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Quantifying Spatial Variability of Available Zinc in Alluvial Soils of Brahmaputra Plains, India

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Occurrence of zinc (Zn) deficiency in soils and plants has been accounted for worldwide including northeastern India. The present study was conducted to determine the spatial distribution and degree of risk of Zn deficiency in Brahmaputra plains of northeastern India using statistics and geostatistics. With the help of handheld global positioning system (GPS), 5494 soil samples were collected using 1 km × 1 km grid at 0-25 cm depth from three districts of Assam state of India namely, Tinsukia, Morigaon and Nalbari representing upper Brahmaputra valley zone (UBVZ), central Brahmaputra valley zone (CBVZ) and lower Brahmaputra valley zone (LBVZ) covering 6249 km^2 area and analyzed for pH, organic carbon (OC) and Zn. Dataset was normally distributed. Geostatistical analyses were carried out, including experimental variogram and model fitting. Analysis of the isotropic variograms indicates that the range values of 3900, 4400 and 5800 m for UBVZ, CBVZ and LBVZ, respectively. It implies that the length of the spatial autocorrelation was much longer than the sampling interval of 1 km. The nugget/sill ratio was 0.506, 0.859 and 0.589 for UBVZ, CBVZ and LBVZ, respectively and it indicates moderate spatial dependence. Further, with the ordinary kriging, spatial distribution map showed that the Zn is deficient for plants in the all the three zones of Brahmaputra plains. The probability map produced based on indicator kriging showed that Zn deficiency was noticed in 34% of crops grown area of the Tinsukia, 70% crops grown area in Morigaon and 85% of crops grown area in Nalbari districts. The correlation analysis showed that Zn was significantly and positively correlated with OC and significantly and negatively with pH in Brahmaputra plains. Thus, the present study is of immense help to minimize both yield loss and environmental threats of Zn toxicity due to under or overdose of Zn fertilizer application in Brahmaputra plains of northeastern India.

Key words: Brahmaputra plains, Zn deficiency, spatial distribution, geostatistics, kriging

The Brahmaputra valley of Assam is a part of vast Indo-Gangetic plains and covers an area of 56578 km^2. Total length of the valley is 722 km and average width is 80 km. Due to the differences in sediment deposited by the tributaries, variability in soil properties has been noticed across the Brahmaputra valley. Brahmaputra plains has been delineated into three distinct agro-climatic zones *viz.*, upper Brahmaputra valley zone (UBVZ), central Brahmaputra valley zone (CBVZ) and lower Brahpamaputra valley zone (LBVZ) based on the rainfall, terrain and soil characteristics of the valley (Deka *et al.* 2012). Rice based cropping sequences were common in the Brahmaputra valley. Four kinds of rice were being cultivated throughout the year namely Ahu, Sali, Boro and Hill. Assam has become 8th largest producer in India in respect of rice production and increase in production by 25% (2010-11 over 2008-09) (Ahmed *et al.* 2011). However, low soil fertility and soil degradation are the critical constrains for sustainable food production in the region (Reza *et al.* 2012a, 2019a).

Zinc (Zn) is one of the essential plant micronutrients and its importance for crop productivity is similar to that of major nutrients (Rattan *et al.* 2009). Zinc plays an important role in different plant metabolic processes like development of cell wall, respiration, photosynthesis, chlorophyll

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formation, enzyme activity and other biochemical functions. Zinc content and capacity to supply Zn for optimal crop growth, in agricultural soils vary widely (White and Zasoski 1999). Soils deficient in their ability to supply Zn to crops are alarmingly widespread across the globe. Over the years, deficiency of Zn in soil has been reported worldwide (Alloway 2008) and specifically in India (Behera *et al.* 2011; Shukla *et al.* 2016; Reza *et al.* 2016a). It was estimated that about 34% of the soils of Assam were deficient in Zn (Takkar 1996). Plant availability of Zn in soil is influenced by many factors and among them soil pH and organic carbon (OC) are important (Bhuyan *et al.* 2014).

Site-specific soil management has received considerable attention due to potential benefits of increasing input use efficiency, improving the economic margins of crop production and reducing environmental risks. Hence, a comprehensive understanding of spatial variability of soil properties is becoming increasingly essential. Variability in soil properties could be attributed to the complex interactions among climate, parent materials, topography, vegetation types and land use as well as management (Patil *et al.* 2010). Geostatistical tools could be effectively used to estimate spatial variability of soil properties at various levels like field, catchment as well as regional scale (Tesfahunegn *et al.* 2011; Reza *et al.* 2016b). Geostatistical techniques help in predicting values at unsampled locations by taking into account the spatial correlation between sampled points (Cambardella *et al.* 1994). Many researchers (Reza *et al.* 2016c, 2017, 2018, 2019b) used variography and kriging to study the distribution of soil properties.

In practice, kriging will often be the precursor to some management decision. For example, Lark *et al.* (2014) and Reza *et al.* (2013, 2015) has been used kriging technique to delineate areas at risk of trace element excess or deficiency. Such management decisions may often be based on threshold values of a soil property. Land use planning may also take into consideration the threshold values of soil properties. When a land manager wants to interpret a kriged map of a soil property with respect to some critical threshold value(s) then the uncertainty of these estimates becomes important. An estimate of the probability that the soil nutrients at a site not exceeding the advisory thresholds (conditional on the observed values at sample sites) may be more useful to the manager than a map of the estimated concentrations of the nutrient.

The general critical levels of Zn deficiency in soils fall in the range of 0.6-1.0 mg kg^{-1} (DTPA extracted) (Katyal and Rattan 2003). Based on the soil test, plant analysis and response of different crops to the application of Zn in greenhouse and field trials, the critical limit of Zn 0.6 mg kg^{-1} (DTPA extracted) for rice has been fixed for alluvial plains of West Bengal, India (Das and Saha 1999). Hence, 0.6 mg Zn kg^{-1} is used as a critical limit as Brahmaputra plains were traditionally a rice growing area and part of Indo-Gangetic plains. An attempt was made to evaluate the soil Zn status of the rice growing soils of the Brahmaputra valley of northeastern, India with the objectives of determining the spatial variability of soil Zn in Brahmaputra plains using ordinary kriging and also to describe the risk of Zn deficiency not exceeding a pre-selected threshold value using indicator kriging techniques.

Material and Methods

Site Description

The Brahmaputra valley of Assam lies in between 25°44′ to 28° N latitudes and 89°41′ to 96°02′ E longitudes. Upper Brahmaputra valley zone (UBVZ) comprises of Golaghat, Jorhat, Sivasagar, Dibrugarh, Tinsukia districts; central Brahmaputra valley zone (CBVZ) comprises of Nagaon, Marigaon districts and lower Brahmaputra valley zone (LBVZ) comprises of Goalpara, Dhubri, Kokrajhar, Bongaigaon, Kamrup, Nalbar and Barpeta districts of Assam. Tinsukia district from UBVZ, Morigaon district from CBVZ and Nalbari district from LBVZ were selected as representative sites for each zone in this study (Fig. 1).

Tinsukia District: Tinsukia district is a part of the UBVZ of Assam (27°07′ to 27°48′ N latitude and 95°02′ to 95°40′ E longitude) covering an area 3790 km^2. The average annual rainfall was 2500 mm with maximum temperature 39 °C and minimum temperature 9 °C. There were four broad soil subgroups in the district according to Soil Taxonomy (USDA) namely, Typic Kanhapludults, Typic Dystrudepts, Aeric Fluvaquents and Typic Udifluvents (NBSS&LUP 1999).

Morigaon District: Morigaon district is a part of the CBVZ of Assam (26°06′25′′ to 26°28′47′′ N latitude and 92°02′50′′ to 92°32′32′′ E longitude) covering an area 1287 km^2. The average annual rainfall is 1860 mm with maximum temperature 39 °C and minimum temperature 10 °C. There are seven broad soil subgroups in the district according to Soil

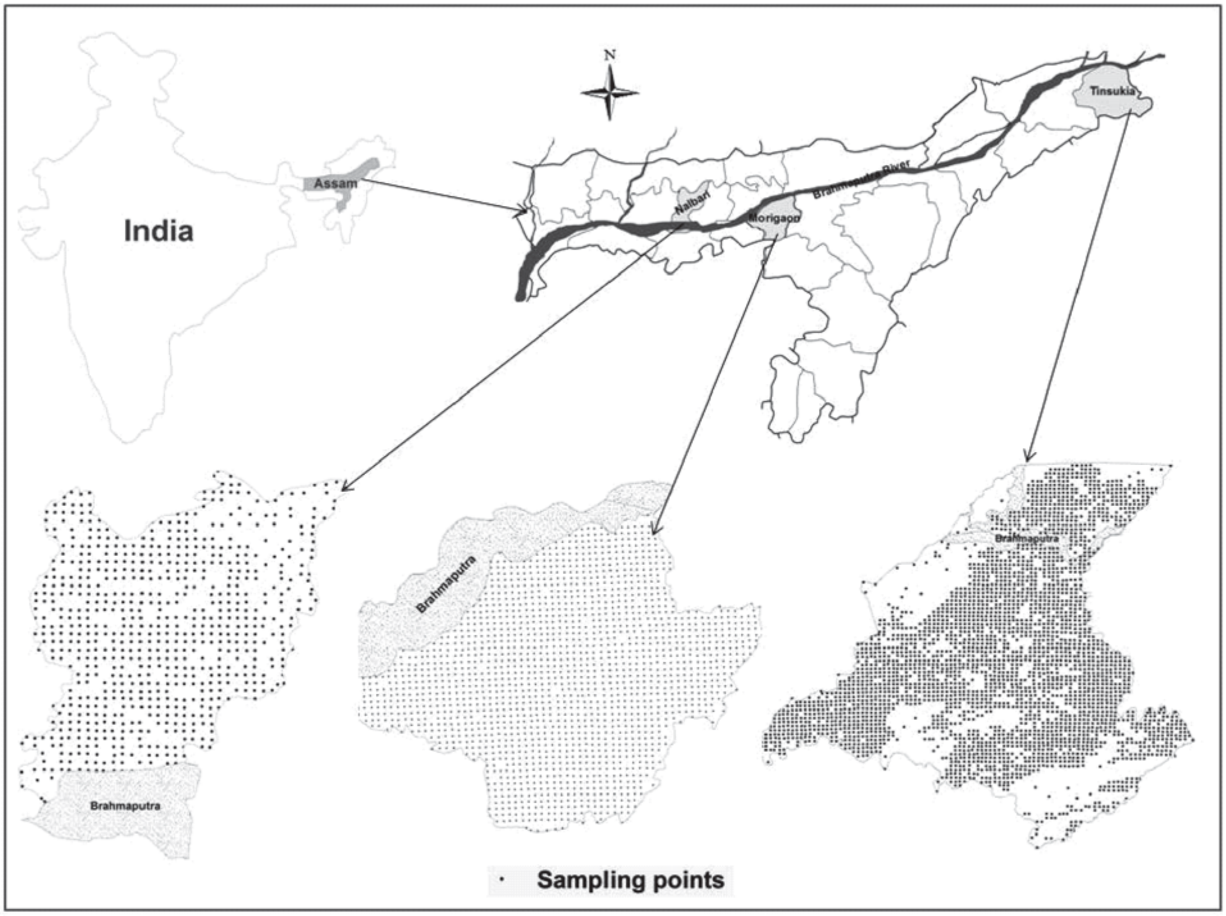

Fig. 1. Location and sampling points map of the study area

Taxonomy (USDA) namely, Aeric Endoaquepts, Aeric Fluvaquepts, Dystric Eutrodepts, Umbric Dystrudepts, Typic Udifluvents, Typic Dystrudepts and Typic Hapludults (NBSS&LUP 1999).

Nalbari District: Nalbari district is a part of the LBVZ of Assam (26°08′ to 26°35′ N latitude and 91°13′ to 91°36′ E longitude) covering an area 1172 km^2. The average annual rainfall is 1500 mm with maximum temperature 37 °C and minimum temperature 12 °C. There are three broad soil subgroups in the district according to Soil Taxonomy (USDA) namely, Aeric Fluvaquents, Typic Udifluvents, and Typic Haplaquents (NBSS&LUP 1999).

Soil Sampling and Analysis

From the entire study area a total of 5494 (Tinsukia district n=3062, Morigaon district n=1722 and Nalbari district n=710) georeferenced soil samples (0-25 cm depth) at an approximate interval of 1 km grid (Fig. 1) were collected with the help of hand-held global positioning system (GPS). Soil samples were air-dried and ground to pass through a 2-mm sieve. Soil pH was measured with 1:2 soil water ratio. The soil samples were sieved through 0.5 mm for determination of OC (Walkley and Black 1934). Available Zn in soils was extracted by DTPA (soil to solution ratio 1:2, shaking time 2 h) (Lindsay and Norvell 1978). Estimation of Zn was done on the clear extract with an atomic absorption spectrophotometer (AAS) (AA6300 model, Shimadzu), with wavelength of measurement being 214 nm.

Statistical and Geostatistical Analysis

The mean, maximum, minimum, standard deviation (SD), skewness, kurtosis and coefficient of variation (CV) for each analyzed soil property were computed. To find out the relationship between soil properties and Zn, Pearson's correlation coefficients were computed. The normal frequency distribution of data was verified by the Kolmogorov-Smirnov (K-S) test.

The spatial variability map of Zn was prepared by ordinary kriging interpolation. The structure of the spatial variability was assessed by calculating semivariograms.

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N} \left[z(x_i) - z(x_i + h) \right]^2 \quad \ldots(1)$$

where, $z(x_i)$ is the value of the variable z at location of x_i, h the lag and N(h) the number of pairs of sample points separated by h.

In this study, omnidirectional semivariogram was computed for Zn because no significant directional trend was observed. Using the model semivariogram, basic spatial parameters such as nugget (C_0), sill ($C + C_0$) and range (A) was calculated. Nugget is the variance at zero distance, sill is the lag distance between measurements at which one value for a variable does not influence neighboring values, and range is the distance at which values of one variable become spatially independent of another. The nugget/sill ratio was used as the criterion to classify the spatial dependence of variables. Ratio values lower than or equal to 0.25 were considered to have strong spatial dependence, whereas values between 0.25 and 0.75 indicated moderate dependence and those greater than 0.75 showed weak spatial dependence (Cambardella *et al.* 1994). Different semivariogram models were evaluated to select the best fit with minimum root mean square error (RMSE). Exponential model was fitted to the empirical semivariograms. The exponential model that fitted to experimental semivariograms is defined below as:

$$\gamma(h) = C_0 + C_1 \left[1 - \exp\left(-\frac{h}{a} \right) \right] \quad \ldots(2)$$

Risk of Zn deficiency not exceeding a pre-selected threshold value was assessed by using indicator kriging. Indicator kriging is a nonlinear geostatistics where the conventional linear kriging estimators are applied to the data after a nonlinear transformation. Here the nonlinear transform is to a discrete (binary) indicator variable.

Let us assume that a soil property *z* at location × take value *z*(*x*). In geostatistics, we treat this value as a realization of the random function *Z(x)*. An indicator transformation of *z*(*x*) can be defined by

$\omega_c(x) = 1$ if $z(x) \le z_c$, 0 otherwise, …(3)

where, z_c is a threshold value of the property. In indicator geostatistics, $\omega_c(x)$ is regarded as a realization of the random $\Omega_c(x)$,

$\Omega_c(x) = 1$ if $z(x) \le z_c$, else 0. …(4)

It can be seen that

$\mathrm{Prob}[Z(x) \le z_c] = E[\Omega c(x)] = G[Z(x); z_c]$, …(5)

where, Prob[], *E*[] denote, respectively, the probability and the expectation of the terms within the square brackets, and $G[Z(x); z_c]$ is the cumulative distribution function of *Z*(*x*) at value z_c. The principal of indicator kriging is to estimate the conditional probability that *z*(*x*) is smaller than or equal to a threshold value z_c, conditional on a set of observations of *z* at neighbouring sites, by kriging $\Omega_c(x)$ from a set of indicator-transformed data.

A set of data on *z* is transformed to the indicator variable $\omega_c(x)$. The variogram of the underlying random function $\Omega_c(x)$ is then estimated by:

$$\gamma_{\Omega c}(h) = \frac{1}{2M_h} \sum_{i=1}^{M_h} \left[\omega c(x_i) - \omega c(x_i + h) \right]^2 \quad \ldots(6)$$

where, M_h pairs of observations that are separated by the lag interval *h*. A set of estimates of this indicator variogram at different lags may then be modeled by one of the authorized continuous functions used to describe variograms.

An estimate of the indicator random function may then be obtained for a location *x* by kriging from the neighbouring indicator-transformed data. Indicator kriging is equivalent to ordinary kriging of the indicator variables $\omega_c(x)$ using the mean within the kriging neighbourhood as the expectation. Geostatistical analysis consisting of variogram calculation, kriging and mapping was performed using the ArcGIS 10.1 for window.

Accuracy of the soil maps was evaluated through cross-validation approach (Davis 1987; Reza *et al.* 2010). Among three evaluation indices used in this study, mean absolute error (MAE), and mean squared error (MSE) measure the accuracy of prediction, whereas goodness of prediction (*G*) measures the effectiveness of prediction (Utset *et al.* 2000). The MAE is a measure of the sum of the residuals (*e.g.*, predicted minus observed):

$$MAE = \frac{1}{N} \sum_{i=1}^{N} \left[\left[Z(x_i) - \hat{z}(x_i) \right] \right] \quad \ldots(7)$$

where, $\hat{z}(x_i)$ is the predicted value at location *i*. Small MAE values indicate less error. The MAE measure, however, does not reveal the magnitude of error that might occur at any point and hence MSE will be calculated.

$$MSE = \frac{1}{N} \sum_{i=1}^{N} \left[Z(x_i) - \hat{z}(x_i) \right]^2 \quad \ldots(8)$$

Squaring the difference at any point gives an indication of the magnitude, for example, small MSE values indicate more accurate estimation, point-by-point. The G measure gives an indication of how effective a prediction might be relative to that which could have been derived from using the sample mean alone.

$$G = \left[1 - \frac{\sum_{i=1}^{N} \left[z(x_i) - \hat{z}(x_i) \right]^2}{\sum_{i=1}^{N} \left[z(x_i) - \bar{z} \right]^2} \right] \times 100 \qquad \ldots(9)$$

where, *z* is the sample mean, G is one of the methods used for accuracies of interpolated maps (Tesfahunegn *et al.* 2011). Accuracies of interpolated maps of studied soil properties were checked by G values. According to Parfitt *et al.* (2009), positive G values indicate that the map obtained by interpolating data from the samples is more accurate than a catchment average. Negative and close to zero G values indicate that the catchment-scale average predicts the values at unsampled locations as accurately as or even better than the sampling estimates.

Results and Discussion

Descriptive Statistics of Soil Properties

Descriptive statistics for pH, OC and Zn were shown in table 1. The minimum and maximum concentration of Zn in UBVZ, CBVZ and LBVZ were 0.1 and 9.8, 0.1 and 2.1, and 0.05 and 5.0 mg kg^{-1}, respectively with mean values of 1.6, 0.6 and 0.5 mg kg^{-1}, respectively. The median values of Zn were lower than the mean in the studied areas, which indicates that the effects of abnormal data on sampling value were not high. pH varied 3.4-8.2 and OC ranged from 0.2-43.4 g kg^{-1} in the Brahmaputra plains. There was difference in the CV of the soil properties in Brahmaputra plains. Zinc exhibited high coefficient of variation (>50%) and OC (25-54%) moderate to high, while pH (<25%) showed low variation, according to guidelines provided by Warrick (1998). Other researchers also documented a smaller variation of soil pH compared to other soil properties (Sun *et al.* 2003). This may be attributed to the fact that pH values are log scale of proton concentration in soil solution, there would be much greater variability if soil acidity is expressed in terms of proton concentration directly. The variability observed in Zn was largely due to variation in soil parent material, rainfall and soil management. Although alluvial plain constitutes the large part of the study region, diversity in the physiography is observed in the UBVZ and LBVZ. Soils of UBVZ are primarily derived from gneisses and schists of the Archaean group while, the soils of the LBVZ are developed on both old and recent alluvium (Sen *et al.* 2003).

The pearson linear correlation analysis results showed that Zn was highly significantly negatively with pH (r = -0.379) and highly significantly negatively correlated with OC (r = 0.279) in Brahmaputra plains (Table 2). Similar observations were also reported by Reza *et al.* (2012b, 2016a) in the Brahmaputra plains of Assam, India.

Spatial Structure of Zn

The best fitted model was exponential for Zn with low RMSE values (Table 3). Analysis of the isotropic variograms indicated that the range values

Table 2. Pearson correlation coefficient of soil properties

Soil properties	pH	Organic carbon	Zinc
pH	1.000		
Organic carbon	0.406**	1.000	
Zn	-0.379**	0.279**	1.000

**Correlation is significant *at P < 0.01* level (2-tailed)

Table 1. Summary statistics for pH, organic carbon and zinc in Brahmaputra plains

Parameters	Minimum	Maximum	Mean	Median	SD*	CV (%)**	Skewness	Kurtosis	Distribution pattern
Upper Brahmaputra valley zone (UBVZ) (Tinsukia district, n=3062)									
pH	3.4	8.2	4.6	4.4	0.7	15	2.12	6.60	-
OC (g kg^{-1})	0.2	43.4	13.8	12.7	5.3	38	1.20	2.77	-
Zn (mg kg^{-1})	0.1	9.8	1.6	1.3	1.3	81	0.78	2.51	Normal
Central Brahmaputra valley zone (CBVZ) (Morigaon district, n=1722)									
pH	4.0	8.2	5.6	5.3	1.0	18	0.76	-0.36	-
OC (g kg^{-1})	0.3	34.5	11.3	10.6	6.1	54	0.57	0.31	-
Zn (mg kg^{-1})	0.1	2.1	0.6	0.5	0.4	67	0.59	1.23	Normal
Lower Brahmaputra valley zone (LBVZ) (Nalbari district, n=710)									
pH	4.0	7.1	5.3	5.3	0.6	11	0.21	-0.06	-
OC (g kg^{-1})	0.2	20.0	8.2	7.9	3.3	40	0.29	-0.06	-
Zn (mg kg^{-1})	0.05	5.0	0.5	0.4	0.47	94	0.98	2.30	Normal

*Standard deviation; **Coefficient of variation

Table 3. Geostatistical parameters of the fitted semivariogram model for zinc

Brahmaputra plains	Fitted model	Nugget (C_0)	Sill ($C+C_0$)	Range* (A) (m)	Nugget/Sill (%)	RMSE**
UBVZ	Exponential	0.326	0.644	3,900	0.506	1.180
CBVZ	Exponential	0.380	0.442	4,400	0.859	0.348
LBVZ	Exponential	0.305	0.517	5,800	0.589	0.427

*Range in m; **Root mean square error

of 3900, 4400 and 5800 m for UBVZ, CBVZ and LBVZ, respectively. It indicates that the length of the spatial autocorrelation was much longer than the sampling interval of 1 km. Therefore, the current sampling design is appropriate for this study and good spatial structure could be visualized on the interpolated map. The different range value for Zn in UBVZ, CBVZ and LBVZ soils might be due to combined effect of parent material, climate and adoption of different land management practices. In agreement with the present study, Behera *et al.* (2012) also reported the range value of 2500 to 9100 m in some acid soils of India. Information on the range in semivariogram of Zn acts as an indicator in future soil sampling designs in similar areas. The sampling interval should be less than half the semivariogram range. It is therefore recommended that for ensuing studies aimed at characterizing spatial dependency of Zn in similar areas, soil sampling should be done at distances shorter than the range found in this study.

To define different classes of spatial dependence for Zn, the nugget and sill ratio was used (Cambardella *et al.* 1994). The nugget/sill ratio was 0.506, 0.859 and 0.589, for UBVZ, CBVZ and LBVZ, respectively and indicated moderate spatial dependence (Table 3). The moderate spatial dependency of Zn in Brahmaputra plains could be attributed to both intrinsic factor (soil forming process) and extrinsic factors (soil fertilization and cultivation practices) (Cambardella *et al.* 1994).

Spatial Distribution and Zn Deficiency Map

Spatial map of Zn prepared through ordinary kriging indicated that low concentration of Zn was mainly observed in the north, northeast and northwestern parts of Tinsukia district and whole district of Morigaon, baring few pockets in the southern region, and whole district of Nalbari except central part (Fig. 2). The spatial distribution maps clearly indicated that Zn was deficient in the all the three zones of Brahmaputra plains. The spatial heterogeneity of Zn concentration in Brahmaputra plain was expected due to physiographic variation *viz.*, hilly and undulating plain features in UBVZ (Tinsukia district), and alluvial plain zones in CBVZ (Morigaon district) and LBVZ (Nalbari district).

Risk map of Zn deficiency not exceeding a pre-selected threshold value was prepared by using indicator kriging. A threshold value 0.6 mg kg^{-1} was chosen, which represents soils with less than 0.6 mg kg^{-1} is deficient in Zn (Lindsay and Norvell 1978) and it showed deficiency symptoms for most of the

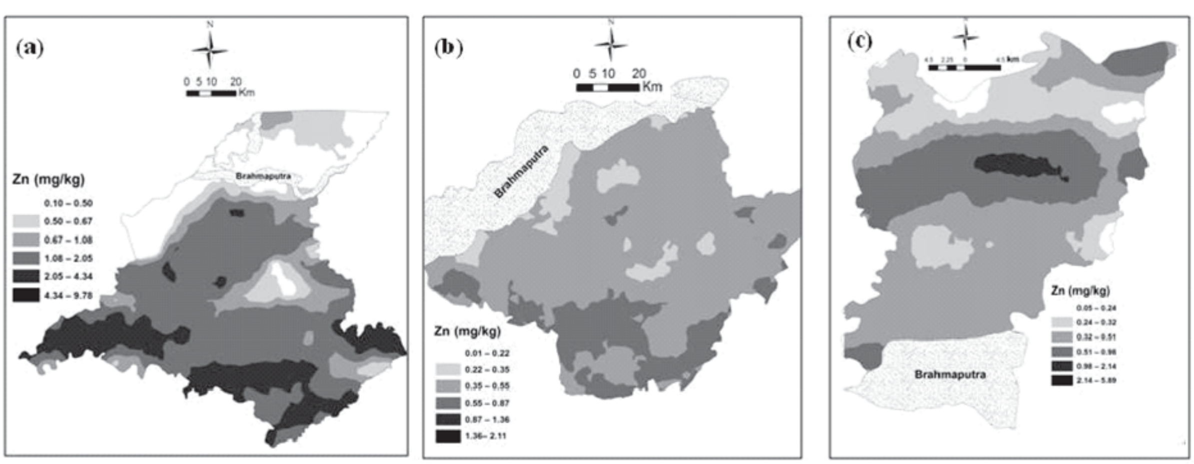

Fig. 2. Spatial distribution map of zinc for (a) Tinsukia district, (b) Morigaon district and (c) Nalbari district of Brahmaputra plains

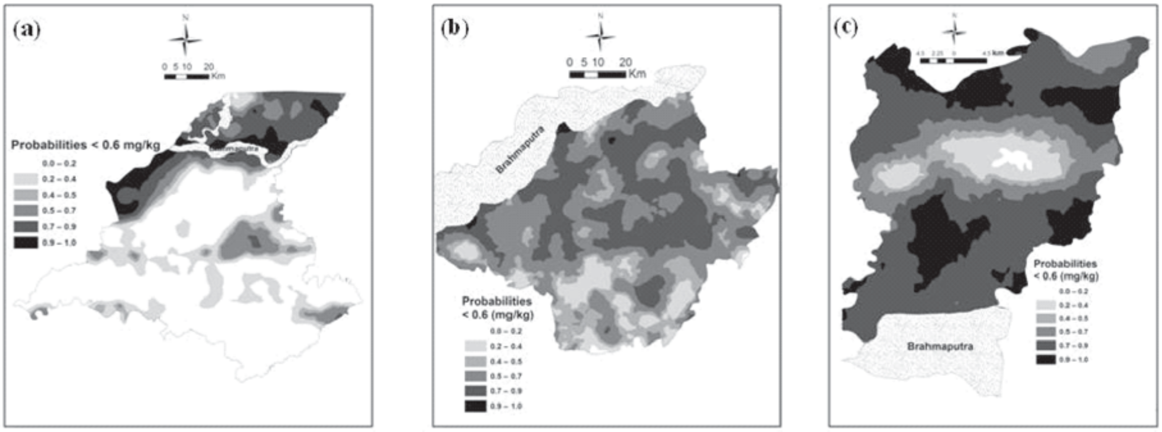

Fig. 3. Probability map of zinc < 0.6 mg kg^{-1} for (a) Tinsukia district, (b) Morigaon district and (c) Nalbari district of Brahmaputra plains

crops. This threshold was used to create probability map (Fig. 3) in order to delineate the deficiency areas of Zn in the study area. The map showed that the probability of deficiency of Zn in the higher class (0.9-1.0) is 11%, whereas, probability greater than 0.5 accounted 34% of the total area of the Tinsukia district, 1% in higher class and 70% in probability greater than 0.5 of the total area of the Morigaon district. Similarly, the deficiency of Zn in the higher class (0.9-1.0) is 25%, whereas, probability greater than 0.5 accounted 85% of the total area of the Nalbari district. It showed that there was chance of 34% area of the Tinsukia district, 70% area of the Morigaon district and 85% area of the Nalbari district showing Zn deficiency in crops like in the early stages the younger leaves become yellow and pitting develops in the interveinal upper surfaces of the mature leaves. As the deficiency progresses these symptoms develop into an intense interveinal necrosis but the main veins remain green, as in the symptoms of recovering iron deficiency.

Accuracy Assessment

Table 4 showed the evaluation indices resulting from cross-validation of spatial maps of Zn. It was observed that**,** Zn had low MAE and MSE however, for CBVZ and LBVZ and relatively large MSE for UBVZ. The G value was greater than 0, which indicated that spatial prediction using semivariogram parameters was better than assuming mean of observed value as the property value for any unsampled location. This also showed that semivariogram parameters obtained from fitting of experimental semivariogram values were reasonable to describe the spatial variation of Zn.

Table 4. Evaluation performance of kriged map through cross-validation

Brahmaputra plains	Mean absolute error	Mean square error	Goodness of prediction
UBVZ	0.0049	1.3944	23.9
CBVZ	0.0055	0.1215	22.6
LBVZ	0.0090	0.1873	18.2

Conclusions

The spatial variability and risk of deficiency of Zn in Brahmaputra plains of northeastern India was evaluated and mapped using geostatistical techniques. The raw data sets of Zn were normally distributed. Exponential model was best fitted with strongly spatially dependent. A good variogram structure of Zn was observed, revealing that there were clear spatial patterns of Zn on the distribution map and also that the current sampling density was ample to reveal such spatial patterns. The spatial distribution maps indicated that Zn was deficient in the all the three zones of Brahmaputra plains. The probability map produced based on indicator kriging provides useful information for identification of Zn deficiency areas, which could be used as a valuable inputs in site specific nutrient management practices and other spatial decision support systems. The maps showing that there was chance of Zn deficiency in crops in about 34% area of the Tinsukia district, 70% area of the Morigaon district and 85% area of the Nalbari district. The study clearly demonstrate that spatial distribution and probability maps of Zn cloud be the primary guide for site specific Zn management and designing future soil sampling strategies in the northeastern India.

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