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Article

Soil-vegetation inventory of an undisturbed Bohai Bay ecosystem of China

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Abstract: The coastal area of Bohai Bay of China has a wide distribution of salt-accumulated soils which could pose a problem to the sustainable development of the local ecology. As a result, the land remains largely degraded and unsuitable for biophysical and agricultural purposes. In this study, we characterized the soil and native plants in the area, to properly understand and identify species with satisfactory adaptation to saline soil and of high economic or ecological value that could be further developed or domesticated, using appropriate cultivation techniques. The goal was to determine the salinity parameters of the soil, identify the inhabiting plant species and contribute to the ecosystem data base for the Bay area. A field survey involving soil and plant sampling and analyses was conducted in Yanshan and Haixing Counties of Hebei Province, China, to estimate the level of salt ions as well as plant species population and type. The mean electrical conductivity (EC) of the soils ranged from 0.47 in more remote locations to 23.8 ds/m in locations closer to the coastline and the total salt ions from 0.05 to 8.8 g/kg, respectively. Each of the salinity parameters, except HCO_3^- showed wide variations as judged from the coefficient of variation (CV) values. The EC, as well as chloride, sulphate, Mg and Na ions increased significantly towards the coastline but the HCO_3^- ion showed a relatively even distribution across sampling points. Sodium was the most abundant cation and chloride and sulphate the most abundant anions. Therefore, the most dominant salinity-inducing salt that should be properly managed for sustainable ecosystem health was sodium chloride. Based on the EC readings, the most remote location from the coastline was non-saline but otherwise, the salinity ranged from slightly to strongly-very strongly saline towards the coast. There were considerably wide variations in the number and distribution of plant species across sampling locations, but most were dominated entirely *Phragmites australis*, *Setaria viridis* and *Sueda salsa*. Other species identified were *Aeluropus littoralis, Chloris virgata*, *Heteropappus altaicus*, *Imperata cylindrica, Puccinellia distans, Puccinellia tenuiflora* and *Scorzonera austriaca*. On average, the sampling points furthest from the coast produced the most biomass, and the point with the highest elevation had the most diverse species composition. Among species, *Digitaria sanguinalis* produced the highest dry mass, followed by *Lolium perenne* and *H. altaicus,* but there were considerable variations in biomass yield across sampling locations, with the location nearest the coastline having no vegetation. The observed variations in soil and vegetation should be strongly considered by planners to allow for the sustainable development of the Bahai bay area.

Keywords: soil salinity stress; vegetation; sustainable development; Bohai Bay; China; ecology

1. Introduction

In a rapidly developing country like China, economic advancement and resource conservation are often in conflict. With increasing urbanization, the ecological services provided by the ecosystem are being gradually impaired, thereby threatening the ecological security (MA, 2005). Sustaining and strengthening the ecological integrity is therefore an important approach to maintaining the structure and function of ecosystems, and balance the relationship between economic and social development and ecological conservation (Opdam et al., 2006, Su et al., 2016; Wang and Pan, 2019).

The Bohai Bay is the only semi-closed sea in China; it is a typical coastal ecosystem with special environmental conditions and rich natural resources. However, soil degradation by salinization or alkalization is a major threat to the general ecosystem, including vegetation in the area (China Geological Survey, 2015; Guo et al., 2019). A key step towards the restoration of such a heavily disturbed fragile coastal ecosystem is to determine the nature of soil as well as the composition and characteristics of the native plant communities. Being approximately 200,000 km^2 large, the Bohai Bay is one of the most important Cenozoic rift basins globally (Lv et al., 2013). The average annual precipitation is 323–533 mm. The high soil salinity in the area is ascribed to its low elevation, high groundwater level, and intense evapotranspiration, which allow salts within soil to easily accumulate on the soil surface (An et al., 2015). The groundwater is also saline and accounts for half of the total groundwater resources in China (Liu, 2009). The amount of salt accumulation in soil is as high as 4% in some areas (Tianjin Binhai New Area Administration [TBNAA], 2007). Salinity in the area ranges from 10 to 20 times that in a normal farmland in the same North China Plain (Zhang et al., 2010) and in our study sites it ranged from 0.47 to 23.8 ds/m. Because of this high salt content, the lands have little agricultural value and are largely degraded. The causes and processes for the formation of saline soils in the area have been amply described in Zhang (2002). Soil organic matter and nitrogen contents exhibit great spatial variations and whereas phosphorus is generally deficient, potassium is abundant in the soil (An et al., 2013).

Vegetation successions of coastal wetlands are governed by the changes in relative surface elevation and soil salinity (Zhang et al., 2021). The cultivation of saline plants is one of the possibilities of land use in the coastal areas of Bohai Bay. However, a detailed characterization of the soil and vegetation of the area is essential to managing the land for cultivation or restoration. The Bay area is rich in salt-tolerant plants, and there are many native species that can be used for food, feed, biofuel, ornamental and medicinal purposes. Their cultivation has the advantage of not competing with agricultural land and not using fresh water. The use of saline plants and cultivation methods that optimize yields will lead to the promotion of new industries and the effective use of salt-accumulated areas. Also, the recent construction activities around the Bohai Sea Rim Economic Zone have made the greening of roads, and parks an urgent issue, especially with the development of industrial zones, ports, and the expansion of towns. At the moment, the greening of key roads involves excavating the soil on both sides of the road and replacing it with new, salt-free soil. Before the new soil is placed, an isolation layer is created with gravel and stones. This process is very expensive, and at some point, the barrier layer may no longer be effective, and trees and other plants used for revegetation may die from rising salinity. A sustainable revegetation method would be to use salt-tolerant plants that are adapted to the local conditions.

The use of saline plants offers various benefits, including economic returns, ecosystem protection, soil de-salinization, and the provision of new products to society. However, they have not been cultivated so far because agronomic techniques have not been fully developed and disseminated due to absence of detailed soil and vegetation data. Also, the natural coastal ecosystem is being continuously altered, transformed or destroyed, resulting to the degraded functions of ecosystem services, including ecosystem goods and services provision, environmental pollution control, biodiversity conservation, and human vulnerability to changing ecosystems (Lichtenberg and Ding, 2008; Ma et al., 2015; Napton et al., 2010).

Quantitative information on historic changes in landscape structure and composition is helpful in understanding the consequences of such changes (Bender et al, 2005; Braimoh, 2006). Thus, there is need to identify and characterize the indigenous plants as well as soil in the Bohai Bay area to generate useful data that could contribute to ecological restoration activities. The aim of this study was to identify and characterize the distribution of salts and common plant species within the Bohai Bay coast, thereby contributing to the database supporting the sustainable development of the area.

2. Materials and methods

2.1. Study area

The study was conducted in Yanshan and Haixing counties of Hebei Province, a coastal area within the Bohai Bay, China (**Figure 1**). The total area of saline-alkali land in the bay area is about 134,478 hm^2 (Gao et al., 2016). The climate is a semi-arid monsoon, characterized by a hot and rainy summer. The annual average precipitation is 588 mm, of which about 80% is concentrated in July to September (Hebei Water Resources Bulletin, 2020).

The annual average evaporation is 1980 mm with monthly average minimum and maximum temperatures of 4.8 and 24.3 °C, respectively. The naturally occurring differentials in vegetation patches made it an ideal site to evaluate the plant species distribution as mediated by variations in soil properties.

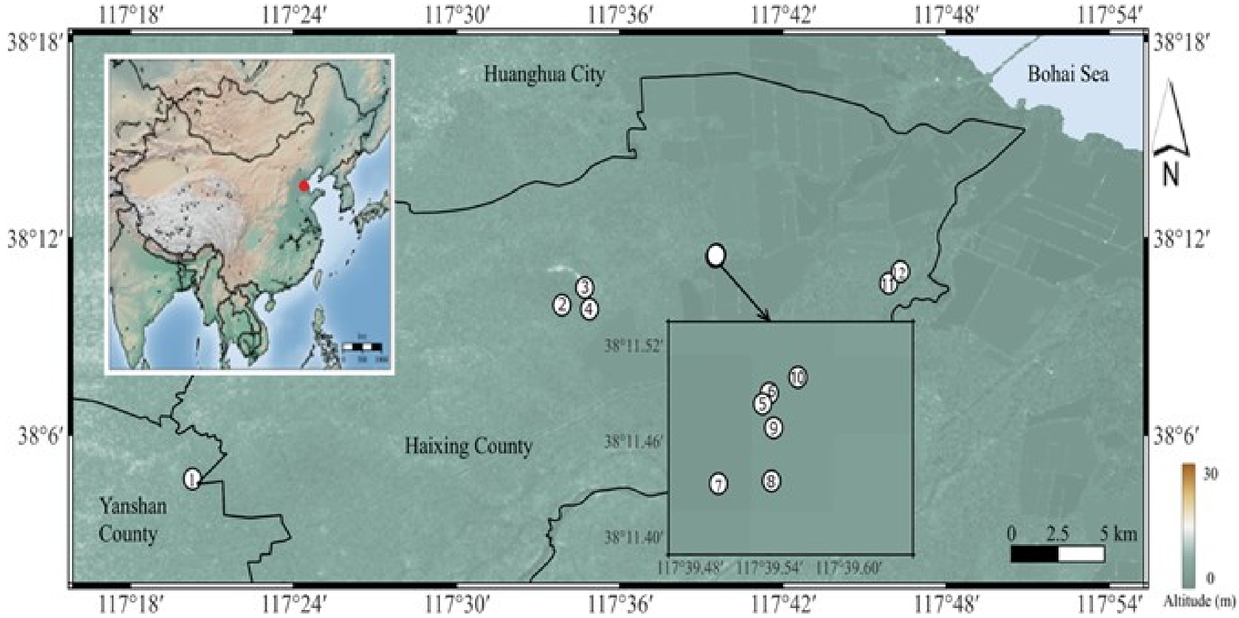

Figure 1. Map of the Bohai Bay of China showing sampling locations.

2.2. Soil sampling and analysis

Based on the Chinese Soil Taxonomy, the soil is classified as a saline-alkali soil (Institute of Soil Science, Chinese Academy of Sciences, 2001). The area was surveyed to identify sampling locations based on distance to the coastline and consistency of vegetation. Field measurements for vegetation and soil indicators were conducted across twelve sampling locations (**Figure 1**). For each sampling location, five points were randomly selected and a composite soil sample (0–30 cm), was obtained using an auger; fresh plant samples were collected from each point using 1m × 1m quadrats. The soil samples were air-dried and screened via a 2 mm sieve for laboratory analysis. The Ca^{2+}, Mg^{2+}, Na^{+} and K^{+} in the soil were extracted with neutral ammonium acetate solution and their concentrations read by atomic absorption spectrophotometry (Lu, 1999). The Cl^{-} was determined by $AgNO_3$ titration method (Edwards et al., 1981) after extracting from samples in boiling water bath for 30 min and diluted to a constant volume (100 mL) with distilled water. The HCO_3^{-} was determined by dual indicator-neutralization titration while the SO_4^{2-} was analyzed by turbidimetric method. Total salt content was estimated as the sum of the seven ions (HCO_3^{-}, Cl^{-}, SO_4^{2-}, Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}). Soil electrical conductivity (EC) was measured from a (1:5) soil-water suspension using an EC meter.

2.3. Plant sampling

The plants were sampled from the site locations (named plots 1 to 12) within coordinates shown in **Figure 1**. Plant height was measured for each species and recorded. The above-ground biomass of plants within the quadrat was harvested, oven-dried (105 ℃) and used to estimate the dry biomass according to species. Both the total number and species number per quadrat was manually counted and then used to determine species composition using the Linneaus binomial nomenclature of plant taxonomy.

2.4. Data analysis

The mean values of salt ion concentrations and plant data were summarized using the StatView software (Statistical Analysis System) following complete descriptive analysis. The spatial variations in soil properties were estimated using coefficient of variation. Correlation analysis was also performed to explore associations among salt ions.

3. Results and discussion

3.1. Plant population

The Bohai coastal region is one of the most densely populated areas in China and has experienced continuous alteration and transformation over the past decades, from wetland, forest and grassland to farmland and urban (Chen et al., 2019). These changes had adverse effects on the ecosystem composition and structure, including the production capacity and ecological attributes of the ecosystems, especially the nutrient transport between soil and vegetation (Zang et al., 2011). In this coastal ecosystem, the vegetation community is composed mainly of salt-tolerant pioneer herbaceous plants, such as *Aeluropus sinensis, Sueada sals*a and *Imperata cylindric*a (Liu et al., 2019). There were significantly wide variations in the distribution of plant species across sampling plots. Plot 3 had the highest density of plants (1900 stands) but it was dominated by Sueda salsa (**Figure 2**), which also dominated plots 2 and 4. Plot 1 (the furthest from the coastline) was dominated by Phragmites australis and *Setaria viridis*. Plot 3 was followed by plot 4 (1262 stands), dominated entirely by *S. salsa*, plot 7 (1237 stands) dominated by *S. viridis* and plot 10 (1132 stands) which was also dominated entirely by S. salsa. Plot 12 was a practically bare plot, being the closest to the coastline with extremely high salt content. *Pragmites australis* was the most populous (with 253 stands) species in Plot 1 and to much lesser extents in plots 6 (20 stands), 4 (13 stands), 2 (13 stands), 5 (4 stands) and 2 (1 stand). *Pragmites australis* is one of the most widespread species in the Yellow River Delta of China (Wang et al., 2012) and provides staging, wintering and breeding sites for birds (Wu et al., 2009; Zhao et al., 2005). *Seteria viridis* was the most popular in plot 7 (1160 stands), and to lesser degrees in plots 6 (82 stands), 1 (72 stands), 5 (31 stands) and 4 (9 stands).

Heteropappus altaicus was only present in plot 1, numbering only 44 stands. *Aeluropus littoralis* was more widely distributed across plots 2 (146 stands), 6 (81 stands), 8 (75 stands), 3 (51 stands), 1 (34 stands) and 7 (11 stands). *Puccinellia distans* (Alkali grass) was mostly distributed (about 98%) in plot 9 (826 stands), with very few stands (21) in plot 1. Alkali grass is a perennial, tufted, pale green plant with erect or geniculate culms, 20–40 cm tall. Less than 2 stands of Kochia scoparia was identified and only in plot 1. Sueda salsa was the most widely distributed across plots, dominating plots 2, 3, 4 and 10, with presence in plots 6 and 8. *Scorzonera austriaca* was most populous in plots 7 (59 stands) and 6 (38 stands), with meagre presence in plots 2 and 3. *Limonium bicolor* was found only in very small numbers (3–7) in plots 2, 6, 7 and 8. Presence of Chloris virgata was limited to plot 3 with 19 stands. *Imperata* cylindrica was identified only in plots 5 (84 stands) and 6 (10 stands), while *Leymus* *mollis* was only found in plot 6 with 5 stands and just one strand of *Puccinellia tenuiflora* occurred in plot 6, as with *Ulmus pumila*, *Calistegia hederacea* and *Taraxacum mongolicum* in plot 5; five stands of *Lagopsis supina* were also found in plot 5. *Raphanus sativus* and *Salsola collina* were present only in plot 5 with 7 stands and a single stand; *Digitaria sanguinalis* was also observed only in plot 5 with 155 stands, as were strands of *Amaranthus retroflexus* and *Eleusine indica*. *Humulus scandens* and *Psammochloa villosa* were observed only in plot 5 with just 5 and 12 stands but strands of *Amaranthus tricolor*, and *Salsola komarovii* were also observed in plot 5.

Other species had very negligible presence across the plots, including *Lysium chinense, Rabdosia rubescens,* and *Ixeris denticulate*. Zhang et al. (2021) found that vegetation successions (including composition and density) in coastal wetlands were influenced by the changes in relative surface elevation and soil salinity and in the case of the Bohai Bay area, these changes were ascribed to climate change, sea-level rise, coastal erosion, sedimentation, storm surge, seawater intrusion, and exploitation of underground brine. A previous report showed that the dominant herbaceous plants in coastal tidal flats were *Artemisia capillaris*, *Atriplex centralasiatica*, *Limonium bicolor*, and *Suaeda salsa*, while the dominating species on coastal inland areas were *Aeluropus littoralis*, *Chloris virgata*, *Cynanchum chinense, Phragmites australis* and *Setaria viridis* (Liu et al., 2017).

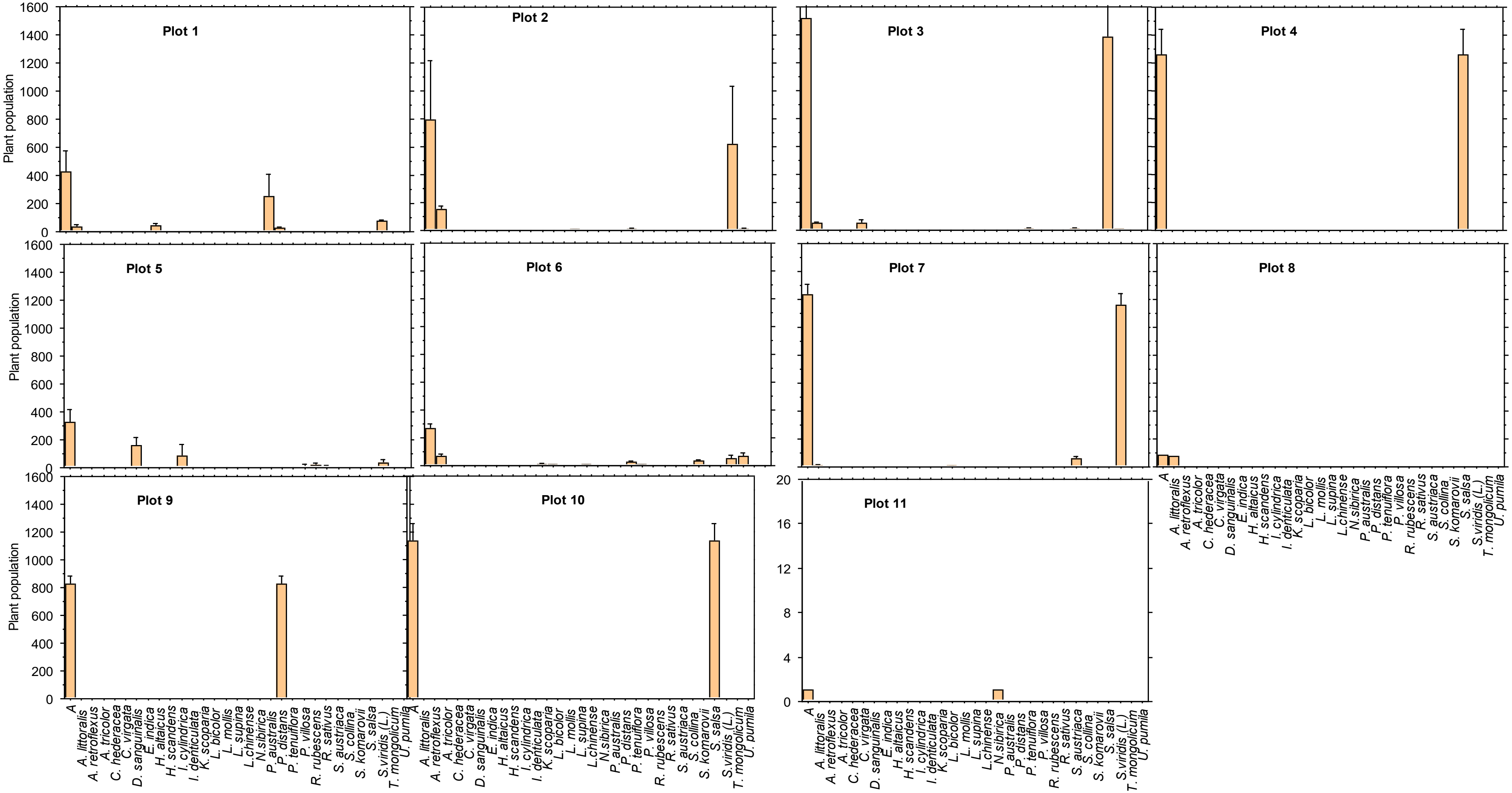

Figure 2. Population of species across plots (locations) in the Bohai Bay area of China (a is total number of plants). Vertical bars represent standard.

3.2. Height

Similar to plant distribution, there were wide variations in plant height, depending on the species (**Figure 3**). *Pragmites australis* and *P. distans* grew up to more than 90cm in plots 2 and 9 but the height varied significantly across plots. *Seteria viridis* was tallest (79.4 cm) in plot 7 and shortest (about 11 cm) in plot 2. *Heteropappus altaicus* was only about a foot tall and *A. littoralis* was tallest (nearly 40 cm) in plot 8. *Sueda selsa* had fairly uniform height variations across plots.

3.3. Biomass

Vegetation biomass is becoming severely reduced in most coastal areas globally. About one-third of global mangrove, seagrass, and salt marsh areas have been lost over the past several decades (McLeoad et al., 2011). The natural coastal wetlands were reduced by more than 53% in China during 1957–2017 (Gu et al., 2018; Wang et al., 2021). These reductions in coastal wetlands largely decrease the blue carbon sink by reducing the aboveground biomass (AGB). The decreased AGB reduces the burial rates of organic matter (Macreadie et al., 2017; Osland et al., 2018) and increases the net ecosystem exchange (Chu et al., 2019). **Figure 4** show the variations biomass production across species and plots. On average, plot 2 produced the most biomass per unit area, followed by plots 4 and plot 5, which had the most diverse species composition. Among species, *D. sanguinalis* showed the highest dry mass, followed by *L. perenne* and *H. altaicus.* For plot 1, *H. altaicus* had the driest mass (97 g/sqm), followed significantly less by *P. australis* (44 g) and *A. littoralis* (36 g). *A. littoralis* dry mass weighed the most (132 g) in plot 2, followed by *S. salsa* (88 g) and *P. australis* (41 g). For plot 3, *S. salsa* produced the highest dry mass (107 g), followed by *A. littoralis* (79 g), *P. tenuiflora* (40 g), *I. cylindrica* (29 g) and *C. virgata* (28 g). Plot 4 was covered entirely by *S. salsa* with mean dry weight of 67 g. *Suaeda glauca* is a native species with high seed oil content (25%), which is effective in fighting cancer, lowering cholesterol, and preventing atherosclerosis (An et al., 2015). The stems and leaves of *S. salsa* seedlings are edible and are sold as vegetables in the local market. The oil content of the seeds is 25%, and the unsaturated fatty acid content is as high as 90%, which is why it is sold at a premium price. The protein content of stems and leaves accounts for about 40% of the dry matter, and the contents of Ca, P, Fe, and riboflavin is higher than that of spinach and tomatoes while the selenium content is more than ten times that of common vegetables (Wang and Liu, 2002). Thus *S. species* are promising as food plants if domesticated.

Plot 5 had the most diverse plant community with *D. singuinalis* having the highest mean dry mass while *A. littoralis* had the highest dry mass in plot 6, followed by *A. viridis, I. cylindrica, S. salsa* and *P. australis*. Plots 5 and 6 share identical location, but because plot 5 was on a higher elevation and therefore less affected by underground water salinity, it had more species diversity than plot 6. Differences in elevation also imply differences in distance from underground saline water table, which may determine the level of soil salinity and thus, the mass of vegetation.

Plot 7 had only four species whose mean dry mass ranged from 1.2 g for *L. bicolor* to 22 g for *A. littoralis*. Similarly plot 8 had three species that weighed even less than those in plot 7 and plots 9 to 11 were populated by single species: *P. distance* for plot

9, *S. salsa* for plot 10 and *N. sibirica* for plot 11Some of the salt-tolerant species identified from this study such as *S. salsa* and *A. littoralis* could be used for remediation work. For example, the cultivation of salt-tolerant plants reduced the salt content by 67% in the species with the highest soil de-salinization effect (An et al., 2015). In addition, these plants can be used as fodder. Native plants adapted to saline soils have a variety of potential uses, but they are not currently cultivated on a large scale for several reasons. However, a few places in China do cultivate and process some saline plants in the form of tender leaves and branches of *Suaeda salsa*, *S. glauca*, as well as *Salicornia europaea* as vegetables. *Sueda salsa* seedlings are patronized by restaurants, and edible oil refined from the seeds, and salt products refined from the plants are in high demand. However, these products, which have high potential uses are rarely found in the market because of their very low production.

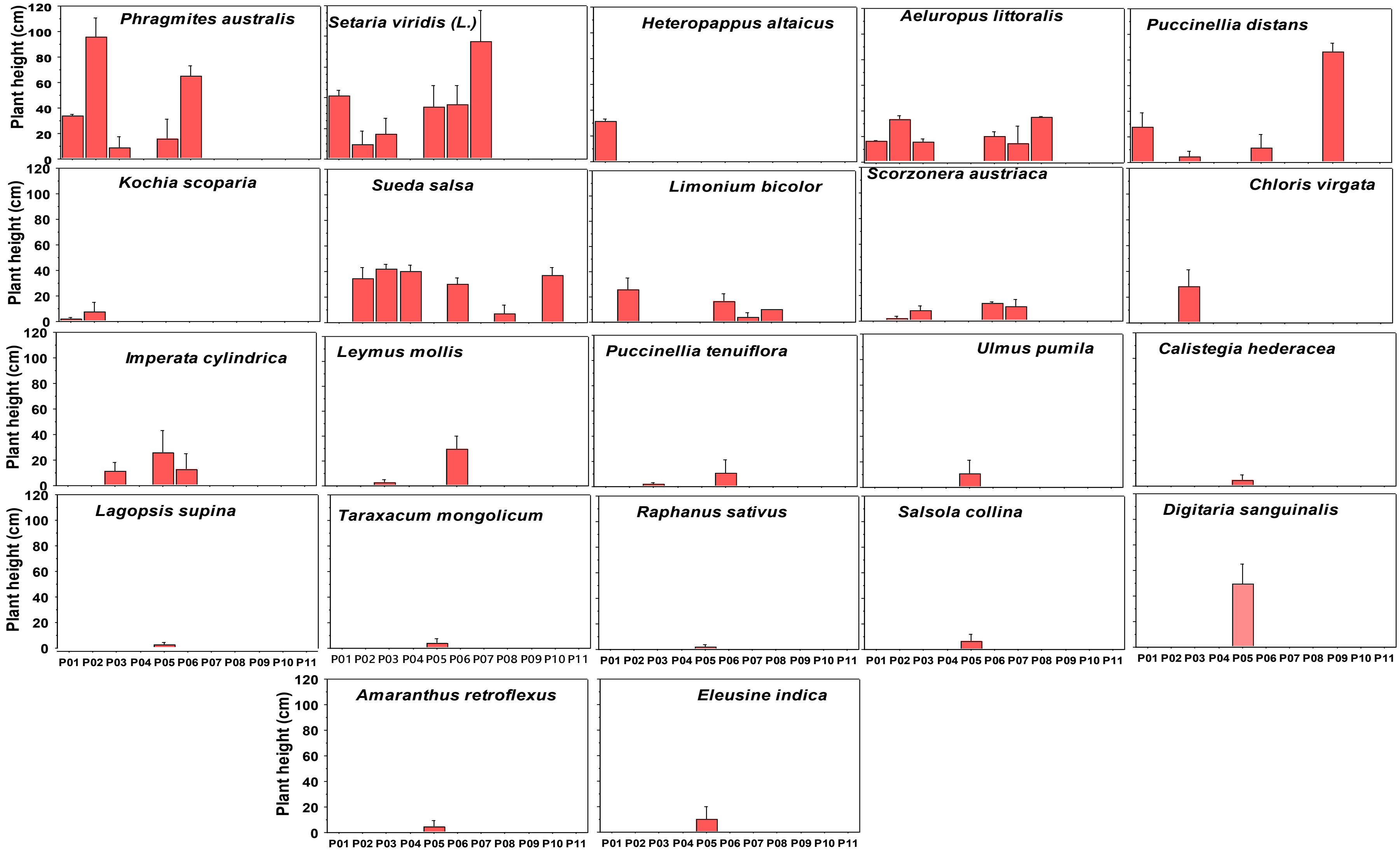

Figure 3. Relative height of local plant species across plots (P01, P02…P11) in the Bohai bay area of China. Vertical bars are standard errors.

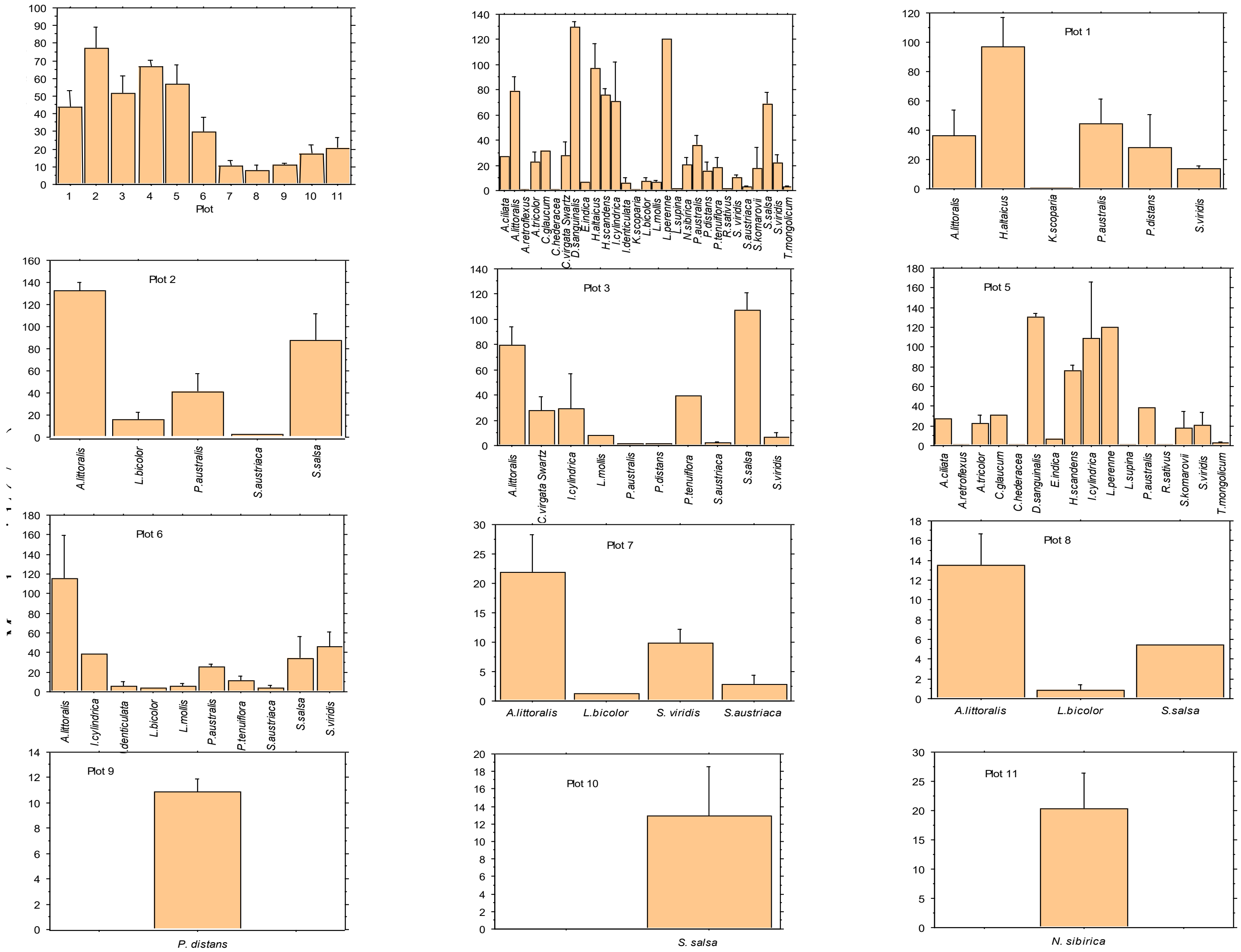

Figure 4. Mean dry weight (g/sqm) by species and sampling plots. Vertical bars represent standard errors.

3.4. Salinity parameters

Soil salinity 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 ions (Dong, 2012; Radhakrishnan and Kumari, 2012). The complete descriptive statistics of soil salinity parameters is shown in **Table 1**. The EC ranged from 0.47 to 23.8 ds/m and the total salt ions from 0.05 to 8.8 g/kg. Each of the parameters in **Table 1**, except HCO_3^- showed strong variations as judged from their coefficients of variation (CV). The CV measures the spatial variability of soil properties and values ≤0.10 are considered to show weak, 0.10–1.0 to show moderate and >1 to show strong variability (Lei et al. 1988). The wide spatial variation in soil salinity observed here may be due to differences in distance to coastline, terrain, groundwater level, groundwater salinity, type of marine sediment particles and anthropogenic perturbations (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 locations. The regional salt distribution described above is mainly caused directly or indirectly by seawater (McLeod et al., 2010; Park et al., 2012; Wahab et al., 2010).

Table 1. Statistical summary of soil salinity parameters across sampling locations.

	Mean	Std.dev.	Std.error	Minimum	Maximum	CV	Range	Skewness	Kurtosis
EC (dS/m)	3.697	5.147	0.670	0.047	23.800	1.393	23.753	2.335	5.391
HCO_3^- (g/kg)	0.026	0.007	0.001	0.012	0.047	0.280	0.035	0.632	0.452
Cl^- (g/kg)	0.732	1.097	0.143	0.007	4.946	1.499	4.939	2.378	5.460
$SO4^{2-}$ (g/kg)	0.127	0.169	0.022	0.016	0.793	1.329	0.777	2.122	4.070
Ca^{2+} (g/kg)	0.028	0.028	0.004	0.004	0.107	1.008	0.103	1.321	0.640
Mg^{2+} (g/kg)	0.040	0.059	0.008	0.003	0.279	1.464	0.276	2.488	5.759
K^+/Na^+	0.437	0.661	0.086	0.003	3.056	1.512	3.052	2.472	5.998
Total ions (g/kg)	1.391	1.983	0.258	0.050	8.833	1.426	8.782	2.311	5.032

The electrical conductivity (EC), as well as chloride (Cl^-), sulphate (SO_4^{2-}), Mg^{2+} and Na^+ ions increased towards the coast and was highest in plot 12 with bare ground and lowest in plot 5 (**Figure 5**). However, Ca^{2+} ion was most prevalent in plots 4, 11 and 12 in that order. The HCO_3^- ion showed a relatively even distribution across plots but was highest in plot 9. The Na^+ ion was the most abundant cation while the Cl^- and SO_4^{2-} ions were the most abundant anions. Therefore, the most dominant salt was sodium chloride. Based on the EC ratings of Abrol et al. (1988), plot 1 was non-saline but otherwise, the salinity ranged from slightly saline in plot 2 to strongly-very strongly saline in plots 11–12. Thus, the soil salinity was highly variable across plots, possibly due to topography and distance from the coast as highlighted above. Similar variations have been reported previously (Akramkhanov et al., 2011; Cetin and Kirda, 2003; Shi et al., 2005; Wu et al., 2015).

Soils in the Bohai Bay area are highly saline because of their generally low elevation, high groundwater level, and intense evapotranspiration, which allow salts within soil to easily accumulate on the soil surface. The causes and processes for the formation of saline soils in the area have been amply described elsewhere (Zhang, 2002). Salinity in the area was estimated to range from 10 to 20 times, with marked abundance of sodium and potassium, compared to normal farmland in the same North China Plain (An et al., 2015). Consistent with previous reports (Li et al., 2002), the most dominant salt ions were Cl^{-}, SO_4^{2-}, and Na^{+} with very low soluble phosphorus, less than 10 mg/kg (Liu et al., 2002). The soils are therefore unsuitable for direct crop cultivation.

However, the area under severely salinized land has been decreasing in recent years because of close attention to its management (Bao et al., 2016; Foronda and Colinet, 2022; Xie et al., 2022), especially through extensive rehabilitation of saline-alkali land (Song et al., 2023). For most halophytes, low salinity treatment promotes plant growth (Flowers and Colmer, 2008; Rozentsvet et al., 2017), but if the NaCl level reaches 200mM, more than 90% of them do not survive (Flowers and Colmer, 2015). However, Li et al. (2019) found that S. salsa survived up to 400mM NaCl, without an adverse effect on its biomass. As salt-accumulating plants, Sueda species have been reported to accumulate substantial amounts of Na^{+} in their shoots with a weak K^{+} selectivity over Na^{+} (Reimann and Breckle, 1993; Wang et al., 2002). As expected, there were highly considerable correlations between the EC and all the salt ions (except HCO_3^{-}) and among most of the other ions (**Table 2**). Of particular note is that between Cl^{-} or SO_4^{2-} and the cations. The major problem with saline soils is the presence of soluble salts, primarily Cl^{-}, SO_4^{2-}, and sometimes NO_3^{-}; small amounts of HCO_3^{-} ions may be present, but soluble carbonates are almost invariably absent.

Table 2. Correlation among salt ions across sampling plots.

	EC	**HCO_3^{-}**	**Cl^{-}**	**SO_4^{2-}**	**Ca^{+}**	**Mg^{+}**
EC						
HCO_3^{-}	−0.239^{NS}					
Cl^{-}	0.999***	−0.240				
SO_4^{2-}	0.899***	−0.261*	0.904***			
Ca^{+}	0.657***	−0.338**	0.646***	0.749***		
Mg^{+}	0.912***	−0.255 ^{NS}	0.921***	0.973***	0.655***	
K^{+} + Na^{+}	0.998***	−0.226 ^{NS}	0.999***	0.894***	0.627***	0.909***

* = significant at $p < 0.05$, ** = significant at $p < 0.01$; *** = significant at $p < 0.0001$.

Salts of low solubility, such as $CaSO_4$ and $CaCO_3$, may also be present (Sparks, 2003) sodium, Ca and Mg are major cations, and the proportion of Na is mostly less than half of the total solute cations in the soil solution. The accumulation of neutral or near-neutral salts like NaCl, $CaCl_2$, Na_2SO_4 and $MgSO_4$ in the surface layer and soil body, which cause the soil to exhibit neutral or alkaline reactions, is what is generally referred to as salinization (Herbert et al., 2015; Kaushal et al., 2018a, 2018b; Li et al., 2018).

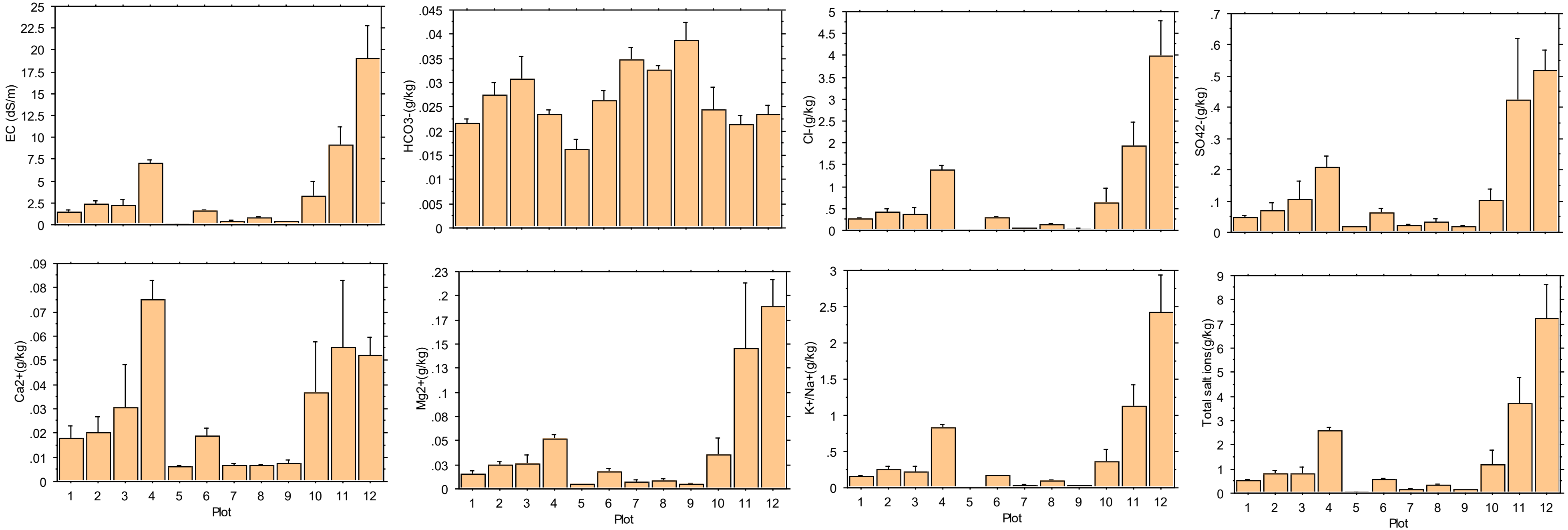

Figure 5. Electrical conductivity and salt ion distribution across plots (locations) in the Bohai Bay area of China. Vertical bars represent standard errors.

4. Conclusion

The Bohai Bay of China is a rapidly developing area, hence there is need to study the bio-physical parameters of the coastal parts to further enrich the existing database for sustainable development by planners. Our data showed that the mean electrical conductivity (EC) and total salt ions in the soil varied widely from 0.47 to 23.8 ds/m and 0.05 to 8.8 g/kg, respectively. The EC, as well as chloride, sulphate, Mg and Na ions increased significantly towards the coastline and the most dominant salinity-inducing salt was sodium chloride. Large variations were also observed in the number and distribution of plant species but the most dominant species were *Sueda salsa*, *Phragmites australis* and *Setaria viridis*. On average, the sampling points furthest from the coast produced the most biomass, and the point with the highest elevation had the most diverse species composition. These variations should be considered in future ecological works to ensure sustainable development and ecosystem health.

Author contributions: Conception of the study, performed field work, PA, WL and XJL; supervision and analytics, XL, HF and YZ; analyzed data and wrote the manuscript, EAE, AP and MI. All authors have read and agreed to the published version of the manuscript.

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References

Akramkhanov, A., Martius, C., Park, S. J., et al. (2011). Environmental factors of spatial distribution of soil salinity on flat irrigated terrain. Geoderma, 163(1–2), 55–62. https://doi.org/10.1016/j.geoderma.2011.04.001

An, P., X. Li X., Y. Zheng, et al. (2015). Distribution of plant species and species-soil relationship in the east central Gurbantunggut Desert, China, Journal of Geographical Sciences, 25(1), 101-112.

Andrade Foronda, D., Colinet, G. (2022). Combined Application of Organic Amendments and Gypsum to Reclaim Saline-Alkali Soil. Agriculture, 12(7), 1049. https://doi.org/10.3390/agriculture12071049

Bao, S., Wang, Q., Bao, X., et al. (2016). Biological treatment of saline-alkali soil by Sulfur-oxidizing bacteria. Bioengineered, 7(5), 372–375. https://doi.org/10.1080/21655979.2016.1226664

Bender, O., Boehmer, H. J., Jens, D., et al. (2005). Analysis of land-use change in a sector of Upper Franconia (Bavaria, Germany) since 1850 using land register records. Landscape Ecology, 20(2), 149–163. https://doi.org/10.1007/s10980-003-1506-7

Braimoh, A. K. (2006). Random and systematic land-cover transitions in northern Ghana. Agriculture, Ecosystems & Environment, 113(1–4), 254–263. https://doi.org/10.1016/j.agee.2005.10.019

Cetin, M., Kirda, C. (2003). Spatial and temporal changes of soil salinity in a cotton field irrigated with low-quality water. Journal of Hydrology, 272, 238–249. https://doi.org/10.1016/S0022-1694(02)00268-8

Cheng, M., Huang, B., Kong, L., et al. (2019). Ecosystem Spatial Changes and Driving Forces in the Bohai Coastal Zone. International Journal of Environmental Research and Public Health, 16(4), 536. https://doi.org/10.3390/ijerph16040536

Chu, X., Han, G., Xing, Q., et al. (2019). Changes in plant biomass induced by soil moisture variability drive interannual variation in the net ecosystem CO_2 exchange over a reclaimed coastal wetland. Agricultural and Forest Meteorology, 264, 138–148. https://doi.org/10.1016/j.agrformet.2018.09.013

Department of Water Resources of Hebei Provence. (2021). Hebei Water Resources Bulletin 2020. Hebei Provincial Administration.

Dong, H. (2012). Technology and field management for controlling soil salinity effects on cotton. Australian Journal of Crop Science, 6, 333–341.

Edwards, I.K., Kalra, Y., Radford, F. (1981). Chloride determination and levels in the soil-plant environment. Environ. Pollut. Ser. B, 2, 109–117. https://doi.org/10.1016/0143-148X(81)90046-X

Flowers, T. J., Colmer, T. D. (2008). Salinity tolerance in halophytes. New Phytologist, 179(4), 945–963.

https://doi.org/10.1111/j.1469-8137.2008.02531.x

Flowers, T. J., Colmer, T. D. (2015). Plant salt tolerance: adaptations in halophytes. Annals of Botany, 115(3), 327–331. https://doi.org/10.1093/aob/mcu267

Gao, H., Liu, J., Eneji, A., et al. (2016). Using Modified Remote Sensing Imagery to Interpret Changes in Cultivated Land under Saline-Alkali Conditions. Sustainability, 8(7), 619. https://doi.org/10.3390/su8070619

Gu, J., Luo, M., Zhang, X., et al. (2018). Losses of salt marsh in China: Trends, threats and management. Estuarine, Coastal and Shelf Science, 214, 98–109. https://doi.org/10.1016/j.ecss.2018.09.015

Guo, L., Sun, M., Wang, X., Lan, H. (2019). Statistical Analysis of the Characteristics Difference of Rainfall over Bohai Bay and the Land. Climate Change Research Letters.

Herbert, E. R., Boon, P., Burgin, A. J., et al. (2015). A global perspective on wetland salinization: ecological consequences of a growing threat to freshwater wetlands. Ecosphere, 6(10), 1–43. https://doi.org/10.1890/es14-00534.1

Institute of Soil Science, Chinese Academy of Sciences. (2001). Chinese Soil Taxonomy. Science Press.

Jamil, M., Anees, M., Rehman, S.U., et al. (2012). Effect of soil salinity on the growth, amino acids and ion contents of rice transgenic lines. Afr J Biotechnol, 11, 15231–15235.

Kaushal, S. S., Likens, G. E., Pace, M. L., et al. (2018). Freshwater salinization syndrome on a continental scale. Proceedings of the National Academy of Sciences, 115(4). https://doi.org/10.1073/pnas.1711234115

Kaushal, S. S., Likens, G. E., Pace, M. L., et al. (2018). Novel 'chemical cocktails" in inland waters are a consequence of the freshwater salinization syndrome. Philosophical Transactions of the Royal Society B: Biological Sciences, 374(1764), 20180017. https://doi.org/10.1098/rstb.2018.0017

Li, J., Hussain, T., Feng, X., et al. (2019). Comparative study on the resistance of Suaeda glauca and Suaeda salsa to drought, salt, and alkali stresses. Ecological Engineering, 140, 105593. https://doi.org/10.1016/j.ecoleng.2019.105593

Li, P., Qian, H., Wu, J. (2018). Conjunctive use of groundwater and surface water to reduce soil salinization in the Yinchuan Plain, North-West China. International Journal of Water Resources Development, 34(3), 337–353. https://doi.org/10.1080/07900627.2018.1443059

Lichtenberg, E., Ding, C. (2008). Assessing farmland protection policy in China. Land Use Policy, 25(1), 59–68. https://doi.org/10.1016/j.landusepol.2006.01.005

Liu, J., Rong, Q., Zhao, Y. (2017). Variations in soil nutrients and salinity caused by tamarisk in the coastal wetland of the Laizhou Bay, China. Ecosphere, 8(2). https://doi.org/10.1002/ecs2.1672

Lv, Z. Z., Liu, G. M., Yang, J. S., et al. (2013). Spatial variability of soil salinity in Bohai Sea coastal wetlands, China: Partition into four management zones. Plant Biosystems—An International Journal Dealing with All Aspects of Plant Biology, 147(4), 1201–1210. https://doi.org/10.1080/11263504.2013.861531

MA (Millennium Ecosystem Assessment). (2005). Ecosystems and Human Well-Being: Synthesis. Island Press.

Ma, F., Eneji, A. E., Liu, J. (2015). Assessment of ecosystem services and dis-services of an agro-ecosystem based on extended emergy framework: A case study of Luancheng county, North China. Ecological Engineering, 82, 241–251. https://doi.org/10.1016/j.ecoleng.2015.04.100

Macreadie, P. I., Nielsen, D. A., Kelleway, J. J., et al. (2017). Can we manage coastal ecosystems to sequester more blue carbon? Frontiers in Ecology and the Environment, 15(4), 206–213. https://doi.org/10.1002/fee.1484

Mcleod, E., Chmura, G. L., Bouillon, S., et al. (2011). A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO_2. Frontiers in Ecology and the Environment, 9(10), 552–560. https://doi.org/10.1890/110004

Napton, D. E., Auch, R. F., Headley, R., et al. (2009). Land changes and their driving forces in the Southeastern United States. Regional Environmental Change, 10(1), 37–53. https://doi.org/10.1007/s10113-009-0084-x

Opdam, P., Steingröver, E., Rooij, S. van. (2006). Ecological networks: A spatial concept for multi-actor planning of sustainable landscapes. Landscape and Urban Planning, 75(3–4), 322–332. https://doi.org/10.1016/j.landurbplan.2005.02.015

Osland, M. J., Gabler, C. A., Grace, J. B., et al. (2018). Climate and plant controls on soil organic matter in coastal wetlands. Global Change Biology, 24(11), 5361–5379. https://doi.org/10.1111/gcb.14376

Radhakrishnan, R., Kumari, B. D. R. (2012). Protective role of pulsed magnetic field against salt stress effects in soybean organ culture. Plant Biosystems—An International Journal Dealing with All Aspects of Plant Biology, 147(1), 135–140. https://doi.org/10.1080/11263504.2012.717543

Reimann, C., Breckle, S. W. (1993). Sodium relations in Chenopodiaceae: a comparative approach. Plant, Cell & Environment, 16(3), 323–328. https://doi.org/10.1111/j.1365-3040.1993.tb00876.x

Rozentsvet, O. A., Nesterov, V. N., Bogdanova, E. S. (2017). Structural, physiological, and biochemical aspects of salinity tolerance of halophytes. Russian Journal of Plant Physiology, 64(4), 464–477. https://doi.org/10.1134/s1021443717040112

Shi, Z., Li, Y., Wang, R. C., et al. (2005). Assessment of temporal and spatial variability of soil salinity in a coastal saline field. Environmental Geology, 48(2), 171–178. https://doi.org/10.1007/s00254-005-1285-3

Song, Y., Gao, M., Xu, Z., et al. (2023). Temporal and Spatial Characteristics of Soil Salinization and Its Impact on Cultivated Land Productivity in the BOHAI Rim Region. Water, 15(13), 2368. https://doi.org/10.3390/w15132368

Sparks, D. L. (2003). The Chemistry of Saline and Sodic Soils. Environmental Soil Chemistry, 285–300. https://doi.org/10.1016/b978-012656446-4/50010-4

Su, Y., Chen, X., Liao, J., et al. (2016). Modeling the optimal ecological security pattern for guiding the urban constructed land expansions. Urban Forestry & Urban Greening, 19, 35–46. https://doi.org/10.1016/j.ufug.2016.06.013

Sun, S., Wang, Y., Song, Z., et al. (2021). Modelling Aboveground Biomass Carbon Stock of the Bohai Rim Coastal Wetlands by Integrating Remote Sensing, Terrain, and Climate Data. Remote Sensing, 13(21), 4321. https://doi.org/10.3390/rs13214321

Wang, F., Tang, J.W., Ye, S., Liu, J.H. (2021). Blue carbon sink function of Chinese coastal wetlands and carbon neutrality strategy. Bull. Chin. Acad. Sci., 36, 3. https://doi.org/10.16418/j.issn.1000-3045.20210215101

Wang, S., Zheng, W., Ren, J., et al. (2002). Selectivity of various types of salt-resistant plants for K^+ over Na^+. Journal of Arid Environments, 52(4), 457–472. https://doi.org/10.1006/jare.2002.1015

Wang, X., Yu, J., Zhou, D., et al. (2011). Vegetative Ecological Characteristics of Restored Reed (Phragmites australis) Wetlands in the Yellow River Delta, China. Environmental Management, 49(2), 325–333. https://doi.org/10.1007/s00267-011-9757-6

Wang, Y., Pan, J. (2019). Building ecological security patterns based on ecosystem services value reconstruction in an arid inland basin: A case study in Ganzhou District, NW China. Journal of Cleaner Production, 241, 118337. https://doi.org/10.1016/j.jclepro.2019.118337

Wu, D., Liu, J., Wang, W., et al. (2009). Multiscale analysis of vegetation index and topographic variables in the Yellow River Delta of China. Chinese Journal of Plant Ecology, 33(2), 237–245.

Wu, Y. P., Zhang, Y., Bi, Y.M, Sun, Z.J. (2015). Biodiversity in Saline and non-saline soils along the Bohai sea coast, China. Pedosphere, 25(2), 307–315. https://doi.org/10.1016/S1002-0160(15)60015-7

Xie, X.F., Pu, L.J., Shen, G.Y., et al. (2022). Dynamics and prediction of soil salinization parameters under the amelioration of heavy coastal saline-alkali land. Acta Pedol. Sin., 59, 1504–1516.

Zang, S., Wu, C., Liu, H., et al. (2010). Impact of urbanization on natural ecosystem service values: a comparative study. Environmental Monitoring and Assessment, 179(1–4), 575–588. https://doi.org/10.1007/s10661-010-1764-1

Zhang, H., Zhang, Y., Yue, Y.J., et al. (2010). Seasonal changes in desalination mechanisms and economicbenefit analysis on the “Raised field-shallow pond” in saline-alkali regions around the Bohai. Resour Sci, 32, 442-447.

Zhang, X., Zhang, Z., Wang, W., et al. (2021). Vegetation successions of coastal wetlands in southern Laizhou Bay, Bohai Sea, northern China, influenced by the changes in relative surface elevation and soil salinity. Journal of Environmental Management, 293, 112964. https://doi.org/10.1016/j.jenvman.2021.112964

Zhang, X., Zhang, Z., Wang, W., et al. (2021). Vegetation successions of coastal wetlands in southern Laizhou Bay, Bohai Sea, northern China, influenced by the changes in relative surface elevation and soil salinity. Journal of Environmental Management, 293, 112964. https://doi.org/10.1016/j.jenvman.2021.112964

Zhao, X., Cui, B., Yang, Z. (2005). A study of the lowest ecological water level of Baiyangdian Lake. Acta Ecologica Sinica, 25(5), 1033–1040.