# Spatial Variability of Nitrate in Irrigated Cotton: I. Petioles[1]

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## ABSTRACT

**Geostatistics, specifically the use of variograms and kriging, was used to determine the spatial variability of nitrates in cotton (*Gossypium hirsutum* L.) petioles. Petiole nitrates were shown to be spatially dependent in seven commercial fields. This spatial dependence can range from insignificant, where the inherent variability of sampling and analysis is relatively large, to strongly dependent. Data from a 360 by 360 m grid indicated an anisotropy of spatial dependence. Isotropic and anisotropic models for the grid-sample field were compared using a "jack-knifing" technique. The variograms and kriged maps of petiole nitrates suggest a strong influence due to cultural practices such as direction of rows and irrigation.**

***Additional Index Words: Gossypium hirsutum* L., variograms, kriging, geostatistics.**

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PETIOLE SAMPLING and analysis is useful in monitoring the N status of cotton fields and allows the farmer to maintain proper N fertility during the growing season (Bates, 1971; Burham and Babikir, 1968; Gardner and Tucker, 1967; Johan, 1951). In general, petiole nitrate concentrations are around 17 000 mg $Kg^{-1}$ of $NO_3$-N before flowering and taper to 4000 or less at the end of the growing season. Based on experience and practicality, field sampling guidelines were developed and recommended for Arizona (Tucker, 1965). The recommendations call for a total of 60 petioles collected from three or four randomly selected, representative, 0.5-ha areas in each field. Although reasonable results were achieved, it was unknown if this was an optimum method of sampling.

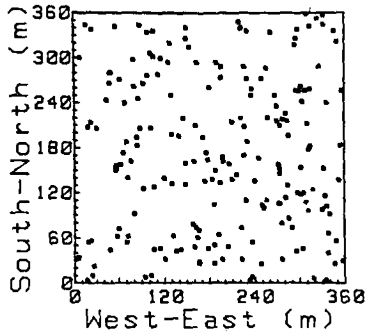


**Fig. 1—Location of 197 locations for the grid samples.**

Geostatistics can be used to quantify the spatial dependence of soil properties and allow unsampled sites to be predicted optimally (Burgess and Webster, 1980a,b; Vieira et al., 1981). We applied this method of analysis, specifically the use of variograms and kriging, to cotton petiole nitrate concentrations in order to quantify spatial variability. The results are relevant to evaluation of sampling schemes and estimation of nitrogen status. Many factors affect spatial and temporal variability of nitrate in cotton plants, such as soil properties, cultural practices and physiological maturity. Preliminary studies showed that sampling variability is lowest and most consistent before heavy fruit set, so the spatial variability was analyzed during this period to reduce inherent variability caused by sampling. Effects on petiole nitrate concentration due to soil moisture and time of day are insignificant compared to the sampling variability and are not considered in this paper (MacKenzie et al., 1963; Batra, 1961.). Correlations of soil properties and cultural practices to petiole-nitrate concentrations are considered in a sequel to this paper.

## SAMPLING AND LABORATORY ANALYSIS

This study was conducted on furrow-irrigated, commercial cotton (*Gossypium hirsutum* L.) fields operated by several members of the Growers Pest Management Group about 100 km south of Phoenix, Arizona in Pinal County. The growing season is long (>200 d) with two flowering periods. Sampling of petioles was of two types: on transects and from randomly chosen sites on a rectangular grid. (Tabor, 1983).

The transects were less intensive and run in seven fields between 15 and 18 June 1981. Six transects were run across the center of the field and consisted of composite samples of three or four petioles at 10-m intervals across rows and over the width of the field. A seventh transect was across the center of the field and contained a composite sample of two petioles every meter (row) for 100 m. An eighth transect was down a row in the center of a field with a composite sample of four petioles every 10 m for the length of the field. The final ninth transect contained a petiole from every plant along 3 m of row.

A 360- by 360-m plot was set up in the center of a 15-ha field for intensive sampling. The field was chosen for its apparent uniformity and size, and because previous sampling indicated it was typical of 28 fields examined in the area. The dominant soil in the field is Mohall clay loam (fine-loamy, mixed, hyperthermic Typic Haplargids) without any apparent contrasting inclusions. The irrigated field had 1-m row spacings.

One hundred and ninety-seven sites were chosen from among the 2- by 2-m intersections of a 180 by 180 regular grid by a random number generator. The locations are illustrated in Fig. 1. A regular grid was chosen for simplicity. Random sites were used to avoid bias caused by systematic variations and to sample from some sites that are close together while still covering a large area. Within each 2- by 2-m site, a composite of 10 petioles was collected, 5 from each row. Sampling was done over the 3-d period of 29–31 July 1981. All petioles were collected from the first dull, but not fully extended leaves.

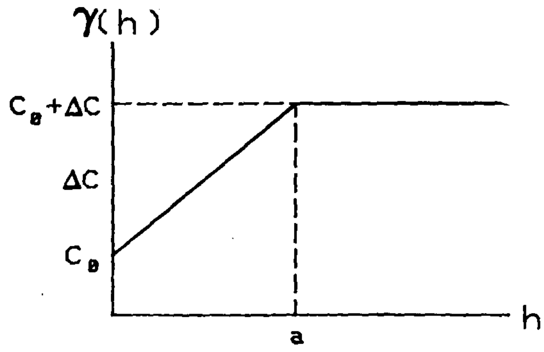


**Fig. 2—A linear variogram model.**

The composite samples were dried, pulverized with a leather mallet and weighed on an analytical balance. The tissue was extracted for 1 h with 23 mL of a 0.025*M* aluminium sulfate solution and analyzed with a nitrate specific-ion electrode. Preliminary studies show no influence of sample size on nitrate concentrations for sample sizes ranging from 0.01 to 0.1 g. Three subsamples of each of the pulverized grid-samples showed an average coefficient of variation (CV) of 3.5% which is close to the electrode manufacturer's stated repeatability of 2%.

## METHODS OF ANALYSIS

Geostatistics is based on the theory of regionalized variables. A comprehensive treatise of geostatistics is by Journel and Huijbregts (1978). Extensive background material in the soils literature includes articles by Burgess and Webster (1980a, b) and Vieira et al. (1981). Unlike most classical statistics, the assumption of independence is not made. A variogram function $\gamma(h)$ (which is basic to geostatistics) is defined from

$$2\,\gamma(h) = \mathrm{Var}[Z(x) - Z(x+h)] \qquad [1]$$

where $Z(x)$ and $Z(x + h)$ are random variables corresponding to sites separated by a vector $h$.

Taking a simplistic one-dimensional case, e.g., along a transect, and assuming stationarity (i.e., the expected value $E[Z(x)]$ equals a constant), Equation [1] is equivalent to

$$\gamma(h) = 1/2\, E[Z(x) - Z(x+h)]^2\,. \qquad [2]$$

An appropriate estimator is $\gamma^*$:

$$\gamma^*(h) = [1/2n(h)] \sum_{i=1}^{n(h)} [Z(x_i) - Z(x_i - h)]^2 \qquad [3]$$

where $\gamma$ is the semivariance (a function of the distance between samples $h$) and $n(h)$ is the number of couples of data within a given range of $h$. Since $h$ and $x$ can be a vector quantities, directional effects can be evaluated to determine if semivariance is anisotropic.

Mathematical models that are fitted to variograms are useful for subsequent applications, e.g., kriging. Valid possibilities include linear, spherical, exponential, gaussian, and power models (Journel and Huijbregts, 1978). To date, there is no foolproof, purely objective method for fitting models to sample variograms. As a result, models are fitted subjectively but weighted more heavily on distances for which large

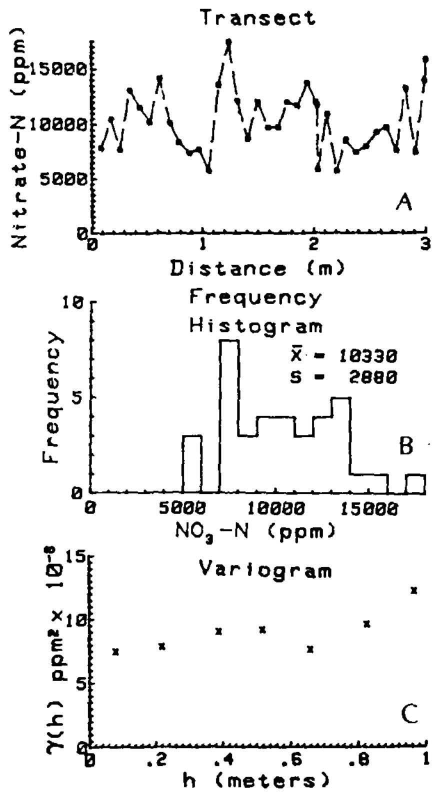


**Fig. 3—Transect, frequency histogram and variogram of Nalbandion's Field 4 where a single-petiole sample was collected from every plant.**

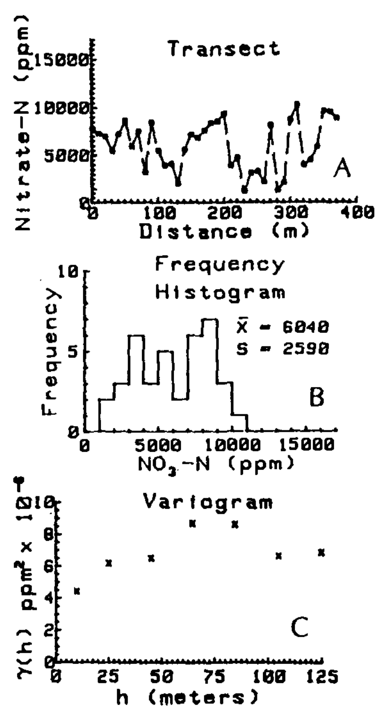


**Fig. 4—Transect, frequency histogram and variogram of M. Marietta's Field 14 where composite samples of 4 petioles were collected every 10 m across the rows.**

numbers of sample pairs are available and for which pairs are relatively close together.

An idealized, linear variogram model is given as Fig. 2. The semivariance starts at $C_0$ for $h = 0$. The limiting "nugget" value $C_0$ is due to inherent variability of the characteristic type of sampling and/or laboratory analysis error. From $C_0$ the value increases linearly with distance between samples, $h$, to a maximum "sill" value, $C_0 + \Delta C$. The semivariance remains constant with intersample distances greater than or equal to the "range", $a$. Thus, samples close together have small semivariances and are more alike than samples further apart which have larger semivariance. Samples are dependent for distances up to range "$a$" where the semivariance then remains constant with increasing distances between samples and samples achieve independence.

Semivariance is related theoretically to variance by the equations,

$$\gamma(h) = \sigma^2 - \sigma(h)$$

or

$$\gamma(h) = \mathrm{Var}[Z(x)] - \mathrm{Cov}[Z(x + h), Z(x)],$$

under the condition of second order stationarity, i.e., $E[Z(x)]$ equals a constant and the $\mathrm{Cov}[Z(x + h), Z(x)]$ exists. From a practical standpoint, the sampling variance will be less than the sill due to interdependence and finite size of the area sampled.

Kriging is an optimal linear interpolation method used to predict unknown site values by appropriately weighting the known values on the predicted site through the use of the variogram. The estimate, $Z^*(x_0)$, for $x_0$ is determined from a linear combination of the known values $Z(x_i)$, $i = 1, 2, \ldots, n$. Thus,

$$Z^*(x_0) = \sum_{i=1}^{n} \lambda_i Z(x_i).$$

The $\lambda_i$ associated with each $Z(x_i)$ are determined by minimizing the expected value of $\mathrm{Var}[Z^*(x_0) - Z(x_0)]$ using a Lagrangian technique with the constraint that

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

which insures unbiasedness. The estimate $Z^*(x_0)$ can be either punctual (i.e., for a point) or for an average over a preselected block size. The estimation is unbiased with minimum variance, thus optimal. This method of analysis can be used to prepare maps of predicted site values with a variance for each site. The variance maps can be used to determine where more sampling sites could be located to improve overall estimates.

## RESULTS AND DISCUSSION

Transects are useful in obtaining preliminary information about the spatial variability in a field without the time and expense of more elaborate sampling programs. The nine transects analyzed indicated petiole nitrate can range from essentially spatially independent where semivariance is relatively constant to strongly dependent where semivariance increases significantly with increasing intersample distances.

The variogram from the transect where every plant was sampled along 3 m (Fig. 3C) indicates spatial dependence of petiole nitrate samples within 1 m of each other is insignificant. The spatial dependence shown by a gradual increase of semivariance with increasing intersample distances is small compared to the inherent variability of the petioles and the laboratory analysis as evidenced by a relatively large "nugget." Therefore, when sampling over small areas less than a square meter, the assumption of independence is valid and $s^2$ will approximate $\sigma^2$. The desired confidence interval for the mean is achieved by collecting the appropriate

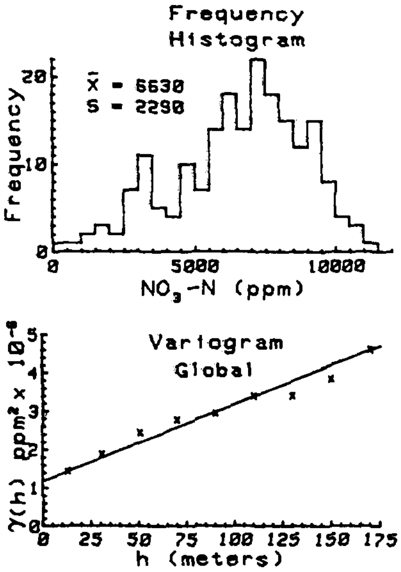


Fig. 5—Frequency, histogram and isotropic variogram of petiole-nitrate concentrations from grid-samples.

number of petioles over the small area. For completeness, the transect values and frequency histogram are also given in Fig. 3 (A and B).

The assumption of sample independence cannot be made for intersample distances > 1 m. The remaining transects analyzed showed varying degrees of spatial dependence. Of the seven transects crossing an entire field (360- to 730-m transects), the two with the largest sample variance (CV > 30%) showed the strongest spatial dependence. This was probably due to an undefined population variance, i.e., the variance continues to grow as larger areas are considered. The other transects indicated no relationship between the magnitude of sample variance and the degree of spatial dependence. This spatial dependence of samples from fields with relatively high sample variances may be the result of nonuniform and spatially dependent irrigation and/or fertilizer application. Also, the high spatial dependence of the petiole nitrate may be a reflection of a high degree of spatial dependence of the soil. Care should be taken in using sample variances (or CV) in suggesting spatial dependence since the type of sample (e.g., number of petioles per sample) will affect sample variance and also the size of mean will affect the CV. An example of petiole nitrate showing strong spatial dependence samples taken every 3 m across rows (M. Marietta Field 14) is shown in Fig. 4. The transect indicates a rough, somewhat regular cycle in petiole nitrate concentrations over distance.

Sampling from a grid rather than transects leads to a better representation of the spatial variability of an area. The frequency histogram of the 197 gridsamples collected from Nalbandion's Field 28 (Fig. 5) approximated a normal distribution. The global (isotropic) variogram, where the orientation of the sample pairs is not taken into account, is shown in Fig. 5. The variogram shows a strong linear increase for intersample distances up to at least 175 m with no apparent sill. This indicates that when sampling from this field, sampling areas should be as far apart from each other as possible. This will allow samples that are spatially dependent to form an unbiased estimate of the field average since samples will not represent one section of the field more than the other.

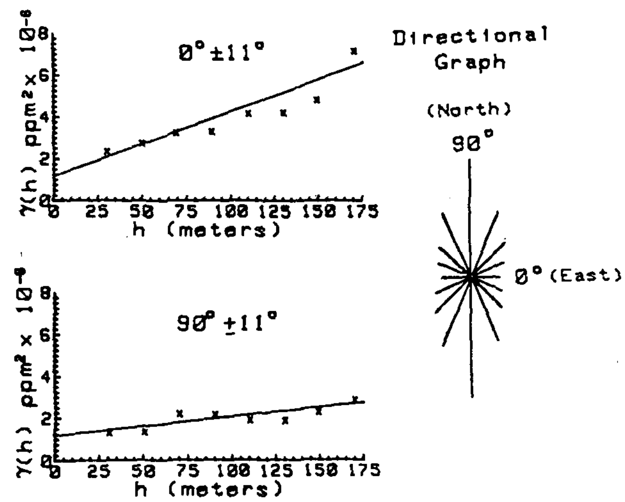


Fig. 6—Two directional variograms from the grid-sample data and a directional graph illustrating the anisotropy of the family of directional variograms.

When orientation of sample pairs as well as the distance between pairs is taken into account, directional variograms result (for detailed discussions of anisotropy and directional variograms, see Burgess and Webster, 1980a, b). The directional variograms indicate that the orientation of the samples affects the variograms and spatial variability is anisotropic. For example, across rows east-west (0°) sample pairs are less alike than along rows north-south (90°) for the same separation distance as evidenced by a higher slope for the 0°-directional variogram of Fig. 6.

In order to better visualize the anisotropy, a directional graph is drawn by taking the reciprocal of the slopes of each directional variogram and letting them represent the magnitude of vectors pointed in the direction of the corresponding variograms as illustrated in Fig. 6 (Journel and Huijbregts, 1978, p. 175). In this case since no sill was determined, the directional graph shows the relative sampling distances from a central sample needed to achieve the same semivariance. This indicates that when sampling this field, unlike the determination above where isotropy was assumed, distances between sample areas should be of the ratio shown in the directional graph. Thus, in this field, area-samples that are in a 90° orientation with each other (which is along rows) should be much further apart than area-samples in a 0° orientation (which is across rows). (Physically, the samples are more alike along the row than across rows.) This will result in an unbiased estimate of the field average. Particularly when only a few areas in the field are sampled, the samples should be as far apart as possible and generally not be from the same rows.

Using linear models to approximate the sample variograms and using an elliptical model to approximate the anisotropy from the directional variograms, data from the grid-samples are kriged. The models are evaluated by using a "jack-knifing" (cross-validation) technique where the value at a measured site is estimated using the surrounding known sites and the estimate compared to the known value. The variance of errors between the predicted and known values can

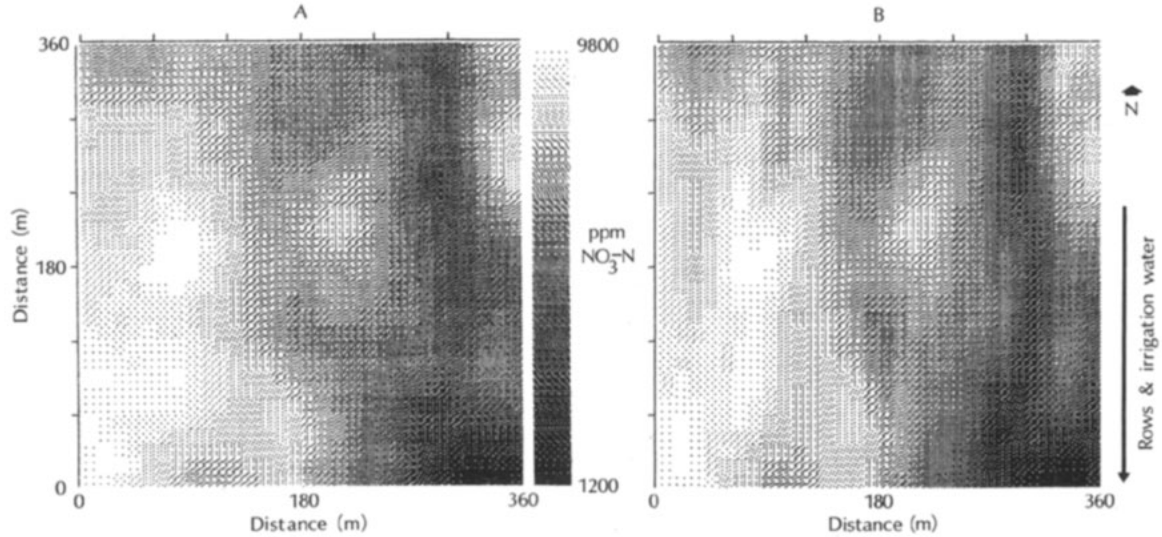


**Fig. 7—Maps of kriged petiole nitrate values using isotropic (A) and anisotropic (B) models for the grid-sample plot.**

be compared to the average kriging variance. Models can be considered appropriate when the average error is close to zero and the variance of errors is close to the average kriging variance.

The cross-validation was performed using the computer code of Baafi (1982). The average error is 3.31 mg $kg^{-1}$ for the isotropic model and 3.60 for the anisotropic model taking the major/minor axis ratio of 2.7. Both average errors are insignificant to the sample average of 6630, indicating the kriged values are unbiased. The isotropic model resulted in an error variance of (1.70) $(10^6)$ $mg^2$ $kg^{-2}$ compared to average kriging variance of 1.91 $(10^6)$ while the anisotropic model resulted in an error variance of (1.51) $(10^6)$ compared to an average kriging variance of 2.30 $(10^6)$. The error variance is smaller in the anisotropic model while the isotropic model has a lower average kriging variance. A poor variogram model can result in low kriging variances therefore lower variances of errors are better indicators of fit. Another anisotropic model could be developed to better fit the observed anisotropy, but would probably not be worth the effort in getting a marginally better kriging estimate.

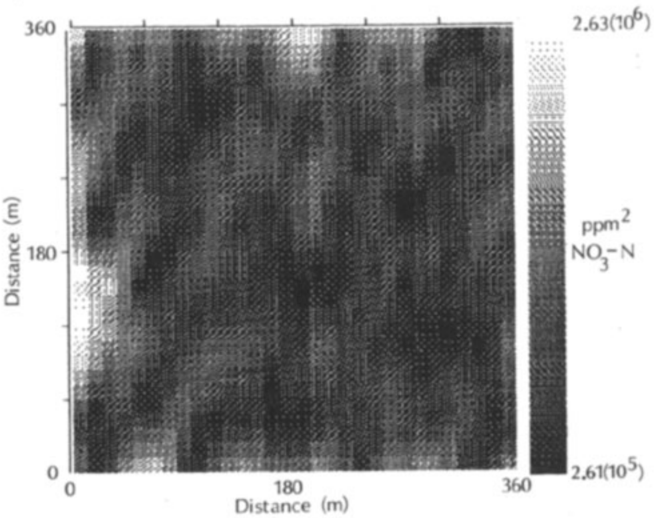


**Fig. 8—Map of kriging variances for the kriged petiole nitrate values using the anisotropic model.**

Using the same models in a block kriging program (Baafi, 1982) resulted in the two kriged maps of petiole nitrate values and an associated map of kriging variances (Fig. 7 and 8). The graphics package SADIE (Schowengert, 1981) is used to illustrate the results. Nine hundred 12- by 12-m areas were block-kriged by averaging 16 kriged points over each area. The kriged points were estimated using the 10 closest measured values to the estimation point. The kriged maps show a banding of similar values along the rows, i.e., north-south direction. More noticeable banding results by using the better fitting anisotropic kriging model. This banding suggests strongly that cultural practices in this field have an influence on the variability of petiole nitrate. Possible influential practices include fertilizer application by side dressing and/or through irrigation more uniform along rows than across the rows. Further analysis of these relationships with soil properties is discussed in a later paper.

The map of kriging variances shows, logically, that higher kriging variances occur where known samples are not close to the estimated sites. Also higher kriging variances occur along borders of the plot. Using a uniform sampling grid with sufficiently fine grid will result in small kriging variances except along the borders. Along the borders the effect of sparse sample locations in close proximity is more pronounced since nearby samples will be further increased. Proper orientation of the sampling grid can compensate for the anisotropy. If the variogram has a finite range and all distances (intersample and sample to estimated site) are longer than the range, then the estimation variance is determined only by sample size and the sill but this will always be greater than the kriging variance obtained using closer sample spacing.

## CONCLUSION

Petiole nitrates showed a definite spatial dependence in the fields studied. However, for sampling areas of < 1 m across, spatial dependence was insignificant compared to the inherent variability of the sample and laboratory analysis. Therefore, for this site and very small sampling areas (<1 $m^2$), classical statistical analysis requiring independent or random samples can be applied. For intersample distances > 1 m, the assumption of independence requires verification and was found generally to not be the case. If these results are somewhat transferable to other sites, then in fields with unknown spatial structure, sample areas should be as far apart as possible for estimating mean values. Also, sample areas should not occur on the same row when the number of samples is small. The anisotropic kriging model fitted this data slightly better than the isotropic model and resulted in a more informative map.

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