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ORIGINAL ARTICLE

Short-Scale Soil Spatial Variability of a Salt-Affected Land Allotment in *Maha-Illuppallama*, Sri Lanka

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Abstract

The development of salt-affected soils is a serious limitation for sustainable agricultural crop production in Sri Lanka. This study was conducted to explore the short-scale spatial variability of a salt-affected land allotment at *Maha-Illupallama* in dry zone, Sri Lanka. Seventy soil samples from a depth of 0 - 30 cm were randomly collected within the study site. Soil Electrical Conductivity (EC), pH, Cation Exchange Capacity (CEC), Exchangeable (Ex.) cations; Ex.K, Ex.Na, Ex.Mg and Ex.Ca were measured using established techniques. Sodium Adsorption Ratio (SAR), Exchangeable Na percentage (ESP), K (EPP), Mg (EMP), and Ca (ECP) were estimated based on the relevant measured soil properties. Exploratory data analysis found considerable spatial variability in EC, ESP, SAR, and EPP while CEC, EMP, and ECP showed moderate spatial variability. The soil pH and BS exhibited lesser spatial variability within the study field. Variogram analyses revealed the presence of strong structured spatial variability for each analyzed soil parameter within the study site. Four Potential Management Zones (PMZs) i.e., PMZ1, PMZ2, PMZ3, and PMZ4 were demarcated using Fuzzy *k* means classification. Highest EC (1.19 ± 0.70 dS m^{-1}) and SAR (19.05 ± 13.09) mean values were observed in PMZ2. Higher EMP mean values were observed in PMZ 1 and 3 in comparison to PMZ 2 and 4. Other evaluated soil properties varied among the designated PMZs. Soils in several places revealed pH > 8.5, EC < 4.5 dS m^{-1}, ESP > 15%, and SAR > 13 values indicating an occurrence of sodic soil. The results underline the considerable potential for the use of Site-Specific Soil Management (SSSM) practices based on the PMZs in the examined salt-affected soil to boost productivity.

Keywords: *Potential Management Zones (PMZs), Short-scale soil spatial variability, Site-Specific Soil Management (SSSM), Sodic soil*

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1. Introduction

The occurrence of salt-affected soils is a common phenomenon in many parts of the world including Sri Lanka. The total global areas with salt-affected soils have been estimated to be 83 million hectares (Martinez-Beltran, 2005; Dagar and Minhas, 2016). According to Amini et al*.* (2016), 75 countries are having extensive salt-affected lands. The arid and semi-arid climates are conducive to developing salt-affected soils. The excessive evaporation from poorly drained soils under arid and semi-arid climates results in the accumulation of salts on the surface horizon (Hailu and Mehari, 2021).

Salt-affected soils occur as a result of primary and secondary salinization processes. Globally, around 95 and 77 million hectares of soil are under primary and secondary salinization respectively (Metternicht and Zink, 2003). In primary salinization, salt is accumulated in the soil through natural processes such as physical and chemical weathering of parent rock, dry and wet deposition of oceanic salts, etc. (Hassani et al., 2021). Irrigation with saline water without sufficient leaching of salt, seawater intrusion, shallow groundwater tables together with poor drainage, high evaporation rate, excessive use of chemical fertilizers, overgrazing, and deforestation are the possible reasons for secondary salinization (Brinck and Frost, 2009; De Souza and Fay, 2012; Gavrichkova et al., 2020; Chu et al., 2023).

Salt-affected soils are designated as holomorphic soils and have been classified into three major categories i.e., saline soils, sodic soils, and saline-sodic soils (Rengasamy, 2010; Choudhary and Kharche, 2018). Soils of which electrical conductivity (EC) in saturated paste extract is greater than 4 dS m^{-1} at 25 °C, exchangeable sodium percentage (ESP) is less than 15% and pH is less than 8.5 are classified into saline soils due to the dominance of neutral salt sulphates and chlorides of sodium, calcium, and magnesium are usually present salts in these soils. White alkali is the synonym for saline soil due to white incrustation on the surface horizon (Richards, 1954; O'Geen, 2015; Negacz et al., 2022).

The soil in which EC in saturated paste extract is greater than 4 dS m^{-1} at 25 °C, and ESP is greater than 15% are classified into saline-sodic soils. The total exchange capacity of these soils is occupied by sodium. The pH of these soils is seldom higher than 8.5 due to the repressive effect of the neutral soluble salts (Richards, 1954; Chaganti et al., 2015; O'Geen, 2015). Soils of which the EC of saturated paste extract is below 4 dS m^{-1} at 25 °C, and ESP is over 15% are classified into sodic soils. These soils do not contain any appreciable quantities of neutral soluble salts, and hence the exchangeable sodium is free to hydrolyze increasing soil pH up to 8.5 and 10. Black alkali soil is a synonym for these soils due to the fine distribution of organic matter through the soil particles resulting in a darkened appearance (Richards, 1954; O'Geen, 2015; Zhao et al., 2021).

Amini et al. (2016) reported that 23% and 10% of arable soils in the world are saline and saline-sodic, respectively while 340 million hectares of arable soils are considered to be sodic (Amini et al., 2016). Development of soil salinity is frequently reported in dry and semi-arid regions belonging to Jaffna, Mannar, Ampara, Batticaloa, Hambantota, Moneragala, Polonnaruwa, and Trincomalee districts of Sri Lanka (Jeganathan and Pain, 1982; Prapagar et al., 2012; Gopalakrishnan and Kumar, 2020). Further, coastal regions and the irrigated lands in dry zones of Sri Lanka have been greatly affected by salinity (Gopalakrishnan and Kumar, 2020). It is estimated that approximately 11,200 ha of coastal lands have been affected by salinity and more than 50% of the coastal paddy lands have been abandoned due to salinity (Perera, 2018).

Soluble salts in the semi-arid region tend to accumulate in the upper part of soils. Higher soil evaporation and lower rainfall in these regions resulted in insufficient leaching and upward movement of soluble salts along with the soil profile. Saline-sodic soils (USDA soil taxonomic name: Natraqualfs; Great soil group: Solodized Solonetz) of which parent material is marine sediment, are common in the drier regions of the lower coastal plain of the country marine sediments (Prapagar et al., 2012).

The development of soil salinity is of greater concern nationally and internationally since it is one of the soil degradation pathways leading to unproductive crop growth. Land degradation due to salinity is estimated to be about 2% (47,000 ha) of the total agricultural land area in Sri Lanka (Prapagar et al., 2015). Salt-affected soils are generally barren with declining productivity. In addition to that, excess salt affects overall soil health resulting in poor physical and chemical properties of soil. Most of the soil's physical (e.g., soil structure and soil texture, etc.) and chemical properties (e.g., exchangeable sodium percentage, electrical conductivity, pH, etc.) are affected by the accumulation of soluble salts in the soil (Qadir and Oster, 2004; Meena et al., 2019). Higher exchangeable sodium and higher pH decrease soil permeability, available water capacity, and infiltration rates through swelling and dispersion of clays as well as slaking of soil aggregates (Qadir et al., 2007). Excessive soil soluble salts adversely affect soil microbial activity followed by soil biological properties (Wong et al., 2008). Additionally, soil salinity existing over a long period causes for decrease in carbon content (Wong et al., 2009; Wong et al., 2010).

Deteriorated physical, chemical, and microbial properties in salt-affected soils decrease the productivity of agricultural crops due to many reasons. Plants grown in these soils often appear to be drought-stressed even when adequate water is available since the greater osmotic potential of the soils prevents roots from taking water (Munns, 2002; Gopalakrishnan and Kumar 2020). Higher soluble salt contents in soils become toxic to the plants leading to root injuries and inhibition of seed germination (Safdar et al., 2019). It has been estimated that soil salinity causes 18-43% losses in crop production in arid and semi-arid regions (Wichelns and Qadir, 2015; Singh, 2021). These facts highlight the importance of reclamation of salt-affected soil to enhance the productivity of salt-affected soils to increase crop yield.

Many reclamation techniques are available to correct salt-affected soils. Leaching with good-quality irrigation water has been identified as the most effective method for removing soluble salts from the rhizosphere in saline soils (Srivastava et al., 2019; Gangwar et al., 2020). Various types of chemical amendments such as gypsum, phosphogypsum, sulfuric acids, sulfur, lime sulfur, pyrite and iron, and aluminum, etc. are used to replace excessive sodium from cation exchangeable sites (Oster et al., 1999; Machado and Serralheiro, 2017; Minhas et al., 2020). Gypsum is the most commonly used amendment due to its availability at a low cost. Makoi and Ndakidemi (2007) have shown the beneficial effect of the combined use of farmyard manure and gypsum for the reclamation of sodic soils. The incorporation of rice husk significantly decreased soil EC, pH, and SAR (Prapagar et al., 2012).

Implementation of the most suitable reclamation technology or technologies is a prime necessity to obtain better crop yields from salt-affected soil. The patterns of soil salinity development in a given salt-affected soil are not uniform. It always shows short-scale spatial variability due to the spatial heterogeneity of the factors governing the salinity development in the shorter distance. Therefore, it is not worthwhile to implement the same management practices to reclaim salinity or sodicity over the larger salt-affected areas if there is considerable soil spatial variability. Delineation of potential management zones (PMZs) in the salt-affected land allotments followed by identifying the best-suited salinity management packages specific to each management zone would be the best approach for reclaiming salt-affected soils. According to the literature, Site-Specific Soil Management (SSSM) based on PMZs is a common approach in non-salt-affected soil (Corwin, 2013; Jin and Jiang, 2002; Khan, et al, 2020). However, the applicability of implementing SSSM based on PMZs for reclaiming salt-affected soils has not been investigated yet in the Sri Lankan context. In this study, short-scale spatial variability followed by the applicability to implement soil management based on PMZs in a salt-affected land allotment in Anuradhapura, Sri Lanka was investigated.

2. Materials and Methods

2.1 Study site

The study site was a salt-affected land allotment (2.94 ha) (Latitude: 8.105074° N; Longitude: 80.461581° E) located in Field Crop Research and Development Institute at *Maha-Illuppallama*, Anuradhapura (Fig. 01). The study area belongs to the agro-ecological zone $DL_{1b.}$ The dominant great soil group in the area is Reddish Brownish Earth (RBE) and the USDA soil taxonomic name is Typic Rhodustalfs (Mapa et al., 2010). The rainfall of this area is between 1000-1500 mm and the mean annual temperature is 27 °C (Punyawardena et al., 2003).

2.2 Preparation of the sampling scheme

The boundary of the study site was delineated using Google Earth Software (version 7.3.6). The study area was divided into smaller grids (20 m × 20 m) and a unique ID number was assigned to each grid. Seventy grids were randomly selected using random number generation. The center coordinates of each selected grid were considered as a sampling location.

2.3 Soil Sampling

The sample locations (70) were identified in the field by navigating using GPS (Garmin Oregon® 750t). Soil from each sample location was collected from 0 - 30 cm depth intervals using a Gouge auger. The real coordinates of the location from which samples were collected were recorded using GPS (Garmin Oregon® 750t).

2.4 Initial soil sample preparation

Collected soil samples were brought to the Field Crop Research and Development Institute in *Maha-Illuppallama*. Each sample was air-dried and passed through a 2 mm sieve to minimize soil heterogeneity, the larger clods in the soil samples were broken using a hammer.

2.5 Soil analysis

Soil analyses were carried out in the soil science laboratory of the Field Crop Research and Development Institute at *Maha-Iilluppallama* and the soil science laboratory, Faculty of Agriculture, Rajarata University of Sri Lanka. Soil pH was measured in soil suspension (soil/distilled water = 1:2.5) using a potentiometric glass electrode/ pH meter system (Rowell, 1994). Electrical conductivity (EC) in the saturated paste extract was measured by a potentiometric approach using a conductivity meter (Rhoades et al., 1989). Exchangeable Na, K, Ca, and Mg were extracted by 1 M CH_3COONH_4 buffered at pH =7 (Simard, 1993) using Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES).

Soil CEC was measured using the Ammonium acetate method (Chapman, 1965). Sodium Adsorption Ratio (SAR) (Equation 02) and Exchangeable individual basic ion percentage (IBIP) (Equation 01) were calculated by using the two equations given below.

$$IBIP = \frac{IBC \times 100}{CEC} \quad \text{(Equation 01)}$$

Where IBIP was the individual basic ion percentage, IBC was the individual basic ion (Na, K, Ca, and Mg) concentration in $cmol_c$ kg^{-1} and CEC was cation exchange capacity in $cmol_c$ kg^{-1}.

Equation 02,

$$SAR = \frac{Na^+}{\sqrt{\frac{Ca^{2+} + Mg^{2+}}{2}}} \quad \text{(Equation 02)}$$

Where SAR was the sodium absorption ratio and Na^+, Ca^{2+}, and Mg^{2+} are sodium, calcium, and magnesium ion concentrations in mmol kg^{-1}.

2.6 Spatial variability analyses

The variograms for each selected soil parameter were calculated to graphically illustrate using Variowin 2.4 software. The relative nugget effect (RNE) was calculated (Equation 03) to explain the strength of structured spatial variability (Cambardella, 1994).

$$RNE = \frac{Nugget}{sill} \times 100\% \quad \text{(Equation 03)}$$

2.7 Spatial variability map preparation

Spatial variability maps of EC, pH, CEC, exchangeable Na% (ESP), exchangeable K% (EPP), exchangeable Mg% (EMP), and exchangeable Ca% (ECP) were prepared using ordinary kriging procedure. Spatial addition of the raster layers of ESP, EPP, EMP, and ECP was performed to produce the raster map of Base Saturation (BS). The accuracy of each map was investigated using leave-one-out cross-validation procedure.

2.8 Delineation of potential management zones (PMZs)

The raster maps of pH, ES, ESP, and SAR were used to delineate PMZs. The fuzzy *k* mean classification technique was used to delineate PMZs. The classification was accomplished using FuzME software3b developed at the Australian Centre for Precision Agriculture (Minasny and McBratney, 2002). The software determines membership in each cluster through an iterative process beginning with a random set of cluster means. Each observation was assigned to the closest of these means. To ensure cluster stability, the process was repeated until either the specified convergence criterion was met or the maximum number of iterations was reached. Settings used in FuzME software were as follows: the maximum number of iterations = 300, the stopping criterion = 0.0001, the minimum number of zones = 2, the maximum number of zones = 8, and the fuzziness exponent = 1.3. Two cluster validity functions; including fuzzy performance index (FPI) and normalized classification entropy were used as indicators of optimum cluster number (McBratney and Moore, 1985).

2.9 Data analysis

The significant differences in the measured soil properties among the delineated management zones were determined using Analysis of Variance (ANOVA). Significantly different PMZs based on the measured soil parameters were investigated using Tukeys’s mean separation procedure.

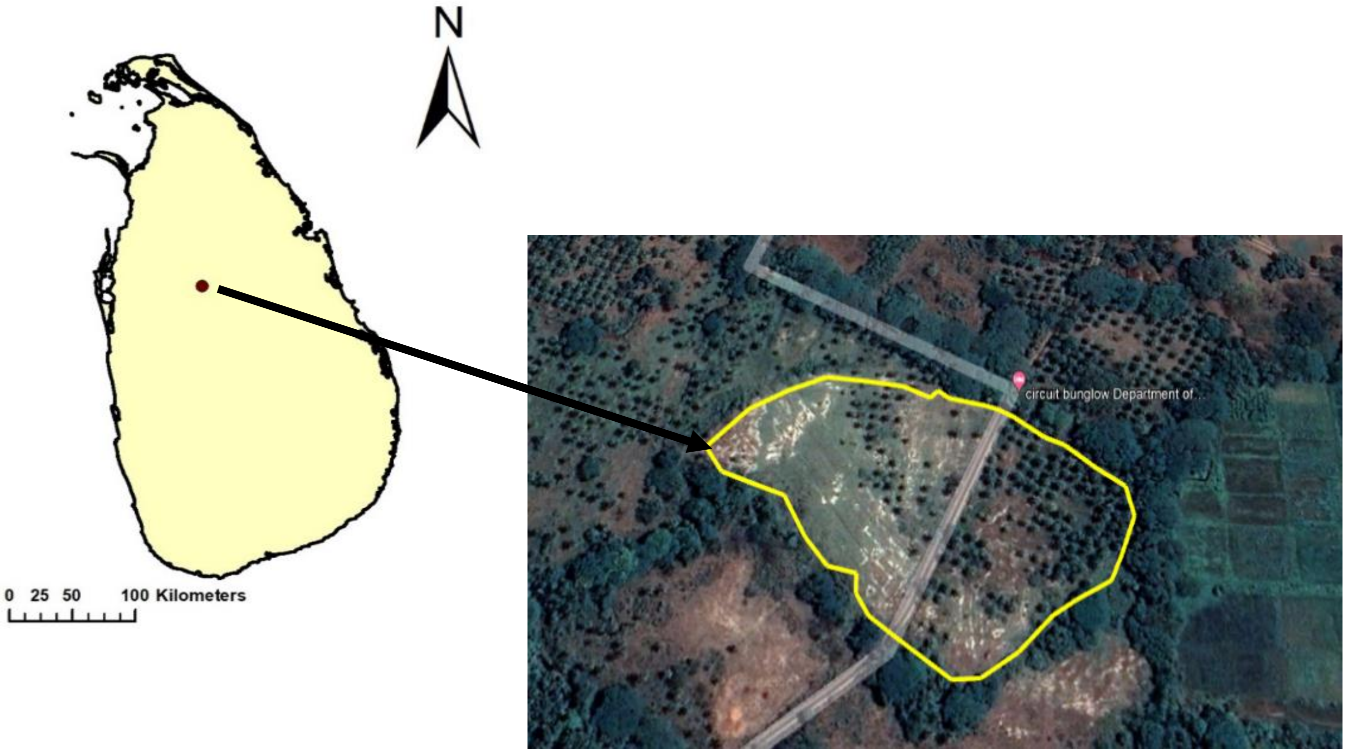


Figure 1: The study site (Latitude: 8.105074° N; Longitude: 80.461581° E) located at *Maha-Illuppallama*, Anuradhapura, Sri Lanka, and Google satellite image showing the bird's eye view of the study site.

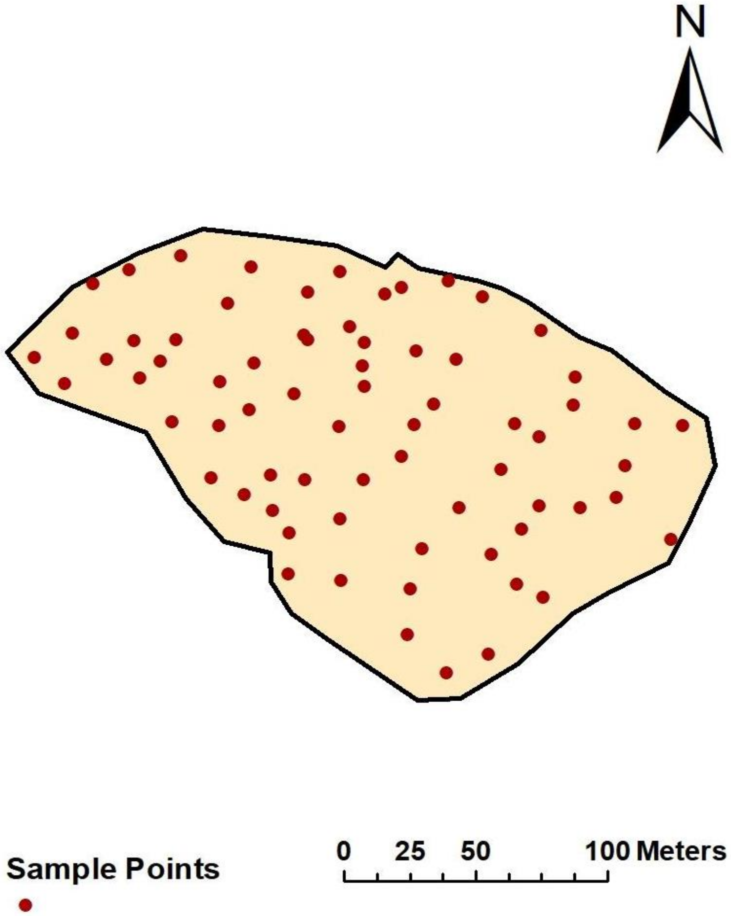


Figure 2: The map showing the spatial distribution of the soil sampling locations in the study site.

3. Results and Discussion

3.1 Variation of the investigated chemical parameters

The results of exploratory data analyses are given in Table 1. According to the CV classification of Warrick and Nielsen (1980), exploratory data analysis revealed high spatial variability in EC, ESP, SAR, and EPP (60% < CV) while CEC, EMP, and ECP showed moderate spatial variability (12% < CV < 60%). Moreover, pH and BS revealed lower spatial variability (12% > CV) within the study field.

Soil pH in the field varied from 6.44 to 10.63 with a mean of 9.11 and a SD of 1.10. Therefore, these results revealed the occurrence of alkaline soil within the study field. The dominance of sodium ions among the cations and carbonates, bicarbonates from anions can be observed with high soil pH (Hussain et al., 2001). Moreover, soil EC ranged from 0.05 dS m^{-1} to 2.06 dS m^{-1} with a mean of 0.56 dS m^{-1} and SD of 0.48 dS m^{-1}. Soil EC is a measurement of the amount of soluble salts available in the soil (Banon, 2021). According to the results, higher soluble salt accumulation was observed in the study field.

The origins of these soluble salts might be irrigation water or bedrock. Weathering of bedrock followed by accumulation of soluble salts in the surface horizon through evapotranspiration might result in high salt accumulation in surface soil. Soil SAR ranged from 0.31 to 31.91 with a mean of 7.06 and SD of 8.04. Moreover, the ESP ranged from 1.10% to 82.70% with a mean of 28.30% and SD of 25.40%. These results revealed a higher accumulation of sodium in the soil of the study field. Sodic soil refers to salt-affected soil with a high proportion of sodium relative to other cations (Shirale et al., 2018; Du et al., 2022). Certain areas of the field showed extremely higher pH (> 8.5), EC (< 4 dS m^{-1}), SAR (> 13), and ESP (> 15%). These results further highlighted the occurrence of sodic soil.

Soil EPP in the study site ranged from 0.31% to 9.44% with a mean of 1.70% and SD of 1.63%. Soil EPP in the study soil was within the acceptable limit. Therefore, the EPP values of some locations were far below the general values of RBE soils in the dry zone of Sri Lanka (Amarawansa et al., 2018). This might be due to the replacement of many basic cations in the exchangeable sites with sodium in the studied soil, suspected to be sodic soil.

EMP in the study site ranged from 3.75% to 53.12% with a mean of 29.69% and SD of 12.24%. Soil ECP ranged from 10.12% to

71.34% with a mean of 39.75% and SD of 16.84%.

Soil CEC in the study site ranged from 1.30 $cmol_c$ kg^{-1} to 23.55 $cmol_c$ kg^{-1} with a mean of 8.88 $cmol_c$ kg^{-1} and SD of 4.15 $cmol_c$ kg^{-1}. Soil CEC is a measure of the soil's ability to hold positively charged ions (Saidi, 2012; Khaledian et al., 2017). Literature reports that soil CEC of Alfisol in the dry zone of Sri Lanka ranges between 5 to 25 $cmol_c$ kg^{-1} (Rosemary et al., 2017; Mapa, 2010). Therefore, some locations in the field showed extremely lower CEC values. Soil organic and inorganic colloids contribute to CEC. Soil clay particles act as an inorganic colloid. Dispersion and leaching down clay particles to subsoil horizons are common phenomena in sodic soil (Shahid et al., 2018). These processes finally result in lower soil CEC. The base saturation of the study site varied from 88.80% to 100.00% with a mean of 99.41% and SD of 1.94%.

3.2 Semivariogram Analysis

Semivariogram is a geo-statistical tool used to model the spatial variability of soil (Han et al., 2010; Weindorf and Zhu, 2010; Rosemary et al., 2017). The variogram shows the relationship between the lag distance (h: the distance between two measurements of a particular property) and the corresponding semi-variance of the spatially varying property. In a highly spatially correlated variable, the semi-variance increases from low values near the origin to larger values as h increases. This indicates a higher spatial correlation at the smaller lag distances and a reduction of the spatial correlation as the lag distance increases (Issaaks and Srivastava, 1989). It is considered that the observations within the range are spatially correlated, whereas those greater than the range are considered spatially independent (Goovaerts, 1997).

Table 1: Summary statistics of measured chemical properties of soil samples (n = 70) collected from the study site

Variable	MEAN	SD	CV%	MIN	MAX
pH	9.11	1.10	11.80	6.44	10.63
EC (dS m^{-1})	0.56	0.48	86.25	0.05	2.06
ESP (%)	28.30	25.40	89.70	1.10	82.70
EPP (%)	1.70	1.63	96.16	0.31	9.44
EMP (%)	29.69	12.24	41.22	3.75	53.12
ECP (%)	39.75	16.84	42.38	10.12	71.34
CEC ($cmol^{+}$ kg^{-1})	8.88	4.15	46.73	1.30	23.55
BS (%)	99.41	1.93	1.94	88.86	100.00
SAR	7.06	8.04	113.87	0.31	31.91

(SD = Standard deviation, CV = Coefficient of variation, MIN= Minimum, MAX = Maximum, EC = Electrical conductivity, ESP = Exchangeable Sodium Percentage, EPP = Exchangeable Potassium Percentage, EMP = Exchangeable Magnesium Percentage, ECP = Exchangeable Calcium Percentage, CEC = Cation Exchange Capacity, BS = Base Saturation and SAR = Sodium Absorption Ratio)

According to this exploratory data analysis, soils of some locations showed pH > 8.5, EC < 4.5 dS m^{-1}, ESP < 15%, and SAR > 13 values indicating an occurrence of sodic soil.

The semi-variograms fitted for different chemical properties i.e. pH, EC, ESP, EPP, EMP, ECP, SAR, and CEC are shown in Fig. 3 a, b, c, d, e, f, g, and h, respectively. The spherical shape variogram was best fitted for each soil property. The variogram parameters of each variogram have been given in Table 2. The longest range (84 m) was reported for EPP. The greater spatial dependency of the measured EPP over a longer distance in the soil resulted in a longer range for the EPP semi-variogram. The second longest range was reported for ECP (66 m). The ranges of pH, EC, ESP, EMP, SAR, and CEC ranged from 61.2 m to 17.64 m.

The relative nugget effect (RNE) is one of the important tools used to explain the strength of structured spatial variability (Goovaerts, 1997). According to the RNE classification proposed by Cambardella et al. (1994), strong structured (RNE < 25%) spatial variability was observed for all the soil parameters except for ECP.

3.3 Spatial variability maps of the investigated soil parameters

The spatial pattern of the soil pH at a depth of 0 - 30 cm is shown in Fig. 4 (a). Soil pH governs the availability of different nutrients in the soil. Moreover, the soil pH value reflects the integrated effect of the acid-base reactions taking place in the soil system. In the study area, soil pH ranged from 6.44 to 10.63 indicating basic conditions. Generally, soil pH values were higher in the study field and extremely higher pH values were distributed in the western and middle areas of the field.

The study area is located in the low country dry zone of Sri Lanka. As a result of low rainfall and high evaporation, basic cations are moving upwards along the soil profile creating soil basic conditions in the soil.

Table 2: Parameters of the modeled semivariogram fitted for each soil parameter

Property	Direction	Model	Nugget	Scale	Sill	Range (m)	RNE%
pH	Omni	Spherical	0.144	0.960	1.104	33.8	13.04
EC (µS cm^{-1})	Omni	Spherical	23000	204700	227700	31.2	10.10
ESP (%)	Omni	Spherical	0.098	1.372	1.47	61.2	6.67
EPP (%)	Omni	Spherical	0.126	0.516	0.642	84.0	19.63
EMP (%)	Omni	Spherical	0.068	0.292	0.36	36.0	18.89
ECP (%)	Omni	Spherical	0.087	0.174	0.261	66.0	33.33
SAR	Omni	Spherical	2.56	64.00	66.56	39.60	3.85
CEC ($cmol^+ kg^{-1}$)	Omni	Spherical	1.70	10.20	11.90	17.64	14.29

(EC = Electrical conductivity, ESP = Exchangeable Sodium Percentage, EPP = Exchangeable Potassium Percentage, EMP = Exchangeable Magnesium Percentage, ECP = Exchangeable Calcium Percentage, SAR = Sodium Absorption Ratio and CEC = Cation Exchange Capacity)

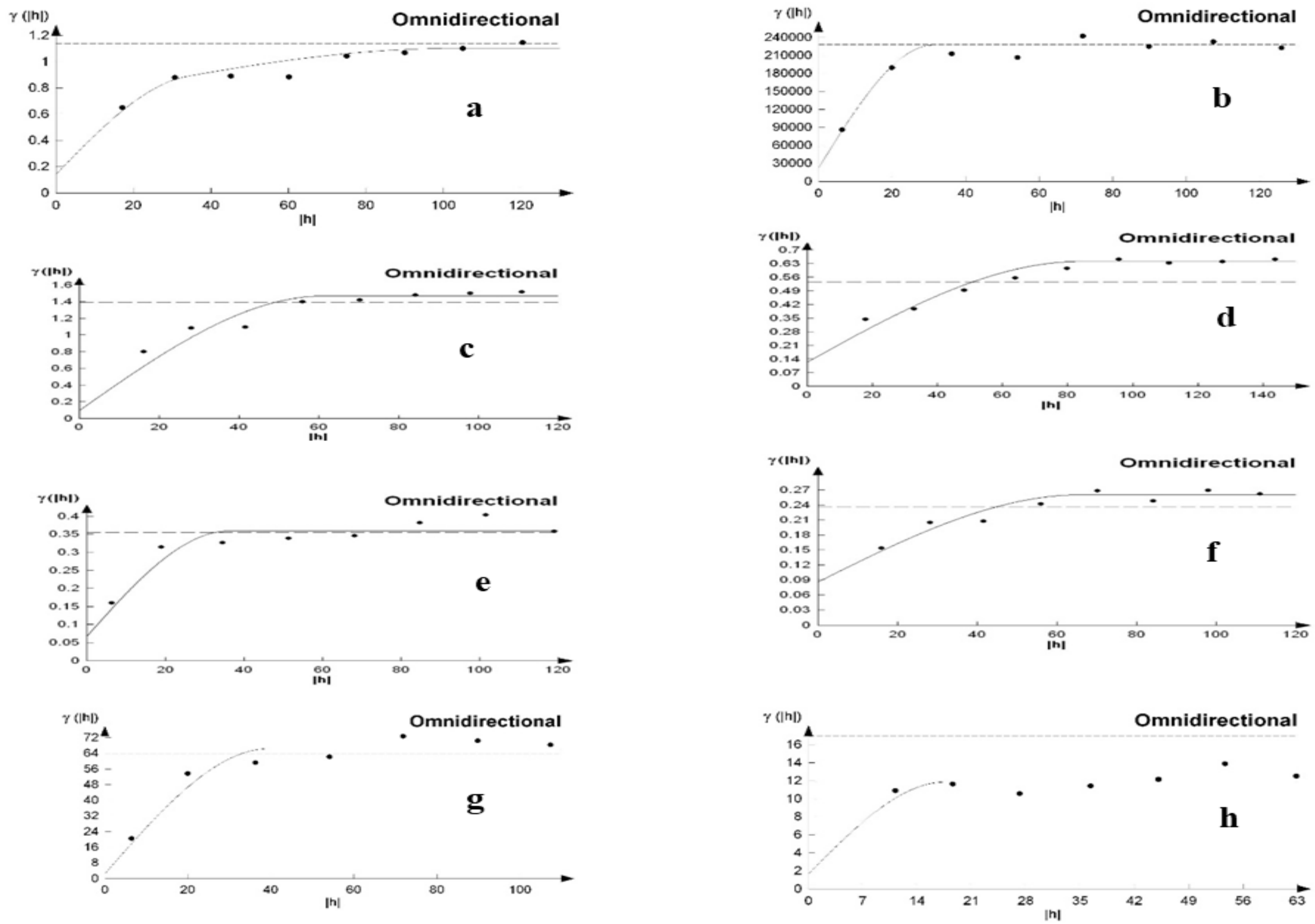


Figure 3: Semi-variograms fitted for measured chemical parameters (a) pH, (b) EC, (c) ESP, (d) EPP, (e) EMP, (f) ECP (g) SAR, and (h) CEC (EC = Electrical conductivity, ESP = Exchangeable Sodium Percentage, EPP = Exchangeable Potassium Percentage, EMP = Exchangeable Magnesium Percentage, ECP = Exchangeable Calcium Percentage, SAR = Sodium Absorption Ratio and CEC = Cation Exchange Capacity)

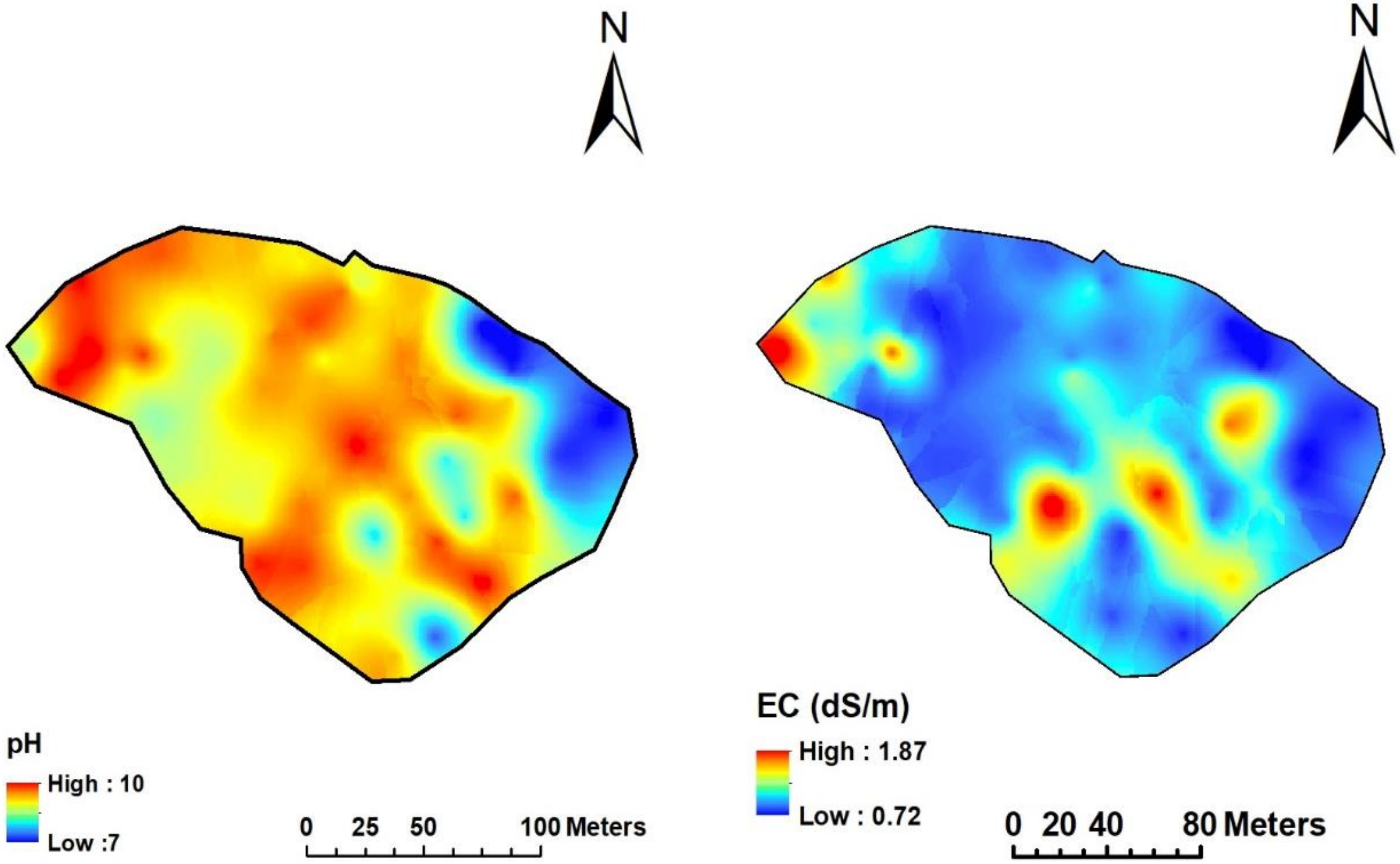
The Electrical Conductivity (EC) is proportional to the soluble salt content of the soil in the study area. The spatial pattern of the soil EC is illustrated in Fig. 4 (b). Soil EC in the study area varied between 0.05 to 2.06 dS m^{-1}. The spatial variability map of EC showed a similar pattern as the spatial variability map of sodium and sodium adsorption ratio.

Spatial variability maps of ESP, EPP, EMP, and ECP are illustrated in Fig. 5 (a), (b), (c), and (d), respectively. Higher accumulation of basic cations such as Na, K, Mg, and Ca occurs in salt-affected soils. Higher soil ESP was observed in the western and middle areas of the field. Moreover, ESP patches have extended from the middle to the peripheral areas as strips.

In the northern area of the study site, a high EPP patch can be observed, and also it is observed that lower EPP in other areas of the field. The spatial variability patterns of EMP and ECP values were very opposite to the spatial variability pattern of ESP.

The spatial variability maps of CEC, SAR, and BS are illustrated in Fig. 6 (a), (b), and (c). Higher CEC values were observed in the eastern and western areas of the study site. Higher SAR and BS values were observed in the sodium accumulated patches in the study field. The patterns of these maps showed a resemblance with the spatial variability pattern of the map of soil sodium content in the study field. Base saturation refers to the percentage of CEC sites that are occupied with bases, Na^+, K^+, $Mg^{2+,}$ and Ca^{2+} (Kabała and Labaz, 2018).

This is a measurement revealing the availability of basic cations (Na^+, K^+, $Mg^{2+,}$ and Ca^{2+}). All the elements except Na are macronutrients. Therefore, BS is considered to be a fertility parameter (Marchuk, 2013). In the sodium-rich area in the field, both individual Na and base saturation were higher indicating the soil imbalance of basic cations. Cross-validation showed strong to moderate agreement ($r > 0.77$) between the actual and predicted values for all the measured parameters.



(a) **(b)**

Figure 4: Spatial variability map of (a) Soil pH and (b) Soil EC
(EC = Electrical conductivity)

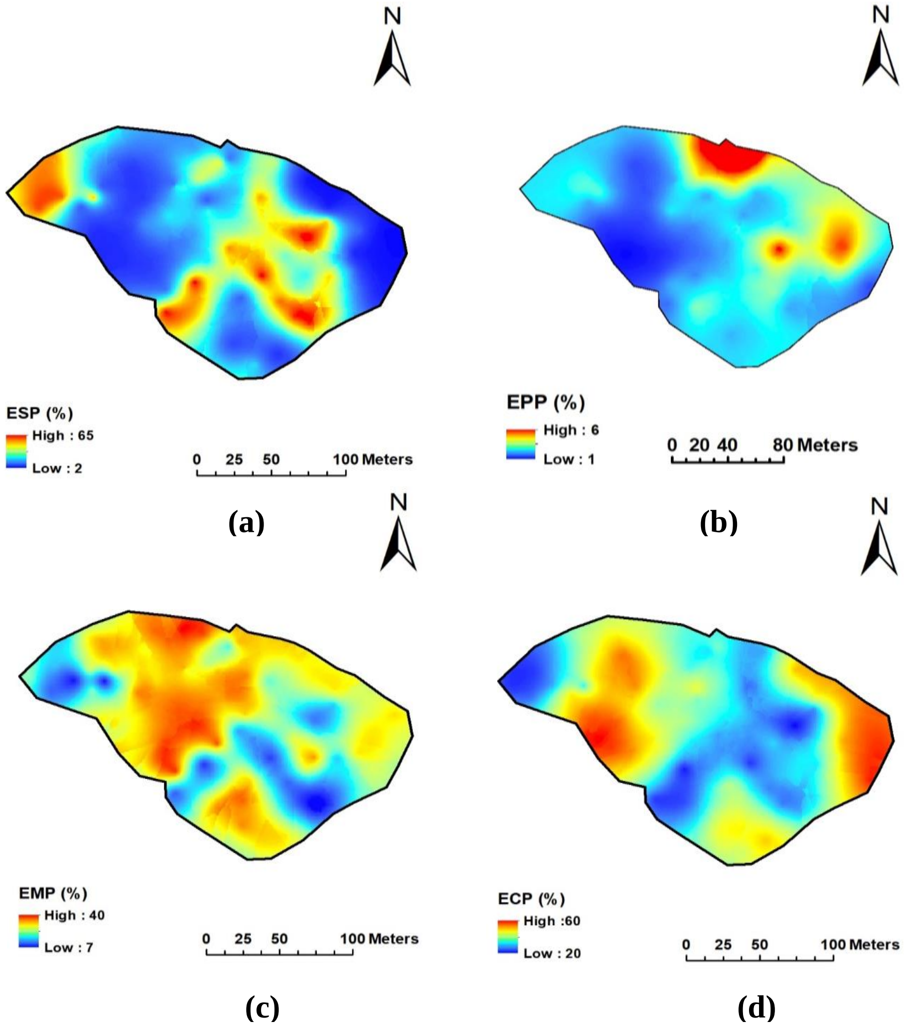
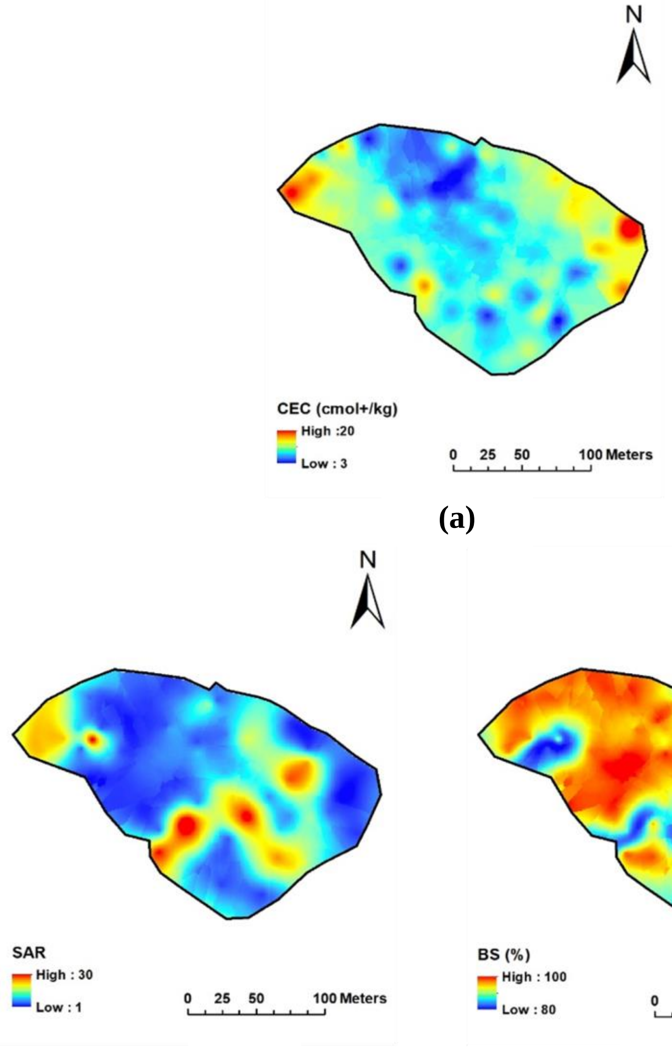


Figure 5: Spatial variability map of (a) Soil ESP, (b) Soil EPP, (c) Soil EMP and (d) Soil ECP

(ESP = Exchangeable Sodium Percentage, EPP = Exchangeable Potassium Percentage, EMP = Exchangeable Magnesium Percentage, and ECP = Exchangeable Calcium Percentage)



(a)

(b) **(c)**

Figure 6: Spatial variability map of (a) Soil CEC (b) Soil SAR and (c) Soil BS

(CEC = Cation Exchange Capacity, SAR = Sodium Absorption Ratio and Base Saturation = BS)

3.4 Potential Management Zones (PMZs) Delineation

The study field was delineated into four PMZs based on the spatial variability of soil pH, EC, SAR, and ESP using Fuzzy *k* mean classification. The Fuzzy *k* classified map is given in Fig. 7.

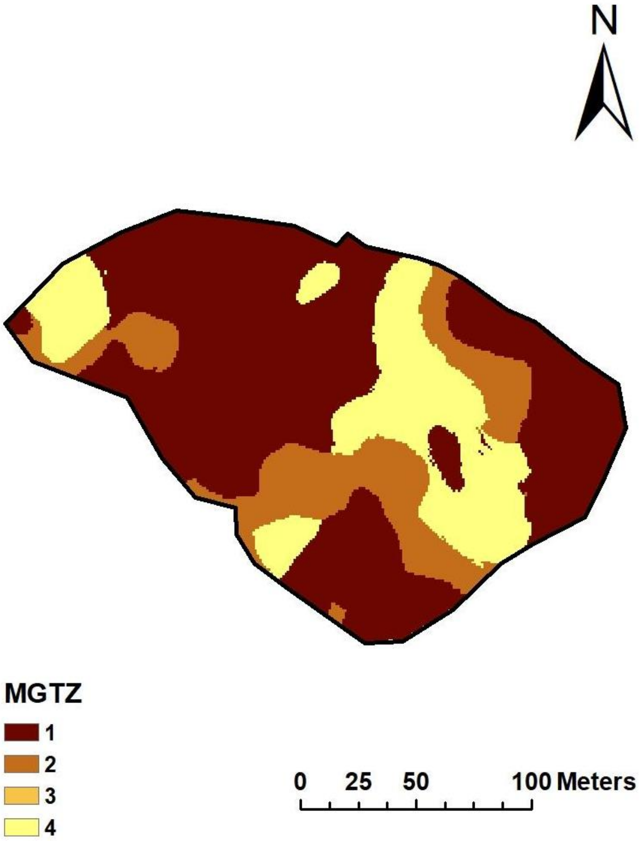


Figure 7: Management zone (MGTZ) map of the study site delineated through fuzzy *k* mean

It is practically impossible to manage individually the smaller areas in the Management zone (MGTZ) map. Therefore, the map should be generalized and the generalized map is given in Fig. 8.

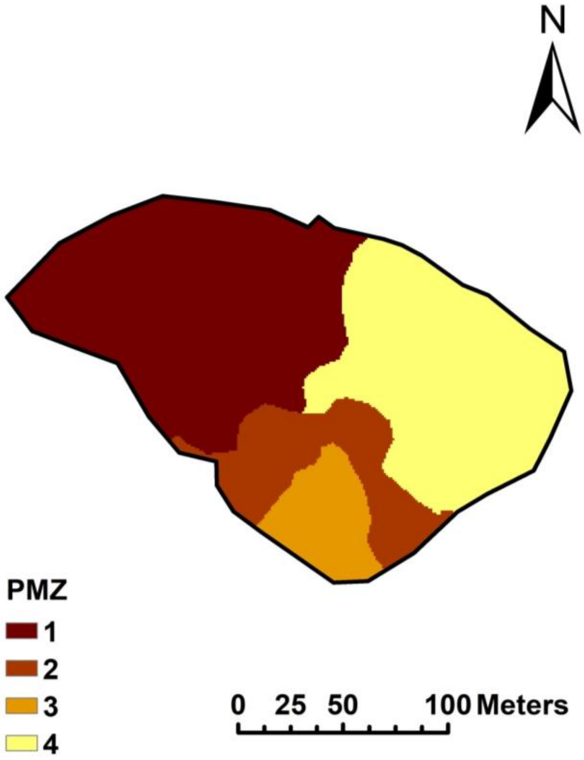


Figure 8: Generalized management zone map of the study site (Potential Management Zones = PMZ)

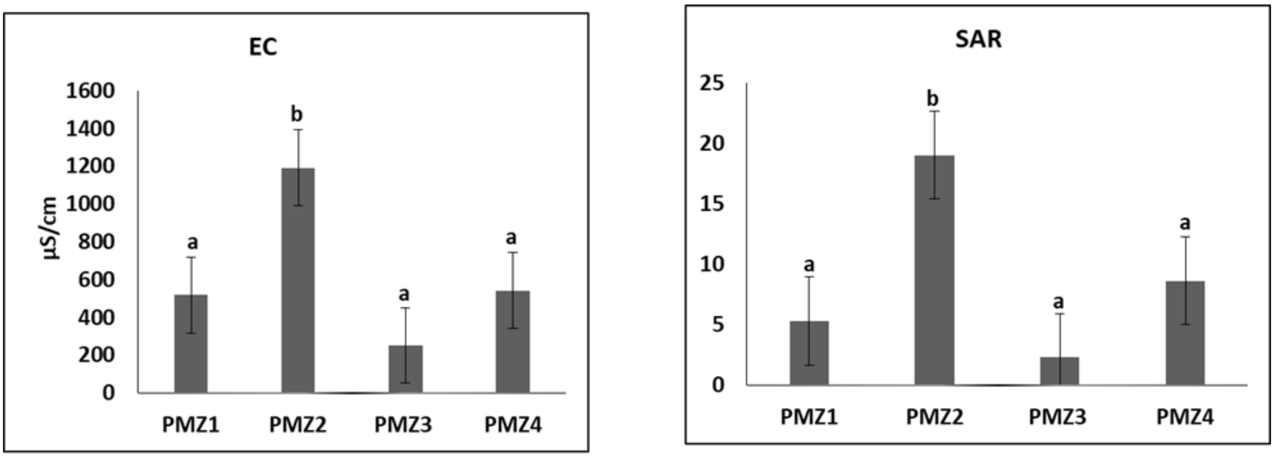
Four PMZs were identified as PMZ1 (1.31 ha), PMZ2 (1 ha), PMZ3 (0.4 ha), and PMZ4 (0.23 ha) based on the spatial variability of pH, EC, ESP, and SAR.

3.5 Variations of the investigated chemical parameters among PMZs

The variations of the soil EC, and SAR among the delineated PMZs (i.e., PMZ1, PMZ2, PMZ3, and PMZ4) are illustrated in Fig. 9 (a) and (b), respectively. Significantly highest soil EC and SAR were observed in PMZ2 in comparison to other PMZs ($p < 0.05$). The variations of soil ESP, EMP, and ECP among the delineated PMZs (i.e., PMZ1, PMZ2, PMZ3, and PMZ4) are shown in Fig. 10 (a), (b), and (c).

A significantly higher ESP was observed in the PMZ2. In contrast, significantly lowest EMP and ECP values were found in the PMZ2.

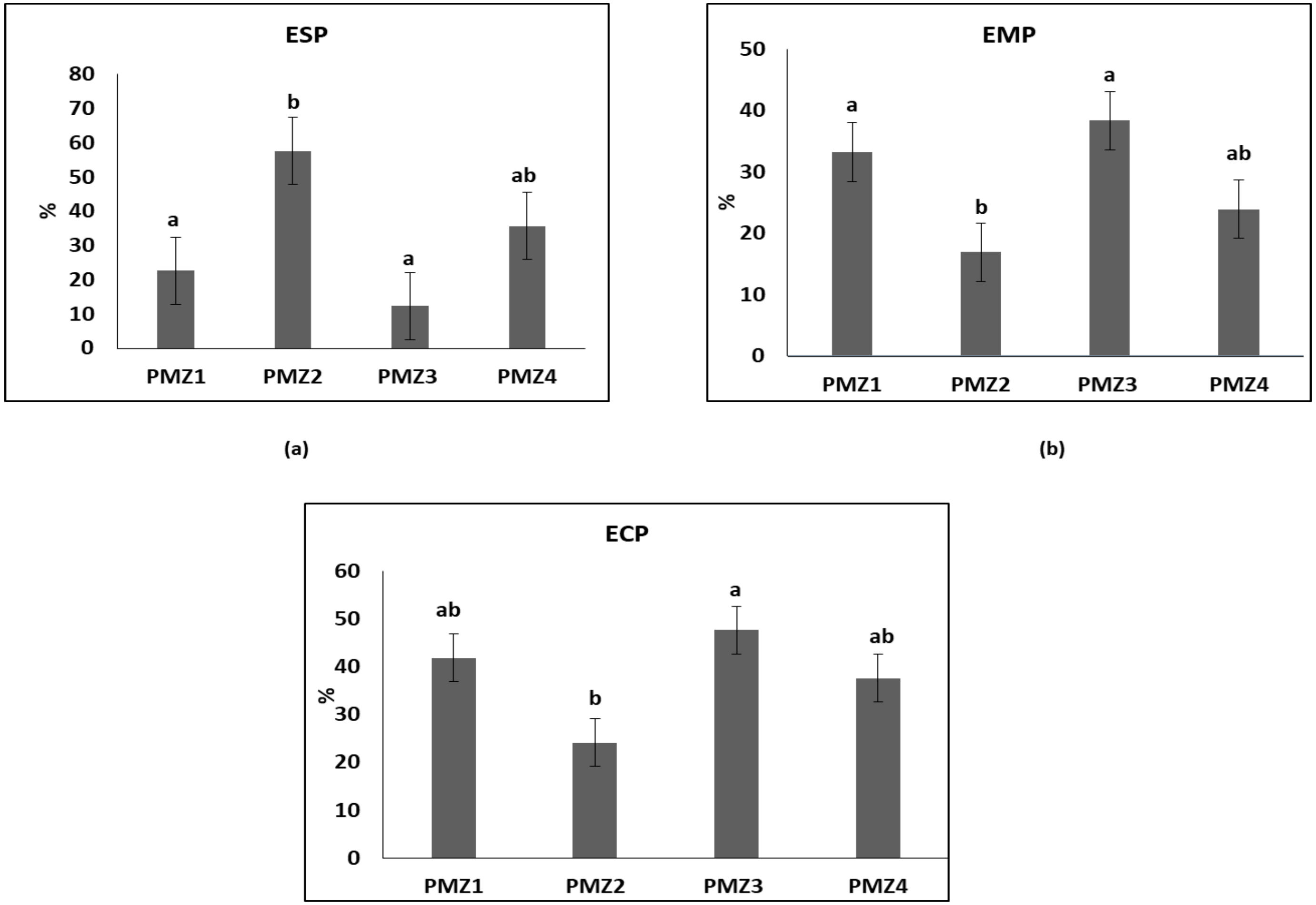
The variations of soil pH, BS, EPP, and CEC are shown in Fig. 11 (a), (b), (c), and (d). There were no significant differences in soil pH, BS, EPP, and CEC among the delineated PMZs. However, a significantly higher pH, and BS, were observed in PMZ2.



(a)

(b)

Figure 9: Variation in (a) Soil EC and (b) SAR

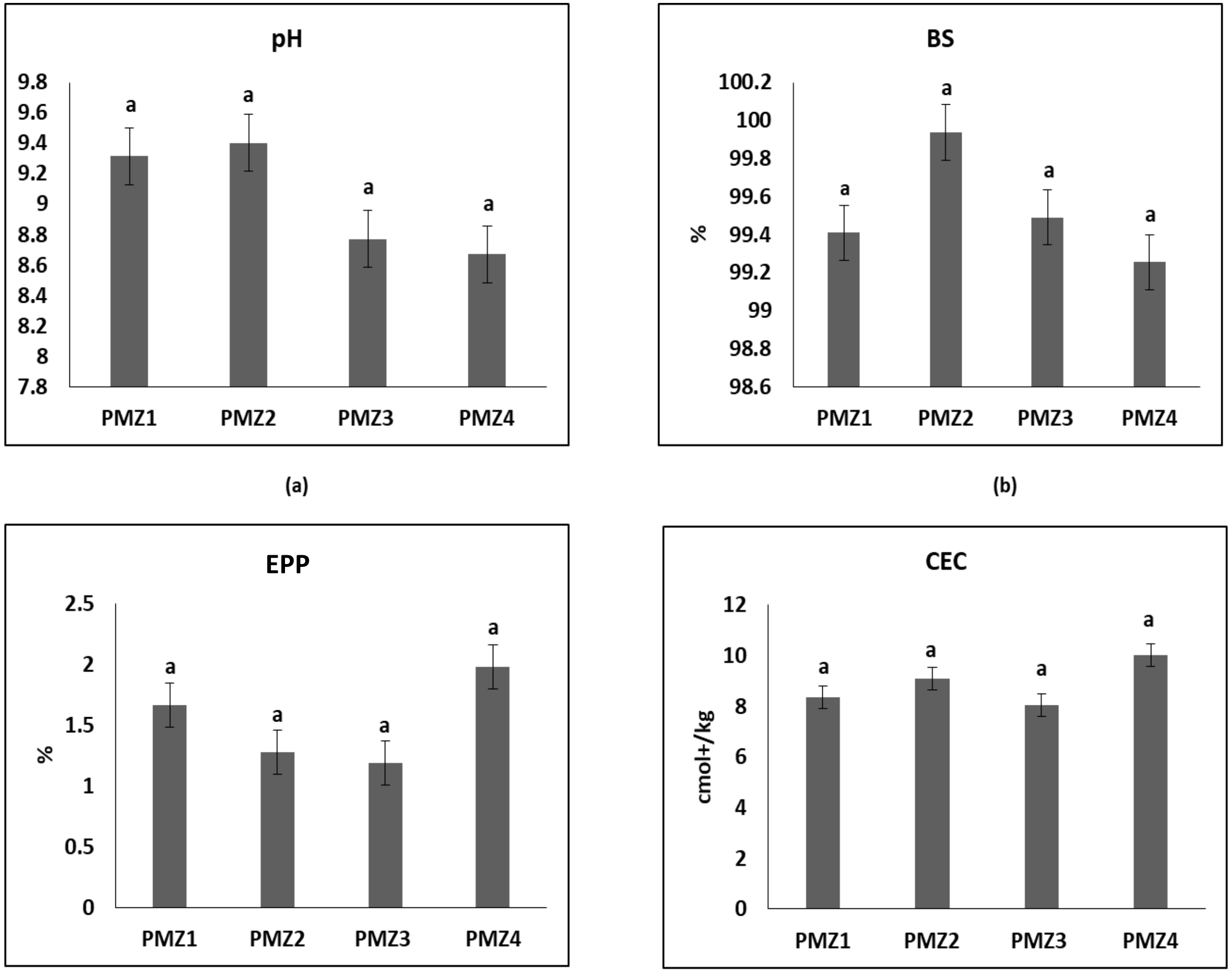


(a)

(b)

(c)

Figure 10: Variation in soil (a) ESP, (b) EMP, and (c) ECP



(a)

(b)

(c)

(d)

Figure 11: Variation in soil (a) pH, (b) BS, (c) EPP and (d) CEC

4. Conclusion

A considerable continuous short-scale spatial variability was observed within the study field. Four main homogenous areas could be identified based on spatial variability of pH, EC, SAR, and ESP. The soils in part of the study areas have been affected by salt accumulation. The salt-affected soil in the study areas can be classified to be a sodic soil. It can be concluded that higher variation of the investigated soil parameters among delineated PMZs. The higher spatial variability of the selected soil properties has been identified within the study field. Moreover, it highlights higher applicability for implementing SSSM based on the PMZs delineated in the study field.

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