SPATIALLY VARIABLE LIMING RATES: A METHOD FOR DETERMINATION

S. C. Borgelt, S.W. Searcy, B. A. Stout, D. J. Mulla

ABSTRACT. *The variability of soil acidity and crop liming requirements in a field in East Texas were examined. Sixty-eight soil samples were taken in a systematic manner from the field. Geostatistical techniques were used to analyze the soil acidity variability of the samples and assist in developing a liming application rate map for the field. Soil pH, soil texture, and buffer pH variations showed spatial dependence. Application of the average recommendation rate for the field would have resulted in an overapplication of lime in 9 to 12% of the field and an underapplication on 37 to 41% of the field. Varying lime application within the field so different areas receive appropriate rates would have caused a greater total lime application of 8 to 28%, depending on recommendation method, compared to the mean application rate. The data indicated the application of lime "where needed" could maximize application benefits.*

Keywords. *Site specific, Spatial variability, Geostatistics, Soil acidity, Lime.*

Agricultural producers often consider the land in each field as a homogeneous, uniform unit. Although a land area may have considerable variation in its character, such as different soil types or topography, the inputs supplied for crop production are applied at constant rates. As the land area in a single field increases, the difference between crop needs and input supply rates for a portion of the field may become more extreme.

A 1986 Harris Survey showed that 84% of the general public was concerned with pesticide pollution and 75% with pollution from agricultural fertilizers. This compares with 65 and 50%, respectively, for farmers asked the same question (Young, 1987). In the report, *Agricultural Technology: The Texas Agenda*, it was recognized that production costs are high in Texas because of the use of high-cost inputs. The Agribusiness Task Force (1986), therefore, recommended the development of new technology to reduce agricultural production costs.

Customizing inputs such as lime, fertilizers, herbicides, pesticides, and irrigation water at every location in a field may help to accomplish the following goals: 1) maximize profitability, by optimizing inputs and yields and 2) protect the environment, by minimizing overapplication.

OBJECTIVES

The thrust of this research project was to examine information that could be used for spatially variable farmland management. The specific variable examined was soil acidity and its use in establishing crop liming requirements. The liming operation was chosen because it constitutes a high-value input operation in parts of Texas. To determine how variable rate technology could be viable, the objectives of this project were to:

- Determine the spatial variability of soil acidity on an East Texas field.
- Use geostatistical techniques to analyze field data and assist in making liming rate management zones.

BACKGROUND

The pH of a soil is perhaps the most commonly measured soil characteristic. Soil solution acidity, measured by pH, probably influences crop yields more than any other soil characteristic (Doane Agricultural Report, 1987). Liming, as the term applies to agriculture, is the addition to the soil of calcium or a calcium and magnesium compound that is capable of reducing acidity (Tisdale et al., 1985).

For producers, the most important consideration of farm management regarding acid soils is the adoption of a liming program to achieve and maintain optimum yield potential. Application of excessive amounts of lime is not economical and can decrease nutrient availability and crop growth. Inadequate applications reduce crop yield (Pratt et al., 1987).

Many farmers perform chemical analyses on soils and plants to determine nutrient needs of plants for greater yields and profits. The basic principle of a soil testing program is to sample a field in such a way that chemical analyses of collected samples will accurately reflect the nutrient status of the field. This is difficult to do, even though it is critical. Usually a composite soil sample, about 0.5 kg (1 lb), is taken from a field. In an 8.8 ha (22 acre) field, there are about 9 million kg (20 million lb) of surface

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soil, giving considerable opportunity for error (Tisdale et al., 1985). The variability of soil properties in a land region is important in determining if lime, fertilizer, or other resources are being recommended and supplied adequately.

The ability to apply fertilizers at variable application rates has been demonstrated by Soil Teq, Inc., using their SOILECTION SYSTEM fertilizer equipment (Elliot, 1987). Based on soil survey maps, aerial photography, or grid sampling, fields to be fertilized were divided into multiple areas. Producers and researchers, in the United States and worldwide, have shown interest in the management of farmland based on spatial variations instead of field boundaries. Schueller (1992) wrote a comprehensive review of relevant and future research for spatially-variable control of crop production. Useful information is available for those interested in learning more about the research in site specific crop management (ASAE, 1991; Robert et al., 1993).

The interest in spatially variable (site specific) farming creates a need to determine the presence of variability, to quantify and analyze that variability, and to determine the best practices for variability management. In other words, just as research for crop varieties, fertilizers, and other farming inputs have required regional research, site specific farming methods require research at various locations, on many soil types, farms, and fields.

Determination of Variability in Soil Acidity

Site Description

A plot on the Stephen F. Austin State University (SFASU) Dairy Farm, Nacogdoches, Texas, was selected for this study. The field was generally rectangular in shape and approximately 8.8 ha (22 acre) in area. A majority of the soil texture was sandy loam, with the remainder being clay loam. The topography varied, generally sloping to the north and Eastwith an elevation change of 10.4 m (34.1 ft) and a 3.8% average slope.

Coastal bermudagrass (*Cynodon dactylon* L. Pers) was the cover crop at the site. Crop height and vigor were variable (no quantitative measures were taken). The variations could be attributed to many factors, including the spreading of dairy manure on the field in a non-systematic pattern.

Sampling Design

The best soil sampling design to quantify spatial variability was somewhat difficult to determine because measured variability and sample spacing were dependent on each other. Yost (1988) stated that in order to develop a surface of pH values that could be adequately interpolated to any location with an associated estimate of variance, soil samples were needed at varying distances from one another. He suggested a modified composite design sampling pattern similar to that used by Trangmar et al. (1987). A 45 × 45 m (150 × 150 ft) grid, yielding 35 sample points, was laid out on the sample area. The grid was overlaid with a large "X" extending from each corner to the opposite corner and through the center sample point, with samples on the centers of the grid squares. A cross pattern (+) was overlaid with sample spacing of 30.5 m (100 ft). This pattern gave a diversity of sample points at varying distances from each other. In addition, several short sample lines, or transects, were identified. These samples were taken to have representative samples from all soil textures. The total number of samples was 68.

The sampling design was laid out with a Gandy measuring wheel, without the assistance of a survey transit so the sampling pattern was regular, but not truly orthogonal. Location data were obtained by triangulation, using a Del Norte Transponder system. Plastic flags were used to identify the sampling locations. Figure 1 shows a plot of the field layout determined by the distance measurements.

Sample Collection and Laboratory Methods

A composite soil sample was taken at each sample location as follows. A stainless steel, 2.5 cm (1 in.) diameter coring sample probe was used to obtain soil cores approximately 10 cm (4 in.) in depth, according to SFASU (1988) procedures for soil samples in permanent sods. At each location, 10 soil cores were taken and mixed to obtain 1 sample. Two cores were taken within 0.15 m (6 in.) of the marker, four cores were taken within a 0.5 m (18 in.) radius, and four cores were taken within a 1 m (3.3 ft) radius.

The samples were air-dried and ground to pass a 2 mm sieve. A portion of each sample was used to measure 2:1 water-soil pH and buffer pH, according to the procedure used by the SFASU soil test laboratory. (For a detailed explanation of procedures and solution components, contact the Stephen F. Austin State University soil test laboratory.) The soil test laboratory director estimated the soil texture classification of each sample as either sandy loam or clay loam.

Analysis of Soil Acidity Variability

Statistical Analysis

The following field data were analyzed using SAS (1985) statistical software, and some simple descriptive statistics were recorded.

- Texture Index (One of three index numbers was given to each sample according to the texture

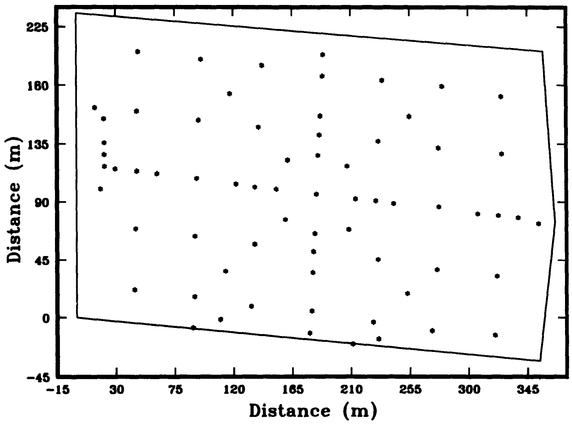

Figure 1–Plot of sample sites using location data.

determination with: one for sands and loamy sands, two for sandy loam, and three for clay loam).

- pH (2:1 water to soil).
- Buffer pH (Adams-Evans buffer pH).

The statistical analysis (table 1) included overall mean, variance, maximum value, minimum value, and coefficient of variation.

GEOSTATISTICAL ANALYSIS

Classical statistical methods do not account for local spatial dependence of samples during estimation, but were based on the assumption that sample variation was randomly distributed within sampling units. For example, the expected value of a soil property z at any location within a sampling area using classical statistical methods is:

$$z(x) = \mu + \varepsilon(x) \qquad (1)$$

where

$z(x)$ = expected value
μ = mean
$\varepsilon(x)$ = a residual value

The deviations from the population mean, $\varepsilon(x)$, are assumed to be normally distributed with a mean of zero and a variance of σ^2 (Trangmar et al., 1985). In other words, every value of z is independent regardless of its position with respect to another.

Actually, many soil properties are continuous variables whose values at any location can be expected to vary according to direction and distance of separation from neighboring samples and, therefore, classical methods do not remain valid. Trangmar et al. (1985) discussed that Krige in the 1950s and Matheron in the 1960s and 1970s developed procedures for analysis and estimation of spatially dependent variables. Matheron (1963) developed a "Theory of Regionalized Variables". Its application to problems in geology and mining led to the more popular name—geostatistics (Clark, 1979). The application of the theory is to describe variations in soil properties quantitatively and to use such descriptions to estimate unknown values at some locations.

Geostatistical methods were used to express that soil properties at close locations were likely to be similar, whereas those at places far from one another were not (Webster and Burgess, 1983). A regionalized variable is a continuously distributed variable with geographic variation too complex to be represented by any workable mathematical function. In this view, there is no mathematical relation between the soil and its location, but there is spatial dependence. The point-to-point variation of a regionalized variable is stochastic in the sense that a sample cannot be precisely calculated from those values at neighboring locations (Knighton and Wagenet, 1987).

Table 1. Summary of all data

Variable	N	Mean	Variance	Minimum	Maximum	Coefficient of Variation (%)
Texture index	68	2.16	0.14	2.0	3.0	17.3
pH	68	5.54	0.18	4.7	6.9	7.7
Buffer pH	68	7.65	0.02	7.3	7.9	1.8

SEMIVARIANCE AND SEMIVARIOGRAMS

A quantification of spatial dependence is called the semivariance. The semivariogram is a graphical model that indicates the spatial relationship between measured values. The semivariance is determined as follows. The intrinsic hypothesis states that for any two locations separated by a lag distance, h, the variance of the differences of the measured property is finite and independent of its (x, y) position. The variance is dependent only on the lag distance h:

$$\mathrm{var}\left[z(x) - z(x + h)\right] = 2\gamma(h) \qquad (2)$$

Therefore, the following is a model of soil variation:

$$z(x) = \mu + \varepsilon(x) \qquad (3)$$

where

$z(x)$ = expected value
μ = mean
$\varepsilon(x)$ = a residual value
$\gamma(h)$ = the semivariance

This equation is the same as equation 1 except $\varepsilon(x)$ is a spatially dependent random component with zero mean and a variance defined by $2\gamma(h)$ (Webster, 1985).

The semivariance, $\gamma(h)$ is calculated as a function of h:

$$\gamma(h) = \frac{1}{2n} \sum_{i=1}^{n} \left[z(x) - z(x + h)\right]^2 \qquad (4)$$

The easiest and most common way to display the semivariance for many different values of h is in a graph, hence, the name semivariogram. A continuous function can be fitted to this graph of points. An example of a semivariogram model is figure 2. The semivariance, $\gamma(h)$, increases as h increases up to a certain level of h after which $\gamma(h)$ remains constant.

FITTING DA[redacted]M MODELS

Webster and Burgess are noted researchers in spatial variations of soil properties and the geostatistical analysis of those properties. In comments about semivariograms and fitting semivar[redacted]ntal data the following statements were made by Webster and Burgess (1983) and still hold true. "It is worth making the point here that the form of the semivariogram can determined absolutely. The resulting semivariog[redacted] only a description and not an explanation, and there is substantial scope for research to understand the physical process or processes that give rise to any particular semivariogram. We are only at the beginning." Although data has been collected and analyzed to determine the existence and location of variations, many of the underlying causes of the variation are still yet to be determined.

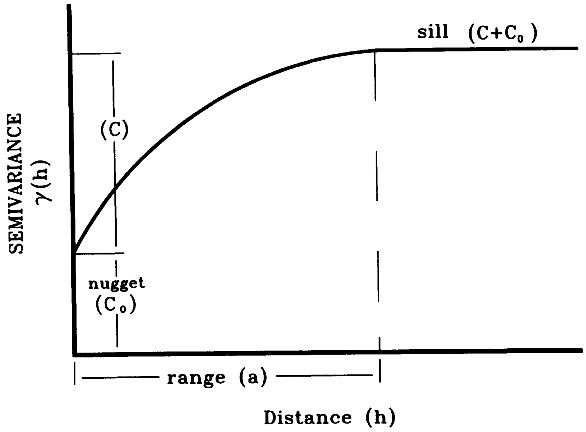

Figure 2–Schematic of a semivariogram.

Both the SEMIVAR and MODELVAR spatial data analysis programs were obtained from Dr. David Mulla, Professor of Crop and Soil Science, Washington State University. Both SEMIVAR and MODELVAR were written in BASIC, adapted from programs developed by Vieira et al. (1983). Using SEMIVAR with the field data, semivariance was calculated using several lag distances (h). SEMIVAR recorded the semivariance that was calculated when at least 15 pairs of points were included at each lag distance.

Isotropy and anisotropy are important considerations in semivariance determination. Isotropy means a property varies in a similar manner in all directions; hence, the semivariogram depends only on distance between samples. Anisotropy means dissimilar property variation throughout the sample space. Anisotropy may be directional in nature or due to some natural process. Laslett et al. (1987) compared several spatial prediction methods using a data set of soil pH from a land tract in Australia. The authors stated that anisotropic models seemed to be indicated by the observed data, but isotropic models performed better in the tests to compare the prediction methods. For this study, isotropic semivariograms were determined because of Laslett et al. (1987) and the software available. Drift or trend analysis was not considered necessary for these data due to the assumption of local stationarity.

MODELVAR can fit as many as 10 different semivariogram models to a set of data using a least squares nonlinear regression technique. When the models were fit to a set of points, values for the sum of squares and standard error were calculated.

The selection of sample intervals, lag distances, and semivariogram models were not automatic nor routine processes. Vieira et al. (1983) state that fitting a theoretical model to the experimental semivariogram was an important aspect of the applications and may be one of the major sources of ambiguity. Marx and Thompson (1987) discussed the arbitrary nature of semivariance computation in terms of sample intervals and lag distance. They suggest 10 to 25 sample intervals, but state that the intervals be chosen so semivariogram estimates remain relatively stable (Marx and Thompson, 1987). Procedures for fitting semivariogram models to each variable of interest were as follows:

SOIL pH

- Semivariance values were calculated with lag intervals of 6, 7, 8, 9, 10, 11, 12, and 15 m.
- Spherical, exponential, and gaussian models were fit to all the semivariance data (which were quite variable).
- Fitted spherical and exponential model parameters showed negative nugget values, so the models were constrained through zero.
- Fitted sill and range values for each lag distance and model type were similar. Determination of the range was important in this process because the smaller-distance semivariance values were the most important. The power and the influence of the spatial dependence depicted in the semivariogram was exerted primarily at smaller distances, particularly at distances smaller than the range.
- Only three to seven pairs of semivariance values were determined before the practical range was reached.

Therefore, the lag intervals of 6 and 7 m were examined, because they had more sample pairs at smaller lags. The first eight semivariance values were used to refit models. The gaussian model was the best fit, with the parameters of sill and range the same for 6- and 7-m lag intervals.

SOIL TEXTURE INDEX

The values of soil texture are index measurements for sandy or clay soils. The Texas A&M University soil texture classifications for use in liming rates were: sands and loamy sands = 1, sandy loams = 2, and clay loams = 3. Because only sandy loams and clay loams were present in this field, the index values of 2 or 3 were recorded for the test field. As before, the best fit linear model for lag intervals of 6 and 7 m were considered, using the first 8 points to fit the model. The model chosen was the linear model from the 7-m-lag interval because it had a slightly greater sum of squares value.

BUFFER pH

- All the data used in the 6- and 7-m-lag interval were used to fit spherical, exponential, and gaussian models to estimate a range.
- The estimated ranges for lag intervals of 6 and 7 m varied from 65 to 150 m.
- Models were refit using 12 semivariance points corresponding to a range of 100 m.

The sill and range varied substantially with lag distance and model type. The gaussian model for a lag interval of 7 m produced the lowest sum of squares and was selected.

Table 2 shows the semivariogram models for pH, soil texture, and buffer pH, with the smallest sum of squares values. Further explanation of the analysis of the data and the procedure of fitting data to the semivariogram model was given by Borgelt (1989).

KRIGING

Kriging is an interpolation process for estimating values of a measured property at unsampled locations. The value

Table 2. Semivariogram models

Variable	Model Parameters (h is in meters)	Type
pH	$\gamma(h) = 0.18\,[1 - e^{-(h/20.4)^2}]$	Gaussian
Texture index	$\gamma(h) = 0.066 + (6.5 \times 10^{-4})\,h$	Linear
Buffer pH	$\gamma(h) = 0.005 + 0.016\,[1 - e^{-(h/50)^2})]$	Gaussian

of a spatial variable at an unmeasured location is estimated from a linear combination of measured values at other locations (Alessi, 1987). This moving weighted average takes into account the known spatial dependence of a variable, expressed by the semivariogram, and the location of known values. Points near an unsampled location carry more weight than distant points. Clustered points carry more weight than lone points (Knighton and Wagenet, 1987).

For example, suppose $z(x_i, y_i)$ is a soil property that has spatial coordinates x_i and y_i. The kriging estimation for unsampled locations is:

$$z^*(x_0, y_0) = \sum_{i=1}^{n} \lambda_i z(x_i, y_i) \tag{5}$$

where

$z^*(x_0,y_0)$ = estimated value for unsampled location x_0,y_0
λ_i = kriging weights
$z(x_i,y_i)$ = known value for sampled location x_i,y_i
x_i,y_i = sampled location
n = number of neighboring points used for interpolation

For the estimate to be unbiased, the following condition must be imposed:

$$\sum_{i=1}^{n} \lambda_i = 1 \tag{6}$$

Therefore, the kriging weights, λ_i, must be determined for the points used in the estimation of a surface. Vieira et al. (1983) discussed and developed the concept of the kriging matrix, written in terms of the semivariogram.

The computer program KRIGE, written in BASIC, was used with the semivariogram models of table 2 and the original sampled data to krige a regular grid of values at 15 m spacings. Every kriged point was determined from its four closest neighbors, as suggested by Vieira et al. (1983), and because it kept the estimation local.

The search radius for kriging neighbors was initially set at 30 m, with the distance increased by 30 m (to 60 m, 90 m, etc.) until the minimum of four neighbors was satisfied. Figures 3, 4, and 5 show the kriged data of pH, soil texture, and buffer pH, respectively, plotted via SURFER graphics software (Golden Software, 1988).

DETERMINATION OF LIMING RATES

Two methods of determining soil liming recommendations were examined and compared. The soil pH and soil texture liming recommendation method called the pH-Texture method was used by the Texas A&M University soil testing laboratory. The Adams-Evans (1962) buffer method was used to determine liming rate recommendations by the SFASU soil testing laboratory. Allen (1978) showed the Adams-Evans buffer method offered more accurate liming recommendations for East Texas soils.

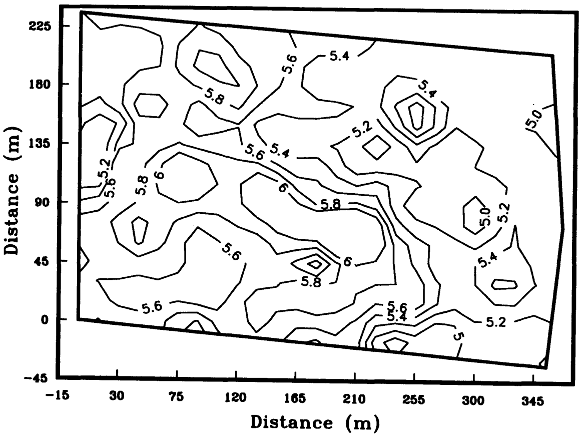

Figure 3–Kriged pH using a gaussian semivariogram model.

THE pH-TEXTURE METHOD

The pH-Texture liming rate recommendation method used by Texas A&M University required three parameters—crop type, soil pH, and soil texture—to determine liming rates with a soil test (table 3) (Gass, 1987; Pennington, 1987). These parameters combined in the form of rules were used to determine a liming rate recommendation for a land area.

ADAMS-EVANS BUFFER METHOD

The Adams-Evans buffer method liming rate recommendations required pH measurements from a soil-water mixture and a soil-water-buffer mixture. The Adams-Evans buffer method was outlined by Allen (1978) and described here.

Soil-water pH is used as a measure of acid saturation of the soil, designated as H sat_1, according to the equation:

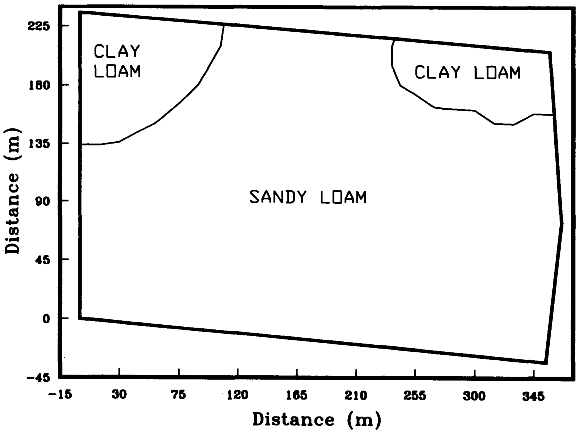

Figure 4–Kriged soil texture using a linear semivariogram model.

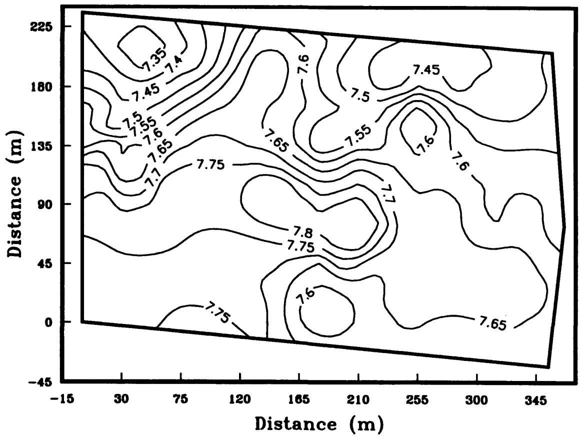

Figure 5–Kriged buffer pH using a gaussian semivariogram model.

$$\text{Measured soil pH} = 7.79 - 5.55\left(\text{H sat}_1\right) + 2.27\left(\text{H sat}_1\right)^2 \qquad (7)$$

where H sat_1 is expressed as a fraction of cation exchange capacity (CEC).

Buffer pH is a measure of soil acids, designated Soil H according to the equation:

$$\text{Soil H} = 8967\left(8.00 - \text{buffer pH}\right) \qquad (8)$$

The CEC is calculated using H sat_1 from equation 7 and Soil H from equation 8:

$$\text{CEC} = \frac{\text{Soil H}}{\text{H sat}_1} \qquad (9)$$

The desired soil pH is expressed in terms of acid saturation, designated H sat_2, according to the equation:

$$\text{Desired soil pH} = 7.79 - 5.55\left(\text{H sat}_2\right) + 2.27\left(\text{H sat}_2\right)^2 \qquad (10)$$

Table 3. pH-texture limestone recommendations for legumes*

	Soil Texture Class					
	1 Sands, Loamy Sands		2 Sandy Loams		3 Clays, Clay Loams	
pH Range	t/ha	(tons/acre)	t/ha	(tons/acre)	t/ha	(tons/acre)
6.0 & above	0	(0)	0	(0)	0	(0)
5.6 - 5.9	2.4	(1.0)	3.4	(1.5)	4.5	(2.0)
5.3 - 5.5	4.5	(2.0)	4.5	(2.0)	6.7	(3.0)
5.2 & below	5.6	(2.5)	6.7	(3.0)	9.0	(4.0)

* Gass, 1987; Pennington, 1987.

Equations 7 and 10 are regression equations, used by Adams and Evans (1962), to relate soil pH to base saturation.

The Adams-Evans buffer method used by the SFASU soil test laboratory assumed that agricultural limestone was about two-thirds effective in neutralizing acidity up to a soil pH of about 6.5 and allowed for this by using a correction factor of 1.5. Thus, the lime requirement was:

$$\text{Liming Recommendation (kg/ha)} = \frac{\text{Soil H}}{\text{H sat}_1}\left(\text{H sat}_1 - \text{H sat}_2\right)1.5 \qquad (11)$$

or

$$\text{LR (kg/ha)} = \frac{8967\,(8.00 - \text{buffer pH})}{\text{H sat}_1}\left(\text{H sat}_1 - \text{H sat}_2\right)1.5 \qquad (12)$$

An example of the liming determinations by the Adams-Evans buffer method follows.

Given:

- Soil – Water pH = 5.90
- Buffer pH = 7.55
- Desired Soil pH = 6.5

Step 1. Solve equation 7 for H sat_1 using the quadratic formula (only one root of the quadratic formula is used because H sat values are expressed as fractions of CEC):

$$\text{H sat}_1 = \frac{5.55 - \sqrt{(5.55)^2 - 4(2.27)(7.79 - \text{Measured Soil pH})}}{2(2.27)} \qquad (13)$$

$$\text{H sat}_1 = \frac{5.55 - \sqrt{(5.55)^2 - 4(2.27)(7.79 - 5.9)}}{2(2.27)} = 0.41 \qquad (14)$$

Step 2. Solve equation 10 for H sat_2 using the quadratic formula (again, only one root of the quadratic formula is used because H sat values are expressed as fractions of CEC):

$$\text{H sat}_2 = \frac{5.55 - \sqrt{(5.55)^2 - 4(2.27)(7.79 - \text{Desired Soil pH})}}{2(2.27)} \qquad (15)$$

$$\text{H sat}_2 = \frac{5.55 - \sqrt{(5.55)^2 - 4\,(2.27)\,(7.79 - 6.5\,)}}{2\,(2.27)} = 0.26 \qquad (16)$$

Step 3. Using the results of Steps 1 and 2, solve for the lime requirement using equation 12:

$$\mathrm{LR\,(kg/ha)} = \frac{8976\,(8.00 - \mathrm{buffer\ pH})}{\mathrm{H\ sat}_1}\,(\mathrm{H\ sat}_1 - \mathrm{H\ sat}_2)\,1.5 \qquad (17)$$

$$\mathrm{LR\,(kg/ha)} = \frac{8976\,(8.00 - 7.75)}{0.41}\,(0.41 - 0.26)\,1.5 = 2215\ \mathrm{kg/ha} \qquad (18)$$

DEVELOPMENT OF RATE MAPS

Soil pH, soil texture, and buffer pH data were pointed kriged on a 15- × 15-m grid. To determine the liming variable rate map by the pH-Texture method, the point kriged data files of pH and soil texture were used to develop liming rate recommendations using table 3 in the form of rules (fig. 6). These liming rate data were stored in a separate data file with the same x-y location identifier. This procedure was similar to overlaying a point kriged pH map and soil texture map, with the resulting outcome a liming recommendation map.

For the Adams-Evans buffer method, point kriged data files of pH and buffer pH were used as input to equations 7, 10, and 12 to determine a liming recommendation for each data point (fig. 7). Lime for agricultural applications is bought and applied in units of tons/acre. Quantities expressed in units less than 1000 lbs/acre or the SI equivalent of 1125 kg/ha was not realistic for field application. A separate data file was formed by rounding the liming rate value of each data point to the nearest 1125 kg/ha (1000 lbs/acre) (fig. 8).

RESULTS AND DISCUSSION

The surfaces formed by the rate and rate level data were variable. The underlying processes causing variability in the parameters were not well known or easily determined from the data collected. Variations may also be due to errors in location determination, laboratory measurements, interpolation, and random occurrence. Semivariograms and kriging describe, but do not explain variations. Geostatistical techniques were useful in data analysis, but have limitations. Perrier and Wilding (1986) evaluated seven computational analysis methods for explaining field variance and found the greatest percentage of information obtained was from kriging analysis, but state that a particular method being better than another depends upon the desired result and nature of the data. Marx and Thompson (1987) state kriging as a preferred method of analyzing spatially dependent data because it assures the return of observed sample values, is an unbiased estimation procedure, and it provides a minimum estimation variance for each interpolated value. They also state the application of kriging to agriculture is both a mathematical tool and an art (Marx and Thompson, 1987).

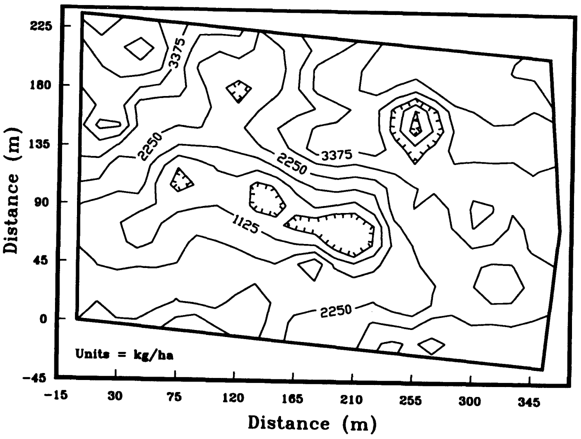

Figure 7–Adams-Evans liming recommendations based on point kriged data.

A control system for a lime applicator could be designed to respond to discrete and/or continuous rate changes. Because of incomplete knowledge of the variations and the ambiguities in the data, it was more realistic to manage zones within a land area. Thus, management zones requiring generally the same liming rates and reasonable size in terms of application equipment and practical management were developed subjectively (figs. 9 and 10) using the following general rules (Borgelt, 1989):

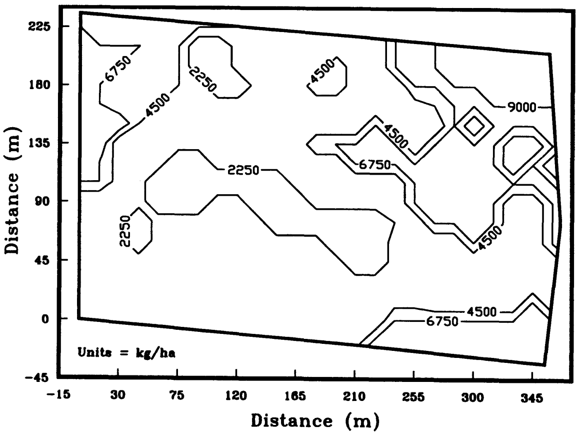

Figure 6–Legume pH-texture liming recommendations based on point kriged data.

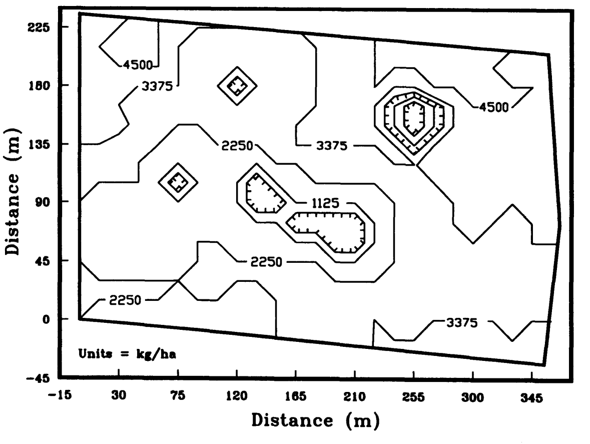

Figure 8–Adams-Evans liming recommendations rounded to the nearest 1125 kg/ha.

- In acidic soils, such as the test field, apply excess lime to regions requiring a lower liming rate embedded in higher rate regions.
- Form zones to which lime can be applied reasonably in terms of width, length, and rates by normal equipment.
- Keep the number of application rates at a reasonable number, four in this case.

Time and experience with this field will be needed to refine the spatial management zones. Field observation through soil sampling and yield monitoring will be needed to determine if the zones remain consistent in size and shape, and become less variable or more variable.

Table 4 shows the amount of limestone required for the field when using the minimum, means (from the regular grid and all the data), and maximum liming recommendations. If only one soil sample was taken for the field, the liming recommendation could vary widely. Tables 5 and 6 show the quantitative summary of the pH-Texture and Adams-Evans variable liming rate plans. The location and size of the regions of relative levels of application (low, medium, high, very high) were similar. However, the liming rate plans vary substantially in the total lime required for the field.

Using the pH-Texture variable rate plan, the lime requirement would be approximately 43.4 t (96,000 lb). With the pH-Texture method, the approximate mean of 4500 kg/ha (4000 lbs/acre) results in 40.0 t (88,000 lb) of lime. Use of the mean value seems to result in a cost savings. However, the application of the mean rate would cause an overapplication on approximately 12% of the field, resulting in increased cost. It would also result in an underapplication on approximately 37% of the field, potentially resulting in reduced yields.

Using the Adams-Evans buffer method, the lime requirement was approximately 23.5 t (52,000 lb). The mean application rate was 2800 kg/ha (2500 lb/acre), which realistically translated into an application rate of 3375 kg/ha (3000 lb/acre). This would give a total field application of 29.5 t (66,000 lb) of lime. Again, the use of the variable rate plan would result in more total lime being applied. However, the application of the mean rate would result in overapplication of lime on approximately 9% of the field and an underapplication on approximately 41% of the field.

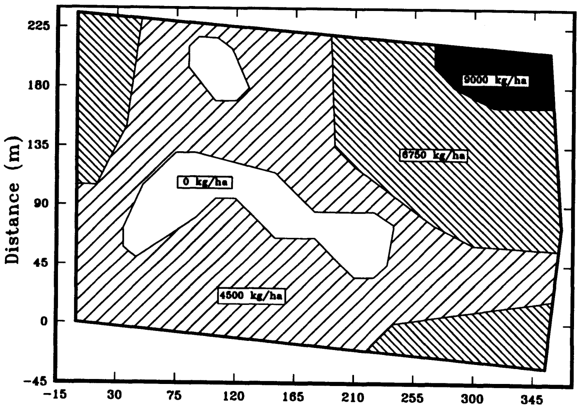

Figure 9–Legume pH-texture liming management zones.

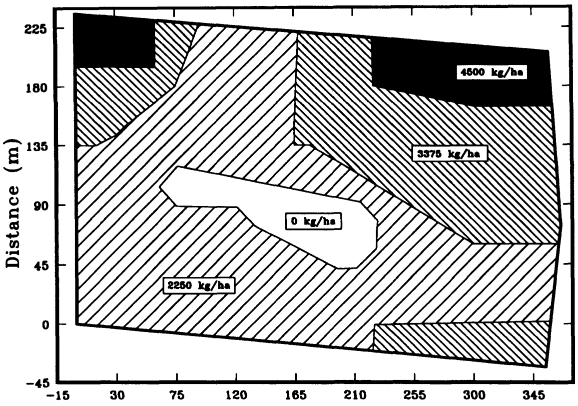

Figure 10–Adams-Evans liming management zones.

This comparison indicates that the application of lime "where needed" could maximize benefits. Quantifying these benefits was difficult for several reasons. The ability to determine the amount of pH increase for a lime application rate that is less than optimal is difficult. Response to acidity varies with crop type (legume, grass, or field crop), soil texture, and the interaction of acidity with other factors such as potassium fertilization and rainfall. Widely accepted models of crop response to liming were not available for forage crops.

Field plot experiments conducted by (Young, 1988) and his students (Cripps et al., 1988) showed significant yield increases from liming soil pH below 5.3. Coastal bermudagrass, which is very acid-tolerant, has shown yield responses of 0 to 29%, depending on the degree of acidity. More acid-sensitive crops, such as arrowleaf or crimson clover, have shown responses of 36 and 43% while a forage sorghum has shown a 34% yield response to liming. Overliming of these plots showed no detrimental effects on crop yield. In a University of Wisconsin field trial, increasing the soil pH from 5.0 to 6.9 by liming increased the dry alfalfa hay yield by 260% and the crude protein yield by 34% (National Stone Association, 1986).

These data indicate that lime application "where needed" could maximize benefits. However, further study on various soils, farms, and regions is needed to determine where spatially variable liming and other crop input management would be beneficial.

Table 4. Summary of liming rate data

	Rate		Total Amount	
Level	t/ha	(1000 lb/acre)	t	(1000 lb)
Legume pH – Texture Method				
Minimum	0	(0)	0	(0)
Mean – all	4.2	(3.8)	37.4	(83.6)
Mean – grid	4.6	(4.1)	40.9	(90.2)
Maximum	9.0	(8.0)	80.1	(176.0)
Adams – Evans Buffer Method				
Minimum	0	(0)	0	(0)
Mean – all	2.5	(2.2)	22.3	(48.4)
Mean – grid	2.8	(2.5)	24.9	(55.0)
Maximum	5.6	(5.0)	49.8	(110.0)

Table 5. Legume pH-texture liming recommendation summary

Limestone Rec.	Area	Area		Lime	
kg/ha (lb/acre)	%	ha	(acre)	t	(1000 lb)
0	12	1.1	(2.6)	0	(0)
4500 (4000)	51	4.5	(11.2)	20.4	(44.8)
6750 (6000)	33	2.9	(7.3)	19.8	(43.8)
9000 (8000)	4	0.4	(0.9)	3.2	(7.2)
Total	100	8.8	(22)	43.4	(95.8)

CONCLUSIONS

- Soil acidity for the test field showed a wide range of variability; pH measurements had a mean of 5.5 and a standard deviation of 0.42. The interpolated surface showed a great deal of variation.
- Soil pH, soil texture, and buffer pH were spatially dependent.
- The development of management zones was assisted using geostatistics to analyze data, but subjective judgment was still needed.
- The possibility of managing acid soils in East Texas on a spatial basis exists. Locations where spatial management is economically justified depends on the variability of the acidity, the tolerance of the crop to acidity, and the crop value.

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Table 6. Adams-Evans liming recommendation summary

Limestone Rec.	Area	Area		Lime	
kg/ha (lb/acre)	%	ha	(acre)	t	(1000 lb)
0	7	0.6	(1.5)	0	(0)
2250 (2000)	52	4.6	(11.4)	10.4	(22.8)
3375 (3000)	32	2.8	(7.0)	9.5	(21.0)
4500 (4000)	9	0.8	(2.0)	3.6	(8.0)
Total	100	8.8	(21.9)	23.5	(51.8)