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Spatio–Temporal Variability Characteristics of Coastal Soil Salinization and Its Driving Factors Detection

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Abstract: The utilization efficiency of land resources in the coastal area of the Yellow River Delta has been deeply affected by salinization hazards. Key to improvement of the utilization efficiency of resources in this area is to grasp the spatio–temporal variability law of soil salinity and identify the driving factors of salinization. Wudi County in the coastal area of the Yellow River Delta is taken as the study area. Based on the data obtained from field measurements and laboratory analysis, the characteristics of soil salinity in spring and summer were analyzed by classical statistical methods; the spatial differentiation characteristics of salinization were analyzed from two–dimensional and three–dimensional perspectives using the geographic information system (GIS) and groundwater modeling system (GMS); the time variation characteristics of salinization were quantitatively analyzed by introducing the salinization severity index (S_i) and the dominant index of salinization degree change (C_i). The results show that: (1) In the study area, the soil salinity of the surface layer (0–15 cm) in summer is lower than that in spring, but the sub–surface layer (15–30 cm), the middle layer (30–45 cm) and the bottom layer (45–60 cm) are all larger than the corresponding layers in spring, and the correlation between the soil salinity of each layer in summer is generally lower than that in spring. (2) In two–dimensional space, the areas with a surface soil salinity greater than 0.4% in both seasons are mainly located in the northern part of the study area; in three–dimensional space, the soil is mainly moderately salinized in both seasons, and the complexity of the distribution of the salt profile is higher in summer than in spring; (3) Mashanzi Town was the area most seriously affected by salinization in both seasons (S_i values were greater than three); In the process of seasonal alternation, the dominant change type of salinized soil is from mild aggravation to moderate, with C_i value of 38.43%, followed by severe alleviation to moderate, with C_i value of 35.49%; (4) The driving factors of soil salinization in spring are mainly the soil salinity of the subsurface and middle layer, and soil water content; and in summer, mainly the soil salinity of subsurface layer, vegetation coverage and vegetation cover type. The interaction between any two factors has greater influence on the spatial variation of salinization than the corresponding single factor.

Keywords: soil salinization; spatio–temporal variation; driving factor; coastal area of the yellow river delta

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1. Introduction

Soil salinization refers to the process whereby salt in groundwater moves up to the surface with water through soil capillaries under evaporation [1]. As one of the main causes of land degradation, salinization usually occurs in areas with an arid climate, high evaporation and low precipitation, high water table and high mineralization [2]. Both primary salinization (mainly influenced by natural factors) and secondary salinization (mainly influenced by human factors) have a serious negative impact on the sustainable use of land resources and sustainable agricultural development [3]. More than 6% of the world's land is affected by salinization hazards, which are widely distributed in more than 100 countries and regions [4]. The total area of modern saline soils in China is as much as 36 million hm^2 [5]. It is of great significance to develop and utilize these saline soil resources reasonably for China, with its large population and small land [6]. The Yellow River Delta is the largest delta in China, with vast reserve land resources. However, due to its close proximity to the Bohai sea and high mineralization of the groundwater, the soil salinization in this region is a prominent problem, under the comprehensive influence of such factors as less precipitation, high evaporation, and significant seasonal alternation of wet and dry [7]. Timely grasp of the spatial distribution characteristics of soil salinization in this region, to find out their seasonal variations, and clarify the factors affecting salinization, will help to formulate targeted measures to effectively prevent, control and mitigate salinization hazards.

At present, many scholars have done a lot of research on the spatial distribution characteristics of soil salinization in a single season. Li et al. [8] analyzed the two–dimensional spatial distribution characteristics of soil salinization in summer in the Wei–Ku oasis by using the ordinary Kriging interpolation method, and pointed out that groundwater mineralization is the main factor causing soil salinization in this area. Su et al. [9] studied the two–dimensional spatial differentiation pattern of soil salinization in the Hetao irrigation area of Inner Mongolia in autumn, through the inverse distance weight interpolation method, and pointed out that the main influencing factors of soil salinization in this region include groundwater level, groundwater salinity, irrigation method and phreatic evaporation. As the research progressed, some scholars began to explore the spatial variation patterns of soil salinity in different seasons. Sun et al. [10] analyzed the two–dimensional spatio–temporal variation of soil salinity in a typical area of the Yellow River Delta by collecting conductivity data in spring, summer and autumn, and concluded that anthropogenic activities and rainfall had a significant effect on the salinity of the surface soil; Liu et al. [11] studied the spatio–temporal variation characteristics of soil salinity profiles in cotton fields in spring, summer and autumn based on conductivity data, and pointed out that soil texture and microtopography are the most direct factors influencing the distribution types of salt profiles. Most of the existing studies focus on the analysis of the two–dimensional spatial distribution of salinity in single or multiple seasons, but fail to intuitively reveal the three–dimensional spatial and temporal variation of soil salinity; and the individual studies involving the three–dimensional variation of salinity in different seasons are mostly focused on the inland field scale [12,13]. However, the research reports on the three–dimensional spatio–temporal variation of soil salinity in the coastal area of the Yellow River Delta are extremely rare. From a three–dimensional perspective, the visualization and analysis of soil salinity distribution in three–dimensional form can help to refine measurement and assessment of soil salinity, and lay a foundation for the development of zonal irrigation to achieve precise regulation of water and salt [13]. Studies on the driving factors of salinization mostly focused on the "fixed" factors such as topography, groundwater depth and groundwater mineralization [9–11], but neglected to analyze "variable" influence factors in different seasons; studies on seasonal variation law also failed to quantify the degree of differentiation.

In this paper, Wudi County in the coastal area of the Yellow River Delta is taken as the study area. Based on the data obtained from field measurement and laboratory analysis, we explored the multi–dimensional spatial distribution characteristics of soil salinity in spring and summer by using two–dimensional and three–dimensional inverse distance weight (IDW) methods, and introduced an index method to quantitatively reveal the spatio–temporal variation characteristics of soil salinization in the study area. The driving factors affecting the spatial distribution of salt in different seasons were explored by using geographic detection methods. The purpose of this paper is to provide a theoretical basis for the precise regulation of soil salinity in the coastal area.

2. Materials and Methods

2.1. Overview of the Study Area

Wudi County, with geographical coordinates of 37°4′~38°16′ N and 117°31′~118°04′ E, is located in the northernmost part of Shandong Province, bordering the Bohai Bay in the northeast. It belongs to the overlapping area of many strategic plans such as the Shandong Peninsula Blue Economic Zone and the Yellow River Delta Efficient Ecological Economic Zone. The total area of the territory is 1998.12 km^2. It belongs to the continental climate of the East Asian monsoon region in the north temperate zone, windy and dry in spring, hot and humid and rainy in summer, with an average annual temperature of about 12.8 °C (the average temperature is 18.1 °C in spring and 26.5 °C in summer), an average annual precipitation of 570.1 mm (the average monthly precipitation in spring is 28.2 mm and 122.3 mm in summer), an average annual evaporation of 1285.5 mm (the average monthly evaporation in spring is 204.3 mm and 236.7 mm in summer), and an ratio of evaporation to precipitation of 2.3 (the monthly average ratio of evaporation to precipitation in spring is 7.3, and that in summer is 1.9) [14]. A total of 68.7% of the precipitation is concentrated in summer and 13.7% in spring. The topography is high in the southwest and low in the northeast, and the main types of landforms include river bank uplands, gently flat slopes and shallow flat depressions. Fresh water resources are scarce in the region, the areas with high underground water salinity are mainly distributed in the coastal area, and saline alkali lands are all over the territory. The northeast of the county is mainly tidal flats and salt fields, so this part of the area is not included in the study area of this paper (Figure 1).

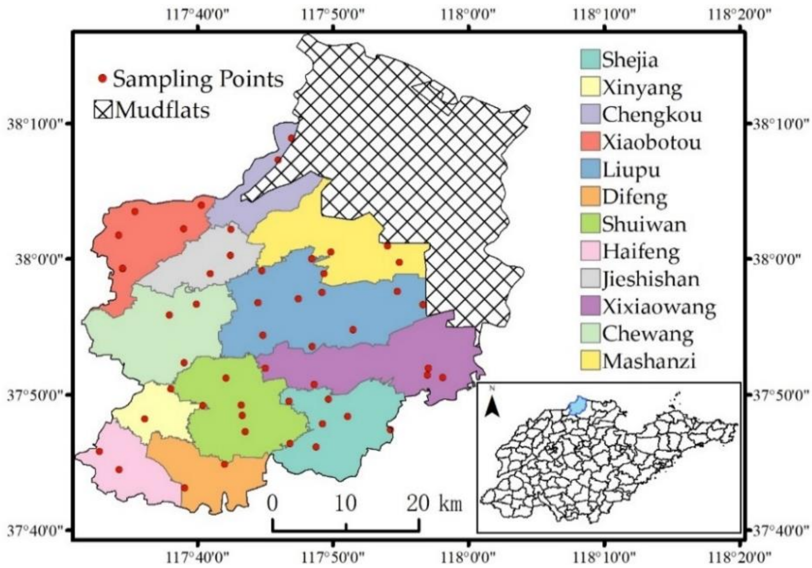


Figure 1. Overview of the study area.

2.2. Sample Collection and Data Sources

2.2.1. Sample Collection

The sampling points were arranged by grid method, covering the remote sensing image map of the study area with 5 × 5 km grids, with one sampling point arranged for each grid, avoiding the northern tidal flat area and the construction land in the area. During actual sampling, it was adjusted or selected according to the actual situation such as traffic accessibility, with 53 sample points actually collected (see Figure 1 for sample point distribution). The sampling was carried out from 26–28 April and 13–15 August 2015, respectively. The coordinates of the sample points were recorded using hand–held GPS, and the current land use type, vegetation coverage, crop growth, etc. were also recorded. Soil conductivity of the surface (0–15 cm), subsurface (15–30 cm), middle (30–45 cm) and bottom (45–60 cm) layers was measured using an EC110 portable conductivity meter (Spectrum Technologies, Inc., Aurora, IL, USA. Which range is 0.00–199.9 ms/cm, accuracy is ±2%).

By referring to previous studies and using the empirical formula of our research team, the soil conductivity measured in the field was converted into salt content data, and the water content data measured in the field was corrected.

The equation for the relationship between the measured electrical conductivity (EC_0, us/cm) and the salt content (S_t, %) is [7]:

$$S_t = 0.000211 \times EC_0 + 0.0875R^2 = 0.9685 \quad (1)$$

The equation for the relationship between the laboratory soil water content (W_0, %) and the field–measured water content (W_i, %) is [15]:

$$W_0 = 0.9112W_i + 0.2418R^2 = 0.9894 \quad (2)$$

According to the grade standard of salinization degree [16], soil salinization can be divided into five grades according to soil salinity (%): non–salinization (0, 0.1), mild salinization [0.1, 0.2), moderate salinization [0.2, 0.4), severe salinization [0.4, 0.6) and saline soil [0.6, +∞). Since there is no non–salinization soil grade in the study area, only four grades are actually involved.

2.2.2. Data Source and Classification of Driving Factors

When analyzing the driving factors of salinization, previous scholars mostly considered "stable" factors such as topography and geomorphology, groundwater depth and groundwater mineralization, but lacked the research on "variable" factors between seasons. Among the driving factors selected in this paper (Table 1), the salt content of the subsurface, middle and bottom layers, together with the water content of the soil, form a water–salt transport system between soil layers at different depths [17], thus influencing the soil salt content of the surface layer; the vegetation coverage influences it through the evaporation of water; and the vegetation cover type influences the soil salt content through whether the vegetation is covered or not, and the degree of salinity tolerance of the vegetation itself. Among them, the data of soil salt content at different depths and soil water content are obtained through the inverse relation formula. Vegetation coverage data are first obtained from NDVI data through the Google Earth Engine (GEE) platform, and then obtained by pixel dichotomy in the ENVI 5.3 platform [18]; Vegetation cover type is obtained through field investigation.

Table 1. Classification of driving factors of soil salinization.

Level	Salinity of Soil Layers (%)			Soil Water Content (%)	Vegetation Coverage	Vegetation Cover Type
	Subsurface	Midlle	Bottom			
1	0.2–0.4	0.2–0.4	0.2–0.4	>30	>0.8	Wheat–Maize
2	0.4–0.6	0.4–0.6	0.4–0.6	20–30	0.65–0.8	Cotton
3	>0.6	>0.6	>0.6	15–20	0.5–0.65	Winter jujube
4				12–15	0.4–0.5	Weeds
5				5–12	<0.4	Bare land

2.3. Research Methodology

2.3.1. Statistical Characteristics and Correlation Analysis of Soil Salinity

Statistical Product Service Solutions (SPSS) software (version: 23.0) [19] was used to statistically analyze the maximum, minimum, variance, mean, median, standard deviation, kurtosis, skewness and coefficient of variation of soil salinity in spring and summer, respectively. The coefficient of variation (CV) reflects the degree of dispersion and relative variation of random variables, and can be classified into three levels of variability: weak [0, 10%), medium [10%, 100%), and strong [100%, +∞) [20]. The correlation between salt contents of different soil layers was analyzed by using the Pearson–bilateral test correlation coefficient matrix.

2.3.2. Spatial and Temporal Distribution Characteristics of Soil Salinity

(1) Spatial distribution characteristics of soil salinity

Using ArcGIS (version: 10.7) [20], inverse distance weight interpolation was applied to soil salinity to analyze its two–dimensional spatial distribution characteristics. The inverse distance weight interpolation method was used to map the spatial distribution of soil salinity, which is more intuitive than Kriging in terms of regional and local trends [21].

Using GMS (version: 10.4.5) software [22], a three–dimensional grid was constructed with grid as the unit, and three–dimensional inverse distance weight interpolation (IDW) on soil salinity was carried out, so as to visualize and analyze the three–dimensional spatial and temporal variability of soil salinity. Three dimensional inverse distance weight interpolation is the application and expansion of two–dimensional inverse distance weight interpolation in three–dimensional space. Its basic principle is that the closer the distance between two points, the more similar the properties are. The distance between the sample point to be measured and the known sample point is used as the weight for weighted averaging, and the farther away the sample point to be measured, the smaller the weight given to the sample point [21]. The formula is as follows [23]:

$$V(x,y,z) = \sum_{i=1}^{n} w_i v_i(x_i, y_i, z_i) \tag{3}$$

$$h_i = \sqrt{(x-x_i)^2 + (y-y_i)^2 + (z-z_i)^2} \tag{4}$$

$$w_i = \left[\frac{R-h_i}{Rh_i}\right]^2 / \sum_{j=1}^{n} \left[\frac{R-h_j}{Rh_j}\right]^2 \tag{5}$$

In Equations (2)–(4), $V(x, y, z)$ is the value of the sample point to be measured, $v_i(x_i, y_i, z_i)$ is the value of the known sample point; h is the distance from the sample point to be measured to the known sample point; w_i is the weight; R is the maximum value of the distance from the n known sample points to the sample point to be measured participating in the calculation.

(2) Temporal variation characteristics of soil salinity

Based on the soil salinity data of two seasons, the change area and direction of different degrees of salinized soils in different seasons were analyzed by using a transfer matrix. The transfer matrix expression is [24]:

$$S_{ij} = \begin{vmatrix} S_{11} & S_{12} & \cdots & S_{1n} \\ S_{21} & S_{22} & \cdots & S_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ S_{n1} & S_{n2} & \cdots & S_{nn} \end{vmatrix} \tag{6}$$

where S_{ij} is the area transferred from saline soil type i to type j during the study period; i is the type of saline soil in spring, j is the type of saline soil in summer; n is the type of soil with different degrees of salinity. In this paper, n = 4.

The salinization severity index (S_i) is used to characterize the spatio–temporal distribution of regional soil salinity [25]:

$$S_i = \sum_{r=1}^{4} \frac{A_r}{A} \times P_r \tag{7}$$

where S_i is the regional soil salinization severity index; A_r is the area of the rth type of saline soil (For example A_1, A_2, A_3, A_4 represent the areas of mild, moderate, severe salinization soil grades and saline soil); A is the area of different townships; P_r is the severity of different types of soil salinity, the weights of mild, moderate, severe salinization soil grades and saline soil are 1, 2, 3 and 4 respectively; the larger the value of S_i, the more serious the soil salinization in this area.

The dominant index of salinization degree change (C_i) is used to determine the main types of seasonal changes in soil salinization degree. The calculation formula is as follows [26]:

$$C_i = \frac{A_r}{\sum_{r=1}^{4} A_r} \times 100\% \quad (8)$$

where C_i is the dominant index of the change area of the rth salinization soil type in the study area, with a value threshold of 0–100% (the larger the rth value, the more dominant the rth salinization soil change type is).

2.3.3. Detection and Analysis of Driving Factors of Salinization

The geo–detection method is a statistical method proposed by Wang et al. to analyze the spatial heterogeneity of geographical phenomena based on the theory of spatial variance [27]. This method can avoid the influence of human subjectivity, efficiently identify the relationship between multiple factors, and overcome the limitations that exist in traditional statistical analysis when dealing with categorical variables [28]. In this paper, two modules of the geo–detector: the factor detector and interaction detector, are used to quantitatively analyze the driving factors affecting soil salinity in the study area.

The factor detector module mainly detects the degree of influence of different driving factors on the spatial differentiation of soil salinity, and the higher the value of explanatory power q, the stronger the influence. The expression is [29]:

$$q = 1 - \frac{\sum_{h=1}^{1} N_h \sigma_h^2}{N\sigma^2} = 1 - \frac{\mathrm{SSW}}{\mathrm{SST}} \quad (9)$$

$$\mathrm{SSW} = \sum_{h=1}^{L} N_h \sigma_h^2 \quad (10)$$

where h is the classification of the salinization influencing factors; N_h and n are the number of units in layer h and the whole area, respectively; ${\sigma_h}^2$ and σ^2 are the variances of Y values in layer h and the whole area, respectively. SSW and SST are the sum of the variances within the layer and the total variance of the whole area, respectively; and the value range of q is [0, 1].

The interaction detection module is used to assess whether the interaction between two different driving factors, X_a and X_b, has an enhancing or weakening effect on the explanatory power of the dependent variable Y [30], which is judged on the basis shown in Table 2.

Table 2. Judgment basis of double factor interaction mode.

Criterion	Interaction
$q\ (X_a \cap X_b) < \min\ [q\ (X_a), q\ (X_b)]$	Non–linear weakening
$\min\ [q\ (X_a), q\ (X_b)] < q\ (X_a \cap X_b) < \max\ [q\ (X_a), q\ (X_b)]$	Single–factor nonlinear attenuation
$q\ (X_a \cap X_b) > \max\ [q\ (X_a), q\ (X_b)]$	Two–factor enhancement
$q\ (X_a \cap X_b) = q\ (X_a) + q\ (X_b)$	Independent Interaction
$q\ (X_a \cap X_b) > q\ (X_a) + q\ (X_b)$	Nonlinear independence

3. Results and Analysis

3.1. Statistical Characterisation of Soil Salinity

3.1.1. Descriptive Statistical Characteristics of Soil Salinity at Different Depths

The results of the descriptive statistical analysis of soil salinity are shown in Table 3. Both kurtosis and skewness of soil salinity in spring and summer were high, which did not conform to normal distribution. In spring, the average salinity values of the soil layers at 0–15 cm, 15–30 cm, 30–45 cm and 45–60 cm were 0.39%, 0.46%, 0.45% and 0.47%, respectively, with only the layer of 0–15 cm being at a moderate salinization level overall and all the layers of 15–60 cm being at the level of severe salinization. From top to bottom, the average values change trend of soil salinity is to increase first, then decrease, and then increase again. The largest variation range of the average soil salinity of the soil layers is found between 0–15 cm and 15–30 cm. The reason of this phenomenon may be that most of the sampling sites are located in farmland. In the natural state, long–term leaching resulted in the formation of a clay layer at about 30 cm, while the plough bottom layer was formed at about 15 cm under the action of mechanical tillage. At the same time, the lack of rainfall and irrigation in spring had hindered the migration of water and salt between soil layers. The coefficients of variation of soil salinity at the 0–15 cm and 30–45 cm layers were 117.49% and 105.41% respectively, which were a strong variation, while the 15–30 cm and 45–60 cm layers were of medium variability. In summer, the average values of soil salinity of 0–15 cm, 15–30 cm, 30–45 cm and 45–60 cm soil layers were 0.32%, 0.46%, 0.56% and 0.62%, respectively. The upper three layers were moderately salinized and the bottom layer was heavily salinized, with a gradual increase in salinity from top to bottom. Except that the soil salinity of 0–15 cm layer was of medium variation, the other soil layers were of strong variation. This is probably due to the uneven spatial distribution of rainfall. The average soil salinity of 0–15 cm layer in the study area is lower in summer than in spring, but the soil salinity of the 15–30 cm, 30–45 cm and 45–60 cm layers is correspondingly higher in summer than in spring, and the topsoil showed a clear characteristics of seasonal desalination. This may be related to the fact that in some areas, summer precipitation is too concentrated and acts as a bridge between highly mineralized groundwater in the soil, and salt is actively transported in the sub–surface layers resulting in higher salinity in each layer.

Table 3. Descriptive statistical characteristics of soil salinity in different seasons and depths.

Season	Soil Depth (cm)	Sample Size	Min (%)	Max (%)	Mean (%)	Variance	SD	Kurt	Skew	CV (%)
Spring	0–15	53	0.11	2.73	0.39	0.21	0.46	14.66	3.69	117.49
	15–30	53	0.21	2.76	0.46	0.19	0.43	15.95	3.71	93.88
	30–45	53	0.19	2.95	0.45	0.23	0.48	16.26	3.82	105.41
	45–60	53	0.21	2.39	0.47	0.15	0.39	12.01	3.24	84.12
Summer	0–15	53	0.14	1.72	0.32	0.087	0.29	18.95	4.30	90.61
	15–30	53	0.18	2.81	0.46	0.32	0.56	12.58	3.62	121.74
	30–45	53	0.22	3.25	0.56	0.41	0.64	12.32	3.56	114.29
	45–60	53	0.23	3.00	0.62	0.37	0.60	10.81	3.32	96.77

3.1.2. Correlation between Soil Salinity at Different Depths

The correlation coefficient matrix between soil salinity at different depth layers is shown in Table 4. It can be seen that the correlation coefficient of soil salinity in each layer is greater than 0.80 both in spring and in summer, showing a very significant positive correlation. In spring, the correlation coefficient between soil salinity of adjacent soil layers tended to increase gradually from top to bottom; 30–45 cm and 45–60 cm soil layers have the strongest correlation, with a correlation coefficient of 0.992; The correlation between 0–15 cm and 45–60 cm soil layers is the weakest, with a correlation coefficient of 0.968; The correlation between adjacent soil layers was greater than that between non–adjacent soil layers. In summer, the correlation between soil salinity of adjacent soil layers was also greater than that between non–adjacent soil layers. The correlation between 15–30 cm and 30–45 cm soil layers is the strongest, and the correlation coefficient is 0.993. The correlation between 0–15 cm and 30–45 cm soil layers is the weakest, and the correlation coefficient is 0.849. In general, due to the uneven spatial distribution of rainfall in summer, the strong water salt movement among soil layers in regions with more rainfall, and the frequent changes in salt content of each soil layer, the correlation between soil salinity of each soil layer in summer was overall lower than that in spring.

Table 4. Correlation coefficient matrix of soil salinity.

Soil Depth (cm)	Spring				Summer			
	0–15	15–30	30–45	45–60	0–15	15–30	30–45	45–60
0–15	1				1			
15–30	0.985 **	1			0.864 **	1		
30–45	0.981 **	0.986 **	1		0.849 **	0.993 **	1	
45–60	0.968 **	0.975 **	0.992 **	1	0.854 **	0.972 **	0.983 **	1

Note: "**" indicates that the significance level is $p < 0.01$.

3.2. Spatial Distribution Characteristics of Soil Salinity

3.2.1. Two–Dimensional Spatial Characteristics of Seasonal Variation of Soil Salinity

The two–dimensional spatial distribution characteristics of surface soil salinity are shown in Figure 2 and Table 5. In spring, the area near the mudflats in the north is dominated by saline soils, with an area of 166.59 km^2, accounting for 12.07% of the total area of the study area. This area has been impregnated by seawater for a long time, with high groundwater mineralization and the most serious salinization. To the south, it is adjacent to the area of severe salinization grade soils, with an area of 201 km^2, accounting for 14.56%, distributed in strips. The area of moderate salinization grade soil is 816.74 km^2, accounting for 59.16%, which is mainly distributed in the western, central, southern and eastern parts of the study area. It is the main type of salinization soil in the study area. Mild salinization soil type is distributed in the southwestern part of the study area, with an area of 196.33 km^2, accounting for 14.22%. In summer, saline soil and severe salinization soil type are still mainly distributed in the northern part of the study area, with a total area of 159.06 km^2; the moderate salinization soil type covers an area of 1184.25 km^2, accounting for 85.77%, which is distributed in a concentrated and continuous manner throughout the study area; mild salinization soil type is patchily distributed in the central part of the study area, accounting for only 2.71% of the area. The two–dimensional distribution map shows that the seasonal changes in surface salinization soils include both the desalination process (mainly in the severe salinization and saline soil areas in the north) and re–salinization process (mainly in the mild salinization areas in the southwest). This shows that the seasonal changes of soil salinization in the study area are more complex.

Table 5. Soil area with different degrees of salinization.

Degree	Saltness (%)	Spring		Summer	
		Area (km^2)	Proportion (%)	Area (km^2)	Proportion (%)
Mild salinization	0.1–0.2	196.33	14.22	37.36	2.71
Moderate salinization	0.2–0.4	816.74	59.16	1184.25	85.77
Severe salinization	0.4–0.6	201.00	14.56	88.38	6.40
Saline soil	>0.6	166.59	12.07	70.68	5.12

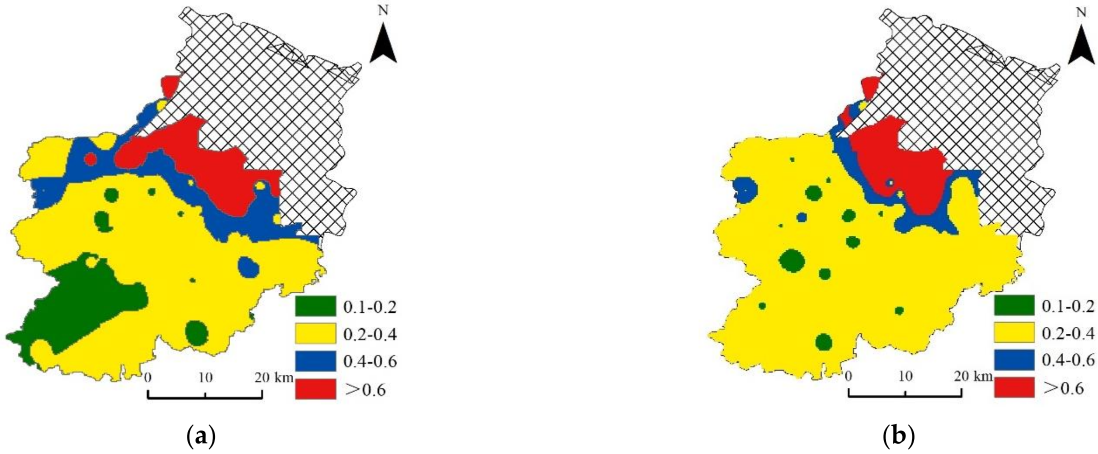


Figure 2. Spatial distribution of surface soil salinity: (**a**) spring; (**b**) summer.

3.2.2. Three–Dimensional Spatial Characteristics of Seasonal Variation of Soil Salinity

The three–dimensional spatial distribution of soil salinity in the study area is shown in Figure 3.

As can be seen from Figure 3a,b, in spring, the soils in the study area are mainly the moderate salinization type, and the profile distribution of soil salinization in most areas is through homogeneous type (similar salinity in all layers). In the northwest part of the study area, there is a local phenomenon of salt aggregation at the bottom (the salinity of the bottom layer is higher than that of the surface layer). This is related to the fact that the land use types of the sample sites are mainly arable land and that it is close to the Zhangwei New River, which has good irrigation conditions and helps the downward migration of salts with water. In the south–western part of the area, there is also localized salt accumulation at the bottom, but the overall salinity is low. This area is the highest terrain in the whole region, where salts do not accumulate easily and most of it tends to migrate out with water. As can be seen from Figure 3c,d, in summer, the soils in the study area are still predominantly the moderate salinization type, and the overall distribution of the soil salt profile is the homogeneous type. However, in the north–western part of the study area, the proportion of severe salinization soil type in the surface layer decreased significantly compared with that in spring, while the salinity degree at the bottom increased, showing a bottom aggregation distribution. This is clearly related to the different precipitation in spring and summer (Figure 4). The average monthly rainfall in summer of 2015 was 153.87 mm, while the average monthly rainfall in spring was only 39.2 mm. The summer rainfall reached its peak in early August, significantly enhancing the leaching of surface soil salt (Figure 3). Compared with spring, the soils in the southwest of the study area showed a slight re–salinization trend. This may be related to the fact that the concentration of rainfall was from July to early August, and the uneven spatial distribution. There was little rainfall in some areas, but the continuous high temperature and strong evaporation (the average monthly evaporation in summer is 236.7 mm) led to the enrichment of salts from lower layers to the surface layer under the action of capillaries.

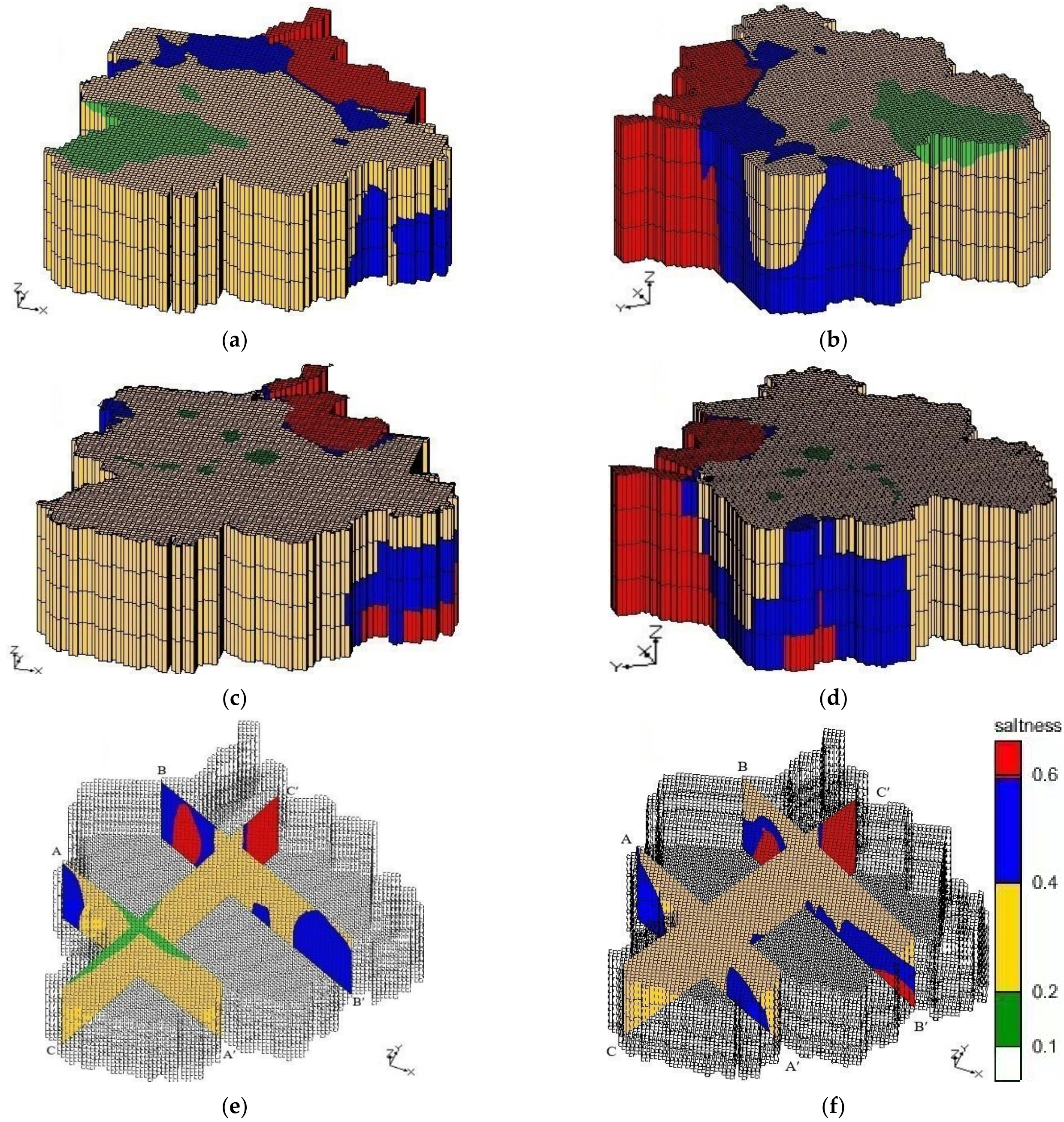


Figure 3. Three–dimensional spatial distribution of soil salinity: (**a**) Three–dimensional spatial distribution map of soil salinity in spring; (**b**) Three–dimensional spatial distribution map of soil salinity after 90° counterclockwise rotation of (**a**); (**c**) Three–dimensional spatial distribution map of soil salinity in summer; (**d**) Three–dimensional spatial distribution map of soil salinity after 90° counterclockwise rotation of (**c**); (**e**) Typical profile of three–dimensional soil salinity in spring; (**f**) Typical profile of three–dimensional soil salinity in summer.

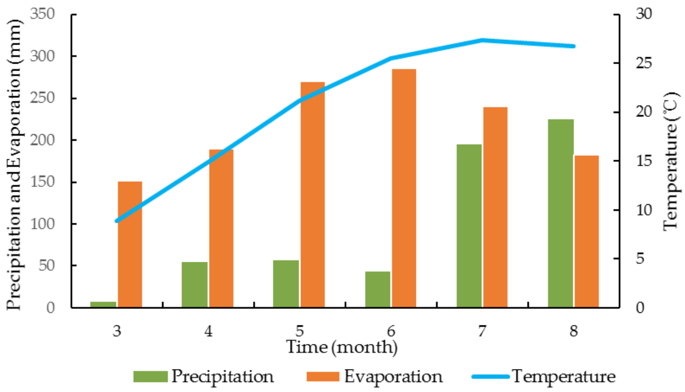


Figure 4. Statistics of monthly average precipitation, evaporation and temperature in the study area from March to August.

Based on the general characteristics of the spatial distribution of soil salinity in the study area in both seasons, and taking into account its topography, three typical cross–sections A–A′, B–B′ and C–C′ (Figure 3e,f) were selected to analyze the distribution of salinity profiles in the study area. As shown in Figure 3, the A–A′ cross–section runs from the south–west corner to the south–east corner of the study area. The soil profile is dominated by the moderate salinization soil type in both spring and summer, while the variation between seasons is more significant. The side at the A end (south–west corner of the study area) has a higher topography, a deeper water table (between 2–2.5 m) and a lower groundwater mineralization (2–5 g/L), which does not easily cause salt reversion even under strong evaporation in summer. The distribution of salinity in the profile changes from the homogeneous type in spring to the bottom accumulation type in summer. The central part of the section is gently sloping, with lower elevation, and although the mineralization of groundwater is also between 2–5 g/L, the burial depth of groundwater is mostly 1.5–2 m; This led to a slight trend of salinity reversion in the surface layer, and the salt distribution in the profile changed from the bottom accumulation type in spring to the homogeneous type in summer. Near A′ (southeast of the study area), the bottom layer of the profile shows a salt accumulation trend, which changes from a homogeneous type in spring to a bottom accumulation type in summer. The difference in seasonal variation of the central part of the B–B′ section is small, but the difference in seasonal variation between the two ends of the section is obvious. The seasonal desalination is obvious on the B side (northwestern part of the study area) and the B′ side (eastern part of the study area), and the distribution of salinity in the section changes from the homogeneous type in spring to the bottom accumulation type in summer. According to the analysis of reasons, although both B and B ′ areas are shallow flat depressions with low terrain, they are mainly cultivated land with good irrigation conditions. The strong rainfall in summer has a significant effect on the leaching and salt pressing of surface salt. The C–C′ section runs from the southwest corner to the northeast corner of the study area, and there is no significant difference between the seasonal changes in the rest of the area, except for a slight local re–salinization trend on the C side (southwest corner of the study area).

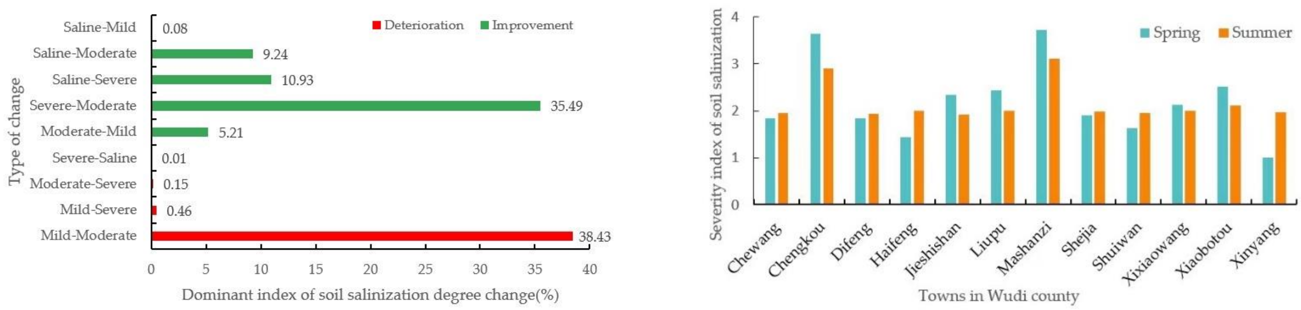
3.3. Temporal Variation Characteristics of Soil Salinity

3.3.1. Characteristics of Soil Salinization Transfer

The surface soil salinization transfer area, dominant index of salinization degree change (C_i) and the salinization severity index (S_i) were used to characterize the temporal variation characteristics of soil salinity in the study area. As can be seen from Table 6, from spring to summer, the area of mild salinization soil type decreased significantly, from 196.44 km^2 to 37.58 km^2, reducing by 80.87%; the moderate salinization soil type increased from 817.44 km^2 to 1185.24 km^2, with an increase of 44.99%. Among them, the area of mild salinization soil type increased to moderate salinization soil type is 181.67 km^2, and the area of severe salinization soil type decreased to moderate salinization soil type is 167.77 km^2. The area of severe salinization soil type decreased from 201.15 km^2 to 87.83 km^2, a decrease of 56.34%. The change range of the saline soil area is the smallest, decreasing by 95.16 km^2. Figure 5a shows the histogram of the change in area of different degrees of salinization soil in the study area. The seasonal change trend of salinization soil area of different salinization degrees is different. The area of mild, severe and saline soil decreased, while the area of moderate salinization soil type increased. Overall, the area with increased salinity from spring to summer is 184.61 km^2, and the area with reduced salinity is 288.09 km^2, with a difference of 103.48 km^2. In terms of area, the study area shows an overall desalination process from spring to summer.

Table 6. Transfer matrix of salinization soil of different degrees from spring to summer.

		Summer				
		Mild Salinization	**Moderate Salinization**	**Severe Salinization**	**Saline Soil**	**Sum**
Spring	Mild salinization	12.60	181.67	2.17	0.00	196.44
	Moderate salinization	24.64	792.10	0.70	0.00	817.44
	Severe salinization	0.00	167.77	33.31	0.07	201.15
	Saline soil	0.34	43.70	51.65	69.95	165.64
	Summation	37.58	1185.24	87.83	70.03	1380.67



(**a**) (**b**)

Figure 5. Change degree of soil salinization: (**a**) Dominant index of soil salinization degree change; (**b**) Severity index of soil salinization.

The dominant index of soil salinization change (C_i) was calculated by Equation (9) to highlight the main types of seasonal changes in salinization soils (Figure 5a). From spring to summer, the change type of soil salinization degree is mainly from mild salinization to moderate salinization soil, with a dominance index of 38.43%. The second is the transition from severe salinization to moderate salinization soil, with a C_i value of 35.49%. The proportion of area change of four types of saline soil–mild salinization, severe salinization–saline soil, moderate salinization–severe salinization, and mild salinization–severe salinization is the smallest, with C_i values less than 1%. In the process of seasonal alternation, the significant degradation of mild salinization to moderate salinization soil type deserves attention. Necessary irrigation control measures should be taken to enhance the desalination effect in summer.

3.3.2. Severity of Soil Salinization in Different Towns

Based on the transfer matrix, the severity of soil salinization in different townships was quantified by Equation (7) (see Figure 5b). In spring, the salinization severity indexes of Mashanzi Town and Chengkou Town were 3.72 and 3.64, respectively, which were the two towns with the most serious salinization hazards in the study area, followed by Xiaobotou Town, Liupu Town, Jieshishan Town and Xixiaowang Town; Xinyang Town was the least affected by salinity hazards, with a severity index of 1. In summer, only Mashanzi Town was located in the area where the salinization severity index was greater than 3. The towns with a salinization severity index between 2–3 were Chengkou, Xiaobotou, Liupu, Haifeng and Xixiaowang town in descending order; Jieshishan Town had the lowest salinization severity index at 1.94.

From spring to summer, Chewang Town, Difeng Street, Haifeng Street, Shejia Town and Shuiwan Town were the towns where the severity of soil salinization increased. Among them, the salinization severity of Haifeng Street was the most obvious, where the change rate of salinization severity index was 38.89%; The second was Shuiwan Town, with a change rate of 19.63%; The change rate of Difeng Street and Shejia Town was the lowest. The towns with a decreasing trend in the seasonal change of salinization severity were Chengkou Town, Jieshishan Town, Liupu Town, Mashanzi Town, Xixiaowang Town, Xiaobotou Town and Xinyang Town. Among them, Chengkou Town had the most obvious degree of salinization reduction, with a salinization severity index change rate of –20.06%, while Jieshishan town, Liupu town and Xiaobotou town had a similar degree of salinization reduction, with a change rate of about −17%.

3.4. Salinisation Driving Factors in Different Seasons

3.4.1. Driving Factors of Salinization Variation of Spring and Summer

The explanatory power of salinization driving factors in different seasons, obtained from factor detection of geographical detectors, is shown in Table 7. It can be seen that, from the perspective of horizontal factor contrast, the explanatory power of the different influencing factors on the spatial distribution of soil salinity in spring is in the order of large to small: subsurface soil salinity, middle soil salinity, soil water content, bottom soil salinity, vegetation cover type, and vegetation coverage. The influence values of subsurface soil salinity, middle soil salinity, soil water content, bottom soil salinity and vegetation cover type were all greater than 0.5, which were the dominant influencing factors of spatial distribution of soil salinization in the study area in spring; The influence value of vegetation coverage was 0.197 which was the weakest explanatory power. In summer, the explanatory power of influencing factors in descending order is: subsurface soil salinity, vegetation cover type, vegetation coverage, middle soil salinity, bottom soil salinity and soil water content. Among them, only the influence values of subsurface soil salinity and vegetation cover type are greater than 0.5, which are the dominant influencing factors of spatial distribution of soil salinity in summer in the study area; The vegetation coverage has strong explanatory power with an influence value of 0.425; The middle soil and bottom soil salinity have average explanatory power with q values between 0.3 and 0.4. Soil water content has the weakest explanatory power with a q value of 0.156.

Table 7. Explanatory power of salinization driving factors in different seasons.

	Spring		**Summer**	
	q	**Rank**	**q**	**Rank**
Subsurface soil salinity	0.666	1	0.555	1
Medium soil salinity	0.623	2	0.398	4
Bottom soil salinity	0.566	4	0.315	5
Soil water content	0.582	3	0.156	6
Vegetation coverage	0.197	6	0.425	3
Vegetation cover type	0.543	5	0.551	2

From the perspective of longitudinal seasonal change, the influence value of subsurface, middle and bottom soil salinity and soil water content on the spatial distribution of soil salinity in the study area showed a significant decreasing trend, that of vegetation coverage showed a significant increasing trend, and that of vegetation cover type showed a slightly increasing trend. Specifically, from spring to summer, the q–value of soil water content decreased from 0.582 to 0.156, with a significant decrease of 73.20% in explanatory power;

the q–value of soil salinity in the middle layer decreased from 0.623 to 0.398, with a decrease of 36.12% in explanatory power; the q–values of subsurface soil salinity and bottom soil salinity decreased by 0.111 and 0.251, respectively, and the reduction amplitude was 16.67% and 44.35%. The q value of vegetation coverage increased from 0.197 to 0.425, a significant increase of 115.74% in explanatory power; while the q value of vegetation cover type only increased by 0.008, an increase of 1.47%. In spring, the study area is dry and rainless, which causes the spatial distribution of soil salinity to be greatly influenced by the salinity of subsurface, middle and bottom soil; In summer, the rainfall increased significantly, relatively weakening the influence of soil water content on the spatial distribution of surface soil salinity; At the same time, with the increase of temperature and evaporation, the intensity of water–salt transport in the soil profile is intense, which led to the weakening influence of subsurface, middle and bottom soil salinity on their spatial distribution. August is the period of flourishing plant growth, when the degree of vegetation coverage is significantly increased compared with spring; this reduced the evaporation of surface soil water, so the influence value of vegetation coverage showed an increasing trend between seasons.

3.4.2. Interaction of Salinization Driving Factors

The interaction detection analysis module of the geographic detector can investigate whether the spatial distribution of soil salinity is driven by a single factor or by multiple factors [31]. On the one hand, the greater the q value of interactive detection interpretation force, the stronger the synergistic effect of driving factors than that of a single driving factor. On the other hand, it is also possible to explore whether the comprehensive effects of driving factors enhance, weaken, or are independent of each other for saline degradation [31]. From the interaction detection results (Figure 6), it is clear that the spatial distribution of soil salinity in the study area is not only influenced by a single driving factor, but also affected by the interaction of multiple factors.

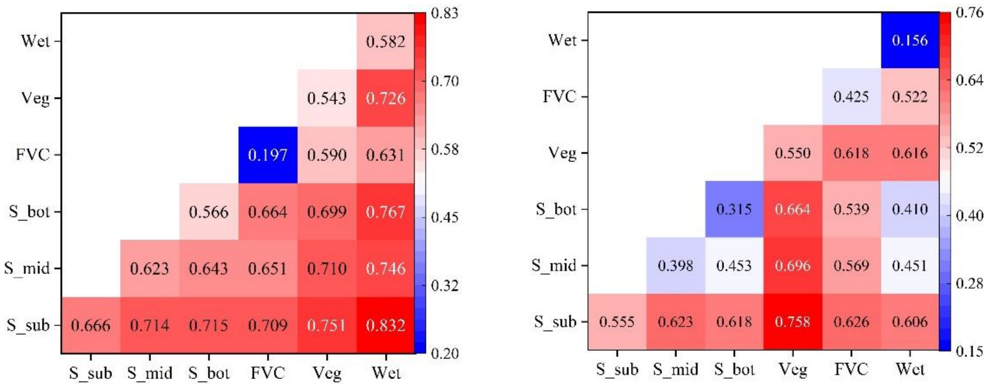


Figure 6. Interactive detection results in different seasons. S_sub, S_mid, S_bot, Wet, FVC, Veg represent subsurface soil salinity, middle soil salinity, bottom soil salinity, soil water content, vegetation coverage, and vegetation cover type, respectively.

In spring, soil water content∩subsurface soil salinity had the strongest explanatory power for the spatial distribution characteristics of soil salinity (0.832), followed by bottom soil salinity∩soil water content (0.767), subsurface soil salinity∩vegetation cover type (0.751), middle soil salinity∩soil water content (0.746), soil water content∩vegetation cover type (0.726), subsurface soil salinity∩bottom soil salinity (0.715), subsurface soil salinity∩middle soil salinity(0.714), middle soil salinity∩vegetation cover type (0.71), subsurface soil salinity∩vegetation coverage (0.709), all having an explanatory power greater than 0.7. In summer, subsurface soil salinity∩vegetation cover type had the strongest explanatory power, with a q–value of 0.758, followed by middle soil salinity∩vegetation cover type (0.696), and bottom soil salinity∩vegetation cover type (0.664), all of which had an explanatory power greater than 0.65. In spring and summer, the single factor with the strongest explanatory power of interaction in the study area included subsurface soil salinity. This indicated that the coordination of subsurface soil salinity and other factors has an important impact on the spatial distribution of soil salinity in spring and summer in the study area.

4. Discussion and Conclusions

4.1. Discussion

When previous scholars studied the spatial and temporal variation characteristics of regional soil salinization, they mostly based their studies on two–dimensional spatial distribution characteristics. Some of the studies involving three–dimensional spatial distribution characteristics of salinity were located in the Yili Valley [12], the Production and Construction Corps of Xinjiang [13], etc. The three–dimensional spatial and temporal analysis of soil salinization in coastal regions is relatively lacking. The climate in the study area is windy and dry in spring, with less rainfall and large evaporation, and hot and rainy in summer, with concentrated precipitation, leading to significant variability in the seasonal variation of soil salinization. However, the exploration of seasonal variation of salinization in this region is still not in-depth. This paper analyzed the spatial and temporal variability of soil salinity in spring and summer of Wudi County in the coastal Yellow River Delta from two–dimensional and three–dimensional perspectives, and made a tentative exploration of the three–dimensional visual analysis of the spatial characteristics of soil salinization and the excavation of the temporal and spatial variation mechanism of salinization. The results of this paper show that the basic characteristics of the soil salinization process in the study area from spring to summer is desalination, which is generally consistent with the findings of Zhang et al. [32]. However, there is a more complex situation of salinization variation in different locations in the study area. The average soil salt content in the study area in spring changes from top to bottom with the trend of first increasing, then decreasing, and then increasing, which is different from the research results of Lv et al. [33]. This is probably due to the fact that there are more cultivated lands in the sampling sites. The clay deposit layer and plough bottom layer were formed at 30 cm and 15 cm, respectively, under long–term natural leaching and mechanical tillage. To a certain extent, they hindered the vertical water–salt transport between soil layers, and the lateral movement was highlighted. However, research on the role of these two "isolation layers" is still not in–depth. Jiang et al. [34] believed that compaction of subsurface soil would lead to a reduction of soil capillary pores, the reduction of soil aeration and permeability, and increase soil infertility. Schneider et al. [35] believed that on a global scale, breaking the bottom of the plough would help improve crop yield. But can it be the same in salinized areas? In the future, these "isolation layers" could be considered to be included in the research on the mechanism of water and salt transport between soil layers as an important aspect of the transfer from the macro to the micro perspective. In this paper, the severity index of soil salinization was introduced to quantify the severity of salinization in different towns. Among them, the soil salinization in Mashanzi Town is the most serious in spring and summer. This is closely related to its proximity to tidal flat, high groundwater mineralization, shallow groundwater burial depth, etc., and therefore Mashanzi Town should be a key area for monitoring and preventing salinization damage in the study area.

Unlike most previous studies that focused on the analysis of "stable" influencing factors [36–38], the influencing factors selected in this paper were mostly "variable" between seasons. The dominant driving factors affecting the spatial distribution of soil salinity in spring and summer were preliminarily identified. However, considering the availability of data, only six types of factors were selected for analysis in this paper. In the follow–up study, more factors can be considered to further clarify the factors influencing the variability of salinity in different seasons.

4.2. Conclusions

(1) The results of mathematical statistics and correlation analysis showed that the soil salinity of the surface soil in the study area was lower in summer than in spring, but

the soil salinity of the subsurface, middle and bottom soil layers was correspondingly higher than that in spring; the surface soil showed obvious characteristics of summer desalination. The variation of soil salinity was obvious, and the variation coefficients of soil salinity at different depths in the two seasons were all greater than 90%. The correlation between the soil salinity of adjacent soil layers was greater than that between non–adjacent layers in both seasons; The correlation between the salinity of each soil layer in summer was lower than that in spring.

(2) In two–dimensional space, the areas where the surface soil salinity was greater than 0.4% in both seasons were mainly located in the northern part of the study area. In three–dimensional space, the soils were mainly of the moderate salinization type in both seasons, and the distribution of the salt profile was mainly the homogeneous type in spring, while more areas had a bottom aggregation distribution in summer in addition to the homogeneous type. Overall, the distribution of soil salt profile is more complex in summer than in spring.

(3) In terms of temporal variability, Mashanzi Town was the most severely affected area by salinization in both seasons, with the salinization severity index *Si* greater than 3. At the change of seasons, the area of mild and severe salinization soil and saline soil tended to decrease, while the area of moderate salinization soil tended to increase. Among them, mild aggravated to moderate salinization soil were the dominant change type, with the dominant index of salinization change value (C_i) of 38.43%, followed by severe mitigated to moderate salinization soil types with C_i value of 35.49%.

(4) The single–factor detection results show that sub–surface soil salinity, middle soil salinity and soil water content are the main factors influencing the spatial distribution of salinity in the study area in spring; sub–surface soil salinity, vegetation cover type and vegetation coverage are the main factors influencing the spatial distribution of salinity in the study area in summer. The influence value of vegetation coverage tends to increase significantly when the seasons change. The results of the interaction detection show that the influence of the interaction between any two factors on the spatial distribution of salinity is greater than that of the corresponding single factor, and that the subsurface soil salinity and other factors act in concert to have an important influence on the spatial distribution of soil salinity in the study area in spring and summer.

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