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Research Article

Assessing spatial variability of soil and drawing location-specific management zones for coastal saline soils in Ramanathapuram District, Tamil Nadu

S. Nagaraj*
Department of Soils and Environment, Agricultural College and Research Institute, Madurai (Tamil Nadu), India
P. Saravana Pandian
Department of Soils and Environment, Agricultural College and Research Institute, Madurai (Tamil Nadu), India
P. Christy Nirmala Mary
Department of Soils and Environment, Agricultural College and Research Institute, Madurai (Tamil Nadu), India
R. Geetha
Department of Seed Science and Technology, Agricultural College and Research Institute, Madurai (Tamil Nadu), India
A. Gurusamy
Department of Agronomy, Agricultural College and Research Institute, Madurai, (Tamil Nadu), India

*Corresponding author. E mail: agri.snagaraj@gmail.com

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Abstract
The production of crops in saline and alkali-degraded areas is difficult due to the heterogeneous and spatial variation of soil fertility. First, their spatial variability was analyzed and maps of the spatial distribution were created using Geostatistical techniques. The fuzzy k-mean clustering analysis was then used to define Management zones in the coastal saline soils of Ramanathapuram district in Tamil Nadu. One hundred and fifty geo-referenced soil samples (30 cm depth) were taken and analyzed for pH, electrical conductivity (ECe) in the saturated paste extract (USSL method), organic carbon (OC) (Walkley-Black chromic acid wet oxidation method), calcium carbonate ($CaCO_3$) (Rapid titration method) and available phosphorus and extractable micronutrients (Multinutrients extraction method), revealing significant variation in soil characteristics throughout the coastal saline soils of Ramanathapuram district. The most significant factors, which together accounted for four principal components and 69% of the overall variability, were pH, electrical conductivity (ECe), calcium Carbonate and available zinc. According to Geostatistical analysis, the Exponential (pH, OC (organic carbon), P, Fe, Mn and Zn) and Stable (ECe) was the best fit semi-variogram ordinary kriging model with weak to moderate spatial dependence. Fuzzy k-mean clustering was also used to identify zone 1, zone 2 and zone 3. For every soil property, there was a significant difference between MZ1(zone 1), MZ2(zone 2) and MZ3(zone 3). These results also showed that cluster analysis gave farmers a chance to use location-specific nutrient management strategies by minimizing variability within the zone. The management zones can decrease agricultural inputs and environmental pollutants while increasing crop productivity.

Keywords: Fuzzy clustering, Geostatistics, Kriging, Management zones, Principal component analysis

INTRODUCTION

Sustainable crop production in coastal areas of arid and semi-arid regions is a daunting task due to extreme climatic variability, land and water degradation, and heterogeneous soil fertility (Yadav, 2003; Moharana *et al.,* 2019). In India, land degradation affects nearly 120.72 million hectares (Mha), with soil salinity affecting 5.50 million hectares (Mha) (Anonymous, 2020). The country loses 16.84 million tons of agricultural production annually, worth US$ 3.1 billion on these SAS (Sharma *et al.,* 2015). Soil and water salinity stress in coastal areas of Ramanathapuram district, India, is associated with seawater intrusion into the aquifer, improper drainage, crop intensification, over-exploitation of groundwater, irrigation mismatch and native $CaCO_3$-rich soils (Qadir *et al.,* 2007; Jalota *et al.,* 2018; Sheoran *et al.,* 2021). A further factor that lowers agricultural production is farmers' lack of understanding and desire to use location-specific management practices that consider soil heterogeneity (Singh *et al.,* 2019). Unsustainable land management is a significant contributor to land degradation, which is a global problem (Zhao *et al.,* 2013). Lower soil productivity and unregulated use of such poor quality water for irrigation in coastal saline soils decline the availability of soil nutrients (Wang *et al.,* 2010) and simultaneously increase the salts on clay lattice, reducing nutrient retention on the exchange sites. Understanding soil spatial variability and creating thematic maps are critical for determining the level of soil nutrient deficiency, crop yield realization and associated management strategies. Thematic maps can be developed by different conventional and simple statistical methods. Geostatistical strategies employing various spatial tools, such as semivariogram, kriging, co-kriging, regression kriging, etc., have been shown to forecast unsampled locations. Based on geographical association, these techniques give better predictions of different soil parameters with minimum error and inconsistency (Mahmoodifard *et al.,* 2014; Bhunia *et al.,* 2018). According to certain studies, the kriging model is one of the geostatistical methods that is most effective for accurately measuring the spatial variability of coastal saline soils. However, a detailed assessment of regional variability for key soil indicators with the strongest association with nutritional status and coastal salinity can be extremely important in helping the restoration of affected soils and developing location-specific management strategies. Delineating uniform and consistent management zones (MZs) has become a highly adaptable strategy to address field variability and offer insightful data with lower sampling costs, anticipated errors and interpolation of information about un-sample regions (Nawar *et al.,* 2017; Moharana *et al.,* 2020).

It was hypothesized that zone-wise fertilizer application assessing key coastal saline soil indicators helps rehabilitate the saline soils, sustain agricultural production and reduce environmental footprints in salt-affected regions of Ramanathapuram district, India. With this background, the present study was undertaken with the objectives (i) To assess the spatial variability in soil properties of Ramanathapuram district, viz., pH, electrical conductivity(EC), organic carbon(OC), calcium carbonate($CaCO_3$), available P and extractable micronutrients using the geostatistical analysis (ii) To find the correlation amongst the soil properties and (iii) To develop spatial distribution maps of soil properties and delineate potential management zones(MZs) in coastal saline soils of Ramanathapuram district using principal component analysis (PCA) and fuzzy c-mean clustering analyses.

MATERIALS AND METHODS

Study area

The research was carried out in the Ramanathapuram district. The district is located on India's East Coast in the southern region of Tamil Nadu. Its geographical coordinates are 9° 05' and 9° 50' of North Latitude and 78° 10' and 79° 27' of East Longitude (Fig. 1). The district's eastern boundary is the East Coastline, which separates it from the Bay of Bengal. The district's total cultivated area is 1,98, 818 ha. It has a tropical climate, which means it is hot and dry. The mean annual rainfall of the district is 823 mm. The dominant soils are the clay, coastal alluvium, sandy loam and black cotton soils. In this district, Paramakudi, Mudukulathur and Nainarkoil blocks were chosen as study areas, and from each block, 50 soil samples were collected.

Soil sampling and analysis

Before the monsoon, 150 geo-referenced composite surface and subsurface (0-30 cm depth) soil samples were collected using a soil auger by employing a stratified random sampling approach and a hand-held global

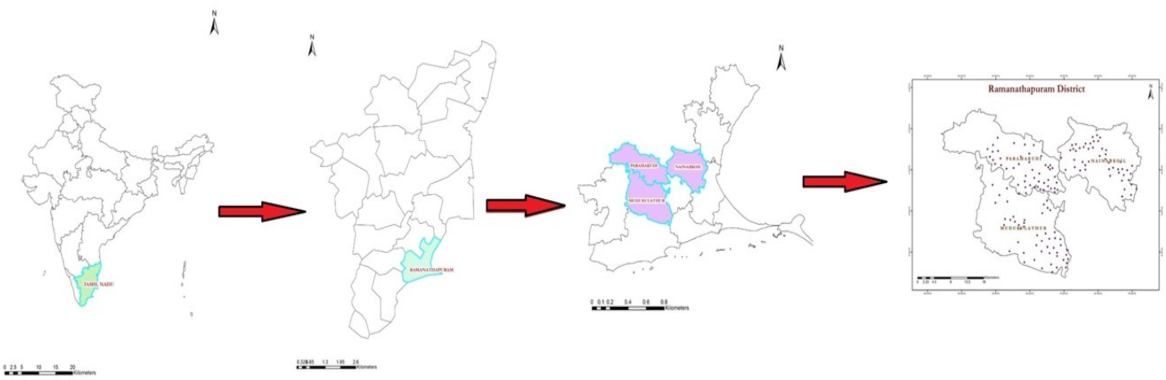

Fig. 1. *Soil sampling locations in Paramakudi, Mudukulathur & Nainarkoil blocks of Ramanathapuram district*

positioning system was used to record the latitude and longitude of the geographical coordinates. The soil samples were transported to the lab and air-dried at room temperature. The pebbles and debris were removed from the samples, crushed and put through a 2-mm sieve before being analyzed in the laboratory for soil properties. Soil reaction (pH) and electrical conductivity (Ece) were measured in the saturated paste and collected aliquot, respectively as per the methodology of USSL (1954). Soil organic carbon (SOC) was determined by oxidizing it with potassium dichromate and then titrating it with ferrous ammonium sulphate. $CaCO_3$ was estimated by the rapid titration method by piper (1966). The available phosphorus and extractable micronutrients, viz., zinc, copper, iron and manganese, were extracted using AB-DTPA reagent and the concentrations were determined by using ICP-OES (Malathi and Stalin, 2018).

Descriptive statistics

An exploratory data analysis was performed to discover the relationship between available nutrients and soil parameters. The descriptive statistics like maximum, minimum, mean, standard deviation (SD), coefficient of variation (CV), skewness and kurtosis were calculated for each property by using SAS 9.2 software. A correlation matrix was done to determine the relationship among nine soil properties under study using Pearson's correlation coefficient analysis.

Geostatistical analysis

Semivariogram modelling was performed to fit the best semivariogram model for assessing the spatial variation of each soil variable. The best fit semivariogram model was utilized for ordinary kriging (Krige 1981) to create the spatial variability map for each soil variable via interpolation. The accuracy of kriging interpolation was assessed by cross-validation analysis (Schepers *et al.* 2004). ArcGIS 10.8 (Geostatistical analyst) was used for semivariogram modeling, kriging and preparing the spatial variability map of soil variables. According to Cambardella *et al.* (1994), the nugget-to-sill ratio was used to evaluate the spatial dependence of soil properties.

Principal component analysis (PCA)

It is a multivariate method for extracting components from a group of variables. The PCs with the greatest eigenvalues were believed to be the most accurate representations of soil properties (Schepers *et al.* 2004). To establish management zones-MZs, PCs with eigenvalues >1 were selected (Shukla *et al.* 2017). The PC loading of examined soil properties has been shown using a bi-plot to help understand the varying relevance of values under different PCs.

Fuzzy cluster algorithm

Different unique MZs were delineated using fuzzy k-mean clustering (Brown 1998) by minimizing the within-group variability while maximizing the among-group variability for creating homogenous groups. This study used XLSTAT software to divide the study area into 3 clusters using fuzzy k-mean (Wang *et al.* 2009).

RESULTS AND DISCUSSION

Descriptive statistics and frequency distribution of coastal saline soil parameters

Crop management techniques in an area have an important impact in determining soil health. The descriptive statistics for the nine soil characteristics are given in Table 1. Based on Wilding's (1985) criteria, the present study revealed that ECe, $CaCO_3$, Fe, Zn, Cu, Mn belonged to highly variable (CV>35%), OC (Organic carbon) and AP (Available phosphorus) falling in moderate (CV- 15-35%) and pHs in the least variable (CV- 6.89%) class. The presence of sodic soils in about half of the entire area, as evidenced by a low CV (6%) for soil pH, was an indicator of decades of continuous irrigation with poor quality water, calcareous parent material, and human activity. These findings are consistent with those of Fu *et al.* (2010), who discovered steady soil pH with minimal CV at a permanent dairy farm in southern Ireland. With regard to ECe ranging from 0.4 to 14.2 dSm^{-1} with CV of 100%. The high CV as well as the geographical maps revealed significant spatial variability in soil parameters. DTPA extractable manganese ranged from 1.04 to 15.13 mg kg^{-1}, with a high CV, whereas DTPA extractable Zn had the greatest CV (43.85%) close to Mn and the mean SOC content is low. Except for the AP median, all other variables had medians that were close to their means. The overall region in the present study had soil OC of 0.5% with substantial spatial variance (CV 27.27). Limited C inputs and higher losses due to intense crop farming, poor biomass turnover, and insufficient residue integration may have permanently impacted SOC accumulation. Due to distributed clay and extended water stagnation in sodic zones, the mechanism of organic matter breakdown was retarded, thus damaging SOC reserves. The observed CV in this study was close to that reported by Bhunia *et al.* (2018), who found a Moderate CV value of OC (22.39%) in laterite soils in West Bengal, India.

Relationships among the soil properties

A simple linear correlation matrix existed between nutrient availability and Physico-chemical characteristics in soils is depicted in Table 2. Soil pH had a significant positive correlation with ECe (r = 0.54**). ECe significantly negatively correlated with $CaCO_3$ (r =-0.32**)

Table 1. Descriptive statistics of soil properties

Variables	Min	Max	SD	Mean	Median	CV(%)	Skewness	Kurtosis
pH	6.26	9.30	0.56	8.12	8.15	6.89	-0.67	0.85
ECe (dSm^{-1})	0.45	14.25	2.65	2.63	1.66	100.76	2.22	5.02
OC (%)	0.09	0.54	0.09	0.33	0.34	27.27	-0.45	-0.19
$CaCO_3$(%)	1.50	11.00	1.93	4.78	4.50	40.37	0.45	-0.49
AP(kg ha^{-1})	6.45	31.53	3.89	12.13	11.29	32.06	1.72	4.78
Fe (mg kg^{-1})	2.07	10.33	1.83	4.88	4.58	37.50	0.63	-0.10
Zn (mg kg^{-1})	0.21	1.64	0.25	0.57	0.52	43.85	1.56	2.95
Cu (mg kg^{-1})	0.60	3.32	0.49	1.37	1.29	35.76	1.45	2.80
Mn(mg kg^{-1})	1.04	15.13	1.94	4.05	3.61	47.90	2.12	7.50

ECe: Electrical conductivity of saturation paste extract; AP: available phosphorous; Fe, Zn, Cu and Mn represent AB-DTPA extractable iron, zinc, copper and manganese in soil, respectively; CV: Coefficient of variation.

and significant positive correlation with available phosphorus and zinc (r =0.21** and r =0.17*). The $CaCO_3$ was negatively and significantly correlated with available Zn (r =-0.46**). The availability of AP was positively and significantly correlated with the availability of Fe (r =0.21**) and Mn (r =0.21**). Manganese and copper have a significant positive relationship with each other (r =0.25**). The existence of calcium carbonate within 30 cm of soil depth was shown to hinder the flow of natural ground water. Such circumstances in the area elevate the water table to a threshold depth, preventing soluble salts from leaching. The same cycle, repeated year after year in such a zone, results in the formation of saline-sodic soils.

Geo-statistical analysis

Geostatistical analysis was performed in ArcGIS 10.8 using a Geostatistical Analyst to identify the best-fitting semivariogram models. The properties of various best-fit semivariogram models that best match soil properties are shown in Table 3. The models that best fit the studied soil properties were found to be four models, viz. Exponential, Stable, K-Bessel and Circular. Spatial distribution maps for these soil properties are shown in Fig. 2. Exponential semivariogram model with the best fit for pH, OC, P, Fe, Mn, and Zn. The Stable semivariogram model proved to be the best-fitting model for EC. However, the most appropriate models for the $CaCO_3$ and Cu semivariogram models were determined to be K-Bessel and Circular, respectively.

In general, strong spatial dependence is influenced by intrinsic soil characteristics, but weak to moderate spatial dependence is impacted by external variables such as the use of mineral gypsum as a soil ameliorant, fertilizer timing, and other soil and crop management methods (Vasu *et al*., 2017). Bhunia *et al*. (2018) also acknowledged farm management methods' involvement in determining the degree of spatial correlation and homogeneity among soil parameters. Low correlation and high nugget values revealed the considerable variability among the studied soil properties. Zn, $CaCO_3$ and OC showed significant spatial dependency (nugget/sill ratio < 25%). The degree of spatial dependency for EC, Fe, Cu and Mn ranged from 25-75% (nugget/sill ratio). Other soil parameters showed moderate spatial dependence (nugget/sill ratio as >75%). Kriged geographic distribution maps of soil parameters were created to provide the current status of pH, ECe, SOC, $CaCO_3$, AP, Fe, Zn, Cu and Mn (Fig. 3).

Principal component analysis

A PC analysis was conducted to identify the key soil properties that can contribute most to improving soil quality so that immediate management actions are prioritized. For this purpose, PCs with an eigenvalue >1.0 were selected. The first four PCs showed eigenvalues greater than 1 and a cumulative variability of 69.5 per cent (Table 4). Therefore these PCs were considered for further investigations of various soil properties. Maps for the four PCs are shown in Figure 4. Principal component 1 (PC1), contributed 22.9 per cent to the overall variability while being dominated by loading of ECe, pH, $CaCO_3$ and Zn. As a result, the spatial distribution maps of EC, pH, $CaCO_3$, and Zn were identical to the kriged map of PC1. DTPA extractable Cu, Fe dominated PC loading of PC2, and Mn, explained 21.9 per cent of the total variance, and the kriged map of PC2 and the map of Cu, Fe, and Mn were comparable. An additional 12.9 and 11.6 per cent of the total variation was explained by PC3 (dominated by OC) and PC4 (dominated by Avail. P and Zn), respectively.

Delineating MZs by clustering analysis

The fuzzy k-means clustering was done using XLSTAT software to split the study area into MZs utilizing the PCA scores for the first four PCs for clustering anal-

Table 2. Correlation matrix of the soil properties in the study area

	pH	ECe	OC	$CaCO_3$	AP	Fe	Zn	Cu	Mn
pH	1								
Ece	0.54**	1							
OC	0.14	-0.00	1						
$CaCO_3$	-0.38**	-0.32**	-0.06	1					
AP	-0.04	0.21**	-0.06	0.08	1				
Fe	0.03	0.10	-0.06	-0.00	0.24**	1			
Zn	0.13	0.17*	-0.07	-0.46**	-0.06	0.00	1		
Cu	-0.00	-0.01	0.08	0.12	0.10	0.48**	-0.08	1	
Mn	0.03	-0.10	-0.13	0.02	0.29**	0.42**	-0.02	0.25**	1

ECe: Electrical conductivity of saturation paste extract; AP: available phosphorous; Fe, Zn, Cu and Mn represent AB-DTPA extractable iron, zinc, copper and manganese in soil, respectively;

Table 3. Semivariogram models for soil variables

Variables	Model	Sill	Nugget	Nugget/sill	Spatial class
pH	Exponential	0.31	0.25	0.80	Weak
Ece	Stable	0.32	0.13	0.40	Moderate
OC	Exponential	0.01	0.00	0.00	Strong
$CaCO_3$	K-Bessel	3.96	0.77	0.19	Strong
AP	Exponential	16.18	12.58	0.77	Weak
Fe	Exponential	4.13	1.74	0.42	Moderate
Zn	Exponential	0.05	0.00	0.00	Strong
Cu	Circular	0.42	0.16	0.38	Moderate
Mn	Exponential	5.11	1.88	0.36	Moderate

yses. Figure 5 depicts the final Management Zone map. The t-test was employed to evaluate the efficacy of this method for delineating MZs. The t-test revealed that various MZs had varying levels of heterogeneity for different factors. All of the variables had a significant difference (p 0.05) between MZ1 and MZ2, but all of the variables were substantially different between MZ1 and MZ3. Yao *et al*. (2014) used a fuzzy c-means clustering approach on the first four PCs scores to delineate site-specific management zones based on diverse soil attributes. On the other hand, Yao *et al*. (2014) employed the first four PCs score for establishing site-specific management zones that correlate crop yields with distinct soil factors.

Tola *et al.* (2017) also defined SMZs using the fuzzy c-mean approach to assess the productivity of Rhodes grass. According to the present study's findings, the delineation of MZs could be quite efficient and resourceful in monitoring and managing soil ameliorants for reclamation, as well as precise fertilizer planning in rice cropping systems under similar agro-climatic situations, thereby reducing environmental pollution across the entire zone. The lower salinity in Zone 1 may be due to less saline water incursion via subterranean flow and streams, which is common in Zones 2 and 3 (Table 5). With the exception of extractable zinc and available phosphorus, there was a significant difference (p0.05) between MZ1 and MZ3, but none of the other variables were. According to the classification of soil nutrient status under Indian circumstances, AP (11-22 kg/ha) was found to be in the medium range in all MZs. Fe, Cu, and Mn were found to be over critical levels in all MZs; however, Zn and OC were found to be below critical limits (1.2 mg/kg, 0.5%). Choudhary *et al*. (2011) researched to study the effect of long-term use of sodic water irrigation, amendments, crop residues on soil properties in calcareous soil.

The results showed that crop residue addition and the use of organic amendments (manures, composts, etc.) are essential to enhancing SOC status, which in turn aids in improving soil structure (water infiltration and permeability), minimizing salinity, increasing nutrient status, and sustaining crop production under stress conditions. Sheoran *et al*. (2021) also demonstrated that plant-assisted (salt-tolerant types) soil remediation (gypsum and press mud-mediated) improved soil and environmental quality while also preserving agricultural production in salty soils. Sundha *et al*. (2020) have de-

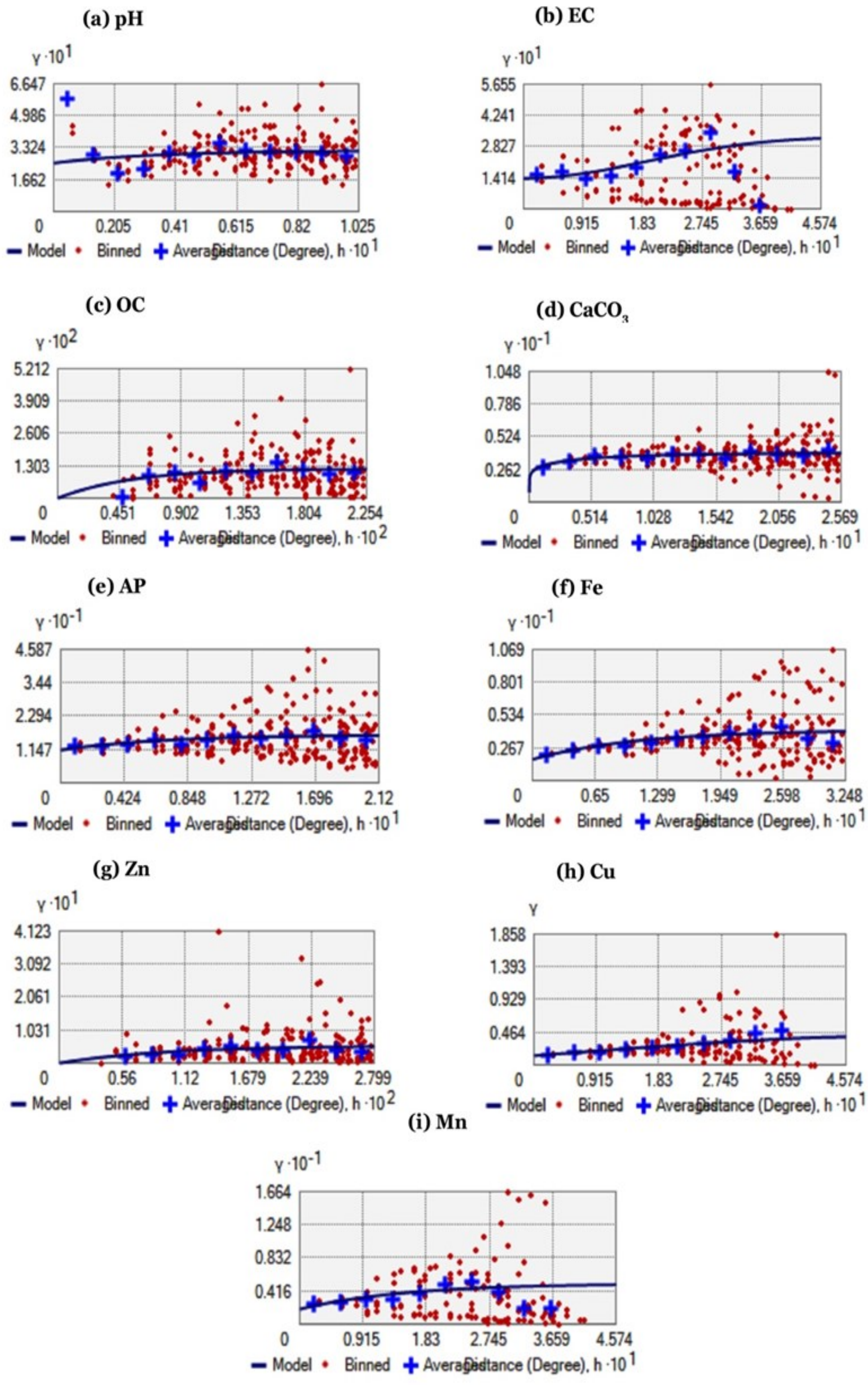

Fig. 2. *Best fitted Semivariogram models for selected soil properties, (a). pH, (b). EC, (c). SOC, (d). $CaCO_3$, (e) Available P, (f). available Fe, (g). available Zn, (h). Available Cu & (i). Available Mn*

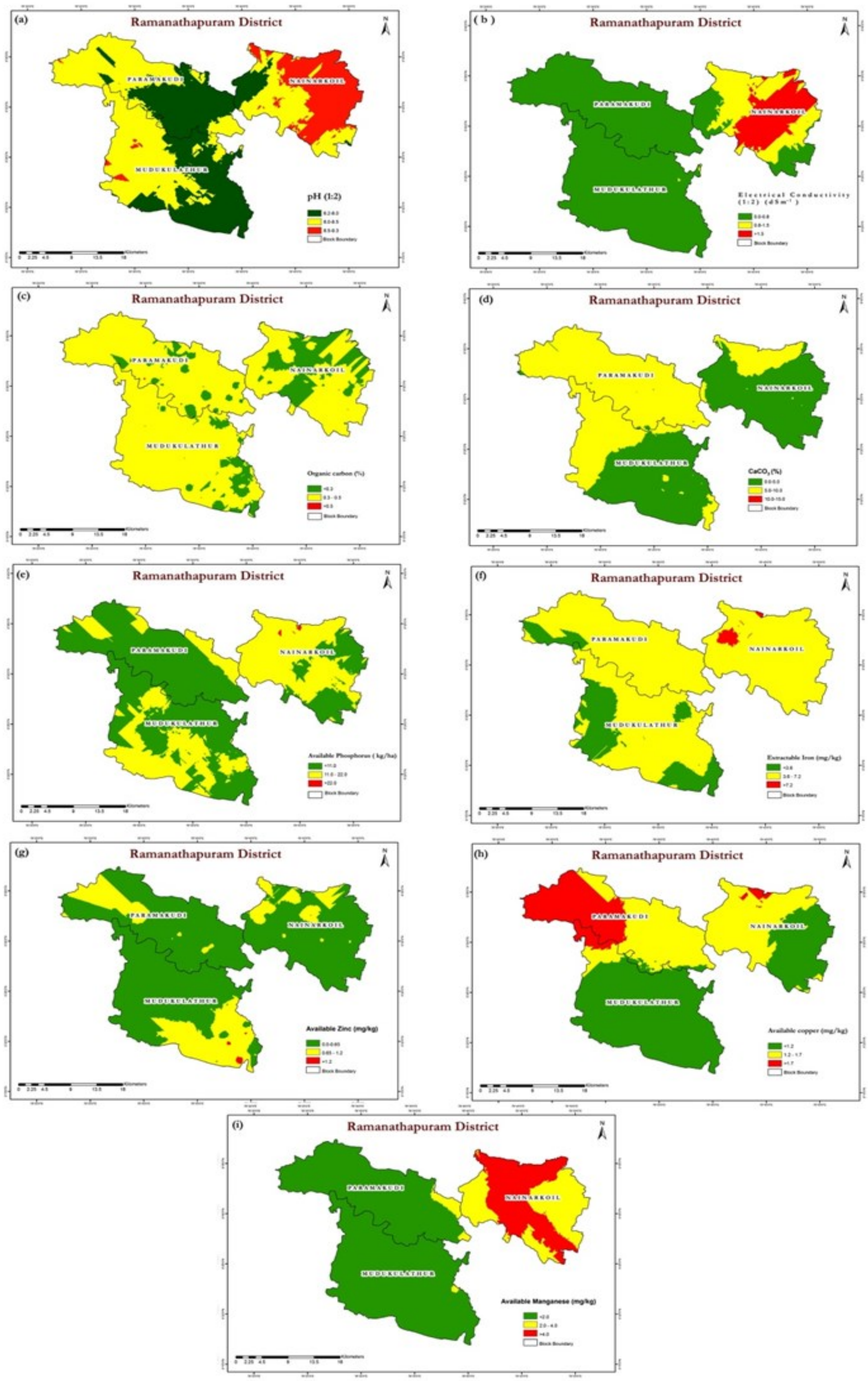

Fig. 3. *Krigged spatial distribution map of soil (a). pH, (b). EC, (c). SOC, (d). $CaCO_3$, (e) available P, (f). available Fe, (g). available Zn, (h). available Cu, & (i). available Mn in Paramakudi, Mudukulathur & Nainarkoil blocks of Ramanathapuram district*

Table 4. Principal component analysis of the variables and loading coefficients for the first four principal components

Principal Component	Eigenvalues	Component loading (%)	Cumulative loadings (%)
PC1	2.06	22.91	22.91
PC2	1.97	21.97	44.89
PC3	1.16	12.92	57.81
PC4	1.05	11.68	69.50
PC5	0.79	8.83	78.33
PC6	0.65	7.24	85.58
PC7	0.48	5.40	90.98
PC8	0.43	4.82	95.80
PC9	0.37	4.19	100.00

PC loadings for each variable:

	pH	ECe	OC	$CaCO_3$	AP	Zn	Cu	Fe	Mn
PC1	0.74	0.76	0.06	-0.71	0.16	0.51	0.04	0.24	0.22
PC2	-0.14	0.02	-0.14	0.32	0.52	-0.26	0.66	0.75	0.68
PC3	0.32	0.05	0.82	0.10	-0.18	-0.41	0.35	0.02	-0.19
PC4	0.19	0.40	-0.07	0.27	0.52	-0.48	-0.41	-0.29	0.02

Table 5. Soil pH, electrical conductivity and nutrient status in three management zones (MZ)

MZ	pH	ECe (dSm^{-1})	OC (%)	$CaCO_3$ (%)	AP (kg ha^{-1})	Zn (mg kg^{-1})	Cu (mg kg^{-1})	Fe (mg kg^{-1})	Mn (mg kg^{-1})
MZ1	7.83	1.41	0.31	6.09	11.23	0.46	1.14	3.91	3.27
MZ2	7.97	2.03	0.34	5.14	13.74	0.52	1.88	6.67	5.31
MZ3	8.57	4.50	0.35	3.10	11.86	0.73	1.21	4.49	3.90

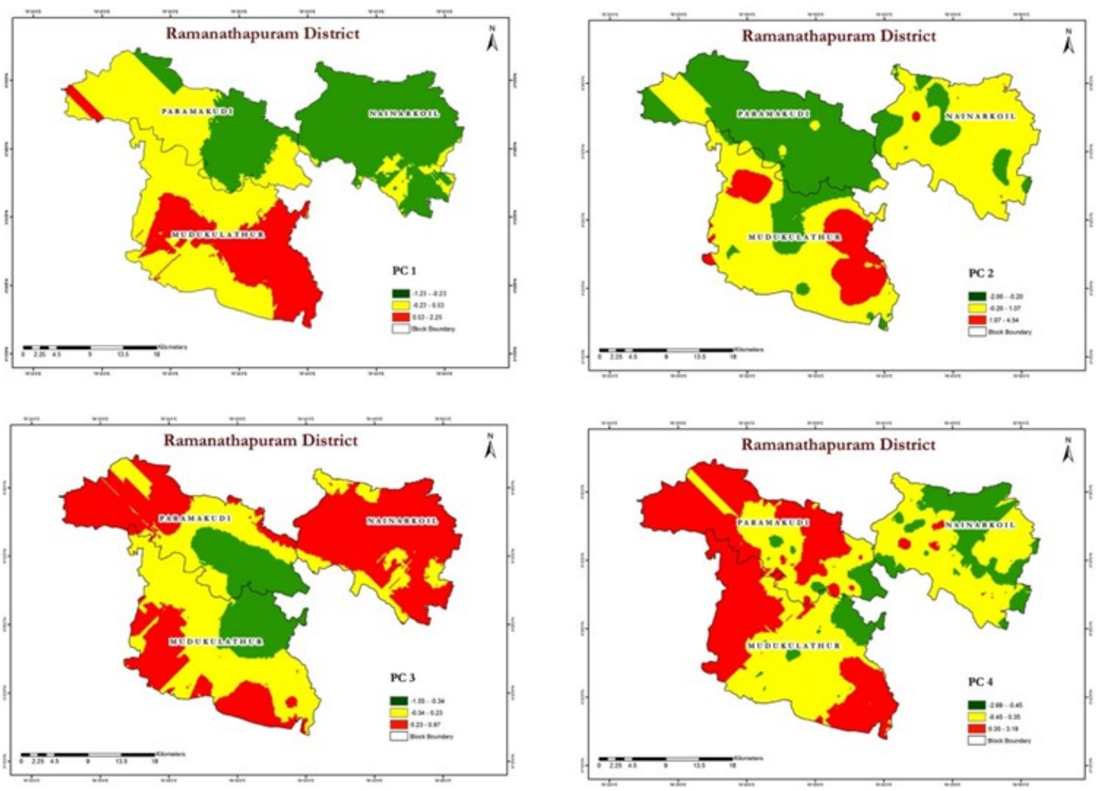

Fig. 4. *Maps of four principal component analysis*

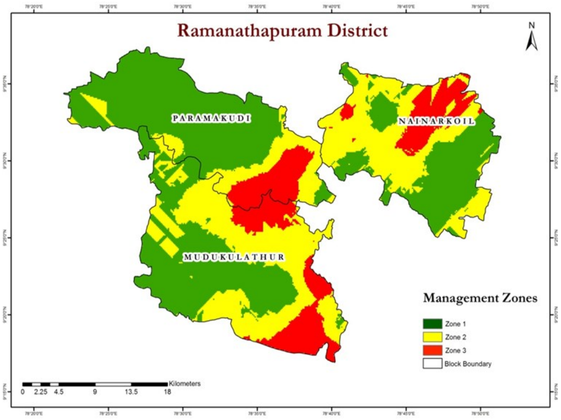

Fig. 5. *Management Zones map for Paramakudi, Mudukulathur & Nainarkoil blocks of Ramanathapuram district*

scribed the use of gypsum in conjunction with municipal waste composts as an environmentally viable method of increasing microbial biomass carbon and nutrient availability in saline-sodic soils. Meena *et al*. (2018) reported that to improve P efficiency, utilizing municipal solid waste compost in conjunction with phosphatic fertilizers can enrich fractional P in soils, resulting in improved P availability in coastal salty soils . The application of primary (PK) and micro (Zn, Cu, Fe, Mn) nutrients should be selected holistically using thematic maps and a cropping system.

Effective technological support and distribution to improve farmers' awareness and acceptance of salt-tolerant cultivars may improve agricultural resilience, stabilize production, and ensure livelihood. Green manuring is beneficial in increasing soil organic matter and lowering fertilizer expenditures in all MZs. Furthermore, the incorporation of farmer-led adaptive innovations regulated by localized variables can be reinforced with zone-wise management techniques to improve their socio-ecological resilience and related hazards (Singh *et al*., 2019). The soil database created in this study and the distribution of soil health cards to farmers may sensitize and influence their attitudes about soil reclamation, balanced fertilization, nutrient cycling, and environmental preservation.

Conclusion

India's food security is being threatened by soil salinization. The reclamation and management of salt-affected soils are possible using several on-farm proven methods. One of the methods is location-specific reclamation strategies. This continuous monitoring, assessment and mapping of spatial variability is an effective strategy for precision farming and countering soil impairments in such fragile ecosystems. Geostatistical analysis of soil indices revealed Exponential, Stable, k-bessel and Circular were best fit semivariogram models with weak to moderate spatial dependence. Developing a concept of management zones would make it easier for farmers to employ location-specific reclamation tactics and fertilizer recommendations in coastal saline soils. These findings would be extremely helpful in developing site-specific reclamation strategies for the saline environment, resource optimization (nutrients) and reducing land degradation in coastal saline soils of Ramanathapuram district, India and comparable conditions worldwide. The fertilizer may be conserved by using MZs at the same time. Additionally, major findings from this study will be very beneficial for policy implications related to sustainable rehabilitation of degraded lands, enhancing soil health and balancing environmental preservation with socioeconomic development.

Conflict of interest

The authors declare that they have no conflict of interest.

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