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RECENT STUDY ON PLANT-SOIL INTERACTIONS IN CHINA - PART I

Spatial variability of soil salinity in Bohai Sea coastal wetlands, China: Partition into four management zones

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Abstract

Soil salinization constitutes an environmental hazard worldwide. The Bohai Sea coastal wetland area is experiencing dramatic soil salinization, which is affecting its economic development. This study focused on the spatial variation and distribution characteristics of soil salinity in this area using geostatistical analysis combined with the kriging interpolation method, based on a large-scale field investigation and layered soil sampling (0–30, 30–60 and 60–100 cm). The results revealed that soil salinity in these layers demonstrated strong variability, obvious spatial structure characteristics and strong spatial autocorrelation. Soil salinity displayed a significant zonal distribution, gradually decreasing with increasing distance from the coastline. Apart from the northern part of the study area, which appeared to be not affected by soil salinization, there were varying degrees of soil salinization in nearly 70% of the total area. With increasing soil depth, the areas of non-salinized and mild salinized soil gradually decreased, while those of moderate salinized and strong salinized soils increased. The area of saline soil first decreased and then increased. The study area could be divided into four management zones according to soil salinities in the top 1-m soil body, and utilization measures, adapted to local conditions, were proposed for each zone. The results of our study present an important theoretical basis for the improvement of saline soils, for wetland re-vegetation and for the sustainable utilization of soil resources in the Bohai Sea coastal wetland.

Keywords: *Bohai Sea coastal wetland, soil salinization, spatial variability, management partition, vegetation*

Introduction

Soil salinity caused by natural or human-induced processes is a major environmental hazard (Metternicht & Zinck 2003; Wang et al. 2008) worldwide, concerning about 6% of the total global land area (Flowers & Yeo 1995; Yeo 1998). Salt accumulation in soil affects physical, chemical and biological processes (Karlen et al. 2008), leading to restricted agricultural productivity (Rady 2011) and sustainability (Manchanda & Garg 2011; Zhang et al. 2012a, 2012b; Eliáš et al. 2013). Salt tolerance varies among different plant species and different varieties of the same plant (Rewald et al. 2011; Eliáš et al. 2013). Soil salinity influences seed germination (Reichman et al. 2006; Li et al. 2012; Zhang et al. 2012a, 2012b; Xing et al. 2013), root development (Shelef et al. 2010; Rewald et al. 2011) and plant growth. The distribution of wetland vegetation plant is influenced by soil salinity (Fan et al. 2011; Minggagud & Yang 2012; Zhang et al. 2013), which even at low levels becomes an abiotic stress factor that influences vegetation patterns and diversification (Bui 2013). Salinization also has an impact on agro-biodiversity (Rahman et al. 2011) and, furthermore, poses a serious threat to the health of many fresh and brackish water wetlands. In coastal saline areas, salinity of soil, groundwater and surface water, and groundwater depth vary greatly (MPO 1986). Several researches demonstrated that the vulnerability of coastal areas to climatic changes such as rising temperature has increased due to several environmental factors: sea level rise, seawater invades, river water level increase, subsidence,

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changes in upstream river discharges, cyclones and erosion of coastal embankment contractions (World Bank 2000; Rawlani & Sovacool 2011). Saline soil and salted silt are widely distributed along the coastal areas of east and southeast China, due to poor groundwater runoff and drainage, high level and salinity of groundwater and seawater intrusion caused by periodic tidal activity. The Bohai Sea coast is one of the economically developed areas in China, characterized by an excellent geological but fragile ecological environment, with a high population density, complex human engineering activities and an unstable geological structure. The environmental changes of the Bohai Sea coastal area are having a major impact on the economic construction in China. The regional environmental conditions, such as greater annual evaporation than rainfall, shallow groundwater, high-salinity groundwater and poor runoff, promote saline soil development. Recently, soil salinity has become one of the most important geological problems in the Bohai Sea coastal region, seriously hampering the economic development of this area.

The spatial distribution of soil salinity has important implications for soil and water resource management (Douaoui et al. 2006). It is necessary to understand and quantify the magnitude and extent of spatio-temporal variability of soil salinity to develop better land-use patterns and ensure high crop productivity (Doerge 1999). Over the last two decades, geostatistical techniques for spatial prediction and interpolation have increasingly become essential components of geographic information systems (GISs; McBratney et al. 2003; Mousavifard et al. 2012). Kriging methods have been widely used to map the spatial distribution of soil salinity (Triantafilis et al. 2001; Cetin & Kirda 2003; Odeh & Onus 2008; Bilgili 2013; Hamzehpour et al. 2013).

Soil salinity plays an important role in plant composition, productivity and distribution in coastal area ecosystems, owing to differences in salt tolerance between plant species (Hughes et al. 1998; Pennings et al. 2005). As salinity poses a severe limit to agriculture and a threat to its sustainability, the need for identification, monitoring and control of soil salinity is increasing in the world (Herrero et al. 2003). Several researchers studied the improvement and utilization of saline soil as well as the spatial distribution of soil salinity in some parts of the Bohai Sea coastal area (Feng et al. 2000; Zhang et al. 2010); however, they seldom touched on spatial variability of soil salinity in the whole area and made partition-use planning mainly according to the degree of soil salinization.

The objectives of this work were (1) to quantify and characterize the spatial variability of soil salinity; (2) to reveal the extent, the area and the distribution of soil salinization in different soil layers and (3) to partition the area into zones for rational land utilization.

Materials and methods

Description of the study area

The study area (117°15′–119°9′ E and 37°34′–40°7′ N) is located on the Bohai Sea coast, covering 28,226.25 km^2 and accounting for 12.08% of the total Bohai Sea area (233,630 km^2). This area covers parts of five provincial-level administrative regions: Shandong, Hebei, Tianjin, Beijing and Liaoning. It is located south of Dongying city in Shandong province and north of Shanhaiguan city in Hebei province, and includes a total of 20 counties (Figure 1).

The site belongs to the warm-temperate zone with a semi-humid monsoon climate and an average annual precipitation ranging from 560 to 916 mm. The annual evaporation is between 1600 and 2000 mm, which is about three times the amount of precipitation, and the evaporation in spring accounts for 36% of the total (Zhao et al. 2004). Annual precipitation in wet years is three to five times higher than that in dry years. Precipitation shows a very uneven distribution within the year, with 60–75% of the total occurring in the period from June to September. The average temperature of this region is 10–13°.

Brown soil and cinnamon soil are the dominant zonal soils in this region, in addition to some non-zonal soils such as paddy soil, damp soil, sandy soil, saline soil, meadow soil and swamp soil. Natural vegetation is sparse, consisting mostly of secondary forest (Liu et al. 2003). The region is very rich in wetland resources.

Soil sampling and analysis

A regular sampling scheme (10 km sampling space) was carried out during the month of September 2011, in the Bohai Sea coastal area, considering local soil texture, vegetation type, land-use patterns and other factors. Each sampling site was geo-referenced using global position system. Soil samples were taken using soil drilling at three different layers (0–30, 30–60 and 60–100 cm) on each regular spacing point. In total, 1296 soil samples were made at 432 sampling points (Figure 1).

Soil samples were natural air-dried and sieved at 2 mm before being used in the laboratory for analysis. Soluble salt content was measured using the ion summation method. The content of sodium, potassium, calcium, magnesium, chlorine, sulphate, carbonate and bicarbonate was analyzed of 1:5 soil to water-diluted extracts using the conventional soil analysis methods described by Lu (1999).

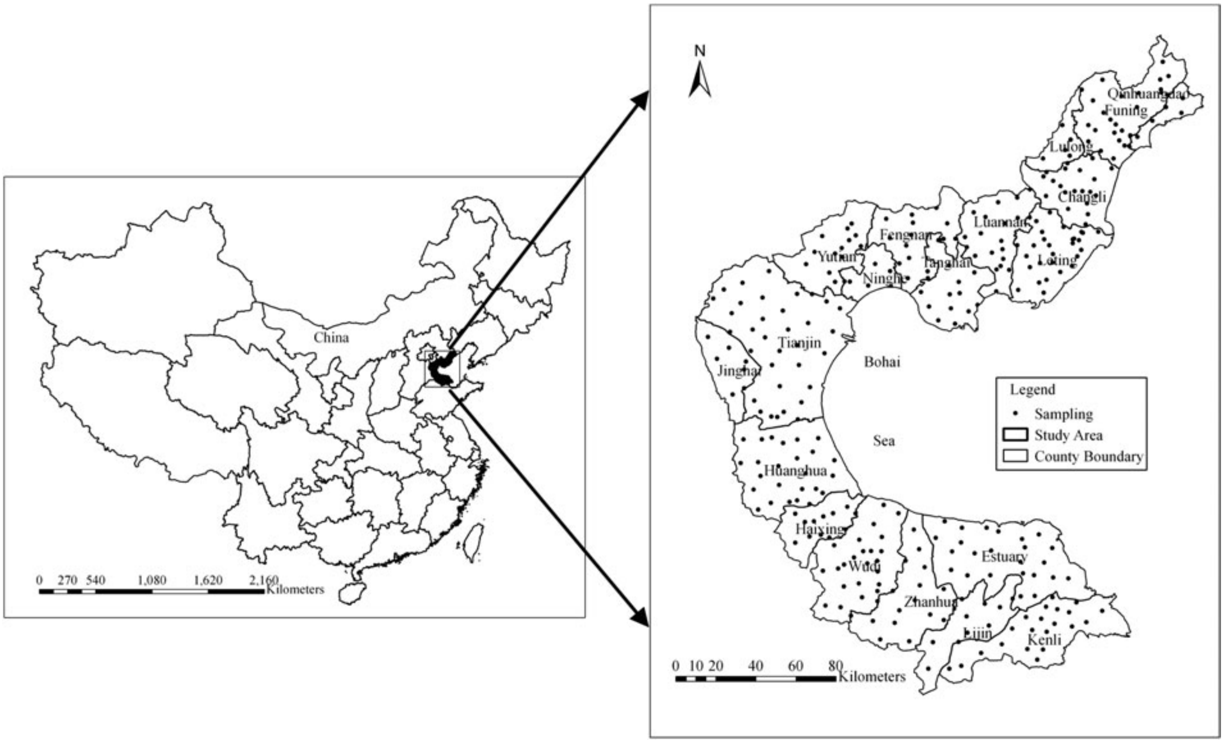

Figure 1. Location of sampling area and distribution of soil sampling points.

Classical statistical analyzes and normality tests of soil salinity were performed using the SPSS 17.0 statistic software package (SPSS Inc., Chicago, USA). Geostatistical software (GS + 7.0, Gamma Design Software) was used to conduct semi-variogram and spatial structure analyses for variables. Values for unsampled locations were interpolated using the kriging technique. Soil salinity maps were plotted and the soil salinization area was calculated with the ArcGis9.3 GIS produced by Earth Satelite Remote Index.

Geostatistical analysis

Geostatistical analysis is a spatial analysis method developed on the basis of classical statistics and the regionalized variable theory. Semi-variance function is the main tool of geostatistics to reveal spatial distribution, variability and characteristics of the property variable. The theoretical justification behind semi-variogram analysis was described by Burgess and Webster (1980). Semi-variance is defined as half of the estimated square difference between sample values at a given distance (lag; Trangmar et al. Yost 1985). Estimated semi-variance at lag h is

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

where z is the regionalized variable, and $z(x_i)$ and $z(x_i + h)$ are measured sample values at x_i and $x_i + h$ points, respectively. N is the number of pairs separated by distances h (lag space).

Ordinary kriging

Ordinary kriging is one of the most basic kriging methods. It estimates for an unobserved location of variable z by the weighted average of adjacent observed sites within a given area. The theory is derived from regionalized variables (Matheron 1965, 1971) and can be briefly described by considering an intrinsic random function denoted by $z(x_i)$, where x_i represents all sample locations, $i = 1, \ldots, n$. An estimate of the weighted average given by the ordinary kriging predictor at an unsampled site, $z\ (s_0)$, is defined by

$$z(x_0) = \sum_{i=1}^{n} \lambda_i z(x_i),$$

where λ_i are the weights assigned to each of the observed sample sites. These weights sum to unity so that the predictor provides an unbiased estimation:

$$\sum_{j=1}^{n} \lambda_i = 1.$$

The weights are calculated from the matrix equation:

$$c = A^{-1}b,$$

where A is a matrix of semi-variances between data points, b is a vector of estimated semi-variances between the data points and the points where the variable z is to be predicted and c is the resulting weights and the Lagrange multipliers ψ.

Results

Classical statistical analyses of soil salinity

The descriptive statistics of soil salinity in all soil layers for the 432 sample sites are displayed in Table I.

Soil salinity of all layers ranged from 19.13 to 33.38 g kg^{-1}. The coefficient of variation (CV) is a useful statistic parameter for measuring the spatial variability of soil properties: values of <0.10, 0.10–1.0 and >1 indicate weak, moderate and strong variability, respectively (Lei et al. 1988). The high CV values of soil salinity in all layers showed that there was strong degree of variation. The variation of soil salinity varied with soil depths, with maximum values found for surface soil. The data of semi-variance analysis fitted a normal distribution to eliminate proportional effect. The Komogorov–Smimov normality test ($p < 0.05$, two tailed) revealed that salinity of each soil layer did not conform to a normal distribution; logarithmic conversion data, on the other hand, fitted normal distribution, so semi-variance analysis used the logarithmic conversion data of soil salinity.

Geostatistical analyses of soil salinity

In order to determine the impact of random factors on soil salinity and the space distance range of soil salinity in all layers, different types of models were repeatedly compared to obtain the optimal $\gamma(h)-h$ scatter plot (Figure 2) and the semi-variance model for soil salinity of different layers in the study area, using GS + 7.0 software (Table II). The soil salinity of each layer could be fitted quite well by spherical models with high coefficients of determination, ranging from 0.879 to 0.927.

The nugget variance or nugget effect (C_0) represents unexplained or random variance, frequently caused by measurement error or micro-variability of the property, which cannot be detected at the scale of sampling. The sill parameter represents structure variance. As shown in Table II, the C_0 values for soil salinity in all layers were small, ranging from 0.289 to 0.323, suggesting that soil salinity variation caused by systematic errors and short-range, random or inherent variability was weak on the scale of this study.

The nugget–sill ratio represents the degree of heterogeneity induced by random factors and accounts for the total spatial heterogeneity: it can be regarded as a criterion to classify the spatial dependence of soil attributes in geostatistics. The ratios 0.25 and 0.75 are two thresholds for the relative strength index of spatial correlations: the ratios $<25\%$, between 25% and 75%, or $>75\%$ accordingly indicate strong, moderate or weak spatial autocorrelation (Cambardella et al. 1994; Chien et al. 1997; Chang et al. 1998). The nugget–sill value of soil salinity at soil layer with increasing depth was 18.04%, 20.02% and 19.33%, respectively, indicating no significant difference between layers. The proportion of random factors first increased and then decreased with increasing soil depths. Fractal dimension expresses the curvature of the variogram curve: the higher the fractal dimension D values the stranger the stochastic factors, and the worse structural and more complex the distribution. Fractal dimensions of soil salinity in the three layers were not significantly different and showed the same

Table I. Descriptive statistics of total soil salinities at different depths.

Layer (cm)	Maximum (g kg^{-1})	Minimum (g kg^{-1})	Range (g kg^{-1})	Mean (g kg^{-1})	Standard deviation	CV	Skewness	Kurtosis	K–SP	Distribution
0–30	33.44	0.06	33.38	3.05	5.94	1.95	0.737	−0.117	0.067	LN
>30–60	22.86	0.06	22.80	2.47	3.81	1.54	0.241	−0.464	0.66	LN
>60–100	19.17	0.04	19.13	2.59	3.85	1.49	0.221	−0.364	0.777	LN

Table II. Semi-variogram models for soil salinity at different depths.

Soil layer (cm)	Theoretical model	Nugget (C_0)	Sill	Nugget–sill (%)	Range A (m)	R^2	Dimension	RSS
0–30	Spherical	0.323	1.790	18.04	65,000	0.927	1.804	0.297
30–60	Spherical	0.312	1.558	20.02	67,600	0.879	1.816	0.306
60–100	Spherical	0.289	1.495	19.33	69,900	0.891	1.811	0.305

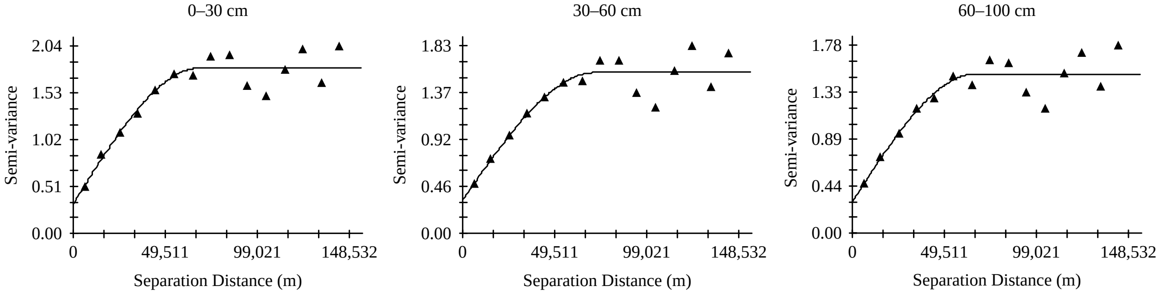

Figure 2. Semi-variance grams of soil salinity at different depths.

tendency with increasing soil depths as the nugget–sill ratio described above.

Range *A* is the maximum spatial correlation distance reflecting the size of the variable spatial autocorrelation range. The range *A* values of the soil salinity in 0–30, 30–60 and 60–100 cm layers were 65.0, 67.6 and 69.9 km, respectively.

Spatial distribution of soil salinity

Soils were reclassified according to salt content into non-salinized ($<1\,g\,kg^{-1}$), mild salinized ($1-2\,g\,kg^{-1}$), moderate salinized ($2-4\,g\,kg^{-1}$), strong salinized ($4-6\,g\,kg^{-1}$) and saline ($>6\,g\,kg^{-1}$) soil (Wang et al. 1993). The soil salinization level and the classification threshold of interpolation were determined based on this grading standard. The kriging maps of the spatial distribution of soil salinity for the three soil layers are presented in Figure 3.

The smoothed interpolation map of soil salinity in each layer displayed quite similar patterns. The degree of soil salinization was high in the south of the study area, while that in the north was low. In the C-type region of this area, the degree of soil salinization showed a continuous ribbon distribution parallel to the coastline, with a gradual increase towards the coastline. Non-salinized soil was mainly distributed in the northern part of the study area, including the whole area of the cities Funing and Lulong, as well as in the north-central parts of Changli, Luannan, Leting and Fengnan. The highest degree of salinization was found in the most-internal part of the C-type region.

For all soil layers, the relative areas of different salinization degrees were calculated (Figure 4). In the 0–30 cm layer, 29.68%, 29.95%, 19.99%, 8.83% and 11.54% of the total area were determined as non-salinized, mild salinized, moderate salinized, strong salinized and saline soil, respectively. Moderate salinized to saline soils occupied 49.83% of the total area in the 30–60 cm layer, while 50.88% in the 60–100 cm layer.

In order to understand the vertical distribution of soil salinization, areas of the same salinization degree in different soil layers were compared. The areas of non-salinized, mild salinized and saline soil in the 30–60 cm layer were reduced by 1404.24, 1266.34 and 726.30 km^2, respectively, compared with those in the 0–30 cm layer, while areas of moderate and strong salinized soil increased by 3213.50 and 183.38 km^2. Similarly, the areas of non-salinized, mild salinized and saline soil at 60–100 cm depth were reduced, while areas of moderate and strong salinized soil increased significantly, compared with those at 0–30 cm depth.

According to the analysis of area changes, areas of non-salinization and mild salinized soil decreased gradually with increasing soil depth; areas of moderate salinized soil in 30–60 and 60–100 cm layers were significantly higher than those in the 0–30 cm soil layer; areas of strong salinized and saline soil did not change significantly among the three soil layers.

Partition management

Coastal saline soil constitutes an important land reserve resource. Improving land utilization and productivity is one of the essential ways to speed up economic development in coastal areas. However, managing the partition of saline–alkali soil, reasonably adapted to local conditions, is the premise for the comprehensive management of saline land. The position of salt accumulation in the soil changed over the season, due to the movement of salt-containing water, which is affected by evaporation and rainfall. Salinity varied mainly in the top 1-m soil body and, therefore, it is one of the dominant obstacles for crop growth. According to soil salinity in the 0–1 m soil body, the study area could be divided into four management zones: (I) non-salinization ($<1\,g\,kg^{-1}$), (II) light salinization ($1-2\,g\,kg^{-1}$), (III) moderate salinization ($2-4\,g\,kg^{-1}$) and (IV) strong salinization and saline soil ($>4\,g\,kg^{-1}$), with an area of 11,186.60, 9903.41, 4358.97 and 2777.26 km^2, respectively (Figure 5).

Zone I constitutes a non-salinized, fresh water-rich region, located in the northern part of the study

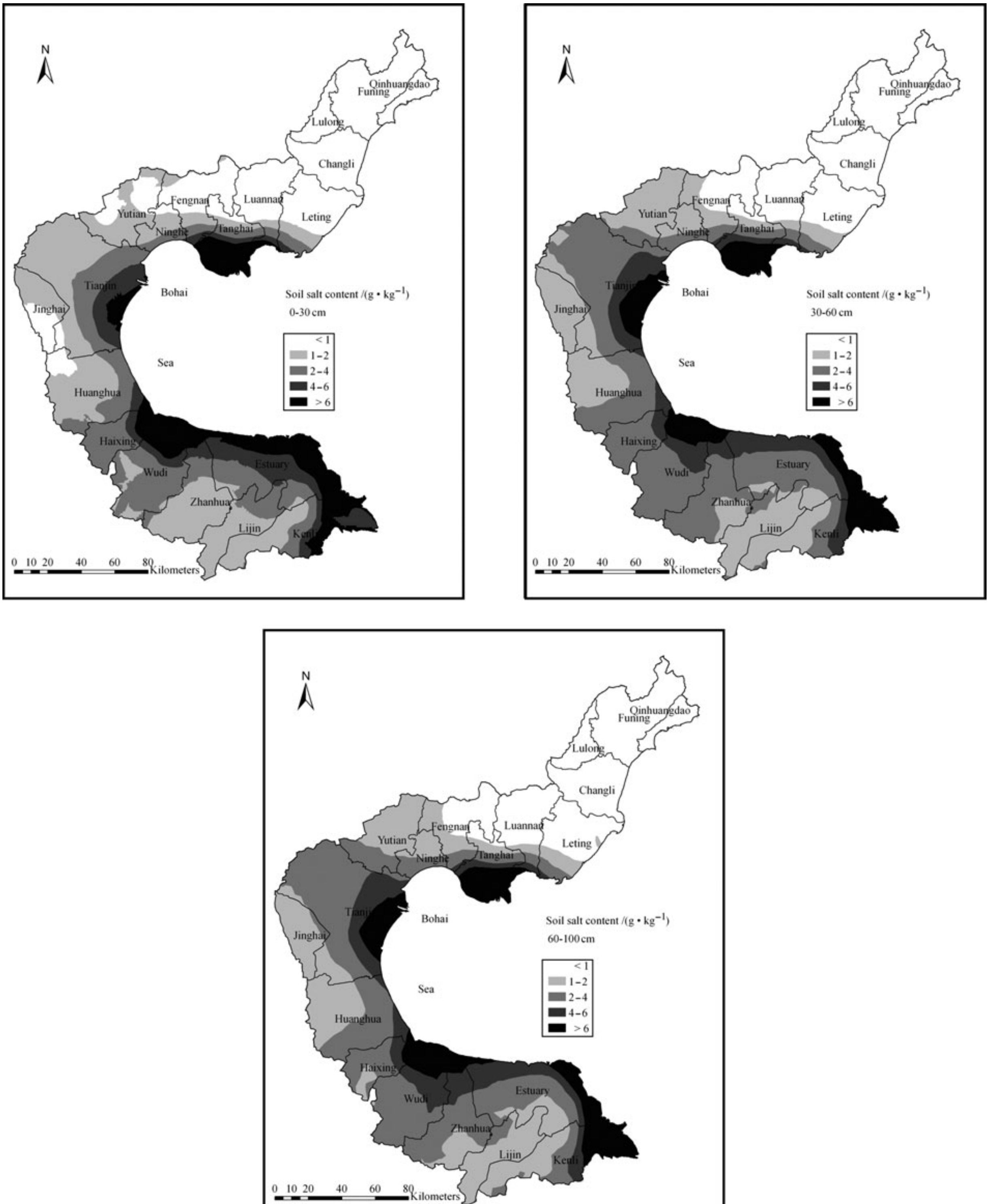

Figure 3. Spatial distribution of soil salinity at different depths.

area. High-yielding and efficient agriculture could be vigorously developed in this zone to meet food supply. Zone II is situated in the mid-western part of the study area and in part of the Yellow River delta. Soil salinity of this zone is low and its land could be easily improved to grow cotton, forest, fruit and grass.

Zone III is moderately salinized and lies in the centre-internal part of the C-type region (the study area). Conventional crops are inhibited here by the high soil salinity and the limitation of fresh water. Salt-tolerant plants and some wild halophytes could be cultivated with a rational utilization of saline water for special benefits, such as pharmaceutical raw

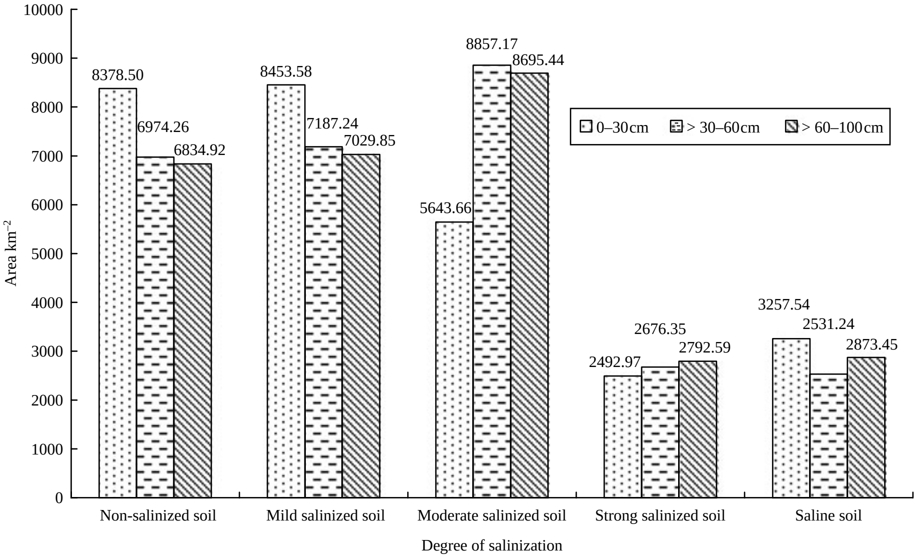

Figure 4. Areas of varying degree salinization at different depths.

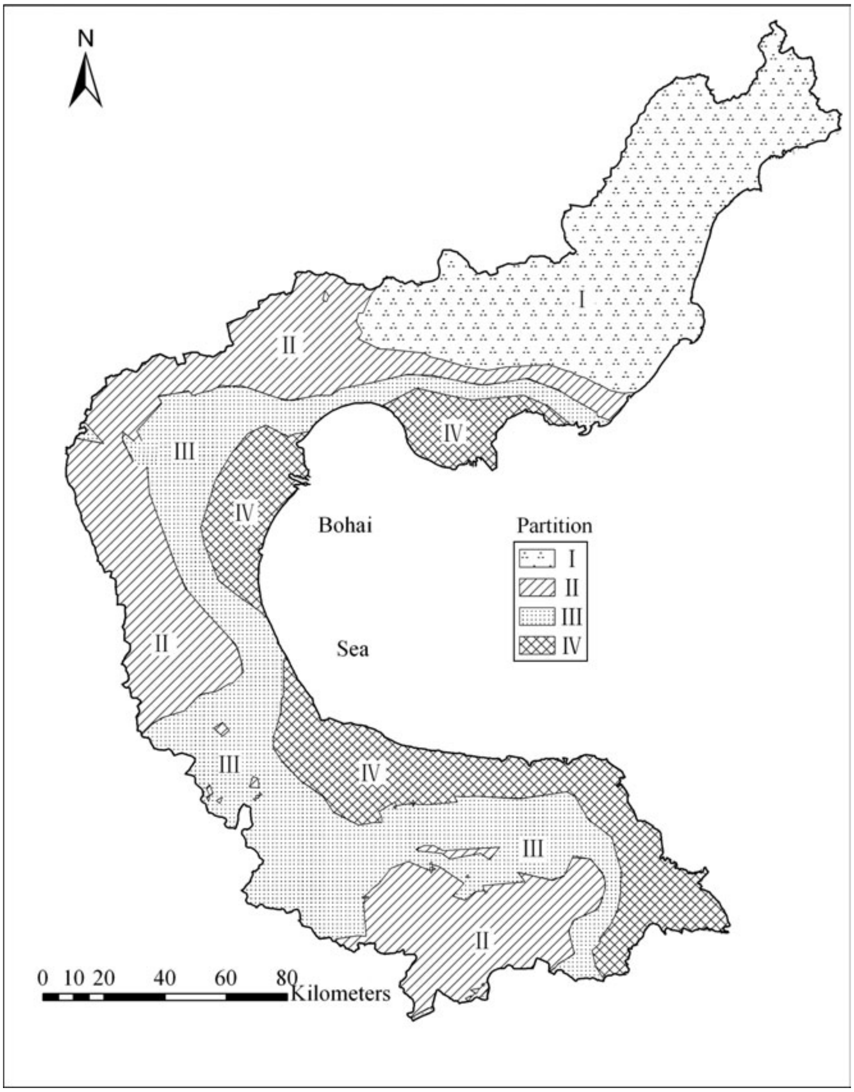

Figure 5. Management zones based on soil salinity of the top 1-m soil body.

material, ecological restoration and saline soil improvement.

Zone IV comprises coastal beaches and strong-salinized areas, situated in the most-internal part of the C-type region. This area is not suitable for plant growth because the salinity of groundwater and soil is too high. The geographical conditions render this zone suitable for the development of aquaculture, including the farming of fish, shrimp and crab.

Discussion

Soil salinity plays an important role in vegetation distribution, plant productivity and biogeochemical processes in coastal wetland ecosystems. In the future, proper utilization of saline soil will be even more essential to meet the increasing population pressure (Sheng et al. 2010), making it necessary to obtain accurate and update information on the spatial distribution of soil-soluble salts. In this study, variability and spatial distributions of soil salinity in different soil layers were explored by traditional statistical and geostatistical analyses combined with the GIS method.

There are many parameters to evaluate soil salinization characteristics, such as electrical conductivity, apparent electrical conductivity, sodium adsorption ratio (SAR), exchangeable sodium saturation percentage (ESP) and soil salt content (soil salinity) (Lesch et al. 2005; Cemek et al. 2007; Odeh & Onus 2008; Adam et al. 2012; Fan et al. 2012). Soil salt affects plant growth mainly by the action of some ions, such as Na^+ and Cl^- (Jamil et al. 2012). Ions taken up by roots not only accumulate at high concentrations in plant tissues but may also inhibit the uptake of other ions, such as nutrient elements (Dong 2012; Radhakrishnan & Kumari 2012). In this study, we selected soil salt content (soil salinity), i.e. the sum of soil soluble ions, as an assessment index for soil salinization.

The spatial difference in soil salinity was mainly caused by structural factors. Soil salinities had a spatial correlation in a wide range. Soils in nearly 70% of the total area showed varying degrees of salinization, with 30% being strong-salinized and saline soil. The total study area could be divided into four management zones according to soil salinities in the 0–1 m soil body.

Descriptive statistics of the salinity in different soil layers showed that there is a serious soil salinization problem in the Bohai Sea costal wetland area. The mean values of soil salinity in all layers were high, classifying the soil as moderate salinized. Many crops and other vegetation are inhibited at this soil salt content. The variations of soil salinity in all layers were strong, although it gradually weakened with increasing soil depth. The reason might be that we considered a large study area with differences in climatic conditions, soil parent material, soil texture, terrain topography, seawater intrusion, land farming methods and other factors in the 1-m soil body.

The low values of the nugget–sill ratio showed a strong spatial autocorrelation for soil salinity in each layer of the study area. Spatial dependence of soil salinity was mainly due to structural factors, such as climate, topography and soil type (Li et al. 2013). The large range showed that soil salinity had a spatial correlation within a wide distance range in the study area, which certified that the sampling distance (10 km) was adequate for exploring the spatial variability in soil salinity.

The different spatial distribution of soil salinity may be due to differences in distance to coastline, terrain, groundwater level, groundwater salinity, type of marine sediment particles and anthropogenic activities (Meng et al. 2013). The higher soil salinity was accorded with a shorter distance to the coastline, higher groundwater level and salinity, and less influence of anthropogenic activities. Thus, soil salinity decreased gradually from the coastline towards inland regions. The regional soil salt distribution described above is mainly caused directly or indirectly by seawater (McLeod et al. 2010; Wahab et al. 2010; Park et al. 2012): (a) seawater invades the coastal terrestrial land by tides, hurricanes and other sea disasters, and salt dissolved in seawater crystallizes via evaporation and accumulates in the soil; (b) seawater directly recharges groundwater after which the dilute salt in the groundwater rises to the surface soil by capillary action and (c) coastal saline soil derived from marine sediments. We propose utilization measures for each zone, adapted to local conditions. Currently, soil salinization presents a serious problem in the Bohai Sea coastal area, slowing down the economic development of this zone. The interaction between soil salinization and vegetation should be further investigated in the Bohai Sea costal wetland, in order to comprehend the ecological systems and to improve the utilization and productivity of the land.

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