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Evaluation of Stratification Criteria for Regional Assessment of Soil Chemical Fertility Parameters in Semi-arid Tropical India

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Statistically sound soil sampling strategy is a prerequisite for assessing the soil fertility status of a region. We tested a stratified, random sampling methodology to ascertain whether surface geology, microwatershed, position on the toposequence, and size of farm holding explained the differences in the fertility parameters of soils in the semi-arid tropical region of Karnataka State, India. Descriptive statistics revealed that out of 119 farmer fields sampled, many were deficient in the following nutrients: 50% in available phosphorous (P), 78% in boron (B), 67% in zinc (Zn), and 72% in sulfur (S). Discriminant analysis indicated that fertility studies on a regional scale need to include good representation of soil heterogeneity based on parent material (surface geology), hydrological properties, and positions on toposequence but not the size of the farm holding. The proposed stratified random sampling technique enabled representation of the heterogeneity in the whole population even with a small sample set size.

Keywords Discriminant analysis, regional-scale fertility evaluation, stratification criteria

Introduction

Regional-scale soil fertility evaluation is an important component of soil management that helps ensure good crop yields and sustainability. The diversity and variability of soils across a given region or zone hinders the ability to draw conclusions based on the results of soil-testing parameters at that scale of study and to draw any inferences. Because of the soil heterogeneity, which is further modified by crop and soil management practices, more of samples are required to represent the fertility status of the soil population (Westerman 1990; Peterson and Calvin 1996). Without a precise soil sampling technique, the soil-test results from randomly taken soil samples will not be effective in providing information

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on nutrient requirements of the production system or the region (Tsegaye and Hill 1998; Sahrawat 2006).

Apart from soil moisture shortages, poor soil fertility and nutrient deficiencies have been considered as constraints to crop productivity in most parts of the semi-arid tropics (SAT) of the world. In the Indian SAT, negative balances of nitrogen (N) and phosphorous (P) (Rego et al. 2003) with widespread deficiencies of sulfur (S), zinc (Zn), and boron (B) have been reported (Rego et al. 2007). Accurate measurement of soil fertility parameters in the regional level would help the crop production planners come up with suitable strategies for efficient management of land use and cropping systems.

Little efforts have been devoted to develop or evaluate robustness of sampling schemes available for fertility evaluations of region or a zone. We used discriminant analysis (DA), which is a classical multivariate analysis tool for simultaneously analyzing correlated variables such as soil fertility parameters. Discriminant analysis is a technique whereby a multivariate data set containing m variables is separated into a number of predefined groups k, using discriminant functions z, which is linear combination of the variables (Sharma 1996). This communication aims to describe the variability of on-farm soil fertility by surface geology, watershed, topo position, and size of farm holding in a typical SAT region of Karnataka, India. The findings of the study are aimed at identifying an appropriate regional-scale soil sampling scheme.

Materials and Methods

Study Area and Sampling Design

We selected the SAT region stretching across two geographical districts in the central Karnataka for the study. The Dharwad district is geographically located between latitudes 15° 02′ 4.13″ and 15° 42′ 8.3″ N and longitudes 74° 43′ 17.17″ and 75° 34′ 00″ E, whereas Haveri district is between latitudes 14° 16′ 18″ and 15° 00′ 36″ N and longitudes 75° 00′ 36″ and 75° 49′ 30″ E. The study area is characterized by four distinct seasons: hot season (from the middle of February to the end of May), southwest monsoon (from June to September), northeast monsoon (October and November), and winter (December to first half of February).

The geological study of the districts reveals that soils of the Dharwad area were developed on the oldest rocks and the main rock types exposed were either of Archaean age (granites) or Archean to Proterozoic age (argillite/grewacke). Soils of Haveri district had their genesis from Chitradurga groups of rocks. Because the soils were formed on different parent materials, we expected a strong influence of parent materials on soil chemical composition and fertility. Hence, at the first level, we stratified the soils in the entire region based on their geological makeup. Two microwatersheds were selected for soil sampling in Haveri and one in Dharwad. Microwatersheds had the maximum land area devoted to the production of field crops. According to the farmers’ information, the microwatersheds selected for the study had diverse production systems during the past five years (Table 1). Microwatersheds were delineated by an eight-stage system of demarcating the water resources region into basin, catchments, subcatchments, watershed, subwatershed, miniwatershed, and microwatershed (KSRSAC 2005). Each microwatershed ranged in geographical size from 500 to 1000 ha. Within each microwatershed, fields for soil sampling were identified by a stratified random sampling technique described in detail elsewhere (Rego et al. 2007; Sahrawat et al. 2008).

Table 1
Description of the microwatershed sites evaluated for the fertility of farmers' fields

Geophysical area	Subwatershed name with code number[a]	Microwatershed name with code number [a]	Geological origin of the geophysical unit	Soil type of the microwatershed	Geographical area of the microwatershed and dominant cropping system
Haveri	Konanathambige 4D4C2L	Aremallapur 4D4C2L2e	Meta-basalt, greywacke/argillite, quartz-chlorite-schist	All 39 samples represented red soils (Alfisols) with good permeability	484 ha of which ca. 40–60% was under maize, and remaining area was under cotton, sorghum, groundnut, and vegetable crops
	Kanakapura 4D4A5K	Chikka lingadahalli 4D4A5K2f		30 samples from red soils with moderate permeability and 20 black cracking soils (Vertisols)	588 ha of which ca. 50–60% was under maize, and remaining area was occupied by cotton, sorghum, and groundnut
Dharwad	Devaragudihal 5B1A4A	Anchatageri 5B1A4A2d	Argillite/greywacke, pink and grey granite	14 samples from red soils with moderate permeability, 16 from black cracking soils	848 ha of which ca. 75% was under soybean, and remaining area was under groundnut, sorghum, maize, and vegetable crops

[a] KSRSAC (2005).

Soil Fertility Evaluation

The composite soil samples were air dried and powdered with wooden hammer to pass through a 2-mm sieve. Soil pH was measured by a glass electrode using a soil-to-water ratio of 1:2; electrical conductivity (EC) was determined by an EC meter using a soil-to-water ratio of 1:2. For organic carbon (C) and total nitrogen (N) analyses, the soil samples were finely powdered to pass through a 0.25-mm sieve and analyzed at the Central Analytical Services Laboratory of the International Crops Research Institute for the Semi-arid Tropics, India. Total nitrogen (TN) was determined by the method described by Dalal, Sahrawat, and Meyers (1984), and organic C (OC) content was found by the Walkley–Black method (Nelson and Sommers 1996). Available P was extracted with sodium bicarbonate ($NaHCO_3$) (Olsen and Sommers 1982), and S was extracted with 0.15% calcium chloride (Tabatabai 1996). Neutral normal ammonium acetate–extractable potassium (K), and sodium (Na) were measured as per the procedure described by Helmke and Sparks (1996), and calcium (Ca) and magnesium (Mg) were determined with the method described by Suarez (1996). Diethylenetriaminepentaacetic acid (DTPA)–extractable contents of Zn, copper (Cu), iron (Fe), and manganese (Mn) were determined according to Lindsay and Norvell's method (1978); available B was extracted by hot water (Keren 1996) and estimated by inductively coupled plasma–atomic emission spectroscopy (ICP-AES). Evaluation of sufficiency or deficiency of a particular soil fertility parameter was done using the ratings proposed by Sahrawat (2006) for pH, EC, OC, P, K, Mg, Ca, Na, B, Zn, Cu, Mn, and Fe, and the ratings given by Hari and Dwivedi (1994) were used for categorizing the soils for the status of S.

Statistical Analysis

Descriptive statistics and multivariate analysis (discriminant analysis) of the data were conducted in StatistiXL version 1.7 software (StatistiXL, Seattle, Wash.; Sharma 1996). Discriminant analysis helps to determine which set of soil variables best predicted group membership and to visualize the data by condensing the multiple soil variables onto one or more axes or functions. Using DA, the relationships of different stratification criteria were studied to determine successive functions and discriminant coefficients that best discriminate between a set of class variables (geology, microwatersheds, topography, and size of farmland). We used 15 soil fertility variables in the DA. Data were transformed to $\log_e$ (pH, EC, OC, available Zn, Cu, Fe, Mn, B) or square root (total N; exchangeable Ca, Mg, and Na; and available S, K, and P) prior to analysis for standardizing the variance.

Results and Discussion

Regional-Scale Soil Fertility Status

The descriptive statistics of fertility status revealed that soils were neutral to alkaline in reaction and that pH values ranged between 6.25 and 9.02 with medium contents of OC (Table 2). Also P, S, and Zn contents had fairly high variability with coefficients of variability (CVs) of 98.1%, 91.9%, and 74.6%, respectively. Among the soil variables, pH, OC, and TN contents had less variability with CVs of 9.2%, 27.5%, and 21.5%, respectively. Deficiency of P was a common problem in more than 50% of farmer's fields (<5 mg kg^{-1}); 78% of fields were deficient in B (<0.58 mg kg^{-1}), and 67% were deficient in Zn (<0.75 mg kg^{-1}) based on the tentative critical limits (Sahrawat 2006; Rego et al. 2007).

Table 2
Descriptive statistics of the fertility parameters

Variables	Mean	Min	Max	SD	CV%	Skew
pH	7.75	6.25	9.02	0.71	9.20	0.01
E. conductivity (dSm^{-1})	0.25	0.06	0.94	0.19	73.6	1.75
Organic C (g kg^{-1})	6.10	3.20	11.70	0.17	27.50	1.20
Total N (mg kg^{-1})	576.0	372.0	930.0	123.8	21.50	0.89
Olsen P (mg kg^{-1})	8.00	0.60	46.00	7.86	98.20	2.07
NH_4OAc-K (mg kg^{-1})	112.4	37.0	333.0	53.4	47.50	1.21
$CaCl_2$-S (mg kg^{-1})	9.74	3.30	55.60	8.90	91.90	3.05
Exch. Ca (mg kg^{-1})	3.05	1.51	8.01	1.44	47.30	1.65
Exch. Mg (mg kg^{-1})	546.0	180.0	1891	291.0	53.40	2.00
Exch. Na (mg kg^{-1})	73.4	13.00	511	89.7	122.4	2.40
DTPA-Zn (mg kg^{-1})	0.74	0.20	3.22	0.55	74.60	2.30
DTPA-Cu (mg kg^{-1})	2.19	0.70	5.10	0.95	43.40	1.04
DTPA-Fe (mg kg^{-1})	17.01	3.800	40.8	8.75	51.50	0.51
DTPA-Mn (mg kg^{-1})	50.60	14.80	112.5	20.40	40.30	0.35
HWS-B (mg kg^{-1})	0.46	0.08	1.06	0.20	43.30	0.78

Notes. Min, minimum; max, maximum; SD, standard deviation; CV%, coefficient of variation; and skew, skewness.

Also, more than 72% of fields were deficient in S ($<$10 mg kg^{-1}), 21.8% of samples were medium in S availability (between 10 and 20 mg kg^{-1}), and 5.9% of samples were high in S ($>$20 mg kg^{-1}; Hari and Dwivedi 1994). The availability of Ca, Mg, Fe, Mn, Cu, and Na was satisfactory in the majority of fields.

Effects of Stratification

The discriminant analysis showed that the positive coefficients of discriminant function were related to higher concentrations of OC, Ca, Cu, and pH at Dharwad sites (Anchatageri) than those in the Haveri sites (Aremallpur and Chikkalingadahalli; Figure 1). The standardized discriminant coefficients for OC, Ca, pH, and Cu were 1.36, 0.82, 0.72, and 0.70, respectively. The discriminant function separated the geophysical areas with low-frequency values of discriminant scores for the fields in Dharwad and high-frequency values for the farmers' fields in Haveri. The two geophysical areas are associated with the difference in elemental composition of the parent material. It is known that parent material (Facchinelli, Sacchi, and Mallen 2001), climate, and geological history have major influences on soil properties at the regional and continental scales (Ramesh et al. 2007).

Discriminant analysis of the fertility parameters with respect to categorization into microwatersheds showed that first and the second functions accounted for 66.1% and 33.9% of the variability, respectively (Figure 2a). Function 1 separated all the microwatersheds studied (Aremallpur, Chikkalingadahalli, Anchatageri) based on fertility status, and function 2 partially separated the discriminant scores for the Chikkalingadahalli and Aremallpur microwatersheds with high positive scores for both microwatersheds. For the discriminant function 1, extractable Ca, Na, and OC have large positive contributions, indicating influence of agroclimatic variation on soil fertility status, whereas Mg, Fe, and TN

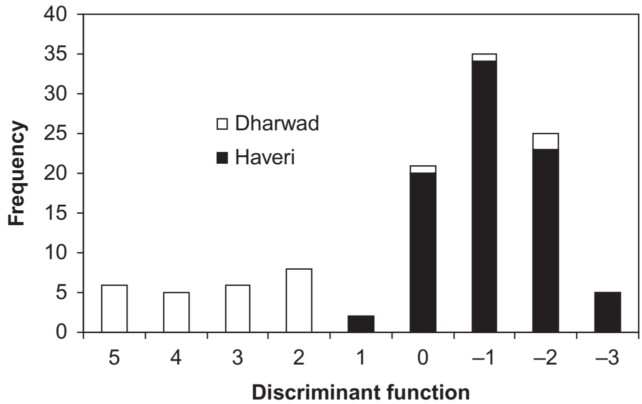

Figure 1. Frequency histogram of scores of a discriminant analysis using 15 soil fertility variables to discriminate farmer's fields by geophysical provinces (districts) in Karnataka. Each bar represents the frequency of plots falling within a 0.5 range of discriminant scores. The discriminant function was correlated to pH, OC, Ca, and Cu contents.

had large negative contribution to soil chemical fertility parameters. Discriminant functions related the variations in concentrations of Ca and Na, which are mainly related to the natural variations in the carbonate contents of the farmers' fields. The watersheds selected are in the SAT region, where climatic aridity and salinization are expected to increase carbonate content (Spijker, Vriend, and van Gaans 2005).

Stratification of the fertility data in to subtypes based on toposequence not only enhanced the statistical power of the analysis but also helped to minimize the effect of soil heterogeneity. Discriminant analysis of the data grouped the variables into two significant functions: the first function explained about 85.9% of variations and the second function explained about 14.1% of the total variations. Scatter plots of the case-wise discriminant scores revealed that positive coefficients for the first function were related to high values of pH and greater concentrations of K and Cu (Figure 2b). The first function separated the toposequence position in the watersheds from the middle and toe positions, with the farmers' fields on the toposequence position corresponding to the negative coefficient values of TN and Mg. The second function was related to Na and appeared to vary across topography within watersheds. A positive score on this function (greater Na contents) generally corresponded to the farmers' fields in the toe slope or bottom positions of the watershed. Out of the 26 farmers' fields sampled in the bottom of the toposequence, only nine fields fell below the origin on the second variate or function axis, indicating high concentrations of Na in most of the fields in toe slope position. The results suggest that for a subset of the soil variables evaluated, mainly pH, K, and Cu stratification strategies by the toposequence explained up to 86% of the observed differences. In particular, fields in the up slope position were well separated from the mid and toe slope fields, with very little overlap, by the first function in the DA. Significantly greater concentrations of Mn, noticed in up land conditions than the middle or toe slope positions within the watershed suggested the continued importance of surface geology on the fertility. Parent materials rich in mafic and ultra mafic rocks with high quantities of Mn, result in soils rich of Mn. Categorization based on land size in to marginal, small and large farmers within each toposequence position did not vary significantly for the measured variables in the DA (Figure 2c). The first function was related to the positive coefficients of pH, EC, Mn, Zn, K, Na, and Ca and

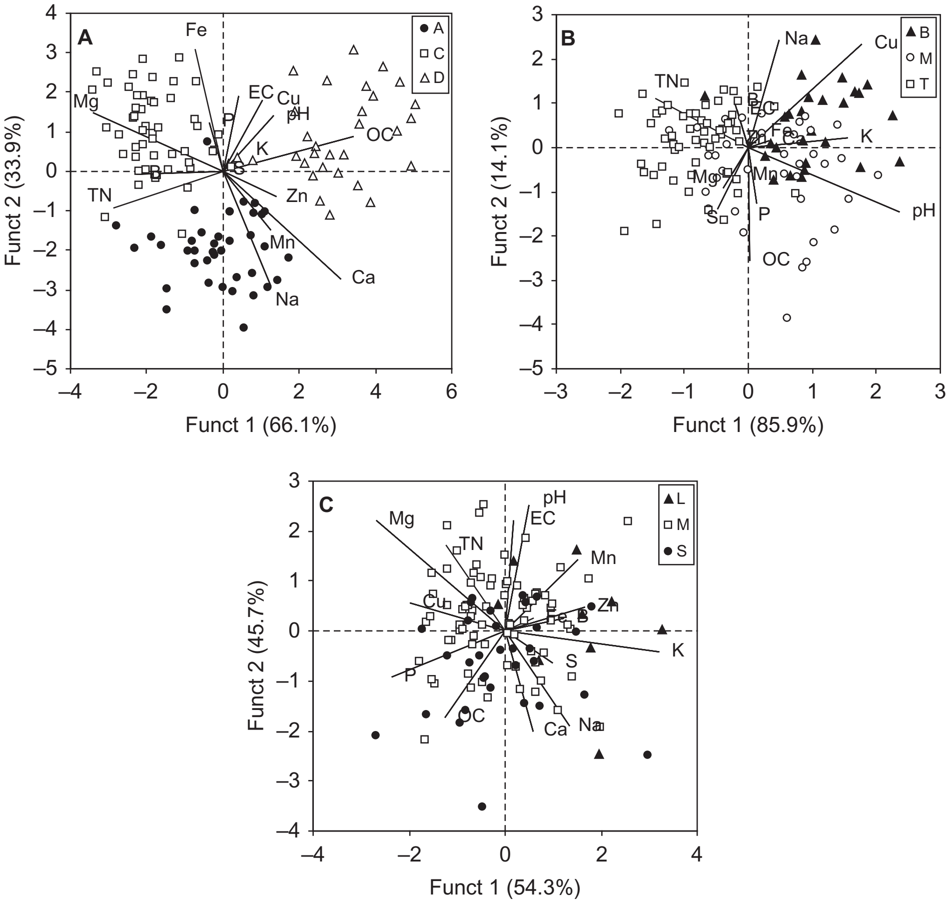

Figure 2. Discriminant plots of 15 soil fertility variables to discriminate farmers' fields across (A) microwatersheds (legend codes are A, Aremallapur; C, Chikkalingadahalli; and D, Anchatageri); (B) topographical position (legend codes are B, toe slope; M, midslope; and T, upslope); and (C) size of land holding (legend codes are L, large farmer; M, marginal farmer; and S, small farmer).

negative coefficients of Mg, TN, P, Cu, and OC. The second function was related to the positive coefficients of Mg, TN, pH, EC, Mn, Zn, and Cu and negative coefficients of P, OC, Ca, Na, and K. The scatter plot of discriminant scores of the individual farmers' fields was not able to clearly separate out the size categories, with respect to the selected soil fertility parameters. Such uniformity across different land size groups might be due to uniform land-management practices such as low fertilizer nutrient applications, recycling of residues, and cultivation practices (Monatagne et al. 2007). Apart from soil geology, land-use and soil-management practices are reported to have profound influence on the nutrient status and the redistribution of nutrients in the soil profile (Hontoria et al. 1999).

Conclusions

The results of our study based on the proposed soil sampling scheme clearly indicated that deficiencies of P, S, Zn, and B are responsible for soil nutrient–related limitations to the crop productivity in the SAT region of Karnataka. Discriminant analysis performed for the data sets revealed that the stratification scheme or methodology followed was able to capture the soil variability and heterogeneity except for the use of the land-holding size. Based on the study, it is recommended that regional-scale fertility evaluation programs in the SAT regions should consider a sampling scheme based on stratifications of the region into geological origin, watersheds based on hydrological properties, and topographic positions. However, such a sampling strategy may be applicable to a region with uniform soil-management practices such as low nutrient input.

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