Field Scale Spatial Analysis of pH on Sodium Soils in Northern Burkina Faso

Lars Krogh & Bjarne Fog

Abstract

Microscale variations of soil properties may have a pronounced impact on crop yields in the low external input agriculture in the Sahel. Using classical and geostatistical methods, spatial patterns of soil pH at 0.0-0.10 m, 0.30-0.50 m and 0.70-0.90 m depth have been analysed and mapped based on two hundred and eighty-one samples collected at 10 m x 10 m grid nodes on a one hectare test plot on a clayey, sodium affected soil used for millet cultivation in northern Burkina Faso. The mean surface soil pH is 7.39 and semivariance analysis shows that the nugget effect accounts for nearly 100% of the sample variance, and therefore surface pH exhibits no spatial dependency at the separating distance. The mean soil pH increases to 7.83 and 7.90 at 0.30-0.50 m and 0.70-0.90 m depth, respectively. However, the coefficient of variation also increases, and at 0.70-0.90 m the field has areas of both alkaline and acid soil. The range of influence for soil pH at 0.30-0.50 m was 60 m, increasing to 80 m at 0.70-0.90 m as a result of stronger dependency on geology. On application of the semivariograms, pH values between the grid points were interpolated by point kriging. The study illustrates that pH of sodium soils varies considerably and that millet roots may grow in a diversity of pH conditions. Furthermore, soil characterization depends very much upon the sampling strategies, but the determination of the range allows for choosing the minimum distance required for spacing of non spatially correlated samples. The application of chemical fertilizers are likely to produce very different effects given the chemically variable soil environment.

Keywords:

Soil microvariability, pH, kriging, Burkina Faso

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Soil microvariability is thought to be the major cause of short range variability in crop growth on the sandy soils in the Sahelian zone of West Africa. Moormang and Kang (1978) defined soil microvariability as permanent variability over relatively short distances (2-50 m) which are too small to warrant separate mapping. It has an intermediate position between localized transient properties and macrovariability, where the latter is related to landscape elements and topography.

The causes of soil microvariability are thought to be 1) differential wind and water erosion and deposition, 2) growth of trees and shrubs before clearing, 3) trees left standing - particularly *Faidherbia albida* ((Del.) Chev.), 4) termite activity, 5) differential leaching and pedogenic processes, 6) human activity, including application of manure, location of dwellings, burning of vegetation and 7) lithological variability (Charreau and Vidal, 1965; Dancette and Poulain, 1969; Beckett and Webster, 1971; Lee and Wood, 1971; Babalola and Lal, 1977; Moormann and Kang, 1978; Van Wambeke and Dudal, 1978; Holt *et al.*, 1980; Glazovskaya, 1986).

While the microvariability of soils in the Sahel is not necessarily greater than elsewhere, the effect of variability on crop performance may be very pronounced as the level of management normally is low, as are the inputs of fertilizers, manure or water via irrigation.

Soil parameters that may determine patterns of crop stand spatial variability are low pH and high Al + H saturation (Scott-Wendt *et al.*, 1988; Chase *et al.* 1989), phosphorus (Gwyn Davis-Carter, 1989), phosphorus, potassium, and SOM (Hebel *et al.*, 1993) and nitrate (Hermann *et al.*, 1994).

Although it is traditionally seen as a constraint to crop production (Manu *et al.*, 1990), Brouwer *et al.* (1993) hypothesized that soil microvariability contributes to interannual yield stabilization and, seen in that light, in fact constitutes an asset under subsistence farming conditions where risk reduction has a high priotity.

Soils in the Sahel are mostly Alfisols, Entisols and Inceptisols according to Soil Taxonomy (Soil Survey Staff, 1992) with weak structures, susceptibility to crusting and hardsetting, low buffering capacity and low levels of SOM, nitrogen and phosphorus (Lal, 1986, 1987; Bertrand, 1989; Pieri, 1992). Pearl millet (*Pennisetum glaucum*, (L.) Leeke) is the major food crop of the region and it is well adapted to the climatic conditions. Millet is typically grown on sandy soils and accordingly, much of the research efforts on the scale and nature of soil variability have concentrated on these soils.

In the Oudalan Province of northern Burkina Faso the interdunal areas are dominated by sodium affected clayey soils (ORSTOM, 1968; BUNASOL, 1991), and millet is also cultivated on these soils. The sodium affected pedons occur as random individuals ('slickspots') in a pedon population having almost similar morphology. Research on the spatial variability of such soil patterns has been very limited, particularly as regards the quantitative aspects. As a preliminary step in analysing the effects of soil microvariability on millet growth, the objectives of this study were to analyse the extent of variation and elucidate patterns of spatial microvariability of pH on a millet field test plot on a clayey soil using classical statistics and geostatistics.

Materials and Methods

Study site

The study site was a field located in the village Bidi-2 in the Oudalan Province of northern Burkina Faso (14° 20'N, 0° 20'W), see Figure 1. Details about the village can be found in Reenberg and Fog (1995). The field is under continuous cultivation with Pearl millet (*Pennisetum glaucum*, (L.) Leeke). Organic manure is applied annually, but the distribution is uneven and there are large variations in total amounts interannually.

The field is situated on the lower margins of a flat, slightly SW inclined pediplain cut in granitic rocks. In the village territory, the predominant soil type according to Soil Taxonomy (Soil Survey Staff, 1992) is a Haplustalf, but soil morphology and properties vary considerably (Krogh, 1995). The soils show moderately acidic, poorly structured, sandy surface horizons, often with duplex properties, i.e. sharply contrasting clayey subsoil with neutral reaction and a coarse blocky structure.Topsoil pH values range from 4.5-8.9, organic C from 1100-2600 $\mu g\ g^{-1}$, total N from 110-400 $\mu g\ g^{-1}$, and total P from 40-90 $\mu g\ g^{-1}$ (Krogh, 1995). Topsoil CEC values range from 2-6 cmol(+) kg^{-1} increasing to 15-25 cmol(+) kg^{-1} in the subsoil as a result of higher subsoil clay contents and a predominance of high activity clays at depth. Spotwise, the subsoil is sodium affected with $pH > 8.3$, ESP 10-23 %, exch. K > exch. Na, and EC 1:1 > 0.5 dS m^{-1}. The excess sodium is derived from calc-alkaline inclusions in the granitic bedrock (Hottin and Ouedraogo, 1975) resulting from weathering *in situ*, and presumably combined with a lateral influx from higher lying parts of the pediplain followed by sodium sieving.

Soil sampling and analysis

A test plot of 1 ha was mapped out on the field and divided into one hundred 10 m x 10 m subplots. The micro-relief was measured using a manually operated levelling instrument on a tripod. In the centre of each subplot, soil cores were collected from the 0-0.10 m, 0.30-0.50 m, and 0.70-0.90 m increments, using a gasoline powered auger with a diameter of 0.049 m. The sampling increments correspond in most cases to the A, upper Bt and mid Bt horizons respectively. Extreme subsoil compaction and hardness in some of the subplots reduced the total sample number from the planned 300 to 291. The soil samples were air-dried and grinded to pass through a 2-mm sieve. The pH was determined in water in a 1:2.5 soil:solution ratio. Soil solutions were stirred, equilibrated for 50 min, centrifuged at 2,500 rpm for 10 min, and measured with the pH electrode in the supernatant. All handling, grinding, and analyses of samples were performed in random order. The soil pH of the samples at 0-0.10 m, 0.30-0.50 m, and 0.70-0.90 m will in the following be referred to as $pH_{0.05}$, $pH_{0.40}$, and $pH_{0.80}$, respectively, as an expression of the middle depth of the sampling increment.

Statistical Analysis

Classical statistics

Classical descriptive statistics, performed by the QPRO V6.1 (Borland, 1996) spreadsheet routines, were used to explore features of the data. A Chi-square test was used to test the normality of data.

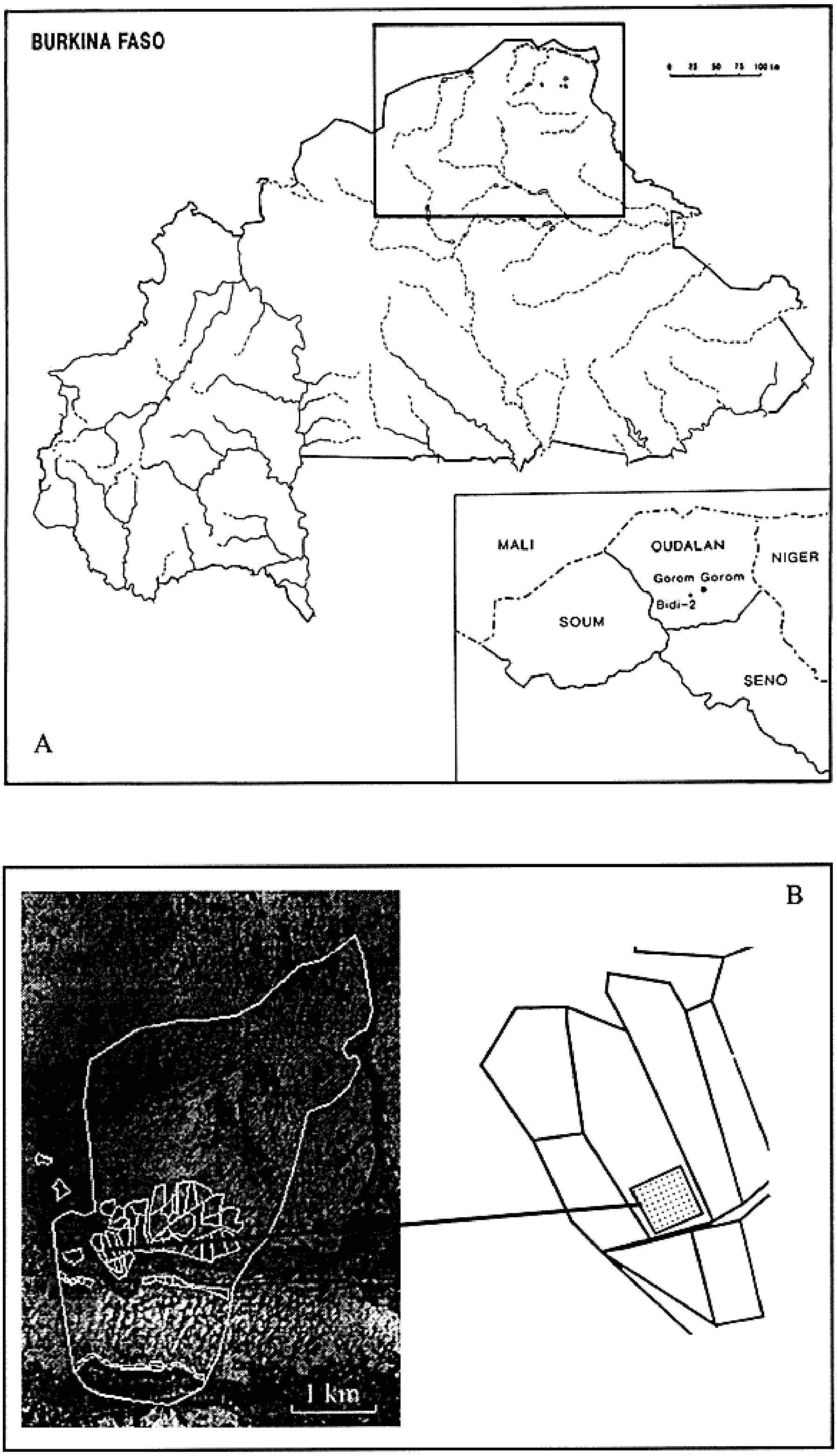

Figure 1: A) Map of Burkina Faso and the location of the village Bidi-2. B) The location of the test field in the 1994/95 fieldpattern and the perimeter of the village territory, projected on top of a SPOT satellite image from October 1991.

Geostatistics

Geostatistics, consisting of variogram analysis and kriging, been applied as a tool for characterizing mapping the spatial pattern of soil pH. Semivariograms are used to characterize and model the spatial variance of data, while kriging uses the modelled semivariograms to estimate values between sampled points.

The semivariogram portrays the relationship between the sample variance and the lateral distance, known as the lag (h), which separates the samples. The lag distance at which the variance approaches an asymptotic maximum, known as the sill, is the range across which data are spatially correlated. Direction independant and dependent semivariance of data was determined using the VARIOWIN software package (Pannatier, 1996). Semivariance is defined in the equation (Journel and Huijbregts, 1978)

$$\acute{o}(h) = \frac{1}{[2n(h)]}\sum_{i=1}^{n(h)} [Z_{(x_i)} - Z_{(x_{i+h})}]^2 \qquad (1)$$

where is the semivariance for n data pairs separated by a distance of h, and Z is the value at positions x_i and x_{i+h}.

Estimation by kriging

Applying the semivariogram, soil pH is interpolated at x m intervals by point kriging.

The linear unbiased estimate obtained by kriging, $Z(x_0)$, at position x_0 is a weighted average of n measured values of Z in the neigbourhood at pos. x_i

$$Z_{(x_0)} = \sum_{i=1}^{n} \acute{o}_i Z_{(x_i)} \qquad (2)$$

where $_i$ is a weighting factor of the neighbours always constrained to sum to unity

$$\sum_{i=1}^{n} \acute{o}_i = 1 \qquad (3)$$

This type of kriging is known as ordinary kriging.

Validation of kriging models

Validation of the kriging procedure was done stepwise by i) random elimination of 25 points and by ii) systematical elimination of 25 and 50 respectively, of the original 100 points of $pH_{0.40}$, thereby thinning the sampling grid in various ways. The kriging model derived from the 'original' 100 points semivariogram and a new model based on a 75 points semivariogram were then used to estimate values of the 25 randomly omitted points. Furthermore, the kriging model derived from the 'original' 100 points semivariogram and new models based on a 75 and a 50 points semivariogram were used to estimate values of the 100 points. The criterion for validation was comparison of means and variances of experimental and kriged values.

Results and Discussion

Classical statistics

The Chi-square test combined with kurtosis (peakedness) and skewness (symmetry) coefficients (zero for a normal distribution) and histograms show that normal distributions do not exactly fit pH at the three depths (Tab. 1 and Fig. 2). As the deviations are only minor and due mainly to a few outliers, the data will be treated as if they are normally distributed without discarding outliers. The lowest and the highest recorded pH are 5.12 and 9.35 respectively, both found at 0.80 m depth. The mean soil pH increases with

Table 1: *Classical statistics summary of soil $pH_{0.05}$, $pH_{0.40}$, and $pH_{0.80}$ on a 1 ha millet field in Bidi-2, northern Burkina Faso. SD = standard deviation, CV = coefficient of variation.*

variable	*n*	*mean*	*SD*	*CV*	*min*	*max*	*kurtosis*	*skewness*
$pH_{0.05}$	100	7.39	0.41	5.5	6.24	9.14	2.67	0.53
$pH_{0.40}$	99	7.83	0.56	7.15	6.36	8.99	-0.34	-0.34
$pH_{0.80}$	92	7.90	1.02	12.91	5.12	9.35	0.38	-1.09

depth from pH 7.39 at 0.05 m depth to pH 7.83 at 40 cm depth and to pH 7.90 at 0.80 m depth, however, only the difference between $pH_{0.05}$, and $pH_{0.40}$ and $pH_{0.80}$ respectively, is significant ($P<0.001$). The coefficient of variation also increases with 12.91% at 0.80 m, a value within the normal range depth, reaching reported in the literature (Wilding, 1983).

Semivariograms

The semivariogram is said to be isotropic if the variance is independent of the direction of the separation vector *h* and only depends on the distance. If, on the other hand, if the semivariogram depends on the direction it is said to be ani sotropic. The variogram surfaces for the three depths show that the variations are anisotropic, perpendicular directions

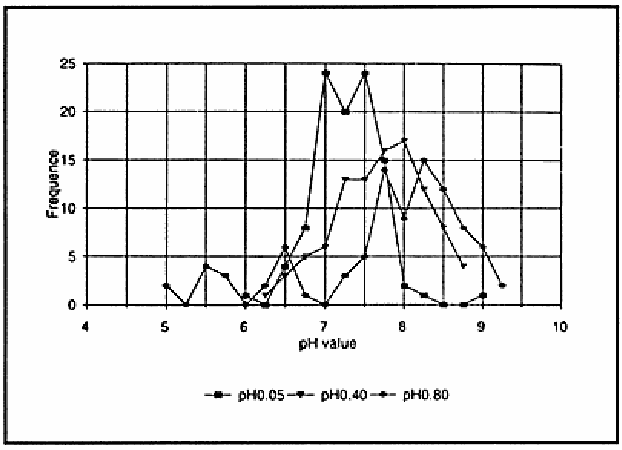

Figure 2: Histogram of distributions of $pH_{0.05}$, $pH_{0.40}$, and $pH_{0.80}$ on a 1 ha millet field in Bidi-2, northern Burkina Faso.

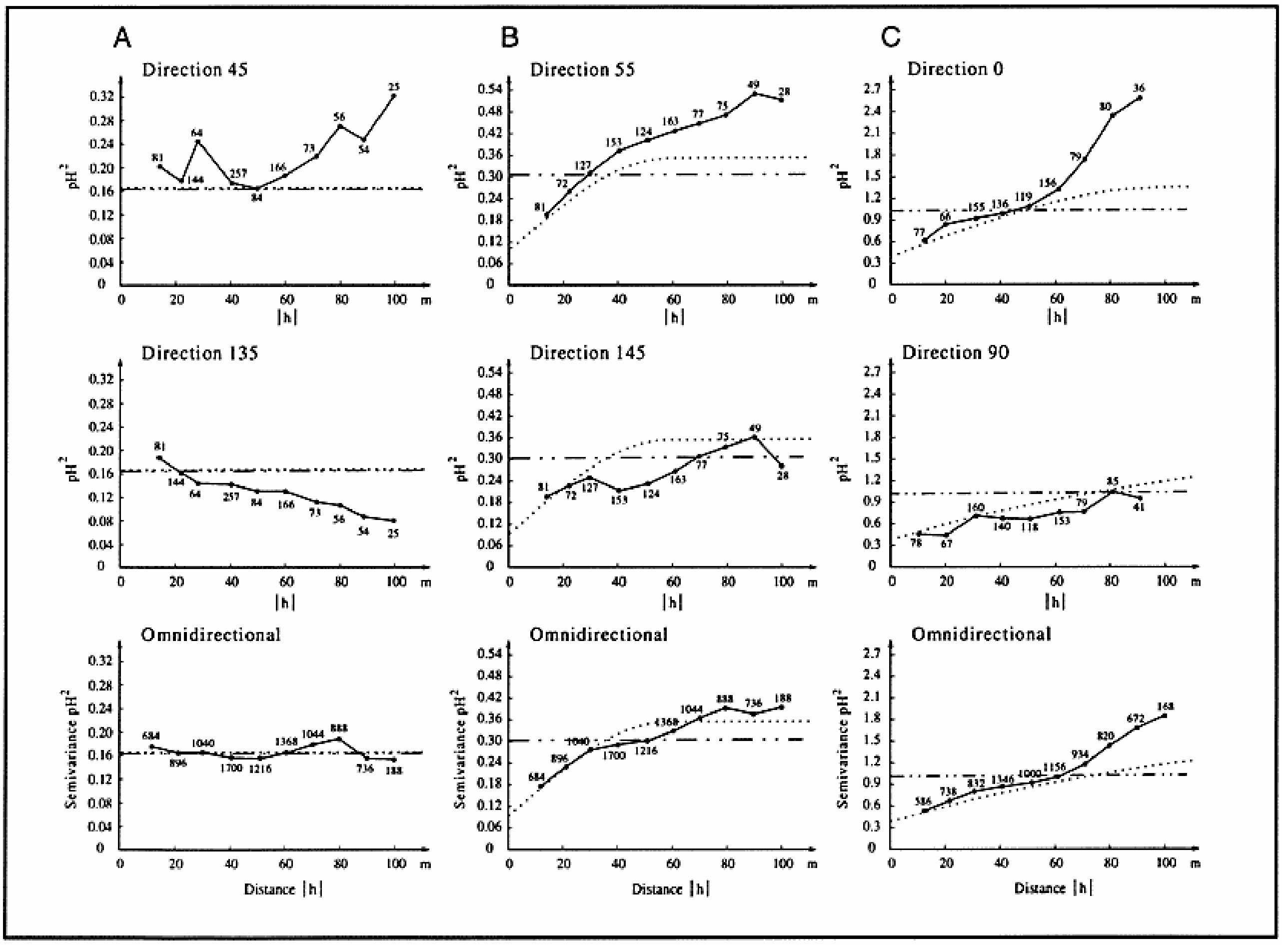

Figure 3: A) Directional semivariograms for $pH_{0.05}$. B) Directional semivariograms for $pH_{0.40}$. C) Directional semivariograms for $pH_{0.80}$. Solid lines connect experimental semivariances, dotted lines are fitted models.

show different semivariances. This anisotropy is geometric and can be accounted for by a linear transformation of the coordinates before the actual kriging. The semivariogram of pH in directionsperpendicular to each other and the omnidirectional semivariogram is shown in Figur 3.a ($pH_{0.05}$), Figur 3.b ($pH_{0.40}$), and Figur 3.c ($pH_{0.80}$).

For each variogram the best fitting model is estimated by an iterative process involving a great deal of common sense and the dimensionless Indicative Goodness of Fit number (IGF (Pannatier, 1996)), defined as

$$IGF = \frac{1}{N}\sum_{k=1}^{N}\sum_{i=0}^{n(k)}\frac{h_{\max}(k)}{\sum_{j=0}^{n(k)}P(j)}\frac{P(i)}{h(i)}\left[\frac{\acute{o}(i)-\acute{o}^{*}}{\acute{o}^{2}}\right]^{2} \qquad (4)$$

where N is the number of nested structures, $n(k)$ is the num- ber of lags for the k'th variogram, $P(i)$ is the number of pairs for lag i, $h(i)$ is the mean distance for lag i, $h_{max}(K)$ is the maximum distance for the k'th variogram, (i) is the experimental variogram for lag i, $(i)^*$ is the modeled variogram for the mean distance of lag i and ^{2} is the variance of the data of for the semivariogram. The closer the value of IGF is to zero, the better the fit. According to Journel and Huijbregts (1978), however, automatic fitting should be avoided and less weight should be given when the number of data pairs declines. For $pH_{0.05}$ the semivariogram shows that the semivariance is relatively constant at all separation distances and varies randomly at a value approximately equal to the total sample variance. The nugget variance accounts for almost 100% of the sample variance, and one can conclude that surface soil pH only exhibits spatial correlation within distances shorter than the sampling interval. For $pH_{0.40}$ the semivariance was fitted with a nested spherical and a gaussian model, showing a range of approximately 60 m. For $pH_{0.80}$ the semivariance was fitted with a nested spherical and a gaussian model, yielding a range of approximately 80 m. The latter two models suggest that the distance of soil pH spatial dependency increases with depth. We interpret this as being due to reduced impact from surface weathering, less influence of 'random' soil management and plants, and thus reflecting a greater degree of geologic influence. The pattern of increasing heterogeneity of pH with depth is the opposite of situations in which the genesis of sodium soils is assumed to be due to capillary rise of salt groundwater and the soil pH becomes increasingly homogenous with depth. Tab. 2 shows a summary of the parameters derived from the semivariograms. In practical terms, the semivariograms indicate that sampling by smaller intervals than the range, i.e 80 m for $pH_{0.80}$ would produce spatially dependent results.

Kriging of soil pH

Although the data is not completely normally distributed, the spatial variability of soil pH $_{0.40}$ and $pH_{0.80}$ on the test plot have been estimated and mapped by kriging, taking into account the geometric anisotropy of the data at the two levels. The resulting maps allow for extraction of soil information corresponding to the sites and areas of millet biomass information, thus facilitating the analysis of the effect of soil micro-variability on millet growth.

On the next page Figur 4a shows the estimated soil $pH_{0.40}$ applying the fitted and its eastern part is more acid with pH values as low as model (nested spherical and gaussian) from the semivariogram (cellsize 2 m and a search radius equalling the range). In Figur 4b the soil $pH_{0.80}$ has been estimated by applying a nested spherical and gaussian model derived from the semivariograms. The isarithmic map of kriged estimates of soil pH show that the test field is heterogeneous with respect to pH values. The general picture that emerges is that while the surface soil pH is slightly above neutral, the subsoil of the western part of the field is more alkaline 5.12. Whether this is part of a larger and recurrent pattern or due to the location of the test field on a distinct border between two contrasting soil types is not known. In both cases the reason for the

variable	*sill (pH^2)*	*nugget (pH^2)*	*range (m)*	*anisotropy*	*model type*
$pH_{0.05}$	-	0.17	<10	-	none
$pH_{0.40}$	0.35	0.10	60	geometric	spheric/gaussian
$pH_{0.80}$	1.15	0.40	80	geometric	spheric/gaussian

Table 2: *Parameters of spatial dependency of soil $pH_{0.05}$, $pH_{0.40}$, and $pH_{0.80}$ on a 1 ha millet field in Bidi-2, northern Burkina Faso.*

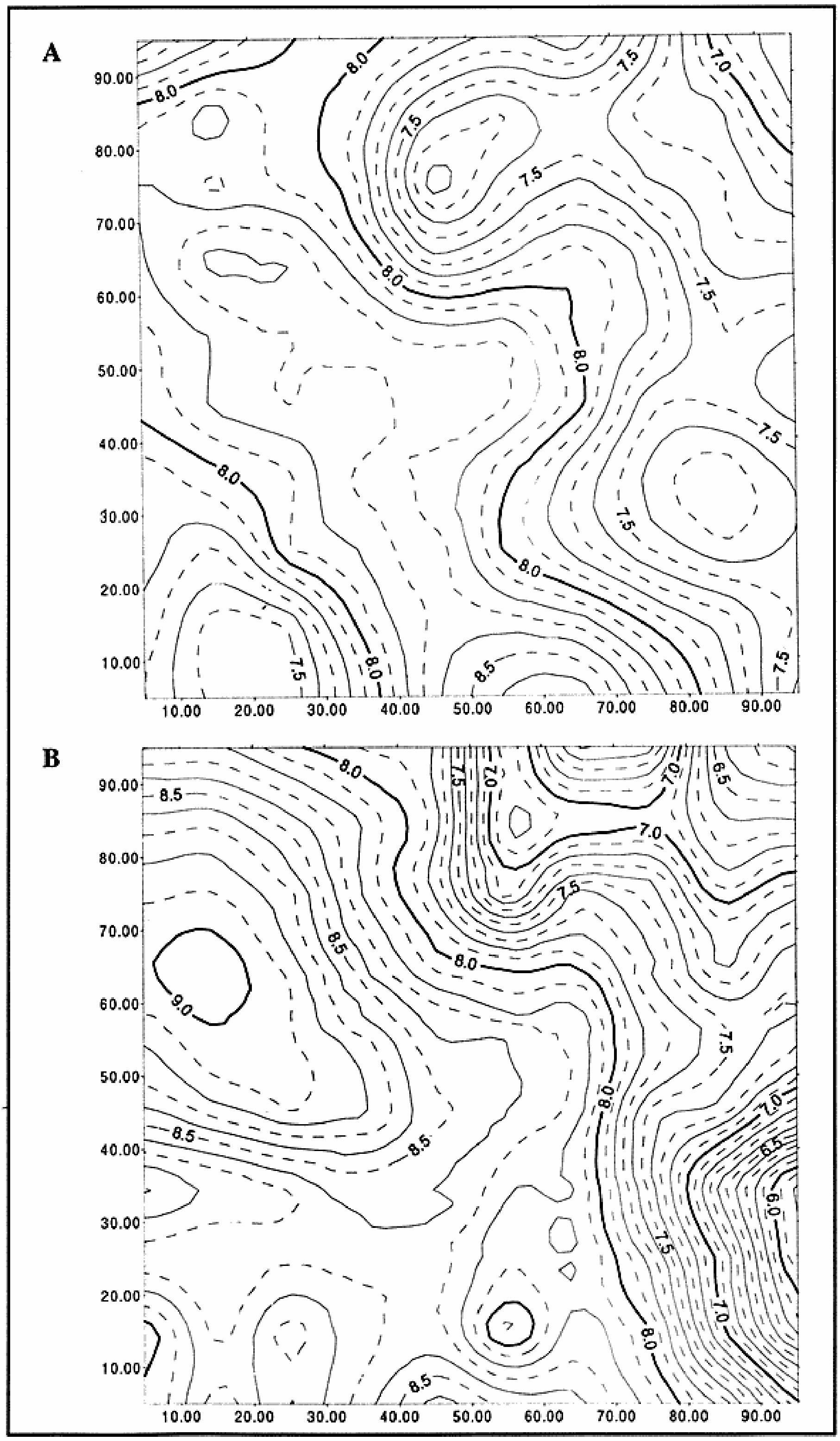

Figure 5: *A) Isaritmic kriged map of* $pH_{0.40}$ *and B)* $pH_{0.80}$ *Isarithms are at intervals of 0.1 pH unit.*

Table 3: Comparison of statistical parameters for $pH_{0,40}$ obtained by using classical statistics and kriging.

	25 points omitted randomly			*25 points omitted systematically*		*50 points omitted systematically*	
Method of estimation	*classical statistics*	*kriging original model*	*kriging new model*	*kriging original model*	*kriging new model*	*kriging original model*	*kriging new model*
Number of points used for estimation	25	100	75	75	75	50	50
Number of points estimated	25	25	25	100	100	100	100
Mean*	7.86	7.88	7.89	7.83	7.83	7.89	7.89
Standard deviation	0.53	0.41	0.40	0.38	0.45	0.38	0.41
Variance	0.28	0.17	0.16	0.14	0.20	0.14	0.17

** means are not significantly different $P < 0.001$*

contrasting gradients probably lies with the bedrock geology of which the mineralogical composition may vary significantly (Hottin and Ouedraogo, 1975). As the predominant soil type in this part of the Oudalan province of is 'sodic' and with high pH, we suggest that weathering of bedrock areas low in albite is responsible for the observed low pH areas, while the high pH areas are due to weathering of albite containing granite. Other reasons contributing to the wide variation may be local fractures in the bedrock which increase the rate of leaching, thus lowering the pH, or small inclusions of pyrite from fresh weathering bedrock.

Validation of Kriging Models

A comparison og the experimental and kriged values are presented in Table 3. The means of experimental and kriged estimates of soil $pH_{0.40}$ are not significantly different ($P<0.001$), and this implies that a minor number of samples may be needed to obtain the precision wanted in interpolation maps.

Summary and Conclusion

The wide range in soil pH of the field implies that the millet roots experience very different environments and therefore also growth conditions that, however, only can be fully appreciated when the scale and extent of variation of other soil parameters have been analyzed. Another implication of the variability is that characterization of the soils in the area will depend very much upon the sampling strategies. In an environment like this a one-off sampling from a profile pit could result in a soil map showing either acid or alkaline soils and thus fail to identify that the actual soil pattern is a complex mixture of both types. The determination of the range for various soil parameters allows for choosing the minimum distance required for spacing of independent samples. Agronomically, various treatments, as fx applying chemical fertilizers, are likely to produce different effects given the chemically variable soils.

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The results presented constitute a contribution to the multidisciplinary research activities of SEREIN (The Danish Sahel Sudan Environmental Research Initiative) (Reenberg, 1995). SEREIN is initiated by the Danish Environmental Research Programme and financed by the Danish Ministry of Foreign Affairs.

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Table 3: Comparison of statistical parameters for $pH_{0,40}$ *obtained by using classical statistics and kriging.*

	25 points omitted randomly			*25 points omitted systematically*		*50 points omitted systematically*	
Method of estimation	*classical statistics*	*kriging original model*	*kriging new model*	*kriging original model*	*kriging new model*	*kriging original model*	*kriging new model*
Number of points used for estimation	25	100	75	75	75	50	50
Number of points estimated	25	25	25	100	100	100	100
Mean*	7.86	7.88	7.89	7.83	7.83	7.89	7.89
Standard deviation	0.53	0.41	0.40	0.38	0.45	0.38	0.41
Variance	0.28	0.17	0.16	0.14	0.20	0.14	0.17

** means are not significantly different* $P < 0.001$

contrasting gradients probably lies with the bedrock geology of which the mineralogical composition may vary significantly (Hottin and Ouedraogo, 1975). As the predominant soil type in this part of the Oudalan province of is 'sodic' and with high pH, we suggest that weathering of bedrock areas low in albite is responsible for the observed low pH areas, while the high pH areas are due to weathering of albite containing granite. Other reasons contributing to the wide variation may be local fractures in the bedrock which increase the rate of leaching, thus lowering the pH, or small inclusions of pyrite from fresh weathering bedrock.

Validation of Kriging Models

A comparison og the experimental and kriged values are presented in Table 3. The means of experimental and kriged estimates of soil $pH_{0.40}$ are not significantly different ($P<0.001$), and this implies that a minor number of samples may be needed to obtain the precision wanted in interpolation maps.

Summary and Conclusion

The wide range in soil pH of the field implies that the millet roots experience very different environments and therefore also growth conditions that, however, only can be fully appreciated when the scale and extent of variation of other soil parameters have been analyzed. Another implication of the variability is that characterization of the soils in the area will depend very much upon the sampling strategies. In an environment like this a one-off sampling from a profile pit could result in a soil map showing either acid or alkaline soils and thus fail to identify that the actual soil pattern is a complex mixture of both types. The determination of the range for various soil parameters allows for choosing the minimum distance required for spacing of independent samples. Agronomically, various treatments, as fx applying chemical fertilizers, are likely to produce different effects given the chemically variable soils.

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