Yusef's suggestion on two highly acid soils from southern Missouri. One soil, from a second growth timbered site, was classified as Captina (fine-silty, mixed, mesic Typic Fragiudult). The second soil, from a farm woodlot, was classified as Hobson (fine-loamy, mixed, mesic Typic Fragiudalf). The A1 horizon was collected after removal of surface organic material. Chemical characteristics of these two soils are summarized in Table SO-1.

Table SO-1. Chemical characteristics of two soils from the Ozark region of Missouri.

	Columns										
	1	2	3	4	5	6	7	8	8	10	11
Soil	Ca	Mg	K	Al	ECEC*	NA**	CEC***	pH_w	pH_s	OM	P-1
	------------------------------- meq/100g -------------------------------									%	mg/kg
Captina	0.51	0.23	0.17	3.34	4.25	9.0	9.91	4.7	4.0	1.9	7
Hobson	0.38	0.28	0.17	2.81	3.64	9.5	10.33	4.7	3.9	1.8	7

*Sum of columns 1, 2, 3, and 4.
**Neutralizable acidity using the New Woodruff buffer.
***Sum of columns 1, 2, 3, and 6.
Except as noted below, the results are based upon the routine Missouri soil testing methods (Brown and Rodriguez, 1983). calcium, magnesium, and potassium extractable with ammonium acetate, aluminum extractable with 1 M KCl.

Study 1 was a greenhouse pot study using both soils and alfalfa as a test crop. Corrective treatments of P, K, B, and S were added to both soils based upon recommendations for establishment and production of alfalfa in Region 7 (central Ozarks) of Missouri (Buchholz, 1983). These corrective treatments were thoroughly mixed in bulk quantities of the two soils. Lime treatments were based upon fractions of the extractable aluminum plus a full lime requirement as estimated using the New Woodruff Buffer. The liming material was analytical grade $CaCO_3$ and $MgCO_3$ mixed in a 6:1 Ca:Mg ratio (Table SO-2). The alfalfa test crop was harvested 5 times at 10% bloom in 30-day intervals. Soil in each pot was sampled for measurement of 1 M KCl extractable aluminum, pH_w, and pH_s after the second and fourth harvests.

Table SO-2. Liming treatments applied to two highly acid soils for a greenhouse study with alfalfa as the test crop.

		Fraction of extractable Al					Woodruff	
Soil	Units	0	0.25	0.50	1.0	2.0	2.7*	3.4*
Captina	meq/100g	0	0.84	1.67	3.04	6.68	9.0	na
Captina	% of WB*	0	9.2	18.50	37.00	74	100	na
Hobson	meq/100g	0	0.70	1.40	2.81	5.62	na	9.5
Hobson	% of WB*	0	7.4	14.70	30.00	59	na	100

*Calculated as an equivalent fraction of the 1 M KCl extractable aluminum. WB = Woodruff buffer.

Alfalfa did not persist without lime (Table SO-3). Lime applied at amounts equivalent to 25 and 50% of the extractable aluminum was unable to sustain even modest yields through five harvests. Lime applied at an amount equivalent to the amount of extractable aluminum was insufficient to maximize yields. In contrast to Yusef's results, application of lime at twice the equivalent amount of extractable aluminum was inadequate to maximize yield. However extractable aluminum was lowered to near zero by a lime equivalent to 2 x KCl extractable aluminum (Table SO-4). Lime, applied at less than 50% extractable aluminum, reduced extractable aluminum in the soils.

Table SO-3. Alfalfa dry matter produced in a greenhouse study in response to differential lime rates (means of 4 replications).

			Harvest					
Soil	Treatment	Fraction of Extractable Al	1	2	3	4	5	Roots
			------------------------------ grams/pot ------------------------------					
Captina	1	0	0.10	0.03	0	0	0	0
	2	0.25	0.62	1.32	0.64	0.18	0.11	0.60
	3	0.50	1.91	2.47	1.06	0.55	0.65	2.23
	4	1.00	3.78	3.91	3.48	5.12	5.03	6.95
	5	2.00	3.47	5.35	5.98	9.38	9.77	11.12
	6	2.96	2.10	6.66	6.60	9.56	10.88	11.00
Hobson	1	0	0	0	0	0	0	0
	2	0.25	0.72	0.52	0.39	0.32	0.19	0.28
	3	0.50	2.01	2.13	1.08	0.69	0.66	1.38
	4	1.00	3.48	4.18	3.25	4.53	5.81	6.26
	5	2.00	4.48	6.06	5.44	8.40	9.49	10.92
	6	3.38	3.70	5.48	6.68	8.71	10.11	9.25

A separate laboratory incubation study on the Captina and Hobson soil material used for the greenhouse helped explain the alfalfa yield responses over successive harvests. Aluminum activity in the soils increased with time (Table SO-5), and in the soils receiving the two largest lime treatments it was zero throughout the length of the incubation. The alfalfa yield data more or less reflected the changes in pH_s and aluminum activity in extracted soil solution.

The pH_s of the soils receiving the most lime declined measurably in the 60 days between the second and fourth harvests. Only those pots that received the equivalent of the Missouri lime recommendation based on the Woodruff buffer maintained a pH_s in excess of 6.0 after four harvests. These greenhouse results suggest that application of lime at twice the equivalent of extractable aluminum is inadequate for sustaining alfalfa yields over time.

Table SO-4 Effects of incremental lime treatments on soil acidity measurements in a greenhouse study.

			Post-harvest 2		Post-harvest 4	
Soil	Treatment	Fraction of Extractable Al	Al	pH_s	Al	pH_s
			------------------- meq/100 g -------------------			
Captina	1	0	1.92	4.10	1.96	4.10
	2	0.25	1.52	4.23	1.60	4.15
	3	0.50	1.19	4.35	1.22	4.20
	4	1.00	0.44	4.62	0.59	4.62
	5	2.00	0.01	6.09	0	5.77
	6	2.96	0	6.91	0	6.24
Hobson	1	0	1.47	4.12	1.52	4.14
	2	0.25	1.08	4.24	1.21	4.16
	3	0.50	0.80	4.33	0.52	4.32
	4	1.00	0.29	4.78	0.41	4.67
	5	2.00	0.01	5.89	0.01	5.60
	6	3.38	0	7.24	0	6.81

Table SO-5. Effects of differential liming of two highly acid soils on aluminum activity in extracted soil solution over 10 months of incubation.

			Months of incubation			
Soil	Treatment	Lime*	1	2	5	10
			-------------------μM -------------------			
Captina	1	0	14	8	11	119
	2	0.25	7	5	27	74
	3	0.50	4	2	45	54
	4	1.00	1	5	8	8
	5	2.00	0	0	0	0
	6	2.96	0	0	0	0
Hobson	1	0	7	3	29	55
	2	0.25	3	3	25	47
	3	0.50	2	3	20	33
	4	1.00	0	3	5	7
	5	2.00	0	0	0	0
	6	3.38	0	0	0	0

*Fractional equivalent of the initial KCl extractable aluminum (see Table SO-2).

Another of Syed Omar's objectives was to evaluate different extractants of aluminum to determine if one might prove best as a basis for lime requirement estimates. Aluminum extracted from differently limed soil by extractants following the second greenhouse harvest is shown in Table SO-6. Syed Omar concluded that $LaCl_2$ was the superior extractant, because both alfalfa yields and soil pH_s were highly correlated with $LaCl_2$ extractable aluminum. The $CuCl_2$ and ammonium citrate extractants extracted aluminum even though the pH_s was at or over 6.9. The question remaining was whether there was an advantage to using extractable aluminum as a basis for estimating lime requirements.

A second greenhouse study was conducted to investigate the addition of plant material and lime upon alfalfa growth. Lime was applied at 0, 0.5, 1 and 2 times the 1 M KCl extractable aluminum (me per 100 g). The plant material treatments were alfalfa and wheat straw ground to pass a 2 mm screen and incorporated into the soils at a rate of 1% (w/w). There was insufficient soil for a true check. The greenhouse study was a 2 x 4 factorial with four replications on each soil. In other respects this second greenhouse experiment was identical to the first.

Table SO-6. Aluminum extracted with four different extractants from two differentially limed soils following 2 harvests.

				Extractant***			
Soil	Lime*	pH_s	NA**	KCl	$LaCl_2$	$CuCl_2$	KCl + NH_4Citrate
				------------------- meq/100 g -------------------			
Captina	0	4.1	6.37	1.92	2.27	3.50	3.64
	0.25	4.2	6.00	1.52	1.92	3.07	3.26
	0.50	4.4	5.50	1.19	1.58	2.68	2,93
	1.00	4.8	4.12	0.42	0.89	2.0	2.29
	2.00	6.1	1.75	0.00	0.22	1.43	2.00
	2.96	6.9	0.00	0.00	0.00	1.31	1.93
Hobson	0	4.1	6.75	1.47	1.85	2.59	2.82
	0.25	4.2	6.00	1.09	1.64	2.17	2.64
	0.50	4.3	5.50	0.80	1.28	2.00	2.56
	1.00	4.8	4.12	0.28	0.81	1.58	2.17
	2.00	5.9	1.75	0.00	0.25	1.18	1.90
	3.38	7.2	0.00	0.00	0.00	1.00	1.89

*Fractional equivalent of the initial KCl extractable aluminum (see Table SO-2).
**Neutralizable acidity using the New Woodruff buffer.
***1 M, 0.33 M, 0.5 M, and 1 M + 0.5 M, respectively.

Dry matter yields showed major interactions between lime and residue treatments (Table SO-7). Alfalfa established well in the unlimed pots that received alfalfa residue. Data in the thesis suggested that mineralization of the low C:N residue resulted in a short-term buildup of ammonium that reduced the toxic effects of active aluminum. Simple organic acids were shown to be present. Calculation of aluminum speciation using GEOCHEM supported the reduction in active aluminum. The beneficial effect of the alfalfa residue lasted only through the second harvest (Table SO-7). Straw addition to the soil did not offset the toxic effects of the unlimed soils.

The lack of a true non-residue treatment weakens conclusions but in greenhouse study 1alfalfa in untreated, unamended soil failed to establish (Table SO-3). The beneficial effects of the alfalfa residues on yields from limed pots lasted longer than with the straw; an effect likely due to the C:N ratio of the plant residues (Table SO-8).

After 4 harvests the lime treatments persisted in reducing extractable soil aluminum, and lime applied at twice the initial equivalent quantity of extractable aluminum kept measurable extractable aluminum from reappearing (SO-9). However, while the lime treatments reduced the aluminum concentration in the harvested alfalfa, aluminum was taken up on all treatments (Table SO-10). Obviously plants are able to take up aluminum even when there was no KCl extractable aluminum. This aluminum in excess of 1 M KCl extractable aluminum reflects slowly available aluminum that over time continues to react with remaining liming material in limed soils. This activity accentuates the need for periodic retesting of limed soils.

Table SO-7. Effects of lime and plant residues on dry matter yields of greenhouse grown alfalfa*.

Soil	Residue	Lime**	Harvest 1	2	3	4
			------------------- grams/pot -------------------			
Captina	Alfalfa	0	2.78	7.28	4.07	0.45
		0.5	4.27	11.66	8.01	2.52
		1.0	2.36	11.75	10.22	8.33
		2.0	1.53	15.22	14.76	21.72
	Straw	0	0.4	0	0	0
		0.5	1.39	2.54	1.72	1.66
		1.0	2.03	3.86	5.10	11.29
		2.0	0.86	4.15	8.22	19.47
Hobson	Alfalfa	0	4.26	10.76	1.77	1.65
		0.5	3.35	9.30	7.30	3.45
		1.0	3.88	13.54	7.78	10.39
		2.0	3.80	14.39	13.39	20.65
	Straw	0	0.05	0	0	0
		0.5	1.75	3.04	2.83	1.51
		1.0	2.94	7.50	9.40	7.48
		2.0	2.50	9.05	12.58	18.09

*Means of 4 replications.
**Expressed as a fraction of the equivalent KCl extractable aluminum at pre-treatment.

Table SO-8. Composition of plant residues used as soil amendments in greenhouse study 2.

Residue	N	P	K	Ca	Mg	C/N
	-------------	-------------	------------- %	-------------	-------------	
Alfalfa	3.40	0.30	3.08	1.77	0.15	12.4
Straw	0.60	0.11	0.62	0.17	0.03	72.5

Table SO-9. Effect of lime and organic residues on soil acidity and KCl extractable aluminum after the fourth harvest (165 days after initial wetting).

Soil	Lime*	pHs Alfalfa	pHs Straw	pHs None	Al Alfalfa	Al Straw	Al None
					------------- meq/100g -------------		
Captina	0	4.1	4.1	4.1	1.41	1.50	1.95
	0.5	4.3	4.3	4.3	0.86	1.21	1.22
	1.0	4.8	4.5	4.6	0.32	0.74	0.59
	2.0	5.9	5.7	5.8	0.00	0.00	0.00
	$HSD_{0.05}$**	0.3	0.3	0.2	0.27	0.32	0.17
Hobson	0	4.2	4.0	4.0	0.79	1.26	1.52
	0.5	4.4	4.2	4.3	0.55	0.70	0.92
	1.0	4.9	4.5	4.7	0.19	0.47	0.41
	2.0	5.5	5.3	5.6	0.00	0.00	0.00
	$HSD_{0.05}$**	0.3	0.2	0.2	0.14	0.15	0.18

*Expressed as a fraction of the equivalent KCl extractable aluminum at pre-treatment.
**Tukey's test.

After 4 alfalfa harvests, exchangeable calcium and magnesium in the potted soils failed to show recovery of calcium and magnesium added in the treatments (Table SO-11). This lack of recovery suggests that undissolved limestone remained in the soils at the end of the experiment.

Syed Omar concluded that KCl extractable aluminum could serve as a basis for estimating lime requirements on highly acid soils, but doubling the calculated lime equivalent to account for extractable aluminum, as suggested by Yusef, was inferior to lime requirement using the Woodruff buffer. Syed-Omar's results indicated that extractable aluminum using 0.33 M $LaCl_3$ might be a better choice, but he had insufficient data to provide a basis for adaptation. Syed Omar also included some data that perhaps explained observations in the field that poor growth of young alfalfa stands established on recently limed soils may be due to induced nutrient deficiencies.

Table SO-10. Effects of lime and organic residues upon the concentration of aluminum in alfalfa tissue from the fourth harvest on a Hobson soil.

Lime*	Alfalfa	Straw	None
	---------------- mg Al/kg ----------------		
0	64	ND**	106
0.5	46	86	73
1.0	36	42	73
2.0	25	23	71
$HSD_{0.05}$***	13	26	22

*Expressed as a fraction of the equivalent KCl extractable aluminum at pre-treatment.
**No plant material available for analysis.
***Tukey's test.

Table SO-11. Ammonium acetate exchangeable cations in the Hobson soil after the fourth harvest of alfalfa grown in the greenhouse.

Lime*	No residue			Alfalfa			Straw		
	Ca	Mg	Ca+Mg	Ca	Mg	Ca+Mg	Ca	Mg	Ca+Mg
	---------------- meq/100g ----------------								
0	0.93	0.42	1.35	1.74	0.56	2.30	1.09	0.48	1.57
0.5	1.98	0.56	1.54	2.56	0.63	3.19	2.04	0.62	2.66
1.0	2.76	0.69	3.45	3.51	0.79	4.30	2.93	0.75	3.68
2.0	4.45	0.90	5.35	4.84	0.64	5.48	4.42	0.90	5.32
$HSD_{0.05}$**	0.70	0.08		0.39	0.13		0.52	0.17	

*Expressed as a fraction of the equivalent KCl extractable aluminum at pre-treatment.
**Tukey's test.

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