Spatial Variability of Nitrate in Irrigated Cotton: II. Soil Nitrate and Correlated Variables[1]

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ABSTRACT

The relation between nine soil variables: soil nitrate, % sand, silt and clay, pH, electrical conductivity (EC_e), sodium, potassium, and phosphorus plus petiole nitrate were analyzed by geostatistics and cluster analysis. The samples were collected from 49 sites in a 360 by 360m plot in a commercial cotton (*Gossypium hirsutum*) field. An intensive soils map of the plot was compared to distributions of the soil variables. Models developed from variograms of highly correlated variables were tested using a "jack-knifing" technique and then the data was block kriged. Soil nitrates were highly correlated with EC_e, which has a similar spatial dependence and spatial structure. Percent clay and petiole nitrate were moderately well correlated and had similar spatial structure to each other.

***Additional Index Words: Gossypium hirsutum,* variogram, kriging, cluster analysis, electrical conductivity, clay percentage.**

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CLINE (1944) noticed that errors due to soil sampling are generally greater than those due to laboratory analysis and soil test results have little value if the soil sample is unrepresentative, even when the analytical aspect of soil testing correlates perfectly with crop response (James and Dow, 1972). Better sampling techniques for nitrate can be developed by knowing its spatial structure and related factors including soil characteristics and cultural practices. Identification of related factors may indicate a variable that provides information on the spatial structure of nitrate and is more easily sampled and analyzed. Co-kriging (Vieira, et al., 1981) then could be used to estimate nitrate values by using data from easily collected samples with only limited sampling of nitrate.

This paper analyzes the spatial structure and possible relationships between plant and soil variables at 49 sites in an apparently uniform production cotton field. The samples were analyzed for petiole nitrate and nine soil variables: soil nitrate, % sand, silt and clay, pH, electrical conductivity of saturated extract (EC_e), sodium, potassium and phosphorus. Variograms and a kriged map are developed for soil nitrate as was done earlier for petiole nitrate (Tabor et al., 1984).

The correlation between variables and between groups of variables is analyzed by a form of cluster analysis. Variogram models of highly correlated variables with petiole and soil nitrate were cross validated by a "jack-knifing" technique as described by Baafi (1982) and our companion article (Tabor et al., 1984). The results give a quantitative and visual comparison of the relationships between the variables.

SAMPLING AND LABORATORY ANALYSIS

This study was conducted on a 15 ha furrow-irrigated commercial cotton field in Pinal County, 100 km south of Phoenix, AZ. The field was chosen for its apparent uniformity, size, and because petiole sampling indicated that it was typical of the 28 fields studied in the area (Tabor, 1983). An intensive soils map (SCS, second order) was made of the study area, Fig. 1. The dominant soil is Mohall clay loam (a fine-loamy, mixed, hyperthermic Typic Haplargid) with only a small area of Gilman silt loam (a coarse-loamy, mixed calcareous, hyperthermic Typic Torrifluvent). The mapping was completed by an experienced soil mapper and based on information readily available to any field scientist.

A 360 by 360 plot was set up in the center of the field with a 20m buffer zone at the head and tail of the rows. The rows were spaced 1 m apart with every row irrigated. By using a random-number generator, 49 sites were chosen from the intersections of a 180 by 180 regular grid and are marked in Fig. 1. At each 2 by 2 m site, a composite sample of 10 petioles was collected (except for one site where the sample

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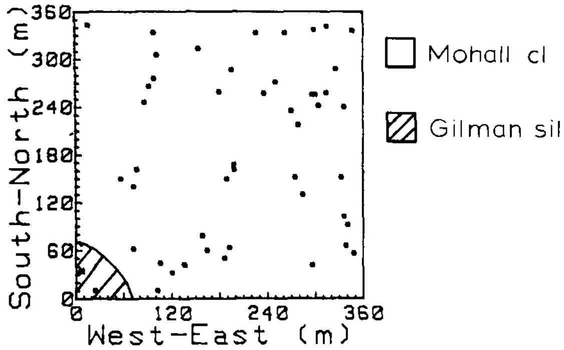

Fig. 1. Intensive soil map and 49 sample-site locations.

was lost), five from each row. Also a composite of eight surface soil samples was collected, two from each side of the row perpendicular to the edge of the furrow and to a depth of 15 to 20 cm. Soil samples were collected with a 2.5 cm diameter probe.

The petiole nitrates were analyzed according to the procedures described in the companion article (Tabor et al., 1984). The soil samples were analyzed for nitrate, % sand, silt and clay, pH, EC_e, sodium, potassium, and phosphorus as follows:

Soil NO_3-N was analyzed by both a nitrate specific-ion electrode and by nitrate reduction and colorimetric determination of nitrite procedure through Univ. Arizona Soil, Water & Plant Tissue Testing Lab (Testing Lab). For the nitrate electrode, air-dried soil was extracted with a $CaSO_4$-Ag_2SO_4 solution (4:1 water to soil ratio), filtered and analyzed. The electrode calibration was difficult to maintain for the soil-nitrate determination so the samples were also analyzed by the Testing Lab as a check. A Technicon AutoAnalyzer II was used following the procedure described in the manufacturer's procedure (Technicon, 1978). Briefly, in a distilled water extract, nitrate is reduced to nitrite, then reacted to form a reddish purple azo dye, and measured colorimetrically at 0.52 μm wavelength. The manufacturer's specification on reproducibility is 0.31% (coefficient of variation) at 1 mg/Kg nitrogen. Nitrite concentration in the soil was assumed to be insignificant. Results of the two methods showed acceptable agreement with a regression relationship of $E = 0.229 + 0.874\ LB$ ($r^2 = 0.819$) where E is the electrode data and LB is the Testing Lab data. The average values from the two methods were used for further analysis.

Soil texture was determined by a standard hydrometer, ASTM 152H, as described in Black et al., (1965). Since the proportions of sand, silt and clay were similar for all samples, readings at 0.7 and 1.0 min bracketed the combined silt and clay concentrations and 620 and 1080 min bracketed the clay concentration. This provided two values close to each fraction boundary. Linear interpolations of the bracketed values were used to estimate the percentages of sand, silt and clay (USDA classification).

Soil pH, EC_e, water extractable sodium and potassium were determined by the Testing Lab from a distilled water-saturated paste extract (Black et al., 1965). A standard pH electrode was used for pH determinations and a conductivity bridge for EC_e determinations. The concentrations of sodium and potassium were obtained by flame emission (Emmel et al., 1976) at 0.59 μm wavelength for sodium and 0.77 μm wavelength for potassium.

Soil phosphorus was determined by the Testing Lab using the Technicon AutoAnalyzer II and the manufacturer's procedure (Technicon, 1976). Phosphate was extracted by bubbling CO_2 into a 5:1 distilled water and soil mixture (McGeorge, 1939). The orthophosphate in the extract reacts in acid with ammonium molybdate, then reduced with ascorbic acid to form a molybdenum blue complex, and is determined colorimetrically at 0.66 μm. The manufacturer's specification for reproducibility is 0.4% CV at 5 mg/Kg phosphorus.

STATISTICAL METHODS

The companion article (Tabor et al., 1984) gave a brief introduction to variograms and kriging used in this paper. For further information on these methods of analysis, see Vieira et al., (1981), Burgess and Webster (1980a,b), and Journel and Huijbregts (1978).

The frequency distributions for each of the variables were prepared for completeness. These help identify possible problems that may occur when variograms are developed, especially with widely-spaced, multimodal distributions. Also when the distributions are non-normal, the variable can sometimes be transformed to a normal distribution to improve fitting the variogram models. The kriged estimates are then transformed back to the original distribution. Block kriging was used (cf. Baafi, 1982; Burgess and Webster, 1980b). This method assigns point-averages of areas to those areas. The maps in this paper used a block size of 12 by 12 m while the samples were collected in 2 by 2 m areas. This averaging smooths the kriged estimates over space.

Hierarchial cluster analysis can be applied to variables or locations in order to establish a hierarchy of clusters. These range from one extreme of each variable being a separate cluster, to the other extreme of all variables in one cluster. The clustering is determined by a measure of similarity such as correlation or a measure of distance. Maximum similarity will correspond to minimum distance and conversely. Linkage in the clusters may be based on minimum, average or maximum distance. The results given in this paper were obtained by using the BMDP package (Dixon et al., 1981) with the correlation or absolute correlation as the measures of similarity and average or minimum distance for linkage.

The resultant clustering may be presented in a tree diagram (such as in Fig. 4). After the similarity is computed for each pair of variables, the most similar pair is identified and a proxy variable obtained by averaging the pair. The similarity between this new variable and all other variables is computed. Again, the most similar pair is determined and a new proxy variable is obtained. When proxy variables are clustered with others, they are weighted according to the number of variables they represent.

RESULTS AND DISCUSSION

The frequency histogram of the soil nitrate data (Fig. 2a) approximated a log-normal distribution. The data was transformed to a normal distribution by taking the natural logarithms of the data. The transformed data results in an isotropic variogram (Fig. 2b), where the variogram depends only on distance. There were 30–120 couples for each point on the plot. The line is not "best-fitted" in that least square criteria are generally inappropriate for variogram modeling. The variogram shows a spatial dependence of soil nitrate for intersample distances greater than 150 m. (Linear models of variables studied which are used to approximate the sample variogram are listed in Table 1). Due to low sampling density (49 samples per 13 ha) and the characteristics of the variable, the directional variograms (where intersample distances and orientation are taken into account) are erratic and did not indicate a strong anisotropy.

A "jack-knifing" technique indicates the isotropic kriging model provided the best fit for the data. The mean error is 0.00739 which is small compared to 2.57 mg/Kg NO_3-N, the mean of the log-transformed data,

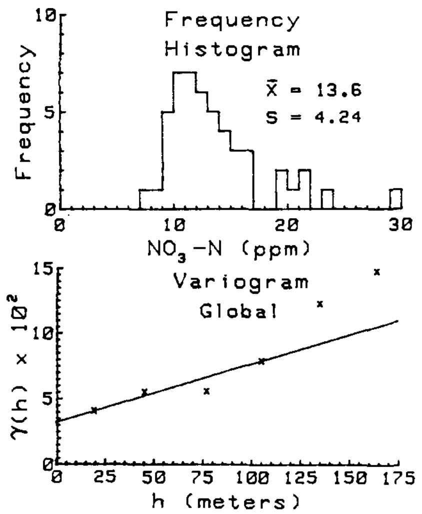

Fig. 2. Frequency histogram (a) and isotropic (global)variogram (b) of soil nitrate.

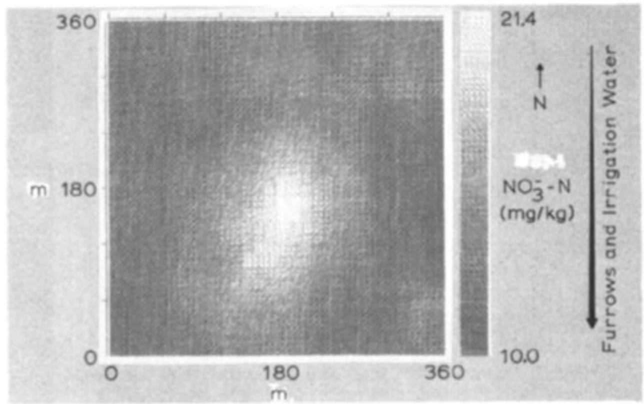

Fig. 3. Block kriged map of soil nitrate.

indicating the kriged values are unbiased. The average kriging variance is 0.0592 mg^2/Kg^2 and is close to the error (estimated to actual) variance of 0.0599 and indicates a reasonable model. The resulting block-kriged map (based on the 10 nearest neighbors) is illustrated in Fig. 3 through the use of the graphics program SADIE (Schowengert, 1981). This map contrasts strongly with the petiole nitrate map (Tabor et al., 1984). The petiole map was developed with a larger sample density of 197 samples per 13 ha. Petiole and soil nitrate would not necessarily be related due to the complicating relationships of other nutrients on petiole nitrates and differences in the sampled soil nitrate and the total soil nitrate available for plant uptake. (The correlation coefficient between petiole and soil nitrate was 0.15).

Cluster analysis was performed on the correlation matrix of the 10 plant and soil variables using the BMDP program (Dixon et al., 1981). Cluster analysis proceeds by using a measure of similarity such as corelation or absolute correlation to identify variables that are similar. Initially each variable is a cluster unto itself. As clusters are formed, it is necessary to have a criterion for determining which clusters are considered and/or to which a variable is joined. Distance and similarity change inversely. The BMDP program allows several choices for distance. The two that were used were average distance and minimum distance. This provides the mechanism for amalgamating or joining two clusters or a variable to a cluster. The two methods yielded equivalent relationships (not shown), indicating little overlap of clustered variables. The analysis by both correlation and absolute correlation, Fig. 4, showed a clustering of soil nitrate with EC_e, and sodium. Petiole nitrate formed a cluster with soil texture, especially clay percentage.

Clay percentage and EC_e showed the highest correlation with petiole and soil nitrates, respectively, The EC_e, like soil nitrate, approximates a log-normal distribution so variograms were developed from the transformed data. The variograms from the nontransformed data were erratic and showed no clear spatial dependence while the variograms from the transformed data are better behaved. The ℓn EC_e variograms exhibited a strong spatial dependence, with no apparent sill for intersample distances up to 150 m.

The jack-knifing results indicated an isotropic model fit the EC_e data best. The mean kriging error was 0.004 dS/m which is small compared to 0.663 dS/m, the mean of the log-transformed data. The average kriging

Table 1. Summary statistics, variograms and correlations for properties considered.

	Mean	Std. dev.	Kurtosis	Skew-ness	Linear variogram $\gamma(h)$	Pet N	Soil N	Sand	Silt	Clay	PO_4	pH	EC_e	Na	K
Petiole nitrate-N (mg/kg)	6630	2290	−0.363	−0.487	$1.18(10^6) + 2.01(10^4)(h)$†	1	--	--	--	--	--	--	--	--	--
Soil nitrate-N (mg/kg)	13.6	4.24	3.10	1.56	$6.66 + 5.56(10^{-2})(h)$	0.1534	1	--	--	--	--	--	--	--	--
ln soil NO_3	2.57	0.280			$3.25(10^{-2}) + 4.43(10^{-4})(h)$										
Sand (%)	41.7	8.44	−0.990	0.235	$15.4 + 0.338(h)$	−0.4812	−0.0746	1	--	--	--	--	--	--	--
Silt (%)	26.2	4.10	1.82	−0.947	$5.06 + 7.86(10^{-2})(h)$	0.2312	−0.0225	0.7949	1	--	--	--	--	--	--
Clay (%)	32.1	5.75	−0.754	−0.112	$1.68 + 0.121(h)$	0.5423	0.1261	−0.9009	0.4528	1	--	--	--	--	--
CO_2 extract. PO_4	4.37	3.17	4.24	1.93	Random‡	0.0313	0.3213	−0.1429	0.1182	0.1254	1	--	--	--	--
ln PO_4	1.27	0.631			$6.70(10^{-2}) + 4.30(10^{-3})(h)$, $h < 80$										
pH	7.33	0.175	−0.255	−0.056	$0.0153 + 1.12(10^{-4})(h)$	0.0028	−0.5159	0.1421	−0.0538	−0.1702	−0.4398	1	--	--	--
Elec. cond. (dS/m)	1.97	0.366	2.57	1.08	Random‡	0.0022	0.8520	0.0396	−0.1581	0.0554	0.2695	−0.4354	1	--	--
ln EC_e	0.663	0.178			$1.38(10^{-2}) + 1.57(10^{-4})(h)$										
Sodium (mg/kg)	8.39	1.23	1.86	1.01	Random‡	0.0822	0.7466	−0.1156	−0.0582	0.2118	0.3426	−0.3124	0.9217	1	--
Potassium (mg/kg)	0.616	0.203	10.6	2.48	Random‡	0.3569	0.4141	−0.3980	0.2834	0.3825	0.2526	−0.3188	0.4269	0.5172	1

† Length h is in meters. ‡ Apparently independent for intersample distances > 45 m.

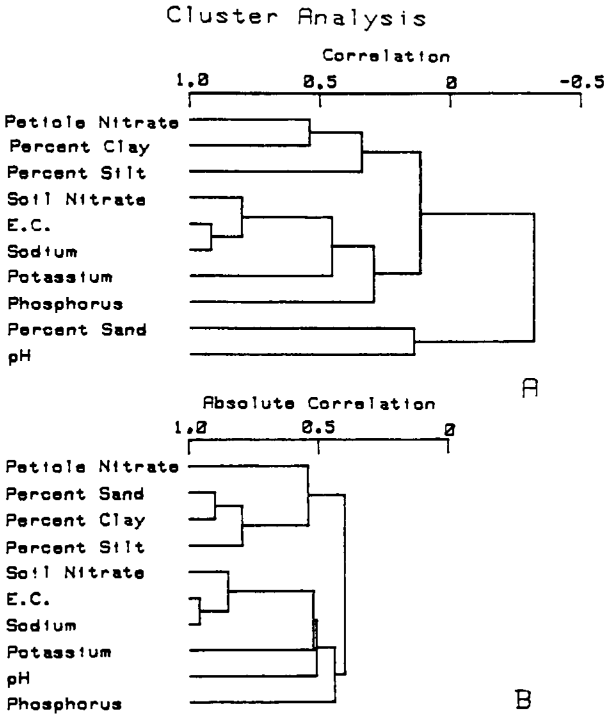

Fig. 4. Cluster analysis of plant and soil variables from 49 sites (version P1M of BMDP package). Figure (A) uses correlation as the measure of association with average distance as the amalgamation method. Figure (B) uses absolute correlation as the measure of association with minimum distance as the amalgamation method.

variance of 0.0255 $(dS/m)^2$ was close to the kriging error variance of 0.0243 $(dS/m)^2$ and indicated a reasonable fit.

The block-kriged map of EC_e is illustrated in Figure 5 and is very similar to that of soil nitrate. The similarity suggests that EC_e in this field is a result of irrigation water application and not residual pedogenic salt concentration since nitrate concentration is a result of cultural practices (the irrigation water used was naturally high in nitrates, also nitrogen fertilization is often through irrigation). The high positive correlation of sodium with both EC_e and soil nitrate (Table 1) suggests that sodium is introduced through irrigation.

Clay percentage, like petiole nitrate, approximates a normal distribution. The isotropic and directional variograms show a strong spatial dependence with no apparent sill for intersample distances up to 150 m and are used to develop kriging models.

The kriging models were cross-validated and the adequacy of an isotropic model verified. The mean kriging error is 0.17% which is small compared to 32.1%, the mean of clay percentage, therefore the estimation is unbiased. The average kriging variance of 9.67% is slightly larger than the variance of kriging error of 6.79%. This indicates that a better model may be found in order to get lower, less conservative kriging variances.

The resulting block-kriged map, Fig. 5, resembles the petiole-nitrate map (Tabor et al., 1984) without the vertical banding. This suggests that petiole-nitrates are influenced by cultural practices along rows. Also the general diagonal pattern of both clay percentage and petiole-nitrate map suggests that texture, especially clay percentage, affects petiole nitrate. Clay percentage shows no relationship with soil nitrate or EC_e.

The type of sample distribution can be the result of sites sampled by chance and is influenced by the spatial structure of the variable sampled. Soil-nitrate's and EC_e's spatial structure could easily result in a variety of sample distributions depending on the chance locations of samples and the sampling scheme.

Table 1 lists mean, standard deviation, kurtosis and skewness of each variable's sample distribution and isotropic, linear variograms for each variable. Nine of the thirteen sample variograms were satisfactorily fitted by linear variograms. Due to the size of the sampled area, inference to the spatial variability of samples greater than 150 m apart cannot be made. Nontransformed sodium, potassium and EC_e sample variograms show no spatial dependence for samples greater than 45 m apart (potassium content in these sampled soils is naturally high and the field has no fertilization history) and the sill values approximate the sample variances. The phosphate sample variogram is extremely erratic but after a log transformation, the sample variogram is well-behaved with a range of 80 m.

CONCLUSIONS

Soil nitrate has the largest correlation with EC_e of the variables studied. The two variables have similar spatial dependence and spatial structure. This particular spatial structure, with extremely high values oc-

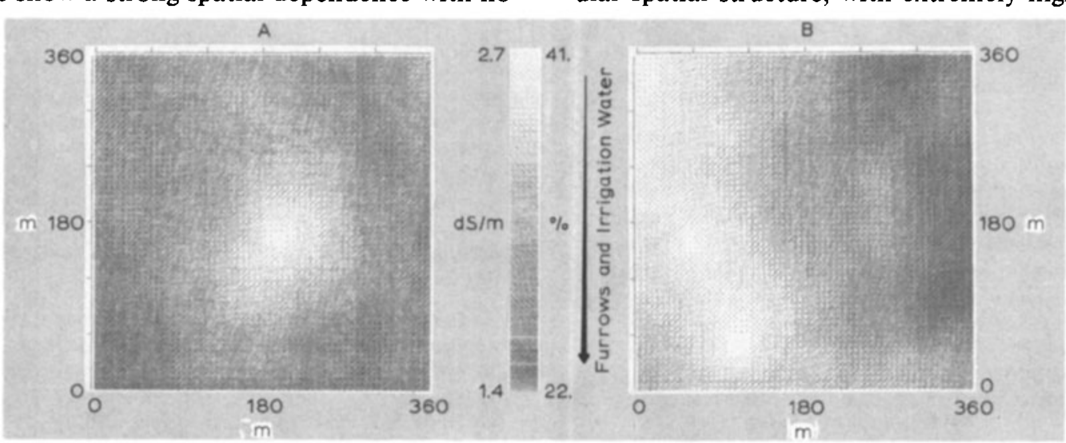

Fig. 5. Block kriged maps of electrical conductivity (a) and clay percentage (b).

curring in relatively small areas and surrounded by a larger area of generally uniform values, can result in strikingly different sample distributions which depend on chance locations of samples and sampling scheme.

Soil nitrate and petiole nitrate show neither correlation nor similarity of spatial structure. Petiole nitrate and clay percentage have moderately high correlation and similar spatial structure, indicating that soil texture, especially clay percentage, has a major effect on petiole nitrate. This suggests that the spatial structure and optimum sampling program for petiole nitrate can be inferred from the spatial structure of clay for a particular soil mapping unit. Also co-kriging may be useful to estimate nitrate values throughout the growing season from relatively permanent clay percentage data with meager sampling of nitrate.

Soil clay percentage shows little correlation and spatial structure with soil nitrate and EC_e, but all three variables show strong spatial dependence. This strong spatial dependence indicates that when estimating the sample mean and variance, the samples should be as far apart as possible.

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