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Establishing management zones of soil sulfur and micronutrients for sustainable crop production

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Abstract

Deficiency of nutrients in agricultural soils of the world is one of the major factors of soil degradation. The deficiency of nutrients especially sulfur (S) and micronutrients in different soils affect global crop production. Delineation of soil management zones (MZs), by understanding spatial distribution of soil parameters, could be an efficient way for devising strategies for effective nutrient management and sustainable crop production. In this study, we aimed at creation of soil MZs for ameliorating S and micronutrients deficiencies in the Narmada River basin (NRB), an important agricultural area of central India. We collected 5,984 geo-referenced top layer (0–15 cm) soil samples from the NRB, India, and analyzed for soil acidity (soil-water suspension), electrical conductivity (soil-water suspension), soil organic carbon (Walkley and Black carbon), phyto-available S (0.15% calcium chloride [$CaCl_2$] extractable), and phyto-available (diethylene triamine penta acetic acid extractable) micronutrients namely zinc (Zn), copper (Cu), manganese (Mn), iron (Fe), and boron (B) (hot-water-soluble). The values of studied soil parameters varied widely with coefficient of variation values ranging from 11.0 to 74.9%. Pearson's correlation coefficient analysis revealed significant correlations among the soil parameters. Geostatistical analysis revealed exponential, pentaspherical, K-Bessel, and circular best-fit semi-variogram models for different soil parameters with moderate to strong spatial dependence. About 41.2, 78.6, 10.1, 2.70, and 32.6% of the area of the NRB had a deficit concentration of phyto-available S, Zn, Fe, Mn, and B, respectively. The principal component analysis and fuzzy c-means clustering produced five MZs. The produced MZ maps could be utilized for prioritization of nutrients supply and adoption of zone-specific soil nutrient management strategies in order to achieve sustainable crop production in the NRB of India.

KEYWORDS
PCA, precision agriculture, river basin, soil micronutrients, spatial variability

1 | INTRODUCTION

Soils of various regions of the world are degrading due to emerging deficiencies of nutrients affecting crop productivity (Lal, 2015). This problem is more severe in developing countries like India where soil nutrients deficiency is one of the main constrains of crop production (St. Clair & Lynch, 2010). The deficiency of sulfur (S) (Piotrowska-Dlugosz, Siwik-Ziomek, Dlugosz, & Gozdowski, 2017) and micronutrients (Alloway, 2008) are widespread in soils and crops of the world. A recent analysis of soil samples collected from agricultural fields revealed an average deficiency of S, zinc (Zn), boron (B), iron (Fe), manganese (Mn), and copper (Cu) in 40.5, 36.5, 23.2, 12.8, 7.1, and 4.2% of area in India, respectively (Shukla, Behera, Satyanarayana, & Majumdar, 2019).

The phyto-availability of S and micronutrients in agricultural soils is mainly influenced by soil types, soil organic carbon (SOC) content, soil pH, nature of crops and varieties, cropping intensification and use of fertilizers free of S and micronutrients. Further, phyto-availability of S and micronutrients in soils vary spatially due to combined effect of intrinsic soil factors as well as anthropogenic factors like soil-crop managements. This warrants the study for spatial distribution pattern of soil parameters using geostatistical tools for balanced and location-specific management of S and micronutrients in order to achieve sustainable crop production, better farm economy and environmental protection (Tesfahunegn, Tamene, & Vlek, 2011).

The effective way to evaluate the spatial distribution pattern of soil parameters is through demarcation of soil management zones (MZs) and preparation of soil MZ maps of a particular area based on the soil attributes of homogenous nature. The demarcation of MZs involves use of techniques like principal component analysis (PCA) and fuzzy clustering, especially fuzzy c-means algorithm. The spatial distribution pattern of soil parameters including phyto-available of S and micronutrients in different areas of world including India have been studied by delineating soil MZ maps (Behera, Mathur, Shukla, Suresh, & Prakash, 2018; Tripathi et al., 2015). But most of these studies are confined to farm units or district or state administrative boundaries. The information pertaining to spatial distribution pattern of soil parameters and soil MZs in a river basin area is limited. The flow of a river affects soil fertility in its basin area due to deposition of sediments and flooding (Kaletová et al., 2019). Thus, the knowledge about spatial distribution pattern of soil parameters is important for site-specific nutrient management in a river basin area. The information on the spatial distribution pattern of the Narmada River basin (NRB), one of the important agricultural areas of central India which is afflicted with soil S and micronutrients deficiencies, is not available. It was, therefore, hypothesized that there is a wide variation in spatial pattern of soil parameters and the technique of soil MZ delineation could be adopted to generate soil MZ maps of NRB area for site-specific nutrient management. We, therefore, carried-out the present study to establish soil MZs in the NRB of India for sustainable crop production by site-specific nutrient management.

2 | MATERIALS AND METHODS

2.1 | Details of study area

The study area was NRB of India located at 72.53° to 81.75° E and 21.33° to 23.75° N and having geographical area of 97,410 km^2 spreading in Madhya Pradesh (85,858 km^2), Maharashtra (1,658 km^2) and Gujarat (9,894 km^2) states (Figure 1). The area is surrounded by Vindhyas, Satpuras, Maikala ranges and Arabian Sea on the northern, southern, eastern, and western sides, respectively. The area, physiographically, consists of hilly and plain regions. It includes northern slopes of the Satpuras and southern slopes of the Vinddhyas. The upper part and lower middle reaches of the area are hilly. The lower reaches are plains and mainly used for cultivation of cereals, pulses and oil seed crops. Soils are predominantly medium-black, skeletal red and yellow with sandy-clay-loamy to clayey texture. Soils belong to Vertisols, Alfisols, Inceptisols, and Entisols soil orders. However, most soils belong to Vertisols. Alluvial deposits are present in banks of the tributaries. The plain coastal portion of the area, lying in the State of Gujarat, has alluvial clays topped with a black soil layer. The area has a humid-tropical climate with some places experiencing extreme hot and cold conditions. The mean annual temperature varies from 7.5 to 20°C in cold (November to February) and from 30 to 42.5°C in hot (March to mid-June) months. The area receives mean annual precipitation of 1,120 mm. The upper portion of NRB receives higher

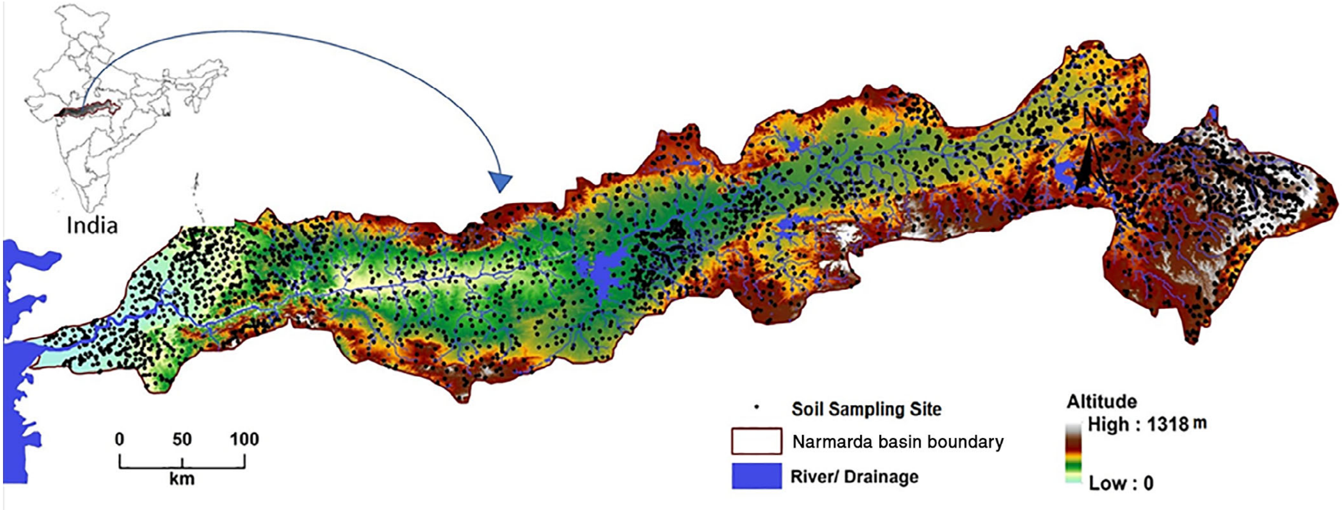

FIGURE 1 Location of the study area showing soil sampling points [Colour figure can be viewed at wileyonlinelibrary.com]

precipitation compared to lower portion. Most of the precipitation is received during July to September. Land uses, slope and soil conditions influence the extent of soil and nutrient loss in the area due to precipitation. The upper part of the NRB has a forest cover with tree species like *Tectona grandis*, *Boswellia serrata*, *Terminalia elliptica*, *Phyllanthus emblica*, *Hardwickia binate*, *Soymida febrifuga*, *Diospyros melanoxylon*, and *Madhuca longifolia*. Forty-five percent area of the NRB is net-sown with prominent crops like *Oryza sativa*, *Triticum aestivum*, *Glycine max*, *Gossypium* sp., *Sorghum* sp., *Arachis hypogaea*, minor cereals and pulses.

2.2 | Soil sampling and analysis

During 2014–2017, a total of 5,984 top layer (0–15 cm) soil samples along with their geographical coordinates were collected from farm lands by adopting a stratified random sampling method, under the aegis of the All India Coordinated Research Project on Micro and Secondary Nutrients and Pollutant Elements in Soils and Plants. Soil samples were collected from small, medium and large land holdings. A stainless-steel auger was used for collection of samples. Three to four (from small [<1 ha] land holdings), six to seven (from medium [1–3 ha] land holdings) and nine to 10 (from large [>3 ha] land holdings) subsamples were collected and mixed physically to make each composite sample. Composite soil samples were prepared to minimize the local effects. The geographical coordinates namely, latitude, longitude and altitude of each sampling point were recorded using a hand-held Global Positioning System (GPS) (Oregon 550, Garmin Ltd, Garmin International Inc., Olathe, KS). The collected soil samples were air-dried. Grinding (using a wooden mortar and pestle) and sieving (using a sieve of 2 mm size) of soil samples were carried out after removal of stones and debrises. After processing, soil samples were kept in polythene containers for analysis. Determination of soil pH and electrical conductivity (EC) was carried out in 1:2.5 (wt/vol) soil–water suspensions (Jackson, 1973). The SOC content was analyzed through Walkley and Black method (Walkley & Black, 1934). Phyto-available S and B concentrations were estimated (using a spectrophotometer [Shimadzu, UV-1800, Kyoto, Japan]) after extracting soil samples with 0.15% $CaCl_2$ (Williams & Steinbergs, 1969) and hot water (Gupta, 1967), respectively. The concentration of phyto-available Zn, Cu, Fe, and Mn in soil samples was estimated (using an atomic absorption spectrophotometer [AAS] [VARIAN-Z240, GTA 120, Varian Inc., Palo Alto, USA]) after extraction of soil samples with diethylene triamine penta acetic acid ($C_{14}H_{23}N_3O_{10}$) extractant (Lindsay & Norvell, 1978).

2.3 | Data analysis

The data set was analyzed using statistics, geostatistics, PCA, and fuzzy c-means clustering techniques. The parameters of descriptive statistics such as maximum, minimum, mean ± standard deviation (SD), coefficient of variation (CV), skewness and kurtosis were determined (SAS Institute, 2011). All the soil parameters had normal distribution as revealed by Kolmogorov–Smirnov test. The relation among the studied soil parameters was tested by Pearson's correlation analysis.

The semi-variogram models (Equation [1]) for each soil property and phyto-available S and micronutrients were estimated using Arc GIS 10.5.1 software (Esri, Los Angeles, CA).Where, γ(h) is the semi-variance with lag distance h. N(h) is the sample pair number separated by lag distance h. z(**x**i) is the value at location **x**i and z(**x**i + h) is the value at location **x**i + h. The selection of different best-fit models of semi-variograms for different soil parameters was performed by cross-validation technique. Cross-validation was performed to find out the prediction performance through estimating mean square error (MSE) (Equation [2]). The MSE for each cross-validation was obtained from estimated semi-variogram values and real observed values. In cross-validation analysis, each point measured in a spatial domain was individually removed from the domain and estimated via kriging as it was never there (Davatgar, Neishabouri, & Sepaskhah, 2012). The parameters *n*, $z(x_i, y_i)$, $z^*(x_i, y_i)$, (x_i, y_i) are number of observations, observed soil parameter, predicted soil parameter and sampling coordinate, respectively.

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

$$\mathrm{MSE} = \frac{\sum_{i=1}^{n} [z(xi, yi) - z*(xi, yi)]^2}{n}, \tag{2}$$

Interpolation mapping was carried out by ordinary kriging (OK) to estimate the values of soil parameters at un-sampled locations. OK is the best unbiased predictor of the values of soil parameters at un-sampled locations. It is having the additional benefit of reducing influence of outliers. PCA is a multivariate analysis that produces new orthogonal variables, called principal components (PCs), from the data set using orthogonal transformation. The correlation analysis values were used as input for PCA. The PCA was carried-out using SPSS software (version 16.0). There were nine PCs in the analysis. It was presumed that PCs receiving high eigenvalues are the best to represent soil parameters. Therefore, PCs with eigenvalues ≥1·0 were selected (Davatgar et al., 2012) to develop the MZs in the present study. A bi-plot using altitude and studied soil parameters was drawn (using R software, R Core Team, 2020) to indicate the effect of altitude on soil parameters and to examine relationships among altitude and phyto-available S and micronutrients.

Two to eight clusters were obtained from the data set by fuzzy c-means clustering, which was carried out through FUZME software. Clustering is used to quantize the available data to extract a set of cluster prototypes for the compact representation of the data set into homogeneous sub-sets. Fuzzy c-means clustering algorithm is one of the most widely used algorithms. The central idea in fuzzy clustering is the non-unique partitioning of the data into a collection of clusters. The data points are assigned membership values for each of the clusters, and fuzzy c-means clustering algorithm allows the clusters to grow into their natural shapes. Eight clusters were considered as the maximum number of practical MZs. The membership in each cluster was determined through an iterative process beginning with a random set of cluster means. Each observation was assigned to the closest of these means. The new means were recalculated for each cluster based on the distance from the observation to the cluster mean. The euclidean distance was used to calculate the distance of data points to cluster centre points according to the result of equal variance and statistical independence. The settings used in FUZME software were: maximum number of iteration = 300, the stopping criterion = 0.0001, minimum number of zones = 2, maximum number of zones = 8, and the fuzziness exponent = 1.5.The optimum cluster number was determined by deriving fuzzy performance index (FPI) (extent of fuzziness) and normalized classification entropy (NCE) (degree of disorganization of specific class) (Equation [3] and [4]). The indices *c*, *n*, μik, $\log_a$ represent number of clusters, number of observations, fuzzy membership and natural logarithm, respectively. The differences in the mean values of soil parameters in different MZs were determined by variance analysis procedure.

$$\mathrm{NCE} = \frac{n}{n-c}\left[-\frac{\sum_{k=1}^{n}\sum_{i=1}^{c}\mu_{ik}\log_a(\mu_{ik})}{n}\right], \tag{3}$$

$$\mathrm{FPI} = 1-\frac{c}{c-1}\left[1-\frac{\sum_{i=1}^{c}\sum_{k=1}^{n}(\mu_{ik})^2}{n}\right]. \tag{4}$$

3 | RESULTS

3.1 | Variation in soil parameters

The soil parameters in NRB varied widely (Table 1). The soils were acidic (4.10) to alkaline (9.32) in pH and were non-saline. The SOC content varied from low (<0.50%) to high (≥0.75%) level. The concentration of phyto-available S, Zn, Cu, Fe, Mn and B ranged from deficiency level to adequate level. However, the mean concentration of phyto-available nutrients followed the order: Mn > S > Fe > Cu > B > Zn. Among the soil parameters, soil pH had the lowest CV and available Mn had the highest CV.

3.2 | Spatial distribution of soil parameters

The best-fit semi-variogram models were exponential for pH, EC, SOC, phyto-available S, Zn and Mn, pentaspherical for phyto-available Cu, K-Bessel for phyto-available Fe and circular for phyto-available B (Figure 2). The nugget values were higher for phyto-available S, Fe and Mn compared to rest of the soil parameters. The values of nugget/sill ratio of best-fit semi-variogram models for soil parameters varied from 0.239 to 0.750 with moderate to strong spatial dependence. The range values were different for various soil parameters. Interpolation mapping by OK exhibited varied spatial distribution patterns for soil parameters (Figure 3). The study area had pH in the range of ≥5.5 to <6.5 (15.2% of area), ≥6.5 to <7.5 (40.6% of area) and ≥ 7.5 to <8.5 (43.4% of area). SOC content was low in 30% of area, medium (≥0.5 to <0.75%) in 42.1% of area and high in 27.9% of area. The status of phyto-available S and micronutrients in the study area was categorized as acute deficient, deficient, latent deficient, marginal sufficient, adequate and high according to the classes outlined by Shukla et al. (2019). Phyto-available S was acute deficient in 12.0% of area, deficient in 18.8% of area, latent deficient in 10.4% of area, marginal sufficient in 24.5% of area, adequate in 22.8% of area and high in 11.4% of area (Figure 3). Phyto-available Zn was acute deficient in 1.2% of area, deficient in 37.0% of area and latent deficient in 40.4% of area. About 2.6 and 97.2% of the study area had adequate and high concentration of phyto-available Cu, respectively. Soils of NRB did not exhibit acute deficiency of available Fe and Mn. About 1.7 and 8.4% of area had phyto-available Fe in deficient and latent deficient range, respectively. Phyto-available Mn was deficient in 0.7% of area and latent deficient in 2.0% of area. Phyto-available B was acute deficient in 0.9% of area, deficient in 17.7% of area and latent deficient in 14.0% of area.

TABLE 1 Descriptive statistics parameters of soil properties and available nutrients in the study area

Soil properties	Minimum	Maximum	Mean ± SD	CV (%)	Skewness	Kurtosis
pH	4.10	9.32	7.14 ± 0.79	11.01	–0.28	–0.33
EC (dS m^{-1})	0.01	0.51	0.20 ± 0.10	48.39	–0.10	0.70
SOC (%)	0.20	1.88	0.67 ± 0.37	55.13	0.32	0.83
S (mg kg^{-1})	0.22	57.0	17.54 ± 11.6	65.94	0.98	1.22
Zn (mg kg^{-1})	0.01	2.68	0.73 ± 0.52	71.21	2.33	1.55
Cu (mg kg^{-1})	0.10	10.44	3.00 ± 2.15	72.80	1.24	1.31
Fe (mg kg^{-1})	0.27	49.1	15.37 ± 11.2	71.60	0.09	0.97
Mn (mg kg^{-1})	0.20	75.5	19.45 ± 14.6	74.97	1.79	1.36
B (mg kg^{-1})	0.05	4.04	1.39 ± 0.80	57.51	–0.50	0.31

Note: CV, coefficient of variation; EC, electrical conductivity; SD, standard deviation; SOC, soil organic carbon; S, Zn, Fe, Cu, Mn and B = phyto-available sulfur, zinc, iron, copper, manganese and boron in soil, respectively.

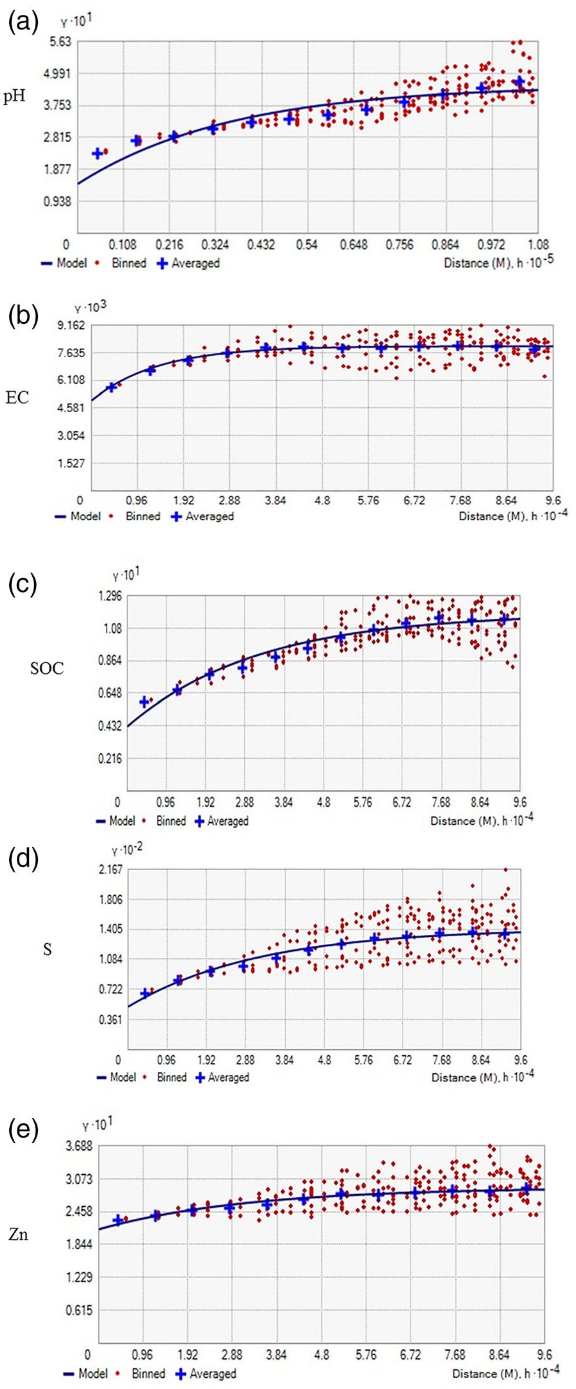

FIGURE 2 Experimental semi-variograms for (a) pH, (b) electrical conductivity (EC), (c) soil organic carbon (SOC), (d) sulfur (S), (e) zinc (Zn), (f) copper (Cu), (g) ion (Fe), (h) manganese (Mn), and (i) boron (B) of the study area [Colour figure can be viewed at wileyonlinelibrary.com]

3.3 | Soil management zones

Aggregation and summarization of variability in the nine studied soil parameters through PCA resulted in nine PCs. Out of nine PCs, first four PCs having eigenvalue >1.00 and accounting for 66.5% of total variance were considered (Figure 4). The PC1 explained 29.5% of total variance and was dominated by pH, phyto-available Cu, Fe, Mn and B. Additionally, PC2, PC3 and PC4 also accounted for total variance. Principal component 2 was dominated by EC and phyto-available Zn, PC3 by phyto-available S and PC4 by SOC. The biplot of PC1 and PC2 exhibited positive relationship of altitude with SOC and phyto-available B and negative relationship of altitude with pH and EC (Figure 5). Further, phyto-available Zn, Cu, Fe and Mn were grouped together. Fuzzy c-means clustering resulted in five MZs (Figure 6).

4 | DISCUSSION

4.1 | Variation in soil parameters

There was wide variation in soil pH (4.10–9.32), EC (0.01–0.51 dS m^{-1}) and SOC content (0.20–1.88%) across the study area (Table 1). This is ascribed to the differences in soil types originated from various parent materials, topographic factors, prevailing climatic conditions and crops/cropping patterns (Alloway, 2008; Shukla et al., 2018). The significant portion of the study area is having underlying deccan traps (derived from basaltic flows). However, some parts also have Gondwana shale, granite, sedimentary rocks and alluvial deposits. Topographic factors such as slope and positions of slope influence degree of soil development and leaching process and thereby soil properties. Though the concentration of phyto-available S and micronutrients varied widely, about 41.2, 78.6, 0, 10.1, 2.7 and 32.6% of the study area were deficit (including acute deficient, deficient and latent deficient) in phyto-available S, Zn, Cu, Fe, Mn and B concentration, respectively (Figure 3). This variation is primarily because of physiography, nature of soils, pattern of land use, and soil-crop management practices of the area. Shukla et al. (2017) reported 38.89 ± 31.76 mg kg^{-1} phyto-available S, 2.24 ± 1.71 mg kg^{-1} phyto-available Zn, 1.49 ± 0.92 mg kg^{-1} phyto-available Cu, 36.76 ± 28.51 mg kg^{-1} phyto-available Fe, 19.01 ± 12.72 mg kg^{-1} phyto-available Mn, and 1.50 ± 0.83 mg kg^{-1} phyto-available B in Shiwalik Himalayan region of India with a deficiency in 2–49% of area. Likewise, Shukla, Behera, Pakhre, and Chaudhari (2018) noted a mean concentration of 0.83 ± 0.36 mg kg^{-1} for phyto-available Zn, 0.99 ± 0.43 mg kg^{-1} for phyto-available Cu, 8.79 ± 4.15 mg kg^{-1} for phyto-available Fe and 8.79 ± 4.06 mg kg^{-1} for phyto-available Mn in a deccan plateau area of India.

As the CV values of soil parameters were in between 10 and 100%, all the studied soil parameters exhibited moderate variability. The lowest CV value for soil pH (among the studied soil parameters) in the present study is ascribed to the estimation of hydrogen ion concentration after logarithmic transformation. Similar to our observation, Behera and Shukla (2015) recorded CV values of 5.37–9.80%, 32.4–74.3% and 31.2–50.9% for pH, EC and SOC content, respectively, in some cultivated acid soils of India. The CV values of 9.0% for pH and 34.4% for SOC were recorded in sandy soils of Poland (Usowicz & Lipiec, 2017). Behera et al. (2016) recorded CV values of 8.64% for pH, 125% for EC and 44.4% for SOC in the coastal area of western India. Furthermore, moderate variability of phyto-available

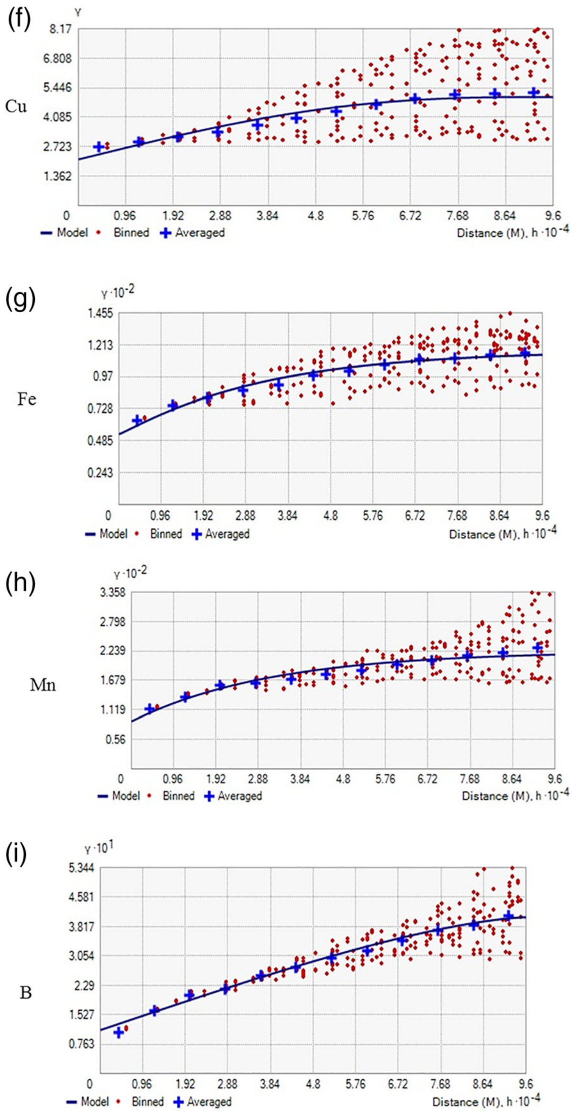

FIGURE 2 (Continued)

micronutrients in Shiwalik Himalayan region (Shukla et al., 2017) and Deccan Plateau region of India (Shukla, Sinha, et al., 2018) were recorded. In comparison to the CV value for pH, EC and SOC, the phyto-available S and micronutrients had higher CV values. This is attributed to the wide variation in nutrients concentration in parent materials especially for micronutrients, their distribution and the pedogenic processes. According to White and Zasoski (1999), crustal abundance, granite, basalt and shale are having different mean concentrations of Zn, Cu, Fe and Mn. Similarly, B concentration is more in sedimentary rocks compared to igneous rocks. B is also found in some minerals like colemenite, tourmaline, axenite, kermite and ulexite.

4.2 | Relationship among soil parameters

Pearson's correlation coefficient matrix revealed the relationship among the studied soil parameters. The negative correlations of soil pH with phyto-available micronutrients revealed the reduction in phyto-availability of these nutrients in soils of NRB with increase in soil pH. This is because of change in solubilization and distribution of soil micronutrients due to variation in soil pH. The negative correlations of soil pH with phyto-available cationic micronutrients were also recorded in loess plateau soils of China (Wei, Hao, Shao, & Gal, 2006) and in some agricultural soils of India (Shukla et al., 2017). This indicates that soil pH manipulation can change the phyto-availability of these nutrients. Soil EC was correlated with all the studied soil parameters except phyto-available Cu and Mn. Soil EC is considered as an indirect estimator of phyto-available nutrients and soil salinity. Therefore, it is used for partitioning different soil management units and predicting levels of soil fertility and crop yield during soil survey. The positive correlation of SOC with phyto-available S and micronutrients indicates higher phyto-availability of these nutrients with increase in SOC content. Because soil organic matter, in which SOC is an important component, helps in storage and solubilization of S, Zn, Cu, Fe, Mn and B and making them phyto-available. The positive correlation among phyto-available cationic micronutrients reveals that similar factors affect the distribution of cationic micronutrients in the study region. Parallel to our findings, positive correlations among phyto-available Zn, Cu, Fe and Mn were recorded in soils of the Indo Gangetic Plain region of India (Sharma, Mukhopadhyay, Sidhu, & Katyal, 2000). Behera and Shukla (2013) also reported positive correlation between phyto-available Fe and Mn in some cultivated acid soils of India. There were positive relations of altitude with SOC and phyto-available B and negative relations of altitude with soil pH and EC. This is due to higher precipitation and forest cover in upper parts as compared to the middle and lower reaches of the basin. Forest cover with trees leads to increase in SOC content over a period of time due to decomposition of leaf litter and root biomass. The higher rainfall in upper part of the basin results in leaching of basic cations from soil.

4.3 | Spatial distribution of soil parameters

The distribution of soil parameters varies spatially. It requires proper knowledge about the spatial distribution pattern of soil parameters in devising strategies for effective site-specific nutrient management and sustainable crop yield. For this purpose, use of geostatistical tools is appropriate. It helps in predicting the values of soil parameters at unsampled places based on spatial dependence information and assessing the uncertainty attached to the prediction. Geostatistical analysis of studied soil parameters resulted in exponential (pH, EC, SOC, phyto-available S, Zn and Mn), pentaspherical (phyto-available Cu), K-Bessel (phyto-available Fe) and circular (phyto-available B) best-fit models. Parallel to this finding, Tesfahunegn et al. (2011) recorded exponential (pH), and spherical (SOC, phyto-available Fe) best-fit models in a catchment area soils of Ethiopia. Shukla et al. (2017) reported spherical, Gaussian, exponential, stable, circular and K-Bessel best-fit models for soil parameters of Shiwalik Himalayan region of India.

The nugget value of a semi-variogram indicates the extent of variance because of sampling error, measurement and other sources. On the other hand, sill speaks about the variance from the sampled

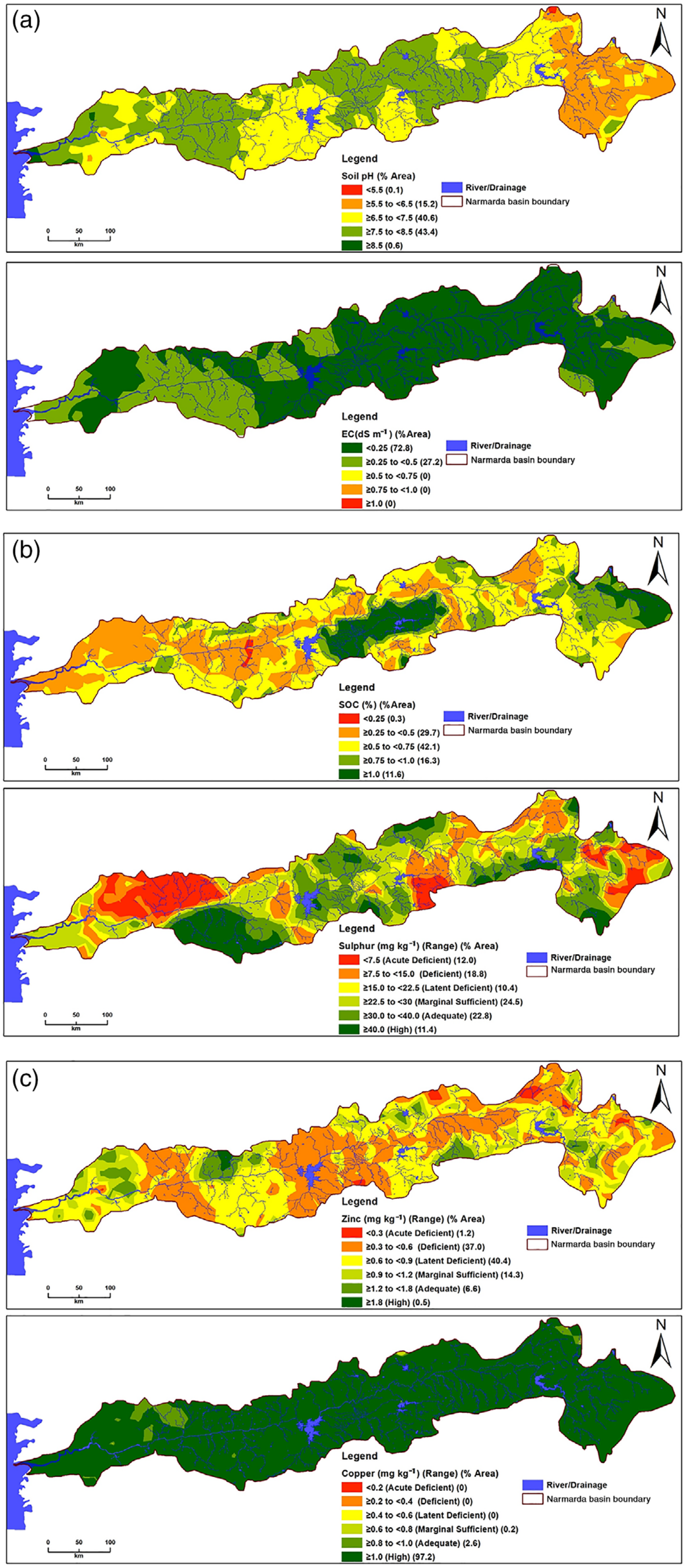

FIGURE 3 Kriged maps of soil pH, electrical conductivity (EC), soil organic carbon (SOC), sulfur (S), zinc (Zn), copper (Cu), iron (Fe), manganese (Mn) and boron (B) [Colour figure can be viewed at wileyonlinelibrary.com]

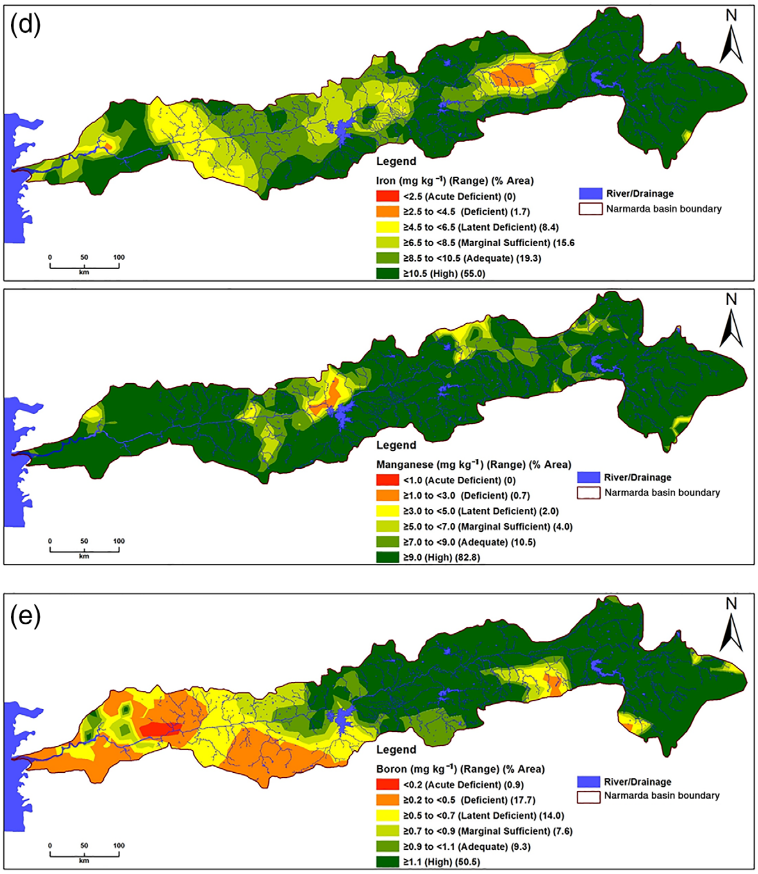

FIGURE 3 (Continued)

observations separated by a large distance if there is no trend in data. The higher values of nugget and sill were recorded for phyto-available S, Fe and Mn in the study area in comparison to other soil parameters. This is ascribed to the inability of sampling distance to obtain spatial dependence for these soil parameters. Based on the values of nugget/sill ratio (N/S), there are three categories of spatial dependence, namely, strong ($N/S \le 0.25$), moderate ($N/S > 0.25–\le 0.75$) and weak ($N/S > 0.75$). The strong spatial dependence for phyto-available B in NRB is attributed to soil type and the climatic conditions. Whereas, moderate spatial dependence for pH, EC, SOC, phyto-available S, and cationic micronutrients is ascribed to the collective impact of soil characteristics and soil-crop manipulation practices. The range value of the semi-variogram indicates the maximum distance within which the autocorrelation exists. It is considered as the important criteria for deciding a particular sampling design for understanding spatial variability of soil parameters. Beyond this distance, no autocorrelation or spatial dependence occurs. Soil EC and pH had the lowest (72,000 m) and the highest (108,000 m) range value, respectively. Phyto-available S and micronutrients had equal range values. The higher range of a particular soil parameter indicates that the particular soil parameter is affected by both natural and anthropogenic factors to a higher distance compared to a lower range soil parameter. The range values for soil parameters, obtained from this study, could be utilized for deciding the design of future soil sampling in the study area and in similar areas for spatial variability study. The sampling distance needs to be nearly half of the range values of the soil parameters (Kerry & Oliver, 2004).

The distribution maps developed for soil properties and phyto-available S and micronutrients reflected a varied pattern of distribution. This is ascribed to combined influence of different soil types, parent materials, climatic conditions, crops and cropping systems and their management in the study area. There were similar reports of varied spatial distribution pattern for phyto-available S and micronutrients in other parts of India (Shukla et al., 2017; Shukla, Sinha, et al., 2018). About 40.6% of the area had pH in the range of 6.5–7.5, which is conducive for proper growth of many crops. However, about 15.2% (pH of ≥5.5–<6.5) and 43.4% (pH of ≥7.5–<8.5) of area needs corrective measures for better crop production. Soil salinity is not an issue in the NRB as 100% of the area had EC < 0.5 dS m^{-1}. The SOC content in about 30% of area was low and predominantly distributed in western and central part. Necessary steps must be undertaken to enhance SOC content in these areas by crop residue retention and decomposition, adoption of conservation agriculture practices and growing suitable crop and cropping systems. The western part and some portions in eastern and southern part of the study area had S deficiency. Whereas, southern and central portion of the NRB had higher concentration of phyto-available S. Zinc deficiency was recorded in almost all parts of NRB except some pockets. It necessitates site-specific Zn management in

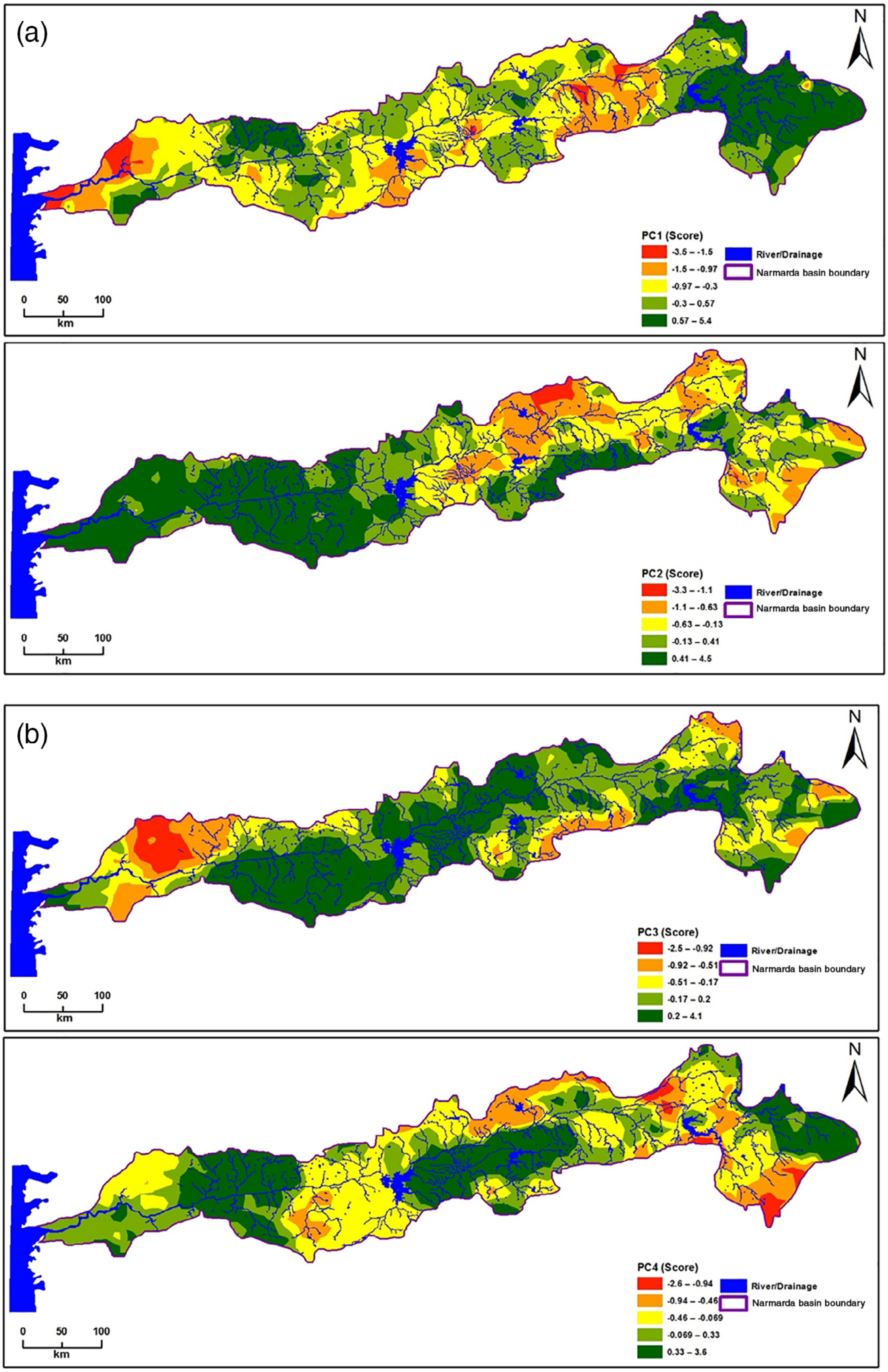

FIGURE 4 Kriged maps of principal component 1 (PC1), principal component 2 (PC2), principal component 3 (PC3) and principal component 4 (PC4) [Colour figure can be viewed at wileyonlinelibrary.com]

the area either by growing Zn-efficient crop cultivars or addition of required amount of Zn fertilizers in order to obtain sustainable and economical crop production. The deficiency of phyto-available Fe and Mn was recorded in few pockets of the study area. However, B deficiency was noted in western and west-southern part of the area. This variation in status of phyto-available nutrients especially micronutrients in the study area is probably because of existence of different soil forming parent materials in various parts. The generated spatial distribution maps could be utilized for having an idea about prevailing S and micronutrient deficiencies in the study area. These maps could also be utilized by fertilizer industries for proper planning, production and distribution of right kind and quantity of fertilizers. Different extension agencies, farmers and farm managers could use these maps for rationale S and micronutrients fertilizer application.

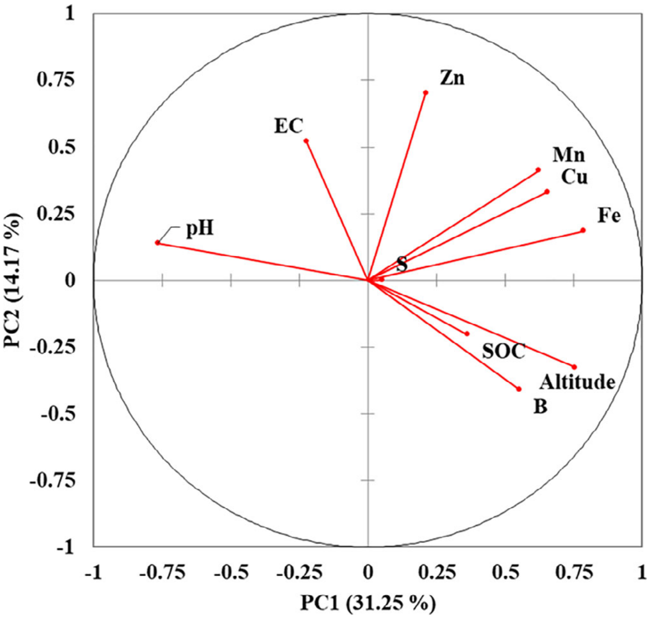

FIGURE 5 Principal component 1 (PC1) versus principal component 2 (PC2) biplot revealing relationship of altitude with soil parameters (EC, electrical conductivity; SOC, soil organic carbon; S, sulfur; Zn, zinc; Cu, copper; Fe, iron; Mn, manganese; B, boron) [Colour figure can be viewed at wileyonlinelibrary.com]

4.4 | Soil management zones

Five soil MZs (Figure 6) were generated, using geostatistical tools, for zone-specific management of phyto-available S and micronutrients in NRB area of India. This is in line with the findings of Davatgar et al. (2012) in paddy cultivated areas of Iran. These generated soil MZs were distinctly different from one another as the values of the studied soil parameters of the MZs differed. This warrants adoption of different soil management strategies in various MZs. For example, the level of SOC content needs to be enhanced in MZ3 and MZ5 through adoption of different management practices for better soil function and nutrient availability. Though the mean concentrations of phyto-available S, Zn and B in different MZs were higher than the critical range of deficiency for respective nutrients, different levels of nutrient deficiencies exist in the MZs. Based on levels of deficiencies, the nutrient management decisions and supply of nutrients to different zones could be prioritized. The MZs having higher deficiency level of a particular nutrient need to receive first attention followed by other MZs having subsequently lower levels of deficiency. More attention needs to be paid in MZ3 compared to MZ2, MZ4 and MZ5 for S management. Similarly, Zn management needs to be prioritized in MZ4 and MZ5 compared to other MZs. This will ensure optimum utilization of resources and better farm economy.

Considering the phyto-available S and micronutrients status in soils and % area deficiency, different quantities of customized fertilizers could be provided to the different MZs for efficient nutrient management. In addition, the farmers and farm mangers could suitably be advised to grow efficient and inefficient crop cultivars in different MZs based on soil nutrient status and resource availability. Because, nutrient efficient and inefficient cultivars of the crops behave differently (in terms of crop growth and yield) under different soil nutrient

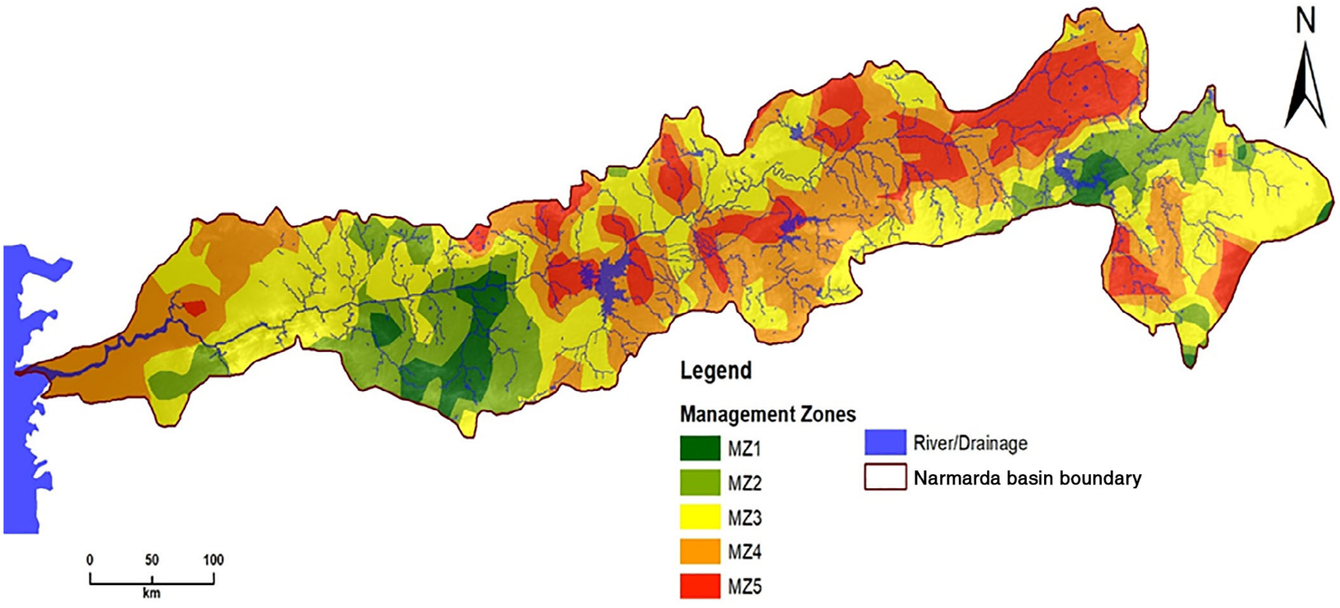

FIGURE 6 Soil nutrients management zones of the study area (MZ1 = management zone 1, MZ2 = management zone 2, MZ3 = management zone 3, MZ4 = management zone 4, and MZ5 = management zone 5) [Colour figure can be viewed at wileyonlinelibrary.com]

status and management practices (Singh et al., 2020). Resource poor farmers could grow nutrient efficient crop cultivars in nutrient deficient soil and could obtain sustainable crop yield without application of that nutrient. This is a short-term solution as this technique may lead to soil nutrient mining on long-run. While resource rich farmers could grow nutrient inefficient crop cultivars with application of the nutrient for good crop yield. Further, farmers could use required levels of S and micronutrients in different MZs based on status of phyto-available S and micronutrients in soils and nature of crops to be grown. The differences in levels of crop responses (in terms of crop yield) to the application of S, Zn, Fe and B fertilizers were recorded in different MZs of NRB. On-farm field trials conducted in Hoshangabad (MZ4) and Dewas (MZ3) districts of Madhya Pradesh exhibited higher crop responses to S and Zn application compared to the crop responses obtained in Khargone District (MZ1). Therefore, it is of paramount importance for the farmers and farm managers of NRB to take proper cognizance of soil parameters status in different MZs to devise simple, easy and cost-efficient soil-crop manipulation strategies for sustainable crop production.

5 | CONCLUSIONS

The present study revealed wide variation in the values of studied soil parameters in the NRB of India. Geostatistical analysis resulted in exponential, pentaspherical, K-Bessel and circular best-fit semi-variogram models for soil parameters. Soil parameters showed spatial heterogeneity with moderate to strong spatial dependence. About 41.2, 78.6, 10.1, 2.70, and 32.6% of study area exhibited deficiency (including acute deficient, deficient and latent deficient areas) in phyto-available S, Zn, Fe, Mn, and B, respectively. The techniques of principal component analysis and fuzzy c-means clustering resulted in development of five MZs having significantly different values of soil parameters. The generated MZ maps could be used for zone-specific management of SOC, phyto-available S, Zn, Fe, Mn, and B in the study area for sustainable crop production. This could be achieved through growing of suitable crop cultivars, adoption of environmentally sustainable soil-crop management practices and site-specific S and micronutrients supply. The study also highlighted that the technique of soil MZ delineation could also be adopted for development of soil MZ maps of other river basin areas for site-specific nutrient management programme.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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