GEOSTATISTICAL TECHNIQUES AND APPLICATIONS FOR MANAGING DEGRADED SOIL FOR SUSTAINABLE PRODUCTION

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ABSTRACT

Geostatistics deals with characterization of spatial dependence of measured soil-properties and helps to predict the values of the properties at unsampleld locations. Spatial patterns identified by geostatistical techniques are used to develop variable rate strategies for the sustainable management of fertility, and salinity/ sodicity of soils. This paper presents examples of using geostatistical techniques to identify and determine the magnitude of spatial variability of soil- properties and develop variable-rate management-strategies for fertility, salinity/sodicity, and mapping of degraded soils, for sustaining their productivity.

INTRODUCTION

Geostatistics is a branch of applied statistics that focusses on the characterization of spatial dependence in the measured variable or variables. It is used to model the spatial dependence of regionalized variable(s) or spatial variability of soil-properties, to interpret spatial patterns and predict values of the attribute(s) at unsampled locations. All the statistical procedures used for analysis and estimation of spatially dependent variables are collectively known as "geostatistics".

Spatial variability of soil-properties means that the sample-value of a soil-property gives some information about its neighbouring data point. In other words, it means that the sample values are not independent of each other but are correlated as a function of distance. Traditionally, it is assumed that the soil-properties are randomly distributed.

GEOSTATISTICAL TECHNIQUES

The basic tool of geostatistics is known as semivariogram analysis which is used to identify and describe the extent of spatial variability of regionalized variables.

i) Semivariogram Analysis: Semivariograms are developed to determine the structure and magnitude of spatial patterns of various measured soil-properties. Semivariance, r(h), as a function of separation distance (lag, h), is computed using the expression:

$$\gamma(h) = \frac{1}{2n(h)} \sum_{i=1}^{n(h)} [Z(x_i) - Z(x_{i+h})]^2 \quad \ldots\ldots \text{Eq. 1}$$

where n(h) is the number of samples separated by a distance h and Z represents the measured value for a soil property.

Ideally, the semivariance equals zero at h=0, since no variation in sample values is expected for measurements made at a given location. As the separation-distance increases, the semivariance function will typically increase, because samples become more poorly correlated (the variance increases). At a critical distance, known as the range, the sample pairs will cease to be correlated and values for the semivariance remain constant at a value known as the "sill", as separation distance continues to increase. Samples separated by distances greater than the range exhibit random variation (Fig.1).

For a quantitative description of these features, it is useful to fit standard models to the semivariance functions. Typical standard semivariograms include linear, spherical, and exponential models. Model-selection is usually based on a criterion of goodness of fit, which, in our case, involved fitting the model to data using non-linear least-squares methods. Expressions for each of the above models are given below:

Linear model: $\gamma(h) = C_o + Bh$ ……………………………Eq.2
Spherical model: $\gamma(h) = C_o + C_1 [1.5(h/a) - 0.5(h/a)^3]$ $0<h<a$…Eq.3
$\gamma(h) = C_o + C_1$ $h>a$………………………..Eq.4
Exponential model: $\gamma(h) = C_o + C_1 [1-\exp(-h/a_o)]$…………………Eq.5

In these expressions, h is the separation-distance between observations, a is a model-parameter known as the range, C_1 is a model parameter which equals the "sill" minus the "nugget", and C_o is a model parameter known as the "nugget". For the linear model, B is simply the slope of the line for a plot of semivariance versus separation distance. For the exponential model, a_o is approximately equal to a/3. Physically, the "sill" is approximately equal to the total sample variance and is

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the maximum value of variance which the model attains at large separation distances. Physically, sample observations separated by distances smaller than the range are statistically correlated to one another, while measurements separated by distances greater than the range are *not* correlated (Fig.1). Classical statistical methods can be applied to the data only if the range has a value which is smaller than the closest sampling distance.

Ideally, the experimental variance should pass through the origin when the distance of sample-separation is zero. However, many soil-properties have non-zero semivariances as h tends to zero. This non-zero variance is called the "nugget variance" or "nugget effect". It represents unexplained or "random variance", often caused by measurement-errors or variability in the measured property, which was not detected at the scale of sampling.

ii) Kriging: The parameters of semivariogram are used for interpolation of soil-properties at unsampled values. This procedure is called "kriging". Kriging is a method for making optimal, unbiased estimates of regionalized variables at unsampled locations, using the structural properties of the semivariogram and the initial set of measured data. A useful feature of kriging is that an error-term, expressing the estimation-variance or uncertainty in estimation, is calculated for each interpolated value. Kriging differs greatly from linear-regression methods for estimation at unsampled locations. Whereas a regression-line never passes through all of the measured data-points, kriging always produces an estimate equal to the measured value if it is interpolating at a location where a measurement was obtained.

The basic equation for interpolation by kriging at an unsampled location x_o is given by:

$$Z_k(X_O) = \sum_{i=1}^{n} a_i \, Z(X_i) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{Eq.6}$$

where n is the number of neighboring samples and a_i are weighing factors for each of the $Z(X_i)$. The weighting factors for neighboring measured points are constrained to sum to unity, i.e.:

$$\sum_{i=1}^{n} a_i = 1 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{Eq.7}$$

Application of Geostatistics to soil-properties: Geostatistics techniques can be used for the following:

- To determine the nature and extent of spatial variability of soil-properties and to identify their spatial patterns;
- Fertility-management of spatially variable soils, based on spatial patterns in soil-fertility and crop-productivity, to avoid over-fertilization and under-fertilization;
- Soil-sampling schemes, based on prior information of spatial patterns of soil properties;
- Environmental studies;
- Mapping of soil-fertility and soil, salinity/sodicity.
- Management of salt-affected soils, based on spatial patterns of salinity/sodicity.
- Design of field experiment e.g.
  - ° Directional patterns - blocking
  - ° To determine optimum plot-size;
- Statistical analysis of field experiments, e.g.
  - ° To identify yield-patterns or trends in field-experiments and presence of correlated errors.

PAST RESEARCH WORK ON THE USE OF GEOSTATISTICAL TOOLS IN PAKISTAN

Geostatistics is a quite new field to the Pakistani Soil Scientists and has been used on a very small scale in Pakistan. A course in Applied Geostatistics was introduced at M.Sc. Hons level in the Department of Soil Science, NWFP Agricultural University Peshawar, North West Frontier Province of Pakistan, in early 1990s. Geostatistical techniques were used to study the spatial variability of soil properties of degraded soils for their fertility and/or salinity/sodicity management, development of soil-sampling schemes, and mapping of soil-fertility and soil-sodicity. A brief review of the research work in this field, especially with regard to the management of degraded lands, is presented here.

1. Fertility management of eroded lands

A management-strategy of variable-rate fertilizer-application was developed to match the fertilizer-rates to the spatial patterns in crop-productivity on an eroded land at Thana, Malakand agency, NWFP, Pakistan. Landscape at the study-site (Fig.2) is characterized by steep land and its slope faces towards a stream. Relative

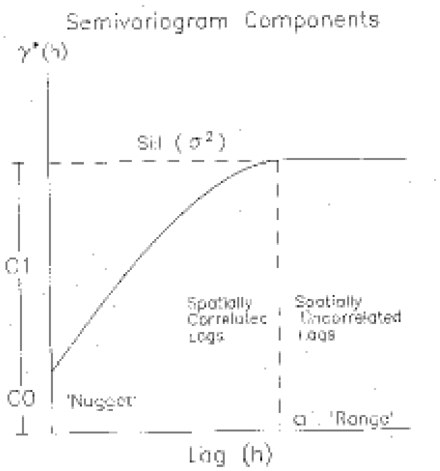

Figure - 1: Components of a Semivariogram

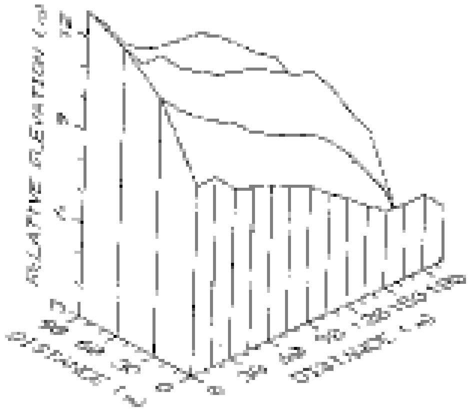

Figure - 2: Relative Elevation of Sampling Locations of Four Transects

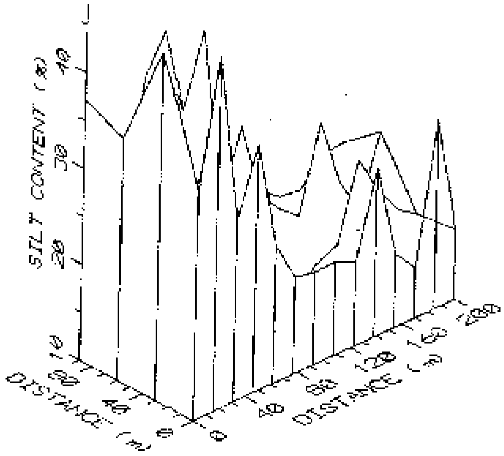

Figure - 3: Variation in Silt Content of the Field

elevation of the sampling locations ranged from 3.14 to 12.82 m. Most of the soil-properties had a very high coefficient of variation (Table 1). This high variability in soil-properties and wheat-yield is a function of position on the landscape and was *not* random. Silt content (Fig.3) and clay content was higher at upper slope positions, and sand content at lower slope positions. Similarly, organic matter was lower at top slope positions, as compared with bottom slope positions. Based on these results, the use of classical statistical procedures was not sufficient to describe and characterize variability in any of the properties.

Geostatistical technique of semivariogram analysis was used to identify and describe the spatial patterns of soil-properties and wheat-yield. Omnidirectional semivariograms were developed for each property and the parameters for the best fitting linear models were estimated (Table 2).

Table-1: Descriptive statistics of soil-properties and wheat-yield

SOIL PROPERTIES	MEAN	MINIMUM	MAXIMUM	CV(%)
Organic matter (%)	0.32	0.12	0.66	34.66
Lime content (%)	5.34	3.05	14.25	46.98
Soil pH	7.29	6.60	7.90	4.88
AB-DTPA ext. P (mgkg^{-1})	2.68	1.35	3.90	23.78
AB-DTPA ext. K (mgkg^{-1})	47.69	32.00	86.00	24.39
AB-DTPA ext. Zn (mgkg^{-1})	0.51	0.28	0.83	24.55
Relative elevation (m)	8.55	3.14	12.82	25.29
Clay content (%)	2.05	0.40	3.95	55.79
Silt content (%)	25.82	14.20	47.14	34.12
Sand content (%)	72.13	50.76	83.60	12.43
Grain yield (kgha^{-1})	3542	1000	6500	37.94
Profile available water (cm)	14.19	9.60	17.82	14.60

Table-2: Summary of parameters for semivariogram models*.

Property	Omnidirectional		
	Nugget	Slope	R²
Organic matter (%)	0.0082	0.00004	0.64
Lime content (%)	1.2637	0.0519	0.96
Soil pH	0.0892	0.0005	0.71
AB-DTPA ext. K (mgkg^{-1})	63.35	0.7151	0.71
Clay content (%)	0.5969	0.0115	0.86
Silt content (%)	16.257	0.6317	0.94
Sand content (%)	23.017	0.5717	0.94
Grain yield (kgha^{-1})	1502900	2987	0.47

* Linear model

Spatial patterns of the potential-yield, calculatedfrom the lime-content, were used to divide the field into zones with low (< 3400 kg ha^{-1}), medium (3400-3600 kg ha^{-1}) and high productivity (> 3600 kg ha^{-1}). Potential wheat-yield of each zone was used to determine the N-fertilizer requirement for that zone, using the following expression:

N fertilizer (kg ha^{-1}) = [(Potential yield x % N in grains) - total mineral soil N (kg ha^{-1})]/0.5,

where a factor of 0.5 is the fertilizer-use efficiency of wheat.

Using this expression, the following rates of fertilizer N were determined, along with proportion of the area for that particular rate (Table 3). These rates were applied to wheat in different zones (Fig.4) and compared with the uniform rate of fertilizer application.

These results (Table 4) showed that the variable rate of fertilizer proved more economical, used less fertilizer and also reduces environmental pollution of groundwater and surfacewater.

2. Reclamation of salt-affected soils (sodic soils), using variable rates of gypsum.

A reclamation strategy for salt-affected soils (sodic soil) was developed, using variable rates of gypsum for different management units in a large field. Soil pH of the study site ranged from 7.4 to 9.0, EC ranged from 0.35 to 4.90 with a mean of 1.64 dS m^{-1} and a coefficient of variation of 49%. The range for GR was wide, from 1.7 to 17.8 t ha^{-1}.

Soil pH, EC and GR showed spatial patterns. Omnidirectional semivariogram models were the best fit. A Spherical model best described EC (Fig.5) as follows: nugget = 0.17 (dS m^{-1})^2, sill = 0.62 (dS m^{-1})^2, range = 31.27 m, r^2=0.94. Similarly GR was described as: nugget = 1.87 (t ha^{-1})^2, sill=2.73(t ha^{-1})^2, range = 50.78 m, r^2 = 0.80. The soil pH was best described by a linear model as: nugget = 0.05, slope = 0.00015, r^2 = 0.91. Therefore, one uniform rate of gypsum was not a judicious application. A new set of criteria was developed, to divide the farm into well defined management-units.

Variable rates of gypsum thus determined were compared with a single uniform rate for reclamation of the salt affected sodic soil. The field was divided into three management zones (Fig.6), with six transects. One strip in each transect received a uniform rate of 4.25 t ha^{-1} , while the other strip in each zone was treated with varying rates of gypsum i.e. low (3.198 t ha^{-1}), medium (6.77 t ha^{-1}) and high (12.802 t ha^{-1}). The farm was planted with wheat. GR at harvest was significantly lower in the variable-management strategy (1.93 t ha^{-1})

Table - 3: Management zones and fertilizer rates

Management Unit	Fertilizer rate N (kg ha^{-1})	Area Proportion
1.	80	0.18
2.	110	0.39
3.	125	0.43

Table-4: Economics of fertilizer application for uniform-rate and variable-rate fertilizer application

Management strategy	Fertilizer $N-P_2O_5-K_2O$ (kg ha^{-1})	Yield (kg ha^{-1})	Net return (Rs ha^{-1})	Cost:Benefit ratio
Variable	111-90-60	3631	11810	4.35
Uniform	120-90-60	3729	12099	4.29

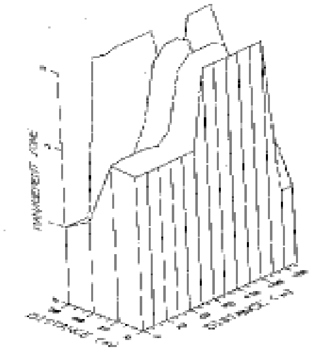

Figure - 4: Map showing Position of Different Management Zones for Variable N Rates

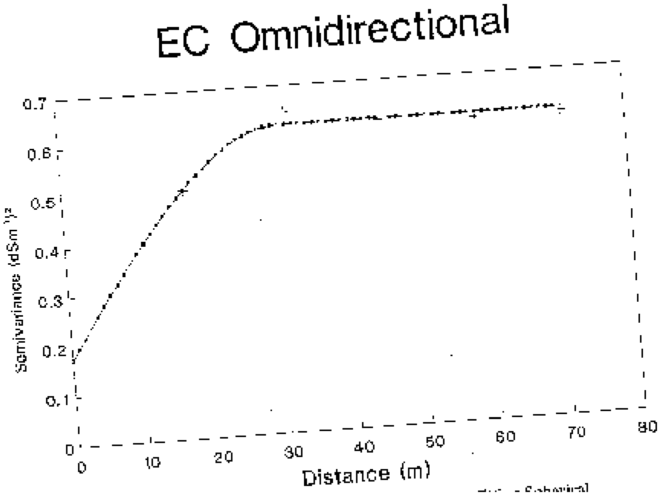

Figure - 5: Plot Showing Semivariance and the best fitting Spherical Model for EC

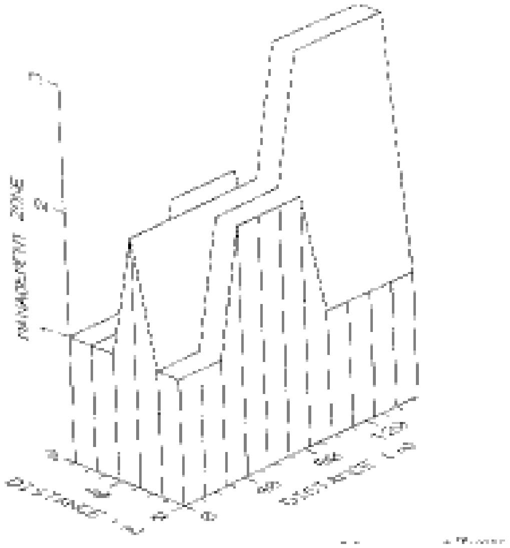

Figure - 6: Map Showing Positions of Different Management-Zones for Variable Gypsum-Rates

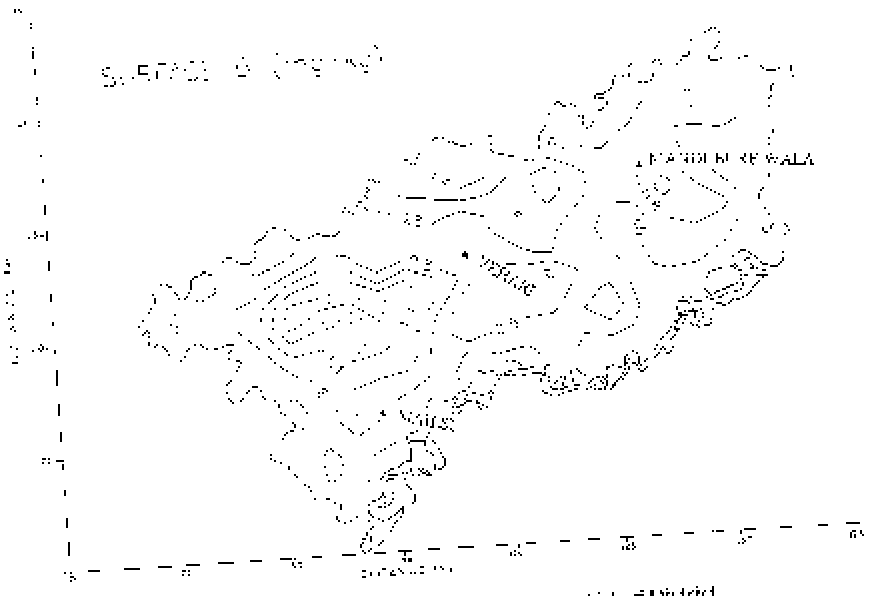

Figure - 7: Map of Soil P (mg kg^{-1}) by Kriging, Vehari District

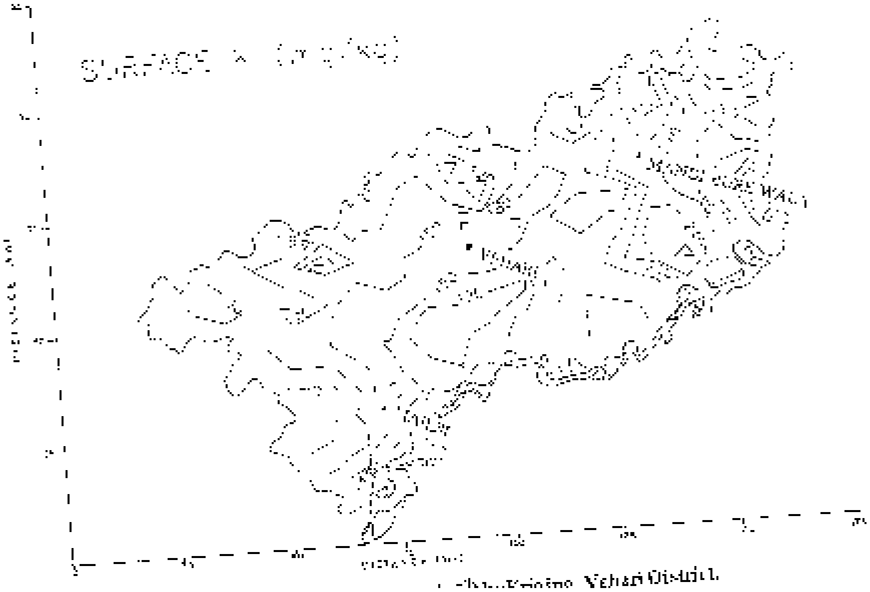

Figure - 8: Map of Soil K (mg kg^{-1}) by Kriging, Vehari District

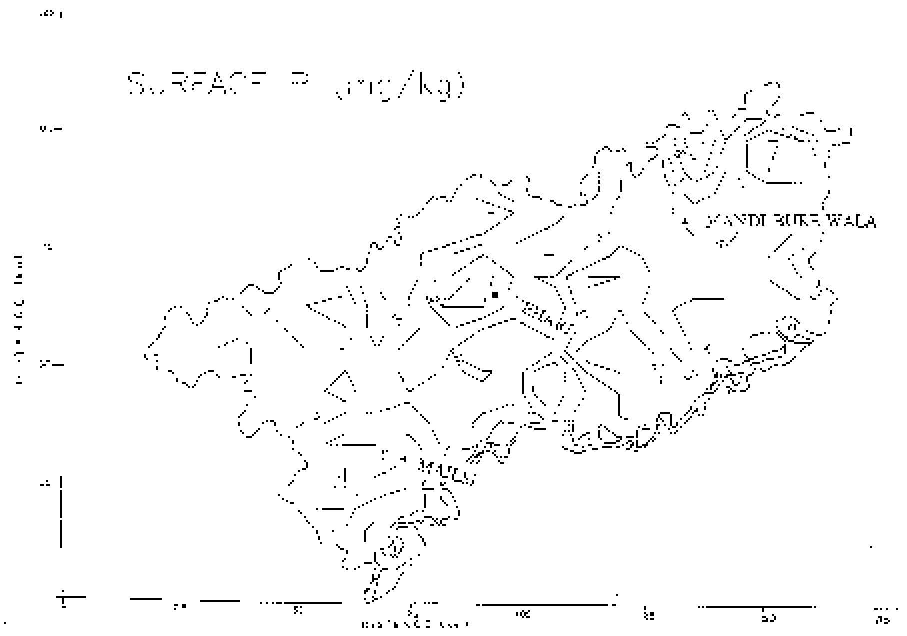

Figure - 9: Map of Soil P (mg kg^{-1}) by Kriging, Vehari District

than in the uniform rate (3.099 t ha^{-1}) (t = -5.2403, P = 0.0000). Wheat-yields were not affected significantly by the two management-strategies. Division of the field into three different management-units, based on the GR of soil, was effective in reclaiming the soil and it increased the efficiency of gypsum application.

3. Mapping of soil fertility

The nutrient contents in soils of cotton-growing areas of districts Lodhran, Khanewal and Multan were subjected to geostatistical technique of semivarogram analysis. Omnidirectional semivarograms were developed for each plant-nutrient, to describe and model the spatial variability. Different semivariogram-models were fitted to these data and parameters for these models were determined.

Values of plant-nutrients under study at unsampled locations were estimated, using the semivariograms and kriging technique. Computer-generated contour maps were developed for delineating areas of nutrient deficiency and adequacy in each district (Fig.7 to 9 for example).

CONCLUSIONS & FUTURE RESEARCH NEEDS

Geostatistical techniques proved to be a suitable tool to identify and describe the spatial patterns of sol-properties and wheat-yield. Use of spatial patterns in soil-properties and wheat-yield identified by geostatistical of semi-variogram analysis helped to divide the field into different management-zones for fertilizer-management, as well as gypsum-application for reclamation of salt-affected soils. Variable rates of N as well as gypsum, thus determined, increased their efficiency. Similarly the use of semi-varogran analysis and Kgriging techniques estimated the values of plant-nutrients at unsampled locations and were used in developing maps of cotton-growing areas of Punjab.

Future Research Needs include:

- Use in soil-survey operation for structural analysis of soil-variation, to help understanding of soil-genesis and for analysis of reconnaissance-data for defining future sampling;
- Kriging, to augment general - purpose information contained in conventional soil-maps, by interpolation of interpretive data and specific measured soil-properties.
- Block kriging, for estimating soil-amendment requirements over areas the size of land-management units.
- Spatial interpretation of critical levels of soil-constraints to crop-production, by using within-field variation of properties, such as soil-moisture content, for improving the efficiency of irrigation water use, nutrient levels for fertilizer application, or soil-chemical properties for amendment needs, such as gypsum requirement;
- Identification of spatially dependent component of error for reducing the confounding effects of within-plot variability on treatment-effects in agricultural experiments;
- Use of spatial dependence in determining optimal plot-size and spacing of samples within plots;
- Mapping of soil-fertility and salinity/sodicity for management of degraded lands.

SOME RESEARCH PRIORITIES

a) Preparation of isarthmic maps of soil-fertility for delineation of deficient areas in major as well as minor plant-nutrients, at field level and at some administrative-unit levels, for proper fertilizer-management to increase efficiency of fertilizer-use and reduce environmental pollution of surface and underground water;

b) Preparation of isarithmic maps of soil-salinity/sodicity for reclamation purposes and to increase the efficiency of amendments;

c) Design of soil-sampling schemes that are less time-consuming and more cost-effective.

d) Design of field experiments, using spatial dependence of soil-properties within plot, to determine the true treatment-effects and making sound conclusions and solid recommendations on fertilizer application.

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