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Soil characteristics and response thresholds of salt meadow on lake beaches of the Ordos platform

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Salt meadow on lake beaches is the most dynamic plant community. Studying its soil characteristics and response threshold allows us to understand the external driving forces of vegetation stable-state maintenance and dynamic changes, and provide a theoretical basis for the utilization and ecological restoration of lake beach wetland resources. In this study, the community diversity, physical and chemical properties of soil, and ecological response thresholds of key soil indexes of four groups of meadows are discussed: (I) succulent salt-tolerant plant meadow, (II) Carex meadow, (III) grass meadow, and (IV) weed grass meadow. The major findings are as follows. First, Group I is easy to form a single-optimal community in the inland salt marsh beach, with patchy distribution. Group II has a lot of associated species, and most of them grew in clusters. Group III often has obvious dominant species, and the populations and individuals are evenly distributed in the community. The dominant species of Group IV are diverse, and the distribution is the most uniform. Second, there are significant differences in water content, salinity, nutrient and particle size composition of the four types of salt meadows. For Groups I-IV, the soil water content (WC) follows I > II > IV > III; the total salt content (TS) of soil follows I > III > II > IV; the pH value follows III > II > IV > I. Third, the diversity of salt meadow plants in lake beaches is closely related to the contents of WC, TS, Na^+, HCO_3^-, particle size, available potassium (AK), alkali hydrolyzable nitrogen (AN) and available phosphorus (AP) in soil. The vegetation of the four formation groups shows different ecological response threshold intervals. Fourth, the response thresholds of salt meadow vegetation to water content, salt content and sand content of soil are inherently related (but the response threshold to nutrients in soil is unclear).

KEYWORDS

ordos platform, salt meadow vegetation on lake beach, soil characteristics, vegetation response, ecological threshold 1

Introduction

The Ordos platform has the largest closed-flow area in China, with a total area of about 42,000 km^2 (Guangcai et al., 2008; Tonghui et al., 2013). There are 358 lakes and marshes with a size of above 1 km^2 developed in this area. However, over the past half-century, most of lake wetlands have evolved into lake beach wetlands because of severe drying and fragmentation (Tonghui et al., 2010; Tao et al., 2015), and some have completely disappeared and turned into sandy land. Wetland ecosystem plays an important role in regulating climate and maintaining biodiversity (Bossuyt et al., 2003; Xiaojiang 2016), and is irreplaceable. It is one of the key ecological landscape ty pes in the Ordos platform (Lei and Qingfeng 2014). Therefore, the local government has launched the Yellow River Diversion and some ecological construction projects for the important lakes and marshes, with the purposes of reversing the trend of wetland shrinkage and desertification and improving the local ecological environment.

Soil supports the material circulation and energy exchange of the ecosystem (Shen et al., 2019). It is characterized by spatial heterogeneity, structural complexity and diversity (Zhu et al., 2018), and is an important factor leading to the complexity of structure and distribution of vegetation. Previous studies on the relationship between soil and vegetation in the Ordos platform mainly focused on the mode of agriculture and animal husbandry (Liu et al., 2018; Guoling 2019) and the differences in zonal vegetation (Zuoming et al., 2004; Yingjuan et al., 2012; Ruihong et al., 2018), and basically did not consider the local environment. The lake beach meadows are hidden vegetation in the Ordos platform, and form ring-shaped salt meadows. They exhibit gradient replacement and spatiotemporal differences from the center to the periphery as well as significant dynamic changes. The study on the relationship between local soil properties and vegetation characteristics can reveal the causes of steady maintenance and dynamic changes of vegetation.

In general, ecological threshold is defined as the "threshold and breakpoint" between ecosystem functions from one steady state to another (May, 1977). In the ecological protection and management of pasture (Mark et al., 1989) and grassland (Jizhou et al., 1995; Jizhou 1997), it was first introduced at the theoretical and practical levels. It has been widely applied in the studies of ecosystems, such as forest, grassland, lake and ocean (Zhang, 2019; Wang et al., 2020; Jianfeng et al., 2021; Stéfano and Oliveira, 2021; Yara et al., 2021). In wetland research, Sim studied the salinity threshold for the disappearance of macrophytes in the saline alkali wetland system (Sim et al., 2006); Devlin et al. investigated the adverse interference of nitrogen on the primary production of wetlands and the nutrient threshold (Michelle et al., 2007); Bai Wang determined the optimum salinity and soil moisture of Suaeda Heteroptera and their respective ecological thresholds through *in situ* experiments using biomass indicators (Bai et al., 2014); Richardsion et al. established the ecological threshold of phosphorus in American Everglades (Richardson et al., 2007). These studies indicate that the determination of ecological threshold is conducive to understanding the dynamic changes of ecosystem, and has important scientific significance for ecological monitoring, early warning and purposeful restoration.

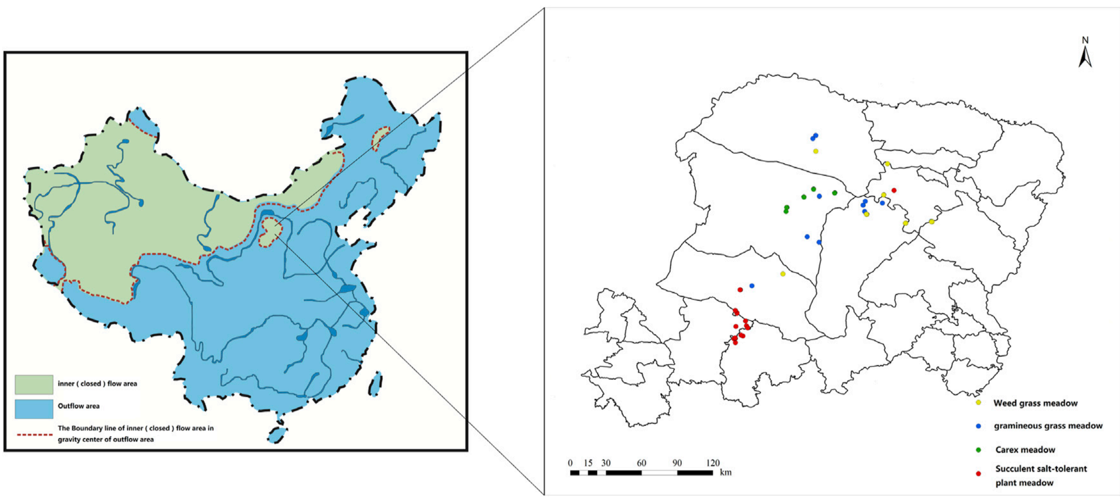

FIGURE 1
Distribution of the study area and sampling points.

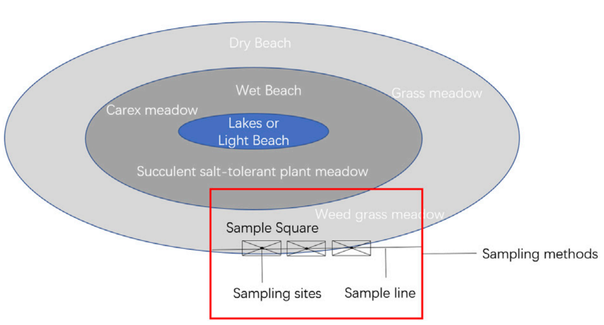

FIGURE 2
Sampling method and meadow ring distribution map.

Research methods

Overview of the study area

The study area (Latitude: 37°36′N-40°7′N, Longitude: 107°26′E-108°25′E) is located in the Ordos platform at the junction of the Loess Plateau in the northern China and the Inner Mongolia Plateau (Figure 1). The annual precipitation ranges 250–450 mm. The area is characterized by continental climate of the northern temperate zone, and is cold and dry in winter, with high temperature and little rain in summer. The annual average temperature ranges 6–7°C (Yanqiong et al., 2020). The west of the platform is dominated by chestnut soil or light chestnut soil, and the middle and east are mostly comprised of aeolian sandy soil (Xingshi 1994). The lakes and marshes in the closed flow area of the Ordos platform are shrinking due to drying and decline of water level, forming a large area of lake beach, on which salt meadow vegetation is developed.

Experimental design and determination methods

Field vegetation surveys were conducted using 1 m × 1 m sample boxes, following the sample square and sample line method (Figure 2). A total of 33 lakes and marshes were surveyed, with a total of 90 samples. Three replicates were set for each group of samples. The surveyed indicators include plant species, abundance, height, coverage, and frequency (Hankins et al., 2004). The topsoil at the depth of 0–20 cm was collected, mixed and evenly packed into a ziplock bag and delivered to the laboratory for determining physical and chemical properties. Among them, there are 37 groups of succulent salt-tolerant plants meadow lake beach wetlands, 20 groups of caryophytes meadow lake beach wetlands, 20 groups of grass meadow lake beach wetlands, and 13 weeds meadow lake beach wetlands groups.

The collected soil samples were naturally air-dried, ground and sieved. Then, the physical and chemical indexes of the soil were determined. The applied determination methods are listed in Table 1.

Data statistics and analysis

The plant diversity indexes were used to comprehensively reflect the plant community level (Yuefei et al., 2012; Ting et al., 2020; Zhenchao et al., 2021), including the Margalef index (D), Shannon-Wiener index (H), Patrick index (R) and Pielou index (E).

The calculation equations are:

$$D = S - 1/lnN$$
$$H = -\sum P_i \, ln \, p_i$$
$$R = S$$
$$E = H/lnS$$

In these equations, N is the sum of the number of individual plants in the quadrat; S is the number of species in the quadrat; and Pi is the relative important value of the *i*th plant, calculated by Pi = (relative height + relative coverage + relative density)/3.

Simple preprocessing of data was conducted using Microsoft Excel 2019. SPSS 26.0 was used for performing one-way ANOVA and least significant difference (LSD) analyses to compare the differences of community composition and soil characteristics of different vegetation types ($p < 0.05$). The interval of ecological response thresholds was determined using the boxplot method. Redundancy analysis (RDA) between vegetation community composition and soil environmental factors was processed using Canoco 5.0. Particle size of

TABLE 1 Determination methods of physical and chemical indexes of soil.

Physical and chemical index	Determination method	Physical and chemical index	Determination method
pH	pH meter	IN	Kjeldahl method
WC	Gravimetric method	IP	Sulfuric acid-perchloric acid method
TS	Conductivity meter	SOC	Potassium dichromate-sulfuric acid method
AK	Flame photometry	PS	Malvern laser particle size analyzer
AN	Alkaline hydrolysis diffusion	CO_3^{2-}, HCO_3^-	Two-indicator titration
AP	Molybdenum antimony anti colorimetry	Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}	Ion chromatograph

TABLE 2 Composition of vegetation formations in the study area.

Formation groups	Formation
Succulent salt-tolerant plant meadow	From. *Kalidium cuspidatum*
	From. *Kalidium cuspidatum + Achnatherum splendens*
	From. *Suaeda prostrata*
	From. *Suaeda glauca*
	From. *Salicornia europaea*
	From. *Salicornia europaea + Phragmites australis*
	From. *Slenderbranch Kalidium*
	From. *Slenderbranch Kalidium + Kalidium cuspidatum*
	From. *Slenderbranch Kalidium + Atriplex centralasiatica*
	From. *Slenderbranch Kalidium + Suaeda glauca*
	From. *Slenderbranch Kalidium + Suaeda prostrata*
Carex meadow	From. *Carex duriuscula*
	From. *Carex duriuscula + Halerpestes ruthenica*
	From. *Carex duriuscula + Phragmites australis*
	From. *Carex duriuscula + Potentilla anserina*
	From. *Carex duriuscula + Taraxacum borealisinense*
	Carex duriuscula + Puccinellia distans
Grass meadow	From. *Achnatherum splendens*
	From. *Achnatherum splendens + Carex duriuscula*
	From. *Achnatherum splendens + Iris lactea*
	From. *Achnatherum splendens + Agropyron cristatum*
	From. *Phragmites australis*
	From. *Phragmites australis + Halerpestes ruthenica*
	From. *Phragmites australis + Achnatherum splendens*
	From. *Phragmites australis + Carex duriuscula*
	From. *Puccinellia distans*
Weed grass meadow	From. *Puccinellia distans + Carex duriuscula*
	From. *Agropyron cristatum*
	From. *Artemisia desertorum*
	From. *Taraxacum borealisinense*
	From. *Iris lactea*
	From. *Potentilla anserina*
	From. *Swainsonia salsula*
	From. *Halerpestes ruthenica*

TABLE 3 Water content, pH value and total salt content of salt meadow soil.

Formation groups	WC (%)	pH	TS (g/kg)
Succulent salt-tolerant plant meadow	0.26 ± 0.18a	8.12 ± 0.5b	11.98 ± 0.65a
Carex meadow	0.2 ± 0.12a	9.21 ± 0.74a	4.87 ± 0.26c
Grass meadow	0.16 ± 0.1b	9.29 ± 0.61a	7.14 ± 0.48b
Weed grass meadow	0.18 ± 0.29b	9.1 ± 0.58a	3.98 ± 0.21c

Note: WC, soil water content; pH, pH value; TS, total salt content. The data in the table is the mean ± standard deviation (the same below).

soil was analyzed by applying GRADISTAT v9.1. The results were plotted using Origin 2018 software.

Analysis of results

Main community of meadow vegetation on lake beaches

According to the classification system of "China Vegetation" (China Vegetation Editorial Committee 1980), vegetation types are those with similar life types and similar community appearance. Within the vegetation type, vegetation subtypes are classified according to the differences in dominant or indicator layers. formations with similar affinities, similar life styles or similar habitats are united as a formation groups. The vegetation on lake beach in the Ordos platform belongs to the salt meadow vegetation subtype, including four formation groups: (I) succulent salt tolerant plant meadow, (II) Carex meadow, (III) grass meadow and (IV) weed grass meadow. There are 11, 6, 9 and 8 formations under the four formation groups, with a total of 34 formations (Table 2).

Diversity of salt meadow on lake beaches

To characterize the diversity of vegetation on lake beaches, we apply the Shannon-Weiner index, Patrick index, Margalef index and Pielou index (Fauvel et al., 2020; Shan et al., 2020). According to Figure 3, the richness of the Margalef community in descending order are III > IV > II > I. The richness of other indexes (Shannon-Weiner index, Patrick index and Pielou index) in descending order are IV > III > II > I. There are significant differences in the diversity of the four types of meadow vegetation ($p < 0.05$).

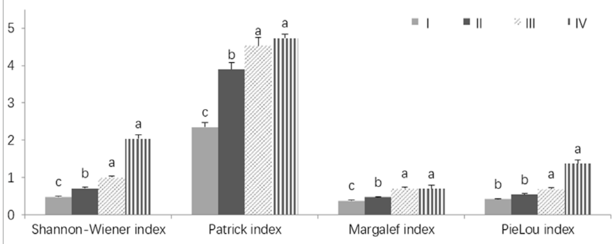

FIGURE 3
Diversity indexes of salt meadow vegetation on lake beaches. Note that different lowercase letters indicate different plots (the same below) ($p < 0.05$).

Physical and chemical properties of salt meadow soil on lake beaches

Water content, pH value and total salt content of soil

There are significant differences in WC, pH and TS for four types of salt meadow soil on lake beaches ($p < 0.05$). As shown in Table 3, the soil of succulent salt-tolerant plant meadow has the highest WC and TS values and the lowest pH value. The weed grass meadow soil has the lowest WC and TS values. The grass meadow soil displays the highest pH value. The three indexes of Carex meadow are somewhere in the middle.

Salt composition of soil

Salt composition of soil is usually characterized by ionic content. As shown in Figure 4, the contents of Mg^{2+}, Ca^{2+}, Na^{+}, SO_4^{2-} and Cl^{-} in the soil of succulent salt-tolerant plant meadow are the highest, which are 0.13 g/kg, 1.07 g/kg, 1.32 g/kg, 0.74 g/kg and 0.26 g/kg, respectively. While the contents of HCO_3^{-} and CO_3^{2-} are the lowest, which are 0.93 g/kg and 0.22 g/kg, respectively. The Carex meadow soil has the highest contents of K^{+} and HCO_3^{-} of 0.05 g/kg and 11.2 g/kg, respectively. The grass meadow soil has the lowest K^{+} content of 0.03 g/kg and the highest CO_3^{2-} content of 5.79 g/kg. The contents of Mg^{2+}, Na^{+}, SO_4^{2-} and Cl^{-} in the weed meadow soil are the lowest, which are 0.02 g/kg, 0.43 g/kg, 0.13 g/kg and 0.07 g/kg, respectively.

Particle size of soil

According to the international soil texture classification standard adopted by the Second International Soil Science Congress (Waksman 1930; Zengming et al., 2021), the particle size of soil can be divided into sand (50–2000 μm), silt (2–50 μm) and clay (<2 μm). Sand and clay can be further subdivided on this basis (Table 4). By comparing representative particle sizes, we find that there are significant differences in the texture of the four kinds of meadow vegetation soils ($p < 0.05$). The soil of succulent salt-tolerant plant meadow contains the highest contents of clay and silt, and the lowest content of fine sand. The Carex meadow soil has the highest contents of fine sand and coarse sand, and the lowest contents of clay and silt.

Nutrient characteristics of soil

As shown in Figure 5, there are significant differences in nutrients in the four types of salt meadow soil on lake beaches ($p < 0.05$). The succulent salt-tolerant plant meadow soil contains the lowest contents of total nitrogen (IN: 0.42 g/kg), organic carbon (SOC: 4.82 g/kg), available potassium (AK: 0.10 g/kg) and alkali hydrolyzable nitrogen (AN: 28.33 mg/kg); and the highest content of total phosphorus (IP: 0.4 g/kg). The Carex meadow soil has the highest contents of available potassium (AK: 0.24 g/kg) and available phosphorus (AP: 9.49 mg/kg). The grass meadow soil contains the lowest content of total phosphorus (IP: 0.32 g/kg). The weed grass meadow has the

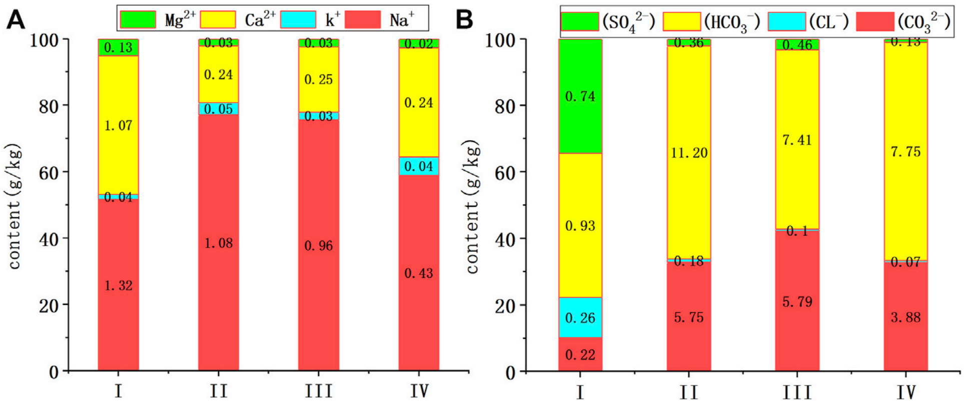

FIGURE 4
Ion composition and structure of salt meadow soil on lake beaches.

highest contents of total nitrogen (IN: 0.69 g/kg), organic carbon (SOC: 7.16 g/kg) and alkali hydrolyzable nitrogen (AN: 47.88 mg/kg); and the lowest content of available phosphorus (AP: 4.11 g/kg).

Correlation between physical and chemical properties of soil and vegetation on salt meadow soil on lake beaches

Redundancy analysis (RDA) was used for dimensionality reduction, and then the main feature components of the data were extracted (Odland and Pedersen, 2015) (Figure 6). We performed correlation analysis between physical and chemical indexes of soil and the diversity index of vegetation on salt meadow soil on lake beaches (Table 5). The results show a significant response of the diversity index of vegetation on salt meadow soil on lake beaches to the physical and chemical indexes of soil (except for Csg). The diversity index is positively correlated with CO_3^{2-}, HCO_3^-, IN, AN, K^+, SOC, AK, pH, Fs and Csg; negatively correlated with Na^+, WC, AP, SO_4^{2-}, Ca^{2+}, TS, Cl^-, Mg^{2+}, S, IP and CP. The factors with high contribution rate are Na+, HCO3-, WC, AP, pH, CO_3^{2-}, SO_4^{2-} and K^+. Previous studies suggested that community plant diversity in arid and semi-arid regions is mainly restricted by WC, TS, particle size and nutrients of the soil (Barrett-Lennard 2002; Iqbal 2016). Sandification can directly affect other physical and chemical properties of soil; while soil coarsening can lead to nutrient loss and depletion and limit plant growth (Barrett-Lennard 2002; Zhao et al., 2005). Considering that the conventional index of soil contains TS, but there is no index of salt ion, Na^+, HCO_3^- and TS were selected in this study to characterize the salinity of salt meadow soil on lake beaches. AP, AK and AN were selected to characterize the nutrient features of soil. WC was used to characterize the moisture content in soil. Due to the low contribution rate of each graded particle size index, and the obvious response of vegetation on salt meadow soil on lake beaches, the total particle size was used to characterize the response of vegetation.

Ecological threshold of salt meadow soil on lake beaches

The salt meadow on lake beaches in the Ordos platform contains the ecological sequence of light beach → succulent salt-tolerant meadow → Carex meadow → weed grass meadow → grass meadow (Qiao et al., 2020). It exhibits obvious community dynamic succession with climate fluctuations (Qiao et al., 2021), which may be directly caused by small changes in soil properties. The vegetation dynamics can be predicted only when the threshold interval and threshold breakpoint are found. Many studies have determined the ecological threshold through model and control experiments (Zhen et al., 2019; Fengkui et al., 2021); while few studies have estimated the ecological threshold based on statistics of field data. On the basis of field sampling and analysis of big data, this study roughly determined the ecological response thresholds of key environmental factors of four types of soil in salt meadow, so as to reveal the process and driving factors of ecological response of hidden vegetation under complex habitat gradients.

Ecological thresholds of water, salt, and sand in the salt meadow soil on lake beaches

The water content, salinity and particle size of soil are the key habitat elements of inland lake and beach wetlands, and have a significant impact on the plant community structure dynamics and population characteristics (Panpan et al., 2015; Fellows and Goulden 2017; Bin et al., 2018). According to the key indicators

TABLE 4 Percentage of particle size in salt meadow soil on lake beaches.

Type	Clay		Silt	Sand					Gravel
	Fine clay	Coarse clay	Silt	Very fine sand	Fine sand	Medium sand	Coarse sand	Very coarse sand	
	<0.01(μm)	0.01–2(μm)	2–50(μm)	50–100(μm)	100–250(μm)	250–500(μm)	500–1,000(μm)	1,000–2000(μm)	>2000(μm)
I	4.69 ± 2.35a	41.45 ± 11.78a	27.50 ± 5.16a	23.34 ± 10.48b	2.66 ± 2.07b	0.31 ± 0.37c	0.05 ± 0.07b	0.01 ± 0.02b	0.00 ± 0.00b
II	3.36 ± 2.49 ab	28.77 ± 14.31b	13.63 ± 3.14b	25.98 ± 8.46 ab	22.11 ± 8.53a	5.63 ± 3.92a	0.38 ± 0.57a	0.12 ± 0.19a	0.02 ± 0.03a
III	2.19 ± 1.86d	25.36 ± 16.6b	17.62 ± 10.8c	33.2 ± 12.58a	18.43 ± 14.21c	2.77 ± 2.19d	0.31 ± 1.47d	0.09 ± 0.67d	0.01 ± 0.1d
IV	2.78 ± 2.28c	30.06 ± 19.54a	15.76 ± 7.07b	31.09 ± 15.48a	17.26 ± 12.39b	2.54 ± 2.53c	0.37 ± 1.36c	0.12 ± 0.66c	0.02 ± 0.1c

of the soil selected above, the box plot (The dispersion statistics of the data were used to find the maximum, minimum, median and two quartiles of the data. Ecological response thresholds were determined from the two quartiles.) was used to generate the ecological response threshold ranges of WC, TS, Na^+, HCO_3^- and particle size of four types of salt meadow soil on lake beaches (Figure 7). The threshold ranges for the succulent salt-tolerant plant meadow are 15.22–34.43%, 6.56–20.61 g/kg, 0.36–1.65 g/kg, 0.03–1.07 g/kg and 29.74–60.95 μm, respectively. The threshold ranges for Carex meadow are 13.97–24.15%, 1.76–3.22 g/kg, 0.07–1.14 g/kg, 3.43–14.18 g/kg and 60.43–162.75 μm, respectively. The threshold ranges for grass meadow are 6.46–20.50%, 3.00–14.00 g/kg, 0.11–0.73 g/kg, 2.50–11.13 g/kg and 50.04–150.29 μm, respectively. The threshold ranges for weed grass meadow are 10.70–24.11%, 3.12–7.35 g/kg, 0.05–0.37 g/kg, 2.31–8.74 g/kg and 35.57–111.96 μm, respectively.

Ecological response threshold of nutrients in salt meadow soil on lake beaches

The population structure and growth status of meadow vegetation have a very significant response to soil nutrients. Nutrients (AK, AN and AP) in the four types of salt meadow soil on lake beaches display different ecological response threshold ranges (Figure 8). The response threshold ranges of AK, AN and AP for the succulent salt-tolerant plant meadow are 0.06–0.11 g/kg, 18.23–33.66 mg/kg and 4.38–10.66 mg/kg, respectively. The threshold ranges for the Carex meadow are 0.09–0.40 g/kg, 13.96–38.88 mg/kg and 1.75–10.57 mg/kg, respectively. The threshold ranges for the grass meadow are 0.07–0.23 g/kg, 18.74–52.33 mg/kg and 1.36–5.72 mg/kg, respectively. The threshold ranges for the weed grass are 0.07–0.32 g/kg, 22.91–66.98 mg/kg and 1.24–2.75 mg/kg, respectively.

Discussion

Diversity and significance of salt meadow vegetation on lake beaches

The lake beach wetlands in the Ordos platform have long been used as grassland for the rotational grazing of cattle, horses and sheep. However, the biomass indexes collected in field experiments remain inadequate to fully comprehend the characteristics of the community. Community diversity index is a composite index that integrates directly observed indexes, such as community height, abundance, frequency, and coverage. Different indexes have different indicative meanings for community properties.

The Patrick and the Shannon-wiener indexes can reflect the diversity of species composition and the complexity of species contribution in plant communities, respectively. The larger the index value, the more complex the composition and structure of

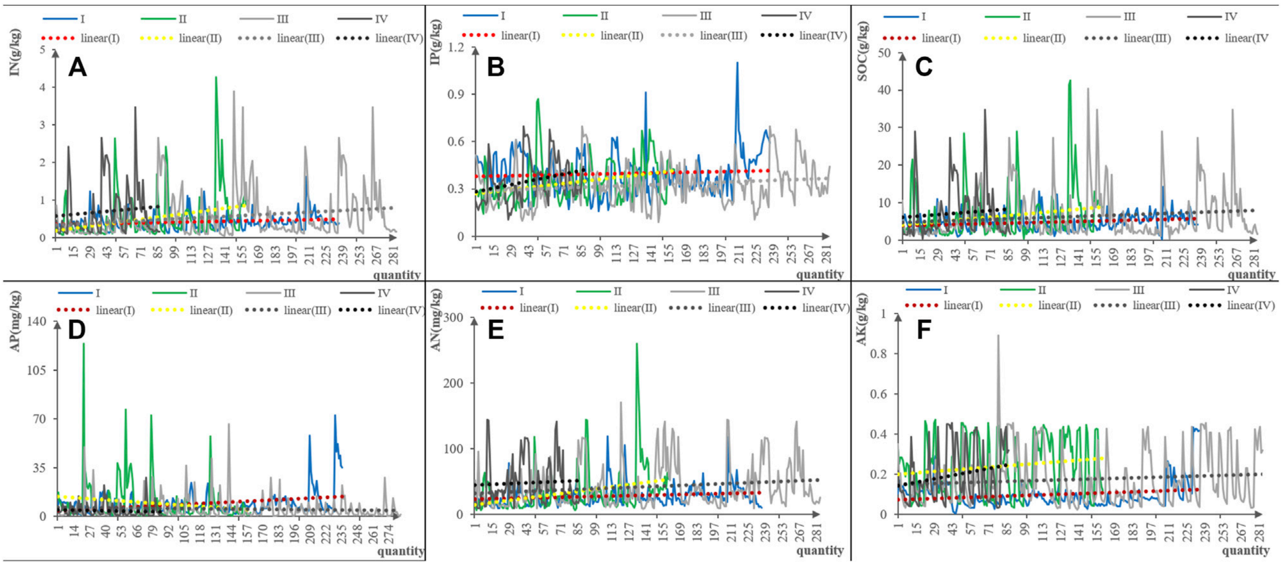

FIGURE 5
Nutrient distribution in salt meadow soil on lake beaches. Note: IN, total nitrogen; IP, total phosphorus; SOC, organic carbon; AK, available potassium; AP, available phosphorus; AN, alkali hydrolyzable nitrogen (the same below).

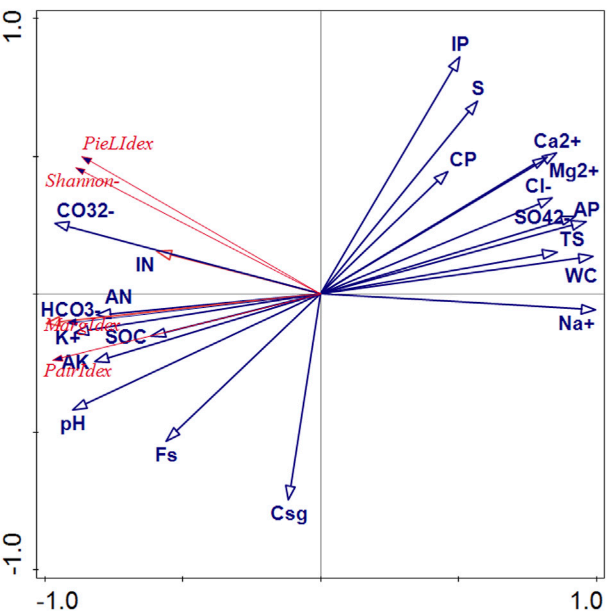

FIGURE 6
Redundancy analysis (RDA) of vegetation diversity and physical and chemical properties of salt meadow soil on lake beaches.

the community population. In the four types of salt meadow on lake beaches, these two indicators showed the same variation tendency. Group IV demonstrated the most complex population composition and structure, followed by Groups II and III. The population composition and structure of the succulent salt-tolerant plant meadow community are the simplest. The maximum value of the Patrick index is nearly twice the minimum value; while the maximum value of the Shannon-wiener index is 2.5 times of the minimum value.

The Margalef index can reflect the number of individual species in a plant community. The larger the value is, the more abundant the species is. The Margalef indexes of the four types of meadows in descending order are III > IV > II > I (despite their small differences). The Pielou index can reflect the uniformity of the spatial distribution of species within a plant community. The larger the index value, the more uniform the distribution of species. The Pielou indexes of the four types of meadows in descending order are IV > III > II > I, indicating the even distribution of the plants of Group IV, while those of Group I are characterized by clustering or patching.

The dominant species of Group I are Kalidium cuspidatum, Kalidium gracile and Suaeda salsa. They can adapt to moderately or severely salinized environments, and often form single-optimal communities in the salt marshes and flatlands of the Ordos platform. They are distributed in patches, with relatively small frequency, abundance and coverage. The dominant species of Group II is carex duriuscula, with a large number of associated species. It grows in groups or clusters in areas with mild salinization and high soil water content. The dominant species of Group III is Achnatherum splendens, which is similar to the Carex meadow. It has a large number of associated species and is evenly distributed in the community. The dominant species of

TABLE 5 Contributions of physical and chemical indexes of soil according to redundancy analysis.

Index	Na^+	HCO_3^-	WC	AP	pH	CO_3^{2-}	SO_4^{2-}	K^+	Ca^{2+}	TS	Cl^-	Mg^{2+}
Contribution/%	88	87.5	86.5	82.9	73.1	82.6	76.5	70.4	67.9	65.3	63.9	62.5
F	14.7	14	13	9.7	5.4	9.5	6.5	4.8	4.2	3.8	3.5	3.3
P	0.052	0.052	0.042	0.048	0.070	0.082	0.108	0.152	0.126	0.168	0.178	0.260

Index	AK	An	S	SOC	IP	In	Fs	CP^-	Csg
Contribution/%	59.8	58.1	34.5	33.5	31.3	31.2	30.7	21.2	7.6
F	3	2.8	1.1	1	0.9	0.9	0.9	0.5	0.2
P	0.244	0.204	0.412	0.406	0.416	0.386	0.450	0.578	0.834

Note: WC, soil water content; pH, pH value; TS, total salt content; AP, available P concentration; AK, available K concentration; AN, alkali hydrolyzed N concentration; SOC, organic carbon content; IP, total P content; IN, total N content; CP, clay content; S, powder content; FS, fine sand content; CSG, coarse sand content; Na^+, HCO_3^-, CO_3^{2-}, SO_4^{2-}, K^+, Ca^{2+}, Cl^- and Mg^{2+} represent the concentrations of Na^+, HCO_3^-, CO_3^{2-}, SO_4^{2-}, K^+, Ca^{2+}, Cl^- and Mg^{2+} in soil, respectively.

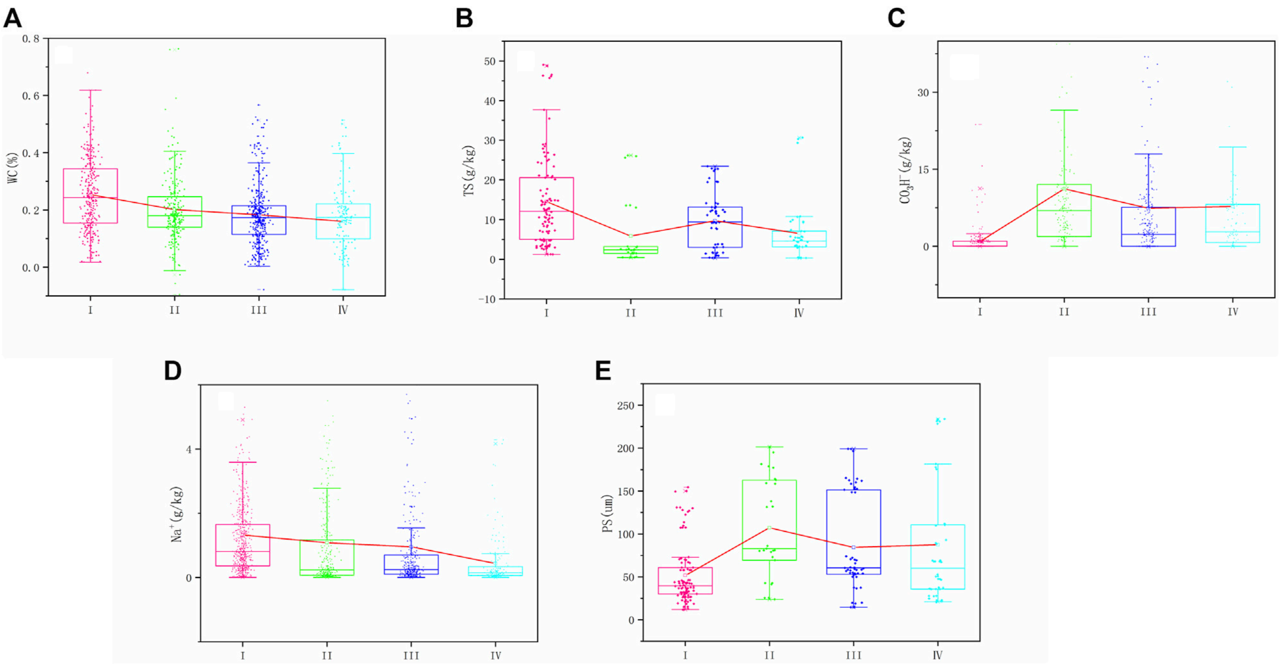

FIGURE 7
Distribution map of response thresholds of water, salinity and particle size in salt meadow soil on lake beaches.

Group IV are diverse, including Potentilla anserina, Taraxacum sinicum, Sphaerophysa salsula, Iris lactea Pall and Halerpestes ruthenica, which are evenly distributed in the community.

Physical and chemical properties of salt meadow soil on lake beaches

Regarding related studies on the structure and distribution of plant communities on salt marshes, the influence of environmental factors (e.g., water content, pH value and salt content) has been investigated (Lu et al., 2006; Qiang et al., 2009). Bin Qiao et al. (Bin et al., 2018) reported the different responses of vegetation on salt meadow in Zhenhu Beach of Ningxia to the pH value and salt content of soil. Guo et al. (Guo, et al., 2003) indicated the negative correlation between the growth rate of reed in the estuary of Yellow River and soil salinity. Guodong Cao et al. (Guodong et al., 2013) suggested a strong interaction between halophytic shrubs and soil on saline-alkali soil in desert areas. In this paper, we demonstrated significant

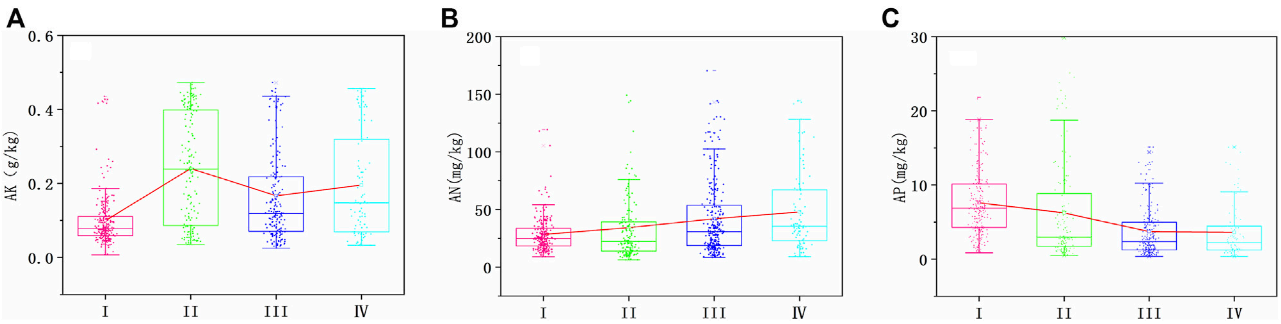

FIGURE 8
Response threshold distribution of nutrients (AK, AN and AP) in salt meadow soil on lake beaches.

differences in water content, pH value and salt content in different types of salt meadows in the Ordos platform. Group I soil has the highest contents of water and total salt, and the lowest pH value. The cations are mainly Na^+ and Ca^{2+}, and the anions are mainly SO_4^{2-} and HCO_3^-, showing the characteristics of high saline soil. Only the succulent salt-tolerant plants with water storage and salt secreting structures (such as Kalidium cuspidatum, Kalidium gracile and Suaeda salsa) can grow. Group IV soil has the lowest contents of water and total salt, with medium pH value and lowest ion content. The cations are mainly Na^+ and Ca^{2+}, and the anions are mainly HCO_3^- and CO_3^{2-}. Due to the relatively low salt content and low stress on plants (Fangyuan et al., 2020), there are many dominant plants and a variety of xerophytes. Group III soil has the lowest water content and the highest pH value. It is located in the transition zone from the periphery of ecological sequence to calcareous soil. It is significantly affected by the high alkalinity of the parent material of calcareous soil, with medium to high total salt content. The ion composition is similar to that of weed grass meadow. Its dominant species Achnatherum splendens has deep root clusters, which are usually 1–2 m deep, with a maximum depth of about 10 m (Muge et al., 2009). The growth of plants is weakly affected by the properties of the surface soil. The water content, pH value and salt content of Group II soil are moderate.

Particle size is one of the physical properties of soil. It can affect the hydraulic characteristics, fertility, carbon sequestration, leaching and erosion resistance of soil; and reflect the structure and productivity of soil (Haiyan et al., 2013). In this study, the representative grain size indexes are selected for comparison, and it is found that there are significant differences in the particle size of different meadow soils. Group I soil is the finest, and is dominated by clay and silt. Group II soil is the coarsest, and is mainly composed of fine sand and coarse sand. The quality of Groups III and IV soil is moderate. This phenomenon is mainly related to the microclimate and microtopography of the distribution area (Qiao 2021). Group I is mainly distributed in the southwest of the Ordos platform, on the tidal flat near the center of the larger lake basin. The development of soil is obviously affected by water. Group II is mainly distributed on the severely sandy lake beach in the middle of the Ordos platform, with shallow groundwater flow. The soil development is jointly affected by wind and water.

Nutrients in soil are the material basis for the growth of aboveground organisms. They are mainly derived from the decomposition of plant litter and roots (Pan et al., 2008). Since the biomass data of the sample plot are seriously affected by grazing, they were not used for control analysis in this study. However, in the four types of meadows, the nutrient indexes in Group III soil are the highest overall. Related to the abundance of biomass, the contents of total nitrogen, organic carbon, and alkali-hydrolyzable nitrogen are the highest; the contents of total phosphorus and available potassium are medium, and the content of available phosphorus is the lowest. Moreover, due to its high community uniformity and diversity as well as the relatively complex ecological structure, the nutrients in the returning soil are abundant and the circulation is vigorous. The contents of available potassium and available phosphorus in Group II soil are the highest. The total phosphorus content in Group III soil is the lowest. These may be related to the nutrient accumulation characteristics of their dominant species, as well as habitat factors (e.g., water content, pH value, salinity and particle size). Due to the high salinity of soil and low plant diversity, it is not conducive to the decomposition of plant litter by microorganisms (Jingheng et al., 2016). The biological microcycle of phosphorus is relatively slow (Zhitun et al., 2019), while that of available potassium is fast (Jie et al., 2015). The differences of total phosphorus, available phosphorus and available potassium contents reflect the transformation capacity of nutrients between vegetation and soil.

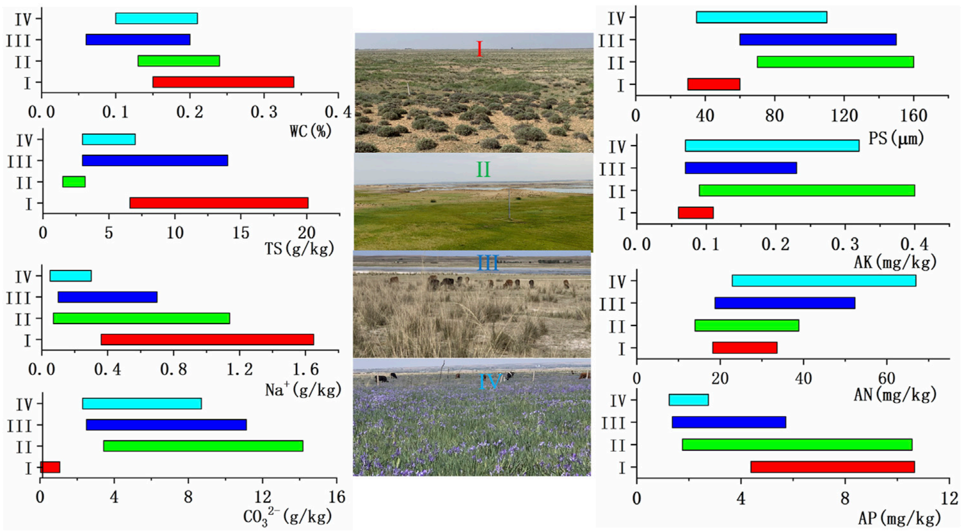

FIGURE 9
Intervals and values of ecological response thresholds.

Ecological response threshold of key influencing factors of salt meadow soil on lake beaches

The threshold is a critical interval, beyond which vegetation patches become unstable and begin to break (Gabriel et al., 2020), and eventually being replaced. Therefore, the response threshold of vegetation to key indicators of soil can explain the succession trend of vegetation and the change process of habitat. It is found that the ecological response thresholds of the four types of salt meadow soils are different (Figure 9). The threshold interval and values of water content, total salt content and Na^+ content in the Group I soil are the largest. The threshold of available phosphorus is the largest. The threshold interval and value of CO_3^{2-} content, particle size and available potassium are the smallest. The threshold interval and values of CO_3^{2-} content and available potassium in the Group II soil are the largest. The threshold value of particle size is the largest. The threshold interval and value of available phosphorus are the largest, and the threshold interval and value of total salt content are the smallest. All indexes of the Group III soil are medium. The threshold interval and value of alkali hydrolyzable nitrogen in Group IV soil are the largest, and that of the Na^+ content and available phosphorus are the smallest.

Water content and salt content are the determinants of the formation and distribution of wetland vegetation (Fangzhen et al., 2021). The threshold range of overall water content of salt meadow soil in the Ordos platform is 6.46–34.43%, and the threshold range of total salt content is 0.05–20.61 g/kg. Since water in arid regions is medium for salt transport, in general, there is a corresponding relationship between water content and salt content. However, in this study, the corresponding relationship between water content and salt content in Group II soil is abnormal. The gradual relationship between the threshold interval and threshold value of Na^+ and CO_3^{2-} in Group I soil is abnormal. Nutrients are highly correlated with the productivity of vegetation, but their relationship with biodiversity is complex. This study found that there are significant differences in available nutrients in the three types of soils.

The threshold interval and threshold values of available potassium and available phosphorus in Group II soil are relatively large. The threshold interval and threshold value of alkali hydrolyzable nitrogen in Group IV soil are relatively large. All the indexes of Group III soil are medium. The threshold interval and threshold value of available phosphorus in Group I soil are relatively large. The threshold interval and threshold values of particle size in descending order are II > III > IV. The threshold interval and threshold value of particle size of Group I soil are the smallest.

The abnormal relationship between water and salt content in Group II soil may be caused by the special hydrogeological structure of the Ordos platform (Guangcai et al., 2008) and microclimate. The strip beach has abundant shallow groundwater, with strong wind and sand and abundant rainfall, so the soil is the coarsest and is dominated by fine sand and coarse sand. However, most of the beaches for Group I were large salt lakes in history, which gradually dried up in modern times and became saline-alkali beaches. The soil is the finest, dominated by clay and silt, with high water content and salt shell and salt spots. The effect of aeolian sand accumulation on the meadow is not obvious. Therefore, the research results of particle size thresholds of soil in the Ordos platform have unique representational significance for the response characteristics of vegetation on salt meadow soil on lake beaches. The study of particle size is equally important with that of water and salt content for characterizing the steady state and dynamics of vegetation.

The threshold interval and threshold values of Na^+ and CO_3^{2-} are closely related to water content, total salt content, and pH value. The threshold interval and threshold value of Na^+ content in Group I soil is the largest, but the proportion is the lowest in the four types of salt meadows (Figure 3), reflecting the strongest salt accumulation process. The CO_3^{2-} content of its alkaline salt is the least. The threshold interval and threshold value are the smallest, but the water content and total salt content are the largest, indicating that the salinity of its aqueous solution is the highest. The distribution of Group I indicates a strong response to the salty soil of the lake beach. The ion structure of salt in the other three types salt meadows has the characteristics of alkaline salt. Groups II, III and IV show the response to alkaline soil, and Group II has the strongest response. The differences in the ecological response thresholds of nutrient indicators may be related to the accumulation characteristics of the respective dominant species and the properties of the nutrient elements. There are some differences in the response thresholds of the four types of salt meadow vegetation to nutrients in the underlying soil, and its significance needs further investigation.

Conclusion

The key findings of this study are summarized below:

1) The succulent salt-tolerant plant meadow forms a single-optimal community in the inland salt marsh beach, which is distributed in patches and blocks. There are a lot of associated species in Carex meadow, and they grow in clusters in areas with mild salinization and high water content. The dominant species in the grass meadow is Achnatherum splendens, and the populations and individuals are evenly distributed in the community. The dominant species of weed meadow are diverse, with the most uniform distribution.
2) There are significant differences in the characteristics of soil in the four types of salt meadows. The contents of water and salt in the soil of succulent salt-tolerant plant meadow are the highest, and the soil is the finest. The matrix is mainly Na^+, Ca^{2+}, SO_4^{2-} and HCO_3^-. The contents of available potassium and available phosphorus in Carex meadow soil are the highest and the soil is the coarsest. The pH value of grass meadow soil is the highest. The nutrient content of weed grass meadow soil is generally high, and the matrix is dominated by Na^+, Ca^{2+}, HCO_3^- and CO_3^{2-}.
3) The ecological response threshold ranges of water content, total salt content, Na + content, HCO_3^- content, particle size, available potassium, alkali hydrolyzable nitrogen and available phosphorus in different types of salt meadow soil are different. The threshold ranges for succulent salt-tolerant meadow are 15.22–34.43%, 6.56–20.61 g/kg, 0.36–1.65 g/kg, 0.03–1.07 g/kg, 29.74–60.95 μm, 0.06–0.11 g/kg, 18.23–33.66 mg/kg and 4.38–10.66 mg/kg, respectively. The threshold ranges for Carex meadow are 13.97–24.15%, 1.76–3.22 g/kg, 0.07–1.14 g/kg, 3.43–14.18 g/kg, 60.43–162.75 μm, 0.09–0.40 g/kg, 13.96–38.88 mg/kg and 1.75–10.57 mg/kg, respectively. The threshold ranges for grass meadow are 6.46–20.50%, 3.00–14.00 g/kg, 0.11–0.73 g/kg, 2.50–11.13 g/kg, 50.04–150.29 μm, 0.07–0.23 g/kg, 18.74–52.33 mg/kg and 1.36–5.72 mg/kg, respectively. The threshold ranges for weed grass meadow are 10.70–24.11%, 3.12–7.35 g/kg, 0.05–0.37 g/kg, 2.31–8.74 g/kg, 35.57–111.96 μm, 0.07–0.32 g/kg, 22.91–66.98 mg/kg and 1.24–2.75 mg/kg, respectively.

This study highlights the obvious response of the salt meadow vegetation in the inland area to the water content, salt content and sand content (represented by particle size) of soil (but the response to nutrient factors remains unclear). The distribution of vegetation types is the result of various direct and indirect factors such as soil, climate and topography. Some physical and chemical indexes of soil are closely related to the structure and composition characteristics of vegetation. The complex interspecific relationship in plant community might be the cause of the dispersion of measured indexes, reflecting the deficiency of single-index threshold research. The index-coupling threshold based on control experiment may need further investigation in the future.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

The first draft of the manuscript was written by MZ, Material preparation, data collection, and data analysis were performed by

CW. All authors contributed to the research concept and design, and have read and approved the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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