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Geostatistical approach for management of soil nutrients with special emphasis on different forms of potassium considering their spatial variation in intensive cropping system of West Bengal, India

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Abstract A large part of precision agriculture research in the developing countries is devoted towards precision nutrient management aspects. This has led to better economics and efficiency of nutrient use with off-farm advantages of environmental security. The keystone of precision nutrient management is analysis and interpretation of spatial variability of soils by establishing management zones. In this study, spatial variability of major soil nutrient contents was evaluated in the Ghoragacha village of North 24 Parganas district of West Bengal, India. Surface soil samples from 100 locations, covering different cropping systems of the village, was collected from 0 to 15 cm depth using 100×100 m grid system and analyzed in the laboratory to determine organic carbon (OC), available nitrogen (N), phosphorus (P), and potassium (K) contents of the soil as well as its water-soluble K (K_{WS}), exchangeable K (K_{EX}), and non-exchangeable forms of K (K_{NEX}). Geostatistical analyses were performed to determine the spatial variation structure of each nutrient content within the village, followed by the generation of surface maps through kriging. Four commonly used semivariogram models, i.e., spherical, exponential, Gaussian, and linear models were fitted to each soil property, and the best one was used to prepare surface maps through krigging. Spherical model was found the best for available N and P contents, while linear and exponential model was the best for OC and available K, and for K_{WS} and K_{NEK}, Gausian model was the best. Surface maps of nutrient contents showed that N content (129–195 kg ha^{-1}) was the most limiting factor throughout the village, while P status was generally very high (10–678 kg ha^{-1}) in the soils of the present village. Among the different soil K fractions, K_{WS} registered the maximum variability (CV 75 %), while the remaining soil K fractions showed

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moderate to high variation. Interestingly, K_{NEX} content also showed high variability, which essentially indicates reserve native K exploitation under intensive cultivation. These maps highlight the necessity of estimating the other soil K fractions as well for better understanding of soil K supplying capacity and K fertilization strategy rather than the current recommendations, based on the plant-available K alone. In conclusion, the present study revealed that the variability of nutrient distribution was a consequence of complex interactions between the cropping system, nutrient application rates, and the native soil characteristics, and such interactions could be utilized to develop the nutrient management strategies for intensive smallholder system.

Keywords Soil nutrient · K fraction · Spatial variability · Site-specific nutrient management · Digital soil mapping

Introduction

About 40 % of the world's absolute poverty is prevalent in four South Asian countries of the sub-continent. The major constraints for livelihood improvement among the farmers in these areas chiefly arise from small farm holdings with high cropping intensity, different field management practices adopted for various crops with generalized nutrient recommendation systems, coupled with poor technological back-up support. This leads to inadequate and imbalanced use of plant nutrients, resulting in low productivity of crops in the region. The variability of soil nutrients is high under such farming practices due to large difference in farmers' knowledge, fertilizer application practices, crop sequence, farm managements, as well as resource availability among the farmers.

Spatial and temporal variability is recognized to be inherent to agricultural production systems. Variability in soil properties results mainly from the complex interactions between geology, topography, climate, as well as soil use (Quine and Zhang 2002). Variability may also occur as a result of land use and management strategies. As a consequence, soils can exhibit marked spatial variability both at the macro- and micro-scales (Xu et al. 2013; Vieira and Gonzalez Paz 2003; Brejda et al. 2000).

Geostatistics, based on the theory of regionalized variables, is the primary tool to capture the spatial variation of soil properties (Cressie 1993; Goovaerts 1998; Liu et al. 2008). Several geostatistical methods have been used by the researchers for developing the spatial variability maps of soil properties, e.g., kriging, co-kriging, regression kriging, etc. (Franzen and Peck 1995; Weisz et al. 1995; Hengl et al. 2004; Santra et al. 2008; Liu et al. 2008), depending upon the requirements and situations of field experiments. Several studies were carried out in the past to compare these geostatistical methods in order to search for the best method, but the results have been rather inconclusive (Warrick et al. 1988; Kravchenko and Bullock 1999; Mueller et al. 2001).

Spatial variability maps of soil properties may be used as guide for better management of farm inputs, such as water, fertilizer, pesticide, etc., in an agricultural farm. For example, Santra et al. (2008) prepared surface maps of soil water retention at two critical soil moisture constants for efficient use of water in an agricultural farm after considering the spatial variability of bulk density, organic carbon, silt, and clay contents. Similarly, studies already revealed that the spatial variability of soil available nutrient content often justifies the variable fertilizer recommendations, rather than a uniform fertilizer recommendation for the entire field (Carr et al. 1991). The former is highly essential for site-specific application of fertilizers (Štípek et al. 2004), which often gets affected by previous cropping and nutrient management practices and vice versa (Yang and Zhang 2008; Yasrebi et al. 2008; Sen and Majumdar 2006; Sen et al. 2007). A fairly recent study by Iftikar et al. (2010) clearly showed that comprehensive understanding of the spatial variability of soil nutrients under intensively cultivated small land holding systems in India helped to develop nutrient management guidelines that improved yield and profit to the farmers in a cropping system.

Alluvial soils are one of the major soil groups in India as well as in West Bengal, which are mainly found along the river plains of the river, Ganges, and they largely contribute to the national food basket. These alluvial soils in West Bengal are intensively cultivated with small land holdings along with blanket recommendations of N, P, and K for individual crops that tend to depletion or excess fertilization. These nutrient imbalances may also cause nutrient antagonism (e.g., Zn–P interactions) and waste of costly inputs like K fertilizer, which is nearly fully imported in India. Besides, the current recommendations for K fertilizer is based on the account of readily available pool of soil K (plant-available soil K) without taking the due cognizance of other relevant K fractions in the soils that contribute to the plant-available K pool and thereby sustain the long-term K supplying capacity in soils under intensive cropping. Therefore, a number of researchers raised questions as to the justification for the exclusive use of just one parameter, namely the plant-available pool of soil K, which includes the soil solution K and the exchangeable K content (K_{EX}), to determine the need for fertilization. Merbach et al. (1999) reported that after more than 40 years of exhaustive cropping without applications of K fertilizer, using only K_{EX} value-based soil test, failed to achieve the desired fertilization in cereals (wheat, barley) as well as vegetables (potato and sugar beet) as the yield of the cereals below the critical K_{EX} levels decreased merely by 8 %, whereas vegetables suffered yield loss to the tune of nearly 40 %. Interestingly, K_{EX} in these soils decreased within the first 10 years from an initial value of 90 mg/kg to around 50 mg/kg and remained at that level for the following 30 years. A long-term experiment with grassland at Rothamsted showed that the content of K_{EX} after 7 years without potash fertilization hardly changed but rather increased slightly in spite of K removal by the harvested grass (Johnston et al. 2001) which, however, was not measured. The dynamics of exchange between different soil K fractions were obviously was enough (compared with the crop growth period) to mask any possible change in the content of post-harvest soil K_{EX} status. Johnston et al. (2001)) also reported a smaller increase in K_{EX} than the K balance or removal of more K from the soil, as compared with the decline in K_{EX} without application of K. This observation raises the question as to the validity of relying on only one parameter while assessing the soil K status in the Garden Clover experiment at Rothamsted. In view of such findings, a systematic study was carried out to explore the spatial variability of OC, available N, P, and K, and different K fractions in intensively cultivated soils of a village in the alluvial zone of West Bengal, India, as well as the bearing, if any, of such variation on the crop and nutrient management practices adopted by the farmers.

Materials and methods

Study area and soil sampling

This study was conducted in an intensively cultivated area of India, namely Ghoragacha village from Chakdah Block, Nadia district, located in the alluvial plains of West Bengal (22° 98′ 34″–22° 98′ 39″ N, 88° 31′ 34″–88° 31′ 49″ E) (Fig. 1). The total cultivated area of the village is ~25 ha. The area is hot and humid with average annual temperature range of 20–31 °C and relative humidity varying between 58 and 91 %. Average annual rainfall is 1443 mm with most of the total annual rainfall (83 %) being received during the period from July to October. The cropping intensity of the village is high (267 %). Paddy and vegetables are the two major crops in this village, while a variety of other crops like jute, pulses, oilseeds, elephant foot yam, banana, guava, etc., are also grown. A detailed list of crops grown in the village along with the applied fertilizer dose is presented in Table 1. Land holding size of the farmers ranges from 0.03 to 0.27 ha with an average of 0.12 ha. Application of fertilizers in the cultivated fields is based on farmers' perception or else the general fertilizer recommendations for the whole state. According to the village level survey with the farmers, it has been found that the average rate of inorganic fertilizer application per calendar crop year was 125 kg N ha^{-1}, 187 kg $P_2O_5 ha^{-1}$, and 75 kg K_2O ha^{-1}. Organic source of nutrients such as cow dung manure, mustard cake, and neem cake are used in crops with an average application rate of 1841, 730, and 375 kg ha^{-1}, respectively.

Soil sampling and analysis

One hundred composite surface soil samples (0–15 cm) were collected using 100×100 m grid from the selected farmers' field in the study area where the crops were either in late maturity stage or already harvested. The geographical coordinates of the sampling points were recorded using a geographical positioning system (GPS; GARMIN GPS Map 60-Garmin USA make). Disturbed composite soil samples were collected in polythene bags from each sampling point and transported to the laboratory. Soil samples were then air-dried, thoroughly

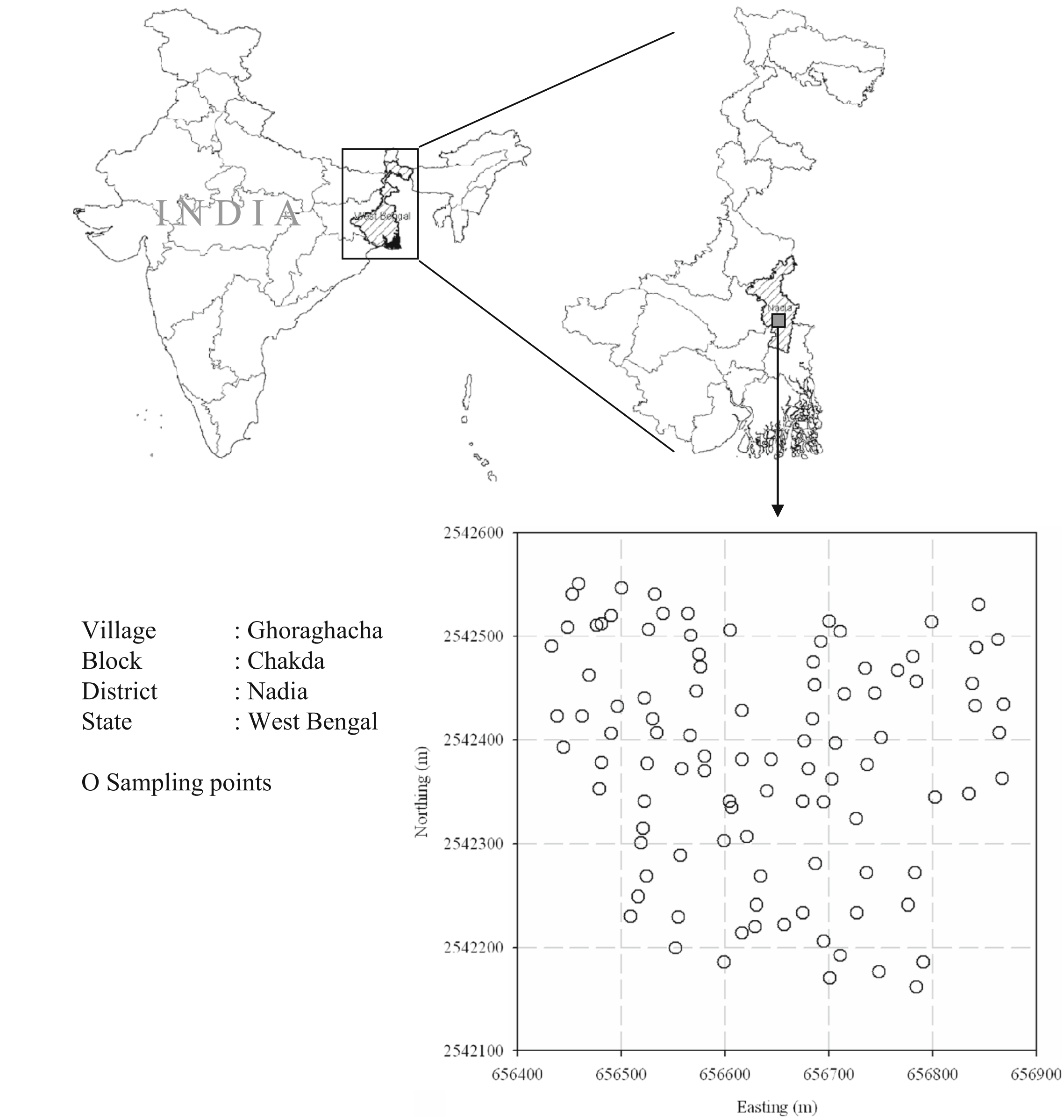

Fig. 1 Study area and soil sampling location in West Bengal, India (n=100)

mixed, ground gently by a wooden mortar, and finally passed through a 2-mm sieve. Organic carbon content of the soil samples was determined by the Walkley and Black (1934) method as described by Jackson (1956). Available N content was determined by alkaline permanganate method as described by Subbiah and Asija (1956). Available P content was measured by Olsen method by way of extracting 2.5 g of soil with 50 ml of 0.5 M $NaHCO_3$ (pH 8.5) for 30 min and determining the phosphorus in the extract by the L-ascorbic acid method (Murphy and Riley 1962). Among the different soil K fractions, water-soluble K (K_{WS}) was extracted by the method adopted by Grewal and Kanwar (1966), using the soil/water ratio of 1:5; exchangeable K (K_{EX}) was extracted by neutral (N) NH_4OAc with a soil: extractant ratio of 1:10 as mentioned in Pratt (1965); K_{EX} and non-exchangeable K (K_{NEX}) were extracted together from soils through gently boiling the samples with 1 M nitric acid (HNO_3) at a ratio of 1:10 for 10 min over sand bath. After extractions of different fractions, K content of each fraction was

Table 1 Average rate of N, P, and K application in soil for cultivation of different crops

Crops	Botanical name	Inorganic fertilizer (kg/ha)			Organic source (kg/ha)		
		N	P_2O_5	K_2O	N	P_2O_5	K_2O
Brinjal	*Solanum melongena* (L)	104	72	180	43	17	17
Banana	*Musa paradisiacal* (L)	690	240	1080	11	9	11
Pointed gourd	*Trichosanthes dioica* (L)	104	72	135	5	2	1
Cabbage	*Brassica oleracea* (L)	86	60	113	11	9	11
Coriander	*Coriandrum sativum* (L)	56	56	56	0	0	0
Sesame	*Sesamum indicum* (L)	0	0	0	11	9	11
Potato	*Solanum tuberosum* (L)	173	144	225	68	30	20
Cucumber	*Cucuumis sativus* (L)	104	72	180	43	17	17
Elephant foot yam	*Amorphophallus companulatus* (L)	173	144	225	77	38	29
Bitter gourd	*Momordica charantia* (L)	141	98	98	0	0	0
Pumpkin	*Cucurbita maxima* (Duch)	57	59	59	8	6	8
Chili	*Capsicum frutescens* (L)	107	98	98	19	4	5
Kharif rice	*Oryza sativa* (L)	68	39	75	4	3	4
Jute leaf	*Corchorus olitorius* (L)	92	59	59	43	17	17
Boro Rice	*Oryza sativa* (L)	76	60	90	11	9	11
Bottle gourd	*Laegenaria leucantha* (Rusby)	57	59	59	8	6	8
Guava	*Psidium guajava* (L)	29	89	116	25	11	7
Mustard	*Brassica juncea* Coss (L)	360	39	39	0	0	0
Radish	*Raphanus sativus* (L)	23	6	6	0	0	0
Jute	*Corchorus olitorius* (L)	420	195	195	8	6	8
Wheat	*Triticum aestivum* (L)	75	59	59	11	9	11
Pigeon pea	*Cajanus cajan* (Millsp)	0	0	0	0	0	0
Tomato	*Solanum melongena* (L)	0	0	0	0	0	0
Ridge gourd	*Luffa acutangula* (Roxb)	104	72	180	43	17	17

measured using the flame photometer (Model: Systronics, 121 of Systronics India Limited). Non-exchangeable K content was estimated by subtracting the amount of K extracted by neutral normal NH_4OAc from the amount of K extracted by HNO_3. Available K content was computed by adding the water-soluble K and exchangeable K contents. Descriptive statistics of determined soil properties were computed through the standard methods (Gomez and Gomez 1976) using SPSS software version 10.

Spatial variability of soil properties

Spatial variability of soil properties is expressed by semivariogram $\widehat{\gamma}(h)$, which measures the average dissimilarity between the data separated by a vector h (Goovaerts 1998). It was computed as half of the average squared difference between the components of data pairs:

$$\widehat{\gamma}(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [z(x_i) - z(x_i + h)]^2 \tag{1}$$

Where, N (h) is the number of data pairs within a given class of distance and direction, z (x_i) is the value of the variable at the location x_i, and $z(x_i+h)$ is the value of the variable at a lag of h from the location x_i.

Experimental semivariogram value for each soil property was computed using Variogram Estimation and Spatial Prediction Error Plus Error (VESPER) (Minasny et al. 2002) and plotted against the lag distance h. During pair calculation for computing semivariogram, maximum lag distance was taken as half of the minimum extent of sampling area to minimize the border effect. Twelve lag classes and 25 % lag tolerance were used during the calculation of experimental semivariogram. In this study, omni-directional semivariogram was computed for each soil property because no significant directional trend was observed. The computed semivariogram values ($\widehat{\gamma}(h)$) for corresponding lag (h) were fitted with the available theoretical semivariogram models using weighted least-square technique. Weight for each lag was assigned according to the number of pairs for that particular lag. Best-fit model with the lowest value of residual sum of square was selected for each soil property. Four commonly used semivariogram models, e.g., spherical, exponential, Gaussian, and linear models were fitted to each soil property. Expressions for different semivariogram models used in this study are given below.

Spherical model:

$$\gamma(h) = C_0 + C\left[1.5\frac{h}{a} - 0.5\left(\frac{h}{a}\right)^3\right] \text{ if } 0 \le h \le a \text{ otherwise } C_0 + C \tag{2}$$

Exponential model:

$$\gamma(h) = C_0 + C_1\left[1 - \exp\left\{-\frac{h}{a}\right\}\right] \text{ for } h \ge 0 \tag{3}$$

Gaussian model:

$$\gamma(h) = C_0 + C\left[1 - \exp\left\{\frac{-h^2}{a^2}\right\}\right] \text{ for } h \ge 0 \tag{4}$$

Linear model:

$$\gamma(h) = C_0 + C_1\left[\frac{h}{a}\right] \text{ if } h < \text{a otherwise } = C_0 + C_1 \tag{5}$$

In all these semivariogram models, nugget, sill and range were expressed by C_0, (C+C_0), and a, respectively. In case of exponential and Gaussian models, a represents the theoretical range. Practical range for these two semivariogram models was calculated as the lag distance for which semivariogram value was 95 % of sill. Nugget (C_0) defines the micro-scale variability measurement error for the respective soil property, whereas partial sill (C) indicates the amount of variation which can be defined by spatial correlation structure.

Kriging

Surface map of soil nutrient contents was prepared using the semivariogram parameters through ordinary kriging. Ordinary kriging estimates the value of soil attributes at unsampled locations, $z(u)$, using weighted linear combinations of known soil attributes $z(u_\alpha)$ located within a neighborhood $W(u)$ centered around u.

$$z^*(u) = \sum_{\alpha=1}^{n(u)} \lambda_\alpha z(u_\alpha) \tag{6}$$

where λ_α is the weight assigned to datum $z(u_\alpha)$ located within a given neighborhood, $W(u)$ centered on u. Weights for n number of neighborhood points were chosen as such so as to minimize the estimation or error variance, $\sigma_E^2(u)=\mathrm{Var}(z^*(u)-z(u))$ under the constraint of no-bias of the estimator. The kriged map for each soil property was prepared using geostatistical analysis tool of ArcGIS 9.1. (ESRI 2005).

Accuracy of the soil nutrient maps was assessed through cross-validation approach (Davis 1987). Root-mean-squared residual (RMSR) was calculated to ascertain the accuracy of prediction, whereas the standard error of prediction was computed as a measure of the uncertainty of prediction. The RMSR is given by.

$$\mathrm{RMSR} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left[z(x_i) - \widehat{z}(x_i)\right]^2} \tag{7}$$

where (x_i) is the predicted value at the location i and N is the total number of sampling points. Small RMSR values indicate more accurate point-by-point estimation.

Result and discussion

Descriptive statistics of soil nutrient contents

Descriptive statistics of soil organic carbon (OC), N, P, K, and different fractions of soil K contents are recorded in Table 2. A large majority of the samples (75 %) had less than 0.6 % of organic carbon. Among the major macronutrients, all soil samples were low in N content, with 75 % samples recording <173 kg/ha of available N. Available P content was generally very high throughout the village. Available K content of 25 % of the samples was low (<200 kg/ha). It is thus evident that N was the

Table 2 Descriptive statistics of major soil nutrients in Goragacha village

Soil properties	Minimum	Maximum	Mean	Standard deviation	CV (%)
Organic carbon (%)	0.28	0.82	0.52	0.11	21.2
Available N (kg/ha)	129	195	161	16.3	10.1
Available P_2O_5 (kg/ha)	10.0	678	362	173	47.8
Available K_2O (kg/ha)	96.0	640	283	109	38.6
Water-soluble K (cmol (p+)/kg)	0.01	0.39	0.08	0.06	75
Exchangeable K (cmol (p+)/kg)	0.08	0.48	0.23	0.08	34.8
Non-exchangeable K (cmol (p+)/kg)	1.91	15.8	7.9	3.32	42

most limiting factor among the macronutrients. Among different fractions of K, water-soluble K (K_{WS}) was found highly variable (CV=75 %) (Table 2). Interestingly, non-exchangeable K (K_{NEX}), a relatively stable parameter of soil, also exhibited high variability (which is ever more than that of the K_{EX}), which essentially indicates the contribution of N_{EX} to plant's K requirement through exchange equilibria in case of sub-optimal application of K fertilizer. Indeed, the scientists have recently questioned the viability of considering only the available K fraction in soil to assess its native K fertility status, especially under intensive cropping on a long-term basis. The underlying argument is that the sub-optimal level of K application to the Indian soils caused continuous depletion of the K reserves and analyzing only the available soil K fraction provides a partial picture of the native K status in the soils (Sanyal 2001). Thus, any recommendation based on such partial picture is likely to influence the dynamics of K in the soil in an unfavorable manner.

Pearman's correlation coefficient among different soil nutrient contents and different fractions of K are presented in Table 3. Organic carbon was found significantly correlated with available N (r= 0.27*), while available P was significantly correlated with available K (r=0.44*). Significant positive correlation was also observed among different fractions of K and available P content (Table 3). Although the water-soluble K and exchangeable K was positively correlated, there was no correlation of non-exchangeable K with K_{WS} and K_{EX}. Such types of correlations among different fractions of K reflect different degrees of exploitation or build-up of K_{NEX} under intensive cultivation that cannot be evaluated from the estimation of only the readily plant-available forms of potassium in soil.

Spatial variability of soil nutrient contents

The experimental semivariogram of the OC and the NPK contents were fitted in theoretical models as given by Eqs. (2–5), and the results are presented in Table 4. Root-mean-squared residuals were found minimum corresponding to the spherical model for available N and P contents and therefore are considered the best-fit model for these soil parameters. Similarly, linear model and exponential model was found best for the OC content and the available K content, respectively. Spatial structural parameters, i.e., nugget, sill, and range corresponding to the best-fit model are also given in Table 4. Nugget component, which describes the small-scale variation, was found to be 17 and 28 % of total spatial variation for OC content and available N content, respectively. However, the nugget component (indicator of micro-scale variation) was found quite high for the available P and the K content (49 and 67 %, respectively). This micro-scale variation of P and K contents might be attributed to the improper does of application in crops by the farmers of the study area. The range of spatial variation was found ~50 m for OC content, available N content and available K content. This indicates that in the field these soil parameters are spatially correlated with each other up to a distance of 50 m, beyond which the variation is considered as random. The range for available P was 283 m, which is higher than the remaining soil nutrient contents. Spatial correlation structure for available P and K were comparatively better than those for OC and available N. Semivariogram structures of all these soil nutrient contents are presented in Fig. 2.

Spatial variations structures of different faction of K were also calculated and computed. The semivariogram parameters for the best-fit model are given in Table 5,

Table 3 Correlation coefficients among measured soil nutrient contents in Ghoragacha village

Major soil nutrients	OC	Available N	Available P	Available K	Water souble K	Exchangeable K	Non-exchangeable K
OC	1.00						
Available N	0.27**						
Available P	−0.05	0.13					
Available K	0.02	−0.01	0.44**				
Water-souble K	−0.08	−0.13	0.38**	0.84**			
Exchangable K	0.10	0.10	0.39**	0.91**	0.53**		
Non-exchangeable K	0.01	−0.08	−0.19	0.16	0.12	0.15	1.00

*0.05; **0.01—levels of significance

whereas the corresponding semivariogram structures are presented in Fig. 3. The Gaussian model was found best for K_{WS} and K_{NEX} whereas the linear model was found best for K_{EX}. Nugget component was noted to be negligible for K_{WS} content. For K_{EX} and K_{NEX}, nugget was 72 and 52 % of total variation, respectively. The range was small (23 m) for K_{WS} content, while it was ~350 m for K_{EX} and K_{NEX}. The variability of K_{EX} and K_{NEX} might be attributed to the disturbances to the potash equilibria between different K fractions in soil, caused by the improper doses of K application in different crops influencing thereby the available K (which is also a component for K equilibrium).

Surface map of OC and NPK contents

Using the semivariogram parameters mentioned above, the surface map of soil nutrient contents was prepared with a grid size of 10×10 m (0.01 ha) and is presented in Fig. 4. The status of available nutrient contents at different portions of the individual farmers' field with average land holding of 0.13 ha may be assessed using these maps. An overview of the pattern of OC and available NPK contents are described below.

The surface map of OC content shows that the south-west portion and the extreme north-east corner of the village had low OC content (0.32–0.44 %), whereas the central and the south-east portion of the village had

Table 4 Semivariogram parameters of major soil nutrient contents

Major soil nutrient contents	Semivariogram models	Root-mean squared residual	Nugget (C_0)	Partial sill (C_1)	Range (a)
OC (%)	Spherical	0.00067	–	–	–
	Exponential	0.00093	–	–	–
	Gaussian	0.00069	–	–	–
	Linear	0.00062	0.0021	0.0102	58 m
Available N (kg/ha)	Spherical	14.21	76.66	199.6	43 m
	Exponential	16.27	–	–	–
	Gaussian	14.45	–	–	–
	Linear	17.88	–	–	–
Available P (kg/ha)	Spherical	706.2	16,320	17,313	283 m
	Exponential	1004.2	–	–	–
	Gaussian	911.0	–	–	–
	Linear	756.4	–	–	–
Available K (kg/ha)	Spherical	641.0	–	–	–
	Exponential	607.4	8222.5	4072.2	55 m
	Gaussian	648.8	–	–	–
	Linear	721.2	–	–	–

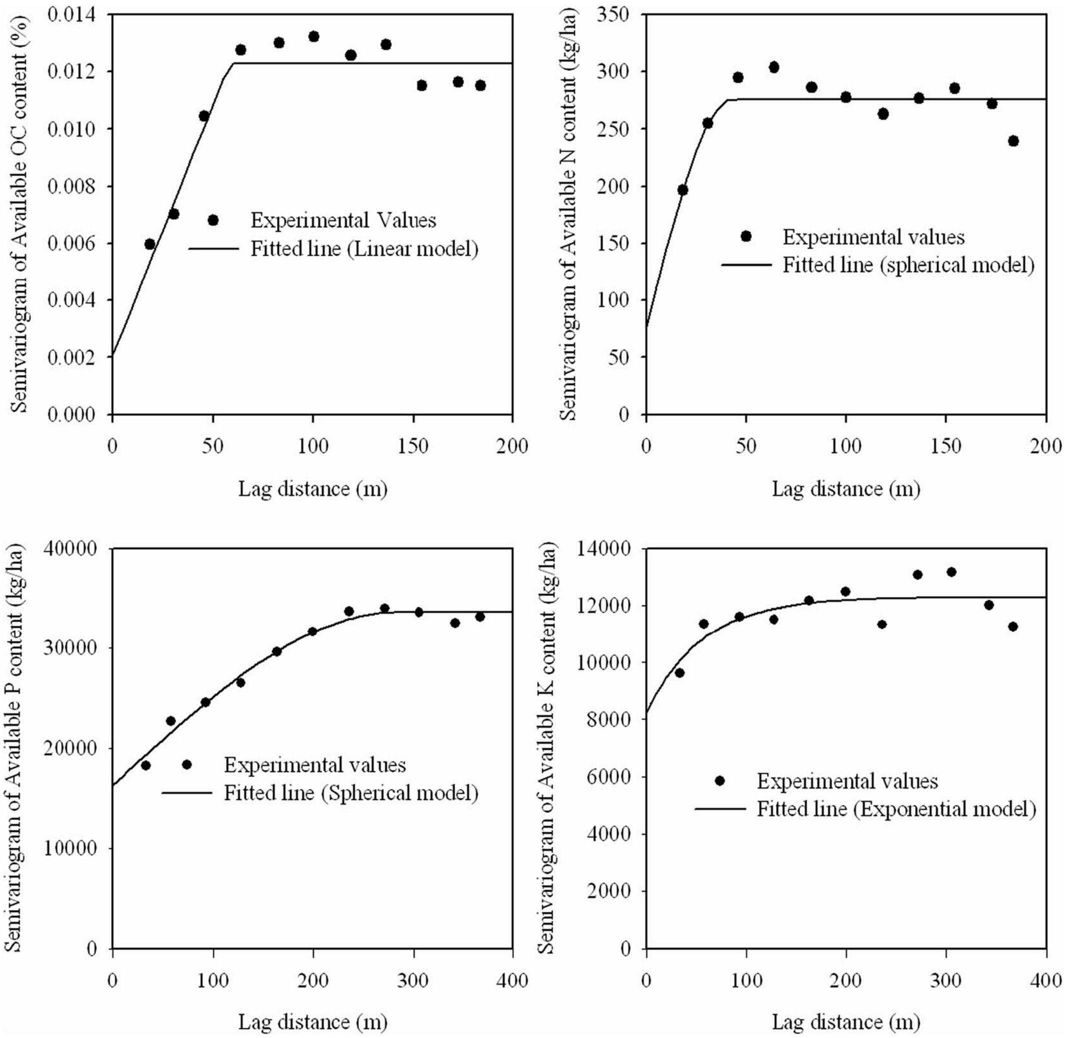

Fig. 2 Semivariogram parameters of organic carbon content, available N content, available P content, and available K content of soil in the Ghoragacha village of Nadia district, West Bengal, India

comparatively high OC content (0.57–0.76 %). The farmer survey data showed that the application rate of organic manures at the south-west and the north-east portions of the village were comparatively lower than the remaining portion of the village.

The available N content of the village was scattered and ranges from 134 to186 kg ha^{-1}. The south-west portion of the village was low in available N content (134–147 kg ha^{-1}) since the application rate of nitrogenous fertilizer was quite lower (~294 kg N ha^{-1}) in those areas compared with other parts of the village (~478–553 kg N ha^{-1}) (Fig. 7). Furthermore, the low OC content in the south-west portion of the village was also responsible for lower nitrogen since these parameters are interlinked via the microbial mineralization processes. Application of organic source of N was also low at the south-west portion of the village.

The available P_2O_5 content of soils was found high throughout the village. Overall, an increasing trend from the west to the east direction was observed. The south-eastern portion of the village was very high in available P_2O_5 content (509–588 kg ha^{-1}) (Fig. 4). Application rate of phosphatic fertilizer was higher at the eastern portion of the village (302–320 kg P_2O_5 ha^{-1}) than in the western portion (202–274 kg P_2O_5 ha^{-1}) (Fig. 7).

The available K content was found less in the central part of the village (196–247 kg ha^{-1}). The south-eastern part of the village had comparatively high amount of available K (379–491 kg ha^{-1}; average, 376 kg K_2O ha^{-1}), where the rate of K fertilizer application is

Table 5 Semivariogram parameters of different fractions of potassium content in soil

Fractions of K content in soil	Semivariogram models	Root-mean squared residual	Nugget (C_0)	Partial Sill (C_1)	Range (a)
Water-soluble K (cmol (p+)/kg)	Spherical	0.0002729	–	–	–
	Exponential	0.0003419	–	–	–
	Gaussian	0.0002706	0.00003	0.00383	23 m
	Linear	0.0004969	–	–	–
Exchangable K (cmol (p+)/kg)	Spherical	0.000211	–	–	–
	Exponential	0.000211	–	–	–
	Gaussian	0.000234	–	–	–
	Linear	0.000202	0.0048	0.0019	349 m
Non-exchangeable K (cmol (p+)/kg)	Spherical	0.3946	–	–	–
	Exponential	0.3957	–	–	–
	Gaussian	0.2556	8.655	8.003	368 m
	Linear	0.3946	–	–	–

low (Fig. 7). This may be attributed to a better reserve pool of K (non-exchangeable K) in this part which did not have a past history of exhaustive cropping, and thus was yet to suffer from a large-scale depletion of the reserve pool, thereby maintaining a larger available pool of K through the equilibrium. It is interesting to note here that the available K was relatively low at the north-east part of the village (196–247 kg ha^{-1}), despite a high rate of potassium application in this part (960± 170 kg ha^{-1}). This tends to suggest a poor reserve pool of K (in this part of the village), which was not sufficient to maintain the available pool of K under the present rate of K fertilizer application to support the given cropping sequence.

The accuracy and uncertainty of prediction (RMSR values) of OC content, and available N, P, and K contents are presented in Fig. 5. The uncertainty of prediction in terms of the standard error was found reliable. The RMSR values were better in soil organic carbon and available nitrogen; hence, these two parameters can be used for farm-level planning. However, the prediction uncertainty, specifically for P and K contents is high which may be improved by application of advanced geostatistical techniques.

Surface map of K fractions

As mentioned above, the surface map of available K, which is the composite of water-soluble K and exchangeable K fractions, is shown in Fig. 4. Surface maps of exchangeable K and non-exchangeable K are presented separately in Fig. 6. Overall, an increasing trend of non-exchangeable K from the east to the west direction of the village was observed. Highest amount of non-exchangeable K was observed at the south-west portion of the village (9.3–11.2 cmol (p+)/kg), which is equivalent to 8.5–10.2 t K ha^{-1}. Research on the semiquantitative analysis of the clay fraction of these Inceptisols showed that all the soils were dominant in mica, followed by smectite, chlorite, and vermiculite (Chatterjee 2008). Indeed many workers reported earlier that the illitic soils of the Indo-Gangetic plain contain large amounts of non-exchangeable K (Bhonsle et al. 1992; Sekhon et al. 1992; Sanyal 2001). Therefore, the high status of non-exchangeable K in the south-west portion of the village could be attributed to the mineralogical composition of the corresponding soils. It was also noted that the potassic fertilizer application during the last three crop cycles was relatively low at 370± 80 kg K_2O ha^{-1} in this part of the village (Fig. 7), as compared with the remaining portions of the said village. Indeed, in this context, it is of interest to note that the surface map of exchangeable K revealed the opposite trend of non-exchangeable K vis-à-vis the exchangeable K contents in soils in the fields under investigation. The highest amount of exchangeable K was found at the south-eastern part of the village (0.283–0.318 cmol (p+)/kg), which is equivalent to 257–289 kg K ha^{-1}. The amount of potassium present in the soil solution is often smaller than the crop requirement for potassium, particularly for soils supporting a highly intensive system as in this study. Studies have shown that intensive cropping for a long period would reduce the exchangeable K to a minimum level and at this level

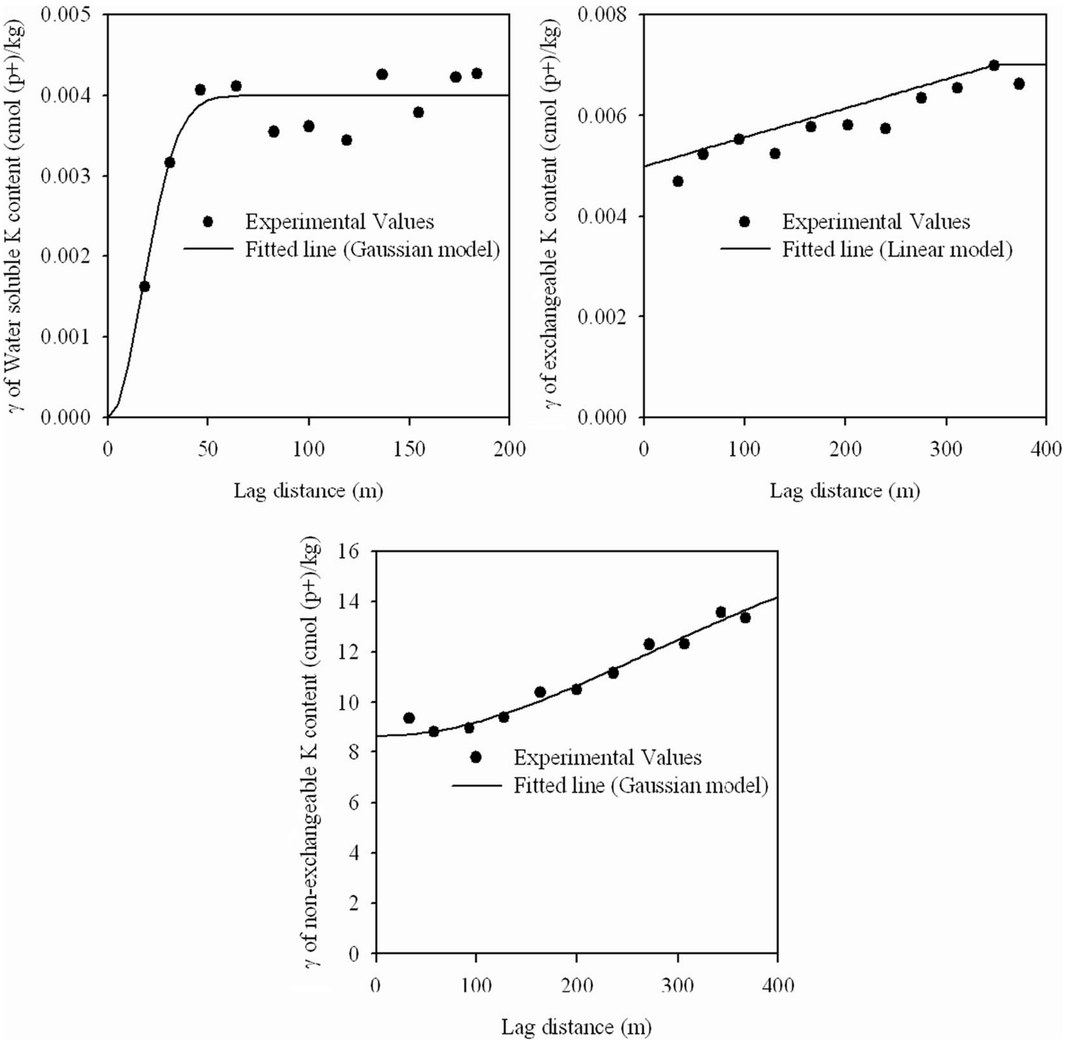

Fig. 3 Semivariogram parameters of water-soluble K content, exchangeable K content, and non-exchangeable content of soil in the Ghoragacha village of Nadia district, West Bengal, India

the release of non-exchangeable potassium gets triggered (Sachdeva and Khera 1980; Datta and Sastry 1988, 1989; Singh et al. 2004). Therefore, the exchangeable pool of K, which is largely influenced by the application of fertilizer (Jessymol and Mariam 1993), is low in the south-west portion of the village where the rate of potassium fertilizer application (370±80 kg K_2O ha^{-1}) is relatively low compared with a much higher rate of potassium fertilizer application (960±170 kg ha^{-1}) in the north-eastern part of the village. Interestingly, the non-exchangeable fraction of K is also quite low (4.5–5.7 cmol (p+)/kg) in the north-east part of the village despite a *recent* history of high rate of K fertilizer application, as stated above. However, the past cropping history showed that banana is cultivated in this part of the village during the last 6–7 years. Banana is known to be a heavy feeder of plant nutrients, especially K, removing about 1000 kg of K_2O at 40 t/ha yield level (Tandon 2000). It may be noted that the recent studies comparing the yields of horticultural crops (5 to 100 t ha^{-1}) and field crops (0.8 to 4.5 t ha^{-1}) emphasized that the soils under horticultural crops are being continuously mined rather than maintaining or building the corresponding native fertility for supporting the sustainable horticulture (Ganeshamurthy et al. 2011). Indeed, it appears that the soils located in the north-east part of the present village had undergone K withdrawal from

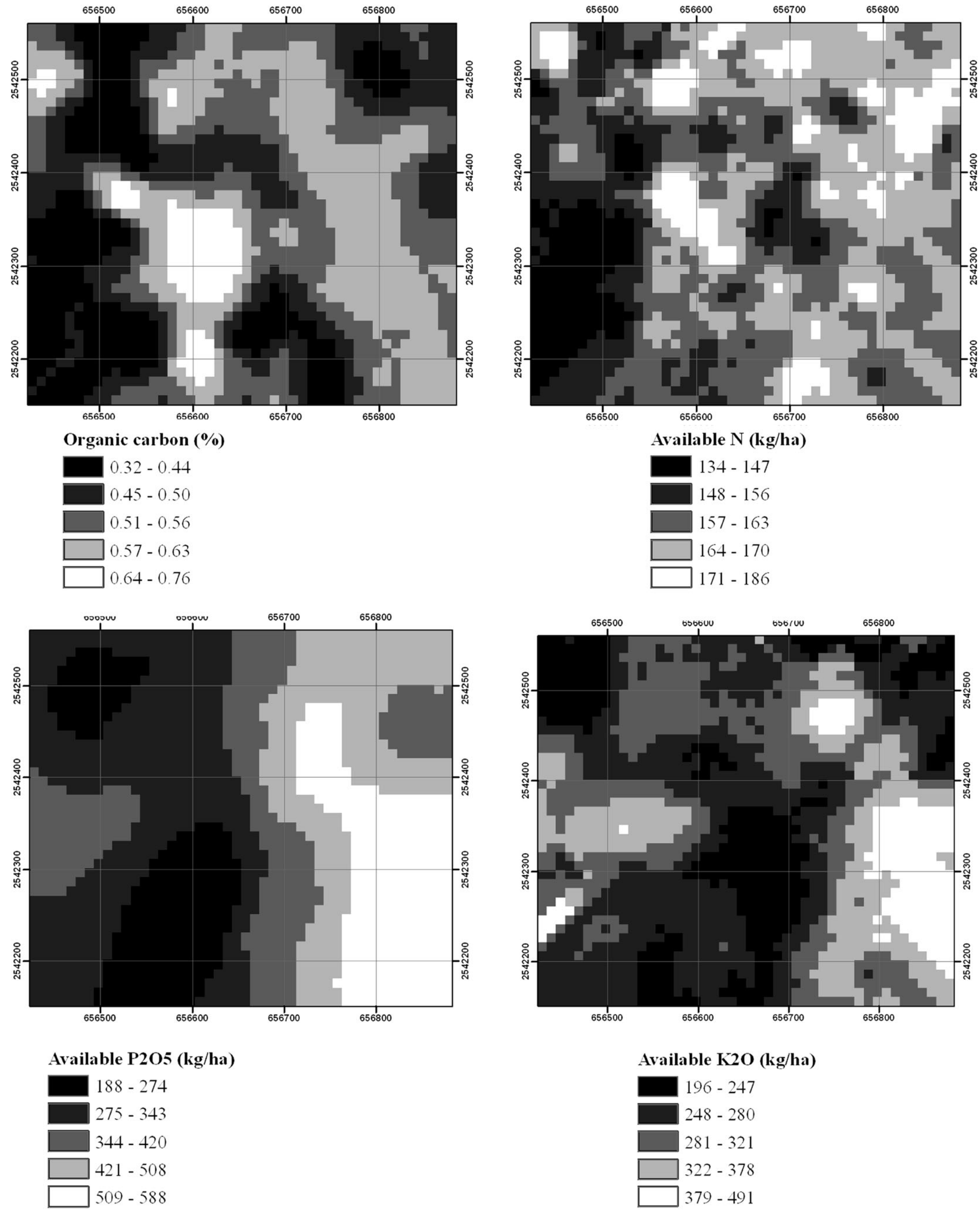

Fig. 4 Surface map of organic carbon content, available nitrogen content, available phosphorus content, and available potassium content of soil in the Ghoragacha village of Nadia district, West Bengal, India

the non-exchangeable potassium pool, even at a higher rate of K application, latter being apparently not sufficient to support the cropping sequence that had banana as a component crop. Earlier studies have shown that excessive depletion of K from the interlayer space of the illitic clays may lead to an irreversible structural collapse of these minerals, thereby severely restricting the release of K from such micaceous minerals (Sarkar et al. 2013). Furthermore, this will also adversely affect the potassium dynamics in soil as the entrapment of excess K (e.g., from the applied K fertilizer) in soil would be hindered and may cause excessive loss of the applied potassium through leaching. This would go a long way to impair the long-term soil fertility in respect of soil K, and is thus thoroughly unwarranted.

Fertilizer recommendation strategies

The present status of spatial variations in the available nutrient (NPK) contents of the soils in the given study brings out the potential of the *site-specific* fertilizer management strategies for applying the exact requirement of nutrients to individual fields and crops within a domain of individual holdings, supported by a range of management practices. This would have definite on-farm economic advantage, while accomplishing several off-farm environmental services as well. The small-scale production systems in India are characterized by a very large number of land holdings and therefore, the implementation of field-specific fertilizer application schedule would be a rather difficult proposition unless one is able to group the fields with similar indigenous nutrient

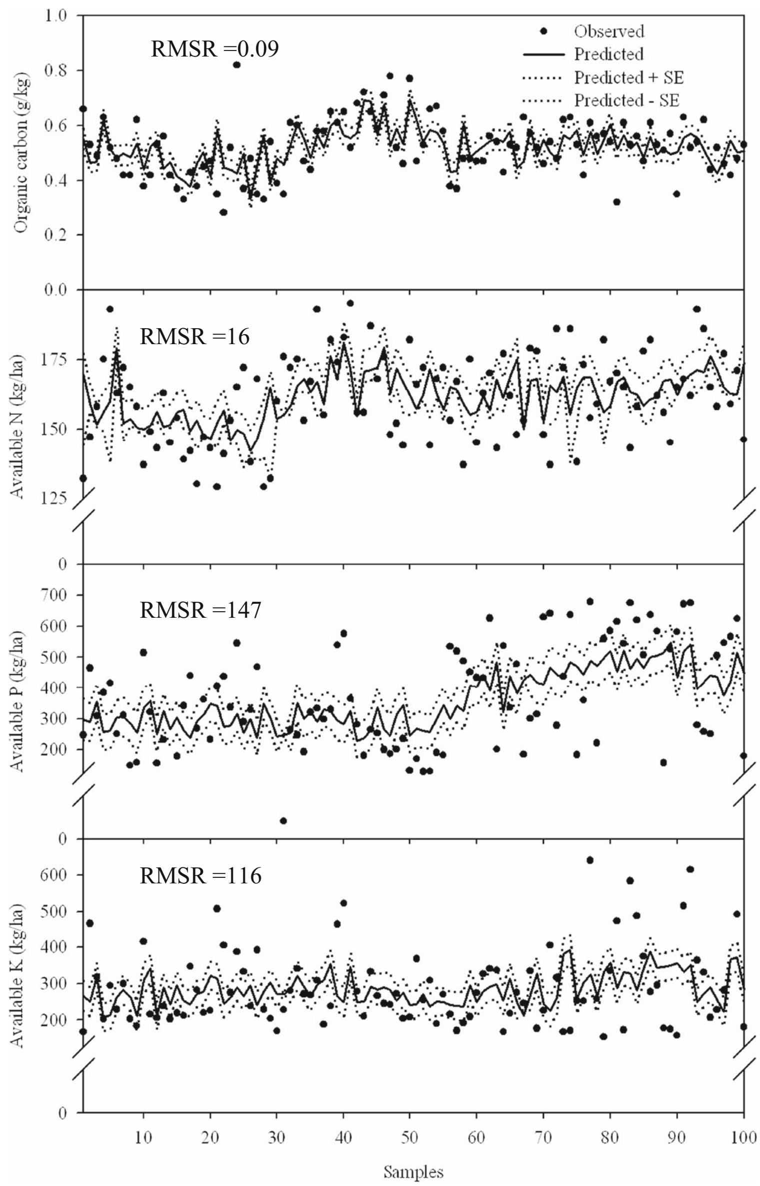

Fig. 5 Observed and predicted values of organic carbon content (%), available N content (kg ha^{-1}), available P content (kg ha^{-1}), and available K content (kg ha^{-1}) along with the corresponding RMSR values and standard error of prediction

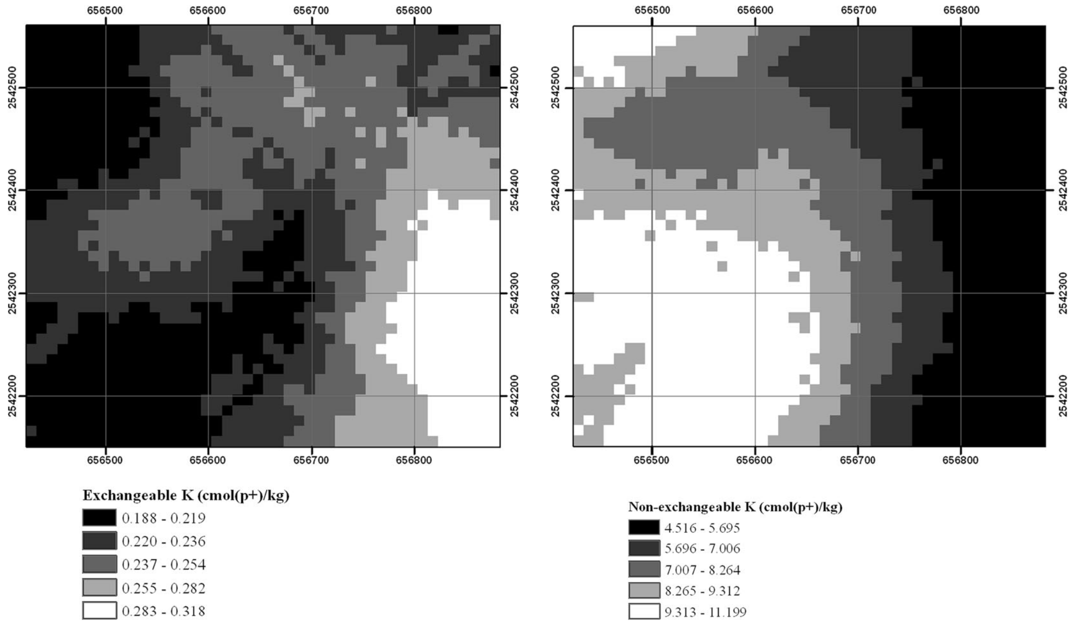

Fig. 6 Surface map of water-soluble K content, exchangeable K content, and non-exchangeable K content of soil in the Ghoragacha village of Nadia district, West Bengal, India

supplying capacity as unique management zones and treat them as one entity.

Field-specific fertilizer recommendation can be viewed as a cyclical process of *within* field data collection, data analysis and optimum decision making, leading to variable rate of fertilizer application, and finally evaluation. Yield goals, nutrient uptake requirement of crops, growing conditions, and soil properties are the necessary data inputs to the system. Describing spatial variability of *between-field* properties in a typical Indian production setting is a fundamental *first* step towards delineating the management zones, followed by the development of the above mentioned field-specific fertilizer recommendations. In order to develop such field-specific fertilizer recommendation for a particular crop, one end-user will have to first know the soil available nutrient status of the field by considering the longitude and latitude of the particular field. In the Indian scenario, one can then use the soil test crop response (STCR) equations, developed by the All India Coordinated Research Project (AICRP), Indian Council of Agricultural Research (ICAR), which are unique for each crop, soil type, and climatic conditions. The latter are used for prescribing the rates of fertilizer application for obtaining targeted yields of crops and have also been since validated with numerous front-line demonstrations in several states. For example, for the most cultivated crop, namely *kharif* rice in the present study area, the STCR equation is $FN=3.60T-0.253N$, $FP_2O_5=2.29T-0.82SP$, $FK_2O=2.61T-0.19SK$, where FN, FP_2O_5, and FK_2O are the fertilizer requirement to obtain the target yield of 0.1 T t/ha, and SN, SP, and SK are the soil test values for N, P, and K. Indeed one may interlink these equations with soil fertility map by putting the calculated soil test values in the equations for determining the fertilizer rates. For example, for a targeted yield of 4.0 t/ha of *kharif* rice in the south-west portion of the village (available N 134–147 kg/ha), the fertilizer N recommendation will be 107–110 kg/ha, while for the north-east portion of village (available N 171–186 kg/ha), it will be lower, i.e., 97–101 kg/ha. As a consequence, such field-specific fertilizer recommendation would minimize the probability of applying higher doses of nutrient inputs to the grid areas with relatively high soil test values and vice versa, and thereby adequately address the common impediment, namely the blanket application of fertilizer inputs. However, because of very high available P status throughout the said village, these equations do *not* stand and in such a case, minimum dose of P fertilizer can be maintained for at least two to three crop cycles in the given village.

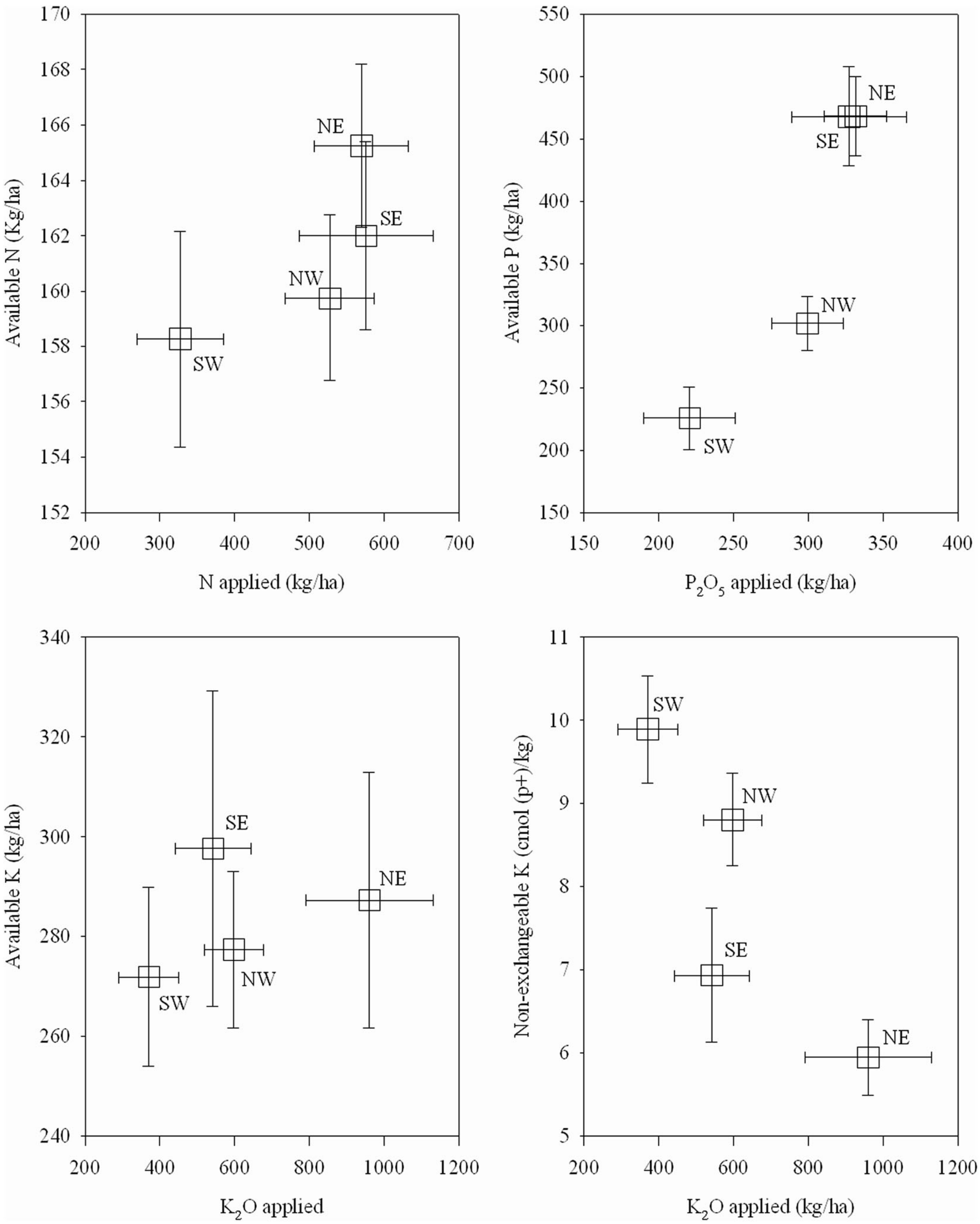

Fig. 7 Available N, P, K, and non-exchangeable K content of soil in relation to applied quantity of N, P_2O_5, and K_2O during the last three crop cultivations in the village

Conclusion

The present study showed that the Geostatistics-based mapping provided an opportunity to assess the variability in the distribution of native nutrients and other yield-limiting soil parameters across a large area. This could facilitate strategizing the appropriate management of nutrients leading to better yield, while ensuring a more effective environmental protection. From a more basic research point of view, these variability maps of nutrient status or other parameters of soils highlight the pattern of variability, including similarity in distribution among soil parameters across areas, thereby providing clues to the processes responsible for such variability. The present study brought out that such variability of nutrient distribution in the study area was a consequence of complex interactions between the cropping system, nutrient application rates and the native soil characteristics. Indeed, the delineation of spatial variability using the present Geostatistical approach also provides some advantages. Firstly, every individual piece of land within a defined cultivated area need *not* be sampled and would *not* require further analysis to know their soil nutrient status, which will be provided by the maps. Secondly, the surface maps developed for any defined area are capable of providing the nutrient or other soil parameter information for any field within that area, even if no soil sample was collected and analyzed from the particular plot. However, technical expertise on spatial data handling from extension workers is required by farmers to know the exact soil nutrient status of a particular area using the digital soil map. Besides, one can also use the handheld computers with GIS and decision support system tool linked with digital soil maps on-board tractor or fertilizer drills to take real-time nutrient management decisions in field (Reetz et al. 2004). So, the surface maps of the available nutrients can provide visual guidance as well as the quantitative information to guide nutrient application, based on the targeted yield of particular crops. Thus, the surface maps of nutrients could be utilized to develop the nutrient management strategies for intensive small-holder systems.

The present study also emphasizes the importance of inclusion of the non-exchangeable K fraction in the soil testing methodology for recommending potassium fertilizer for a particular soil/crop system, rather than depending only on the plant-available pool of soil K. It seems that depletion of potassium from the non-exchangeable pool in some of the study areas had resulted from the relatively low rates of K application in the past. These maps, particularly the non-exchangeable potassium distribution map, highlights the necessity of including these soil K fractions in the conventional soil test for arriving at the overall picture before making any K fertilizer application recommendation. However, a ratio of exchangeable/non-exchangeable K in soil may also provide an additional index for recommendation of K fertilizer. For instance, the higher the ratio for a soil, the more will be the fertilizer K requirement for obvious reasons explained above. Indeed, such recommendation has led to better yield and economic benefit for a group of farmers in the selected rice-growing soils of the alluvial tract of West Bengal, India (Chatterjee 2008).

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