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Effects of Salinity and Oil Contamination on the Soil Seed Banks of Three Dominant Vegetation Communities in the Coastal Wetland of the Yellow River Delta

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Abstract: In view of the important role of vegetation in the integrity of structures and functions of coastal wetland ecosystems, the restoration of degraded coastal wetland vegetation has attracted increased attention. In this paper, the newborn coastal wetland in the Yellow River Delta (YRD) of China was selected to research the effect of salinity and oil exploitation on the germination of soil seed banks of three dominant vegetation communities. The germination experiment with three concentration gradients of NaCl and three concentration gradients of diesel treatments showed that there were 14 species present in the soil seed bank of the multi-species community: three species in the *Phragmites australis* community, and five species in the *P. australis*—*Suaeda glauca* community. The species in the seed bank of the three communities were much richer than the above-ground vegetation in this study. Soil salinity had a significant inhibitory effect on the seedling numbers of germinated species, the seedling density, and the species diversity of the soil seed banks, while the inhibitory effect of diesel was indistinctive under the designed concentrations. There existed significant interactions between the vegetation community type and soil salinity on the number of germinated species, the seedling density, and the Margalef index. Soil salinity is considered an important factor for wetland vegetation restoration in the YRD, but its effect had species-specific differences. Soil seed banks of the present three communities could be used to promote the restoration of degraded wetlands within certain soil salinity and oil concentration ranges.

Keywords: wetlands; Yellow River Delta; soil seed bank; restoration; oil contamination; salinity

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1. Introduction

Coastal wetlands are an important ecological barrier between the sea and the land [1]. However, wetland areas around the world have degraded by approximately 87% since 1700 [2]. The total area of China's wetlands larger than 1 km^2 decreased from 3.85 × 10^5 km^2 in the First National Inventory of Wetland Resources (1999–2001) to 3.51 × 10^5 km^2 in the Second National Inventory of Wetland Resources (2009–2011), and the natural wetland accounted for 99.4% of the total degraded wetland area [3]. Pollution, excessive exploitation of biological resources, reclamation, bio-invasion, and infrastructure construction are considered the main drivers of wetland degradation [4]. Many wetland-dependent species, including 21% of bird species, 37% of mammal species, and 20% of freshwater fish species,

are either extinct or globally threatened [5]. The loss of area and biodiversity has had a large adverse impact on the integrity of structures and functions of wetland ecosystems [6].

A soil seed bank is the sum of all surviving seeds present on the soil surface and in the soil. Seeds can spread in soils over time to maintain species populations in the face of harsh environments [7]. The bank has the potential to restore the vegetation of damaged wetlands and regain some species that have disappeared from the surface vegetation [8–10]. The soil seed bank has been regarded as an important source of regenerative material in wetland restoration [11–13]. The assessment of the restoration potential and the impact of environmental conditions on the seed bank have great importance for the vegetation restoration of degraded wetlands. Although most studies are focused on seed germination potential [14], growth inhibition effects of contaminants [15], or the relationships between the soil seed bank and above-ground vegetation [16], little information is available regarding the effects of intense human disturbances on wetland soil seed banks in coastal regions.

The coastal wetland in the Yellow River Delta (YRD) is an important site for birds to migrate, overwinter and breed in Northeast Asia and the Pacific Rim. The natural wetland area of the YRD region decreased by 991.1 km^2 from 1986 to 2008 due to economic development and human activities [17]. The YRD region is also the third-largest oil field in China, the average total petroleum hydrocarbon (TPH) concentration is more than 2100 mg kg^{-1} in the soil surrounding the oil wells due to long term oil exploitation [18,19]. The light fraction of the crude oil is toxic to the growth of vegetation and the germination of seeds, but the toxic effects vary greatly and are species-specific [15,20]. However, the effects of crude oil contamination on seed banks in coastal wetlands are not well studied. Moreover, due to the large evaporation and precipitation ratio, the soil salinity in the YRD region is very serious, with a mean soil salt content of approximately 10.45 g kg^{-1} [21]. High salinity has a serious inhibitory effect on the germination of seeds and the growth of vegetation [22]. However, little is known about the seeds' germination under the dual environmental stresses of oil contamination and salinity. In the present study, we measured the above-ground vegetation characteristics of three dominant wetland plant communities in the YRD region; analyzed the soil's physical and chemical parameters; and evaluated the germination ability of the sampled soil seed banks under different salinity and diesel concentration conditions. We hypothesize that: (1) the inhibitory effects of diesel and salinity on the germination of different seeds vary; and (2), there exists an interaction between diesel and salinity on the germination of soil seed banks. The aim of this study was to evaluate the potential of soil seed banks for vegetation restoration in the degraded wetlands of the YRD.

2. Materials and Methods

2.1. Site Description

The present study site is located in the Yellow River Delta Nature Reserve (YRDNR), Dongying City, Shandong Province, China. It is located in the warm temperate zone and belongs to the temperate semi-humid continental monsoon climate zone. The annual average temperature of the YRD is 11.7–12.6 °C; the frost-free period is 211 days; the annual average precipitation is 530–630 mm, 70% of which is distributed in summer. The annual evaporation is about 1962 mm. The vegetation coverage is about 53.7%, and the main plants, such as *Phragmites australis* and *Suaeda glauca* are saline-tolerant coastal wetland species [23].

2.2. Sampling Method

Three dominant vegetation communities named: the multi-species community, *P. australis* community, and *P. australis*—*S. glauca* community, were selected based on the above-ground vegetation in the wetlands of the YRD (Table 1). For each community type, four replicates with an area of 50 m^2 were selected as the sampling plots (Table 1). In each sampling plot, 5 sampling sites with a size of 1 m × 1 m were set randomly. The above-ground vegetation communities were investigated firstly to record the species of

plants in each site. Then, 6 soil cores (Φ = 10 cm) of the surface layer soil (0–10 cm) were sampled randomly at each sample site. All 30 soil cores were mixed as one seed bank soil sample. Therefore, there were 12 seed bank soil samples altogether. At the same time, in each sampling plot, soil with a depth of 0–10 cm was sampled at the four corners and at the center and mixed together to determine the soil's physical and chemical parameters of the sampling plot. Therefore, there were 12 soil samples collected for the following physical and chemical parameters test altogether.

Table 1. Geographic information of the sampling plots in the Yellow River Delta.

Community Type	Code of Sampling Plots	Longitude and Latitude of The Sampling Plots
Multi-Species Community	1	37°44′16.46″ N, 119°9′38.05″ E
	2	37°44′13.44″ N, 119°9′46.43″ E
	3	37°44′4.18″ N, 119°10′6.48″ E
	4	37°43′50.69″ N, 119°10′53.69″ E
Phragmites Australis Community	1	37°45′47.33″ N, 119°3′16.76″ E
	2	37°45′49.92″ N, 119°4′35.92″ E
	3	37°45′37.36″ N, 119°5′17.1″ E
	4	37°45′35.67″ N, 119°5′22.05″ E
Phragmites Australis–Suaeda Glauca Community	1	37°44′52.99″ N, 119°7′38.76″ E
	2	37°44′58.62″ N, 119°7′58.62″ E
	3	37°45′48.58″ N, 119°3′1.51″ E
	4	37°45′50.84″ N, 119°4′6.43″ E

2.3. Analysis of Soil Physical and Chemical Parameters

The soil samples were air-dried and passed through a 2-mm sieve prior to analysis of the soil's physical and chemical parameters. The pH and electrical conductivity (EC) were determined in a 1:5 sample/water mixture by using a SevenExcellence^{TM} S-470K multifunction pH meter (Mettler Toledo, Schwerzenbach, Switzerland) at 25 °C after shaking for 30 min. Soil total carbon (TC), total organic matter (TOM), total nitrogen (TN), available nitrogen (AN), and available phosphorus (AP), were analyzed at the laboratory of Suez NWS Limited, China. The analysis methods include TC: ISO 10694-1995; TOM: NY/T 1121.6-2006; TN: APHA 4500 N_{org}/NO_3; AN: NH_3-N: APHA 4500 NH_3-H; NO_3-N: APHA 4500 NO_3-I; NO_2-N: APHA 4500 NO_2-I; AP: HJ 704-2014.

2.4. Soil Seed Germination Experiment

Firstly, the broken plant roots, leaf litter, and stones in the soil seed bank samples were picked out. Then, the soil seed bank samples were sieved (0.178 mm) and washed using distilled water to remove the soil. Finally, the treated seed bank samples were sealed in separate bags and stored in a refrigerator at 4 °C for 1 week for vernalizing. To investigate the effects of salinity and oil contamination on seed germination, an experiment with three concentration gradients of NaCl (0%, 1%, and 2%) and three concentration gradients of diesel (0%, 1%, and 2%) were designed, there were nine treatments altogether, and each treatment had four replicates. The seed bank germination experiment was carried out in plastic germination boxes the size of 12 cm × 12 cm × 5 cm. According to the design, different amounts of diesel and NaCl were weighed out separately according to the weight of each soil seed bank sample. The sterilized commercial nutrient soil was dissolved with the weighed NaCl and the same amount of distilled water. The weighed NaCl and diesel were then added to the nutrient soil and mixed thoroughly. Each seed bank sample was mixed thoroughly and divided equally into four portions and spread on the surface of the treated commercial nutrient soil with a thickness of ≤1 cm, respectively. The treated

commercial nutrient soil was spread in the box to a height of 2–3 cm. The germination experiment was carried out at room temperature in a sunny greenhouse, and the soil in the germination box was kept moist with regular replenishment of water. The counting of germinated seedlings and the species identification were carried out regularly in the following 2 months.

2.5. Data Analysis

2.5.1. Diversity and Similarity Indicators Calculation of the Soil Seed Bank and Vegetation Community

The biodiversity indicators, such as the Margalef index, Simpson index, and the Shannon–Wiener index, of the soil seed bank, were characterized using the following Equations (1)–(3).

$$\text{Margalef index} = \frac{S-1}{\ln N} \quad (1)$$

$$\text{Simpson index} = 1 - \sum P_i^2 \quad (2)$$

$$\text{Shannon–Wiener index} = -\sum (P_i \times \ln P_i) \quad (3)$$

$$P_i = \frac{N_i}{N} \quad (4)$$

where S is the total number of species in the vegetation community, N is the total number of all species, and N_i is the number of individuals in species i.

The Sørensen index was used to characterize the species similarity between the above-ground vegetation community and the below-ground seed bank Formula (5).

$$\text{Sorensen Index} = \frac{2j}{a+b} \quad (5)$$

where a is the number of species present in the above-ground vegetation community, b is the number of species present in the seed bank, and j is the number of species present in both the vegetation community and its seed bank.

2.5.2. Statistical Analysis of Data

One-way ANOVA was used to analyze the physical and chemical properties of the sampled soil, respectively (SPSS Version 18.0, SPSS Inc., Chicago, IL, USA). The difference in the AP, TC, TN, AN, TOM, EC, pH, and C/N ratio was performed using Duncan's multiple comparison test at the significance level of $p = 0.05$. Three-way ANOVAs followed by Duncan's multiple range test ($p = 0.05$) were performed to identify the differences among the germination characteristics of the soil seed banks, vegetation community types, and the environmental stress conditions based on the normal distribution of the variables (SPSS Version 18.0, SPSS Inc., Chicago, IL, USA). The germination characteristics of the soil seed banks included the number of germinated species, number of seedlings, the Margalef index, Simpson index, and the Shannon–Wiener index. The species-level analysis was limited to the plant species (seedling numbers > 20).

3. Results

3.1. Soil Physical and Chemical Parameters of the Three Dominant Vegetation Communities in the YRD

The main environmental parameters of the soil in the three dominant vegetation communities are presented in Table 2. The TC concentration of the soil in the multi-species community was significantly higher than the *P. australis–S. glauca* community. Although the TN concentration of the soil in the *P. australis–S. glauca* community was significantly higher than the multi-species community and the *P. australis* community. In addition, the C/N ratio of the soil in the multi-species community was significantly higher than the *P. australis–S.* glauca community. The EC in the soil of the multi-species community was significantly lower than the P. australis community and the *P. australis–S. glauca* community.

There were no significant differences between the TOM, AN, AP, and pH, among the three vegetation communities.

Table 2. Soil physical and chemical parameters of the three dominant vegetation communities in the YRD.

	Multi-Species Community	***Phragmites Australis* Community**	***Phragmites Australis*–*Suaeda glauca* Community**
AP (mg/kg)	2.30 ± 0.41 a	1.75 ± 0.21 a	1.80 ± 0.11 a
TC (g/kg)	13.03 ± 0.81 b	11.53 ± 0.29 ab	10.90 ± 0.20 a
TN (mg/kg)	743.75 ± 90.32 a	775.75 ± 76.45 a	1008.75 ± 27.48 b
AN (mg/kg)	24.00 ± 0.82 a	25.25 ± 1.97 a	24.50 ± 0.29 a
TOM (g/kg)	8.20 ± 0.74 a	9.30 ± 0.38 a	8.38 ± 0.23 a
EC (μS/cm)	557.18 ± 260.70 a	4303.28 ± 842.28 b	3658.63 ± 649.75 b
pH	7.99 ± 0.04 a	7.91 ± 0.04 a	7.90 ± 0.03 a
C/N ratio	18.17 ± 1.95 b	15.31 ± 1.26 ab	10.83 ± 0.40 a

Notes: The variables: mean ± S. E.; AP: available phosphorus; TC: total carbon; TN: total nitrogen; AN: available nitrogen; TOM: total organic matter; EC: electrical conductivity; C/N ratio: ratio of total carbon and total nitrogen; different letters (a, b) within the row indicate a significant difference at $p = 0.05$ (Duncan test, $N = 4$).

3.2. The Main Plant Species Presented in the Three Dominant Soil Seed Banks and the Above-ground Vegetation Communities

There were 14 species present in the multi-species community, 3 species present in the *P. australis* community, and 5 species present in the *P. australis–S. glauca* community (Table 3). *P. australis*, *Artemisia mongolica*, and *Setaria viridis* were the three dominant species in the multi-species community. *P. australis* was the monodominant species in the *P. australis* community. *P. australis* and *S. glauca* were the two dominant species in the *P. australis–S. glauca* community. The species composition had significant differences among the three dominant vegetation communities in the soil seed germination experiment (Table 4). In addition, the seedling density in the multi-species community, the *P. australis* community, and the *P. australis–S. glauca* community were 19.60 ± 5.90 × 10^3 seedlings m^{-2}, 3.01 ± 0.55 × 10^3 seedlings m^{-2}, and 3.85 ± 0.60 × 10^3 seedlings m^{-2}, separately, under 0 salinity and 0 diesel concentration germination condition (Table 4).

The survey of the above-ground community species showed that there were more plant species in the soil seed banks than in the above-ground communities. The Sørensen similarity index of the above-ground species and the soil seed bank species was significantly higher in the *P. australis–S. glauca* community (0.75 ± 0.17) than the multi-species community (0.55 ± 0.08) and the *P. australis* community (0.54 ± 0.09) (Table 4).

3.3. Effects of Salinity and Diesel Contamination on the Germination of Seeds

The result of the seedling density of all species under different salinity and diesel treatment has been shown in Table 3. The inhibitory effects of salinity and diesel on the germination of the seeds increased with the increase in the concentration of salinity and diesel (Figure 1). Furthermore, the number of germinated species, seedling density, and species diversity (Margalef index, Simpson index, Shannon–Wiener index) had a marked difference among the three dominant vegetation communities (Table 5). Soil salinity had a significant inhibitory effect on the above-mentioned germination characteristics, while the inhibitory effect of diesel was indistinctive (Table 5). The interactions between the vegetation community type and soil salinity significantly affected the number of germinated species, seedling numbers, and the Margalef index (Table 5).

Table 3. Seedling number in the seed banks of the three dominant vegetation communities in the YRD.

Community Type	Species	Seedling Density (Seedlings/m^2)								
		0 (S), 0 (D)	**1% (S), 0 (D)**	**2% (S), 0 (D)**	**0 (S), 1% (D)**	**1% (S), 1% (D)**	**2% (S), 1% (D)**	**0 (S), 2% (D)**	**1% (S), 2% (D)**	**2% (S), 2%(D)**
Multi-Species Community	*Phragmites australis*	4404 ± 1269	1165 ± 263	459 ± 87	5579 ± 1689	2895 ± 1654	630 ± 369	2369 ±655	1662 ± 251	678 ± 186
	Suaeda glauca	258 ± 65	153 ± 35	115 ± 41	267 ± 91	134 ± 59	105 ± 42	344 ± 102	210 ± 123	163 ± 29
	Sonchus arvensis	363 ± 236	48 ± 36		115 ± 66	29 ± 18		124 ± 61	48 ± 29	
	Typha orientalis	38 ± 27			248 ± 171	19 ± 19		229 ± 122	10 ± 10	
	Atriplex patens	105 ± 80	96 ± 63		267 ± 131	29 ± 18		86 ± 74	29 ± 18	10 ± 10
	Artemisia mongolica	10976 ± 4116	3353 ± 1483	640 ± 301	7499 ± 3728	2417 ± 1006	564 ± 180	7002 ± 3459	2350 ± 1237	736 ± 421
	Setaria viridis	2723 ± 1452	659 ± 290	220 ± 153	2025 ± 1142	927 ± 630	191 ± 191	2302 ± 911	1395 ± 489	115 ± 115
	Glycine soja	19 ± 19			38 ± 16			10 ± 10	10 ± 10	
	Tripolium vulgare		10 ± 10							
	Artemisia fauriei	172 ± 89			57 ± 37			67 ± 67		
	Suaeda salsa	287 ± 250	325 ± 226	220 ± 207	143 ± 83	392 ± 366	229 ± 182	172 ± 135	287 ± 225	210 ± 150
	Chloris virgata	86 ± 86	48 ± 48		57 ± 57	19 ± 19				
	Capsella bursa -pastoris		10 ± 10							
	Cirsium arvense var. integrifolium	115 ± 102			86 ± 74					
	Ixeris polycephala	19 ± 19						19 ± 19	19 ± 11	
	Conyza canadensis	29 ± 18	10 ± 10					29 ± 29		
	Ranunculus sceleratus				10 ± 10					
	Artemisia capillaris		10 ± 10					29 ± 29		
Phragmites Australis Community	*Phragmites australis*	2961 ± 571	1404 ± 362	95 ± 57	2293 ± 356	1079 ± 223	76 ± 27	2178 ± 421	1013 ± 123	191 ± 68
	Sonchus arvensis	105 ± 24	19 ± 19		57 ± 25	29 ± 18	10 ± 10	57 ± 25	29 ± 18	19 ± 19
	Typha orientalis				19 ± 11			29 ± 18		
Phragmites Australis–Suaeda Glauca Community	*Phragmites australis*	1824 ± 696	831 ± 366	152 ± 128	1652 ± 409	888 ± 441	162 ± 83	1757 ± 583	898 ± 456	487 ± 231
	Suaeda glauca	1948 ± 801	2407 ± 740	1538 ± 508	2502 ± 709	1719 ± 510	1136 ± 404	2502 ± 986	1242 ± 525	850 ± 366
	Sonchus arvensis	57 ± 37	10 ± 10		67 ± 45	29 ± 29		48 ± 48		
	Typha orientalis	19 ± 19			10 ± 10			27 ± 27		
	Suaeda salsa			38 ± 38	10 ± 10					

Notes: The variables: mean ± S. E.; S: soil salinity; D: diesel concentration; N = 4.

Table 4. Seedling density in the seed banks of the three dominant vegetation communities in the YRD.

Community Type	Seedling Density (Seedlings/m^2)	Sørensen Index
Multi-Species Community	$19.60 \times 10^3 \pm 15.90 \times 10^3$ b	0.55 ± 0.06 a
P. Australis Community	$3.01 \times 10^3 \pm 0.55 \times 10^3$ a	0.54 ± 0.09 a
P. Australis–*S. Glauca* Community	$3.85 \times 10^3 \pm 0.60 \times 10^3$ a	0.75 ± 0.17 b

Notes: The variables: mean ± S. E.; different letters (a, b) within the column indicate a significant difference at $p = 0.05$ (Duncan test, $N = 4$).

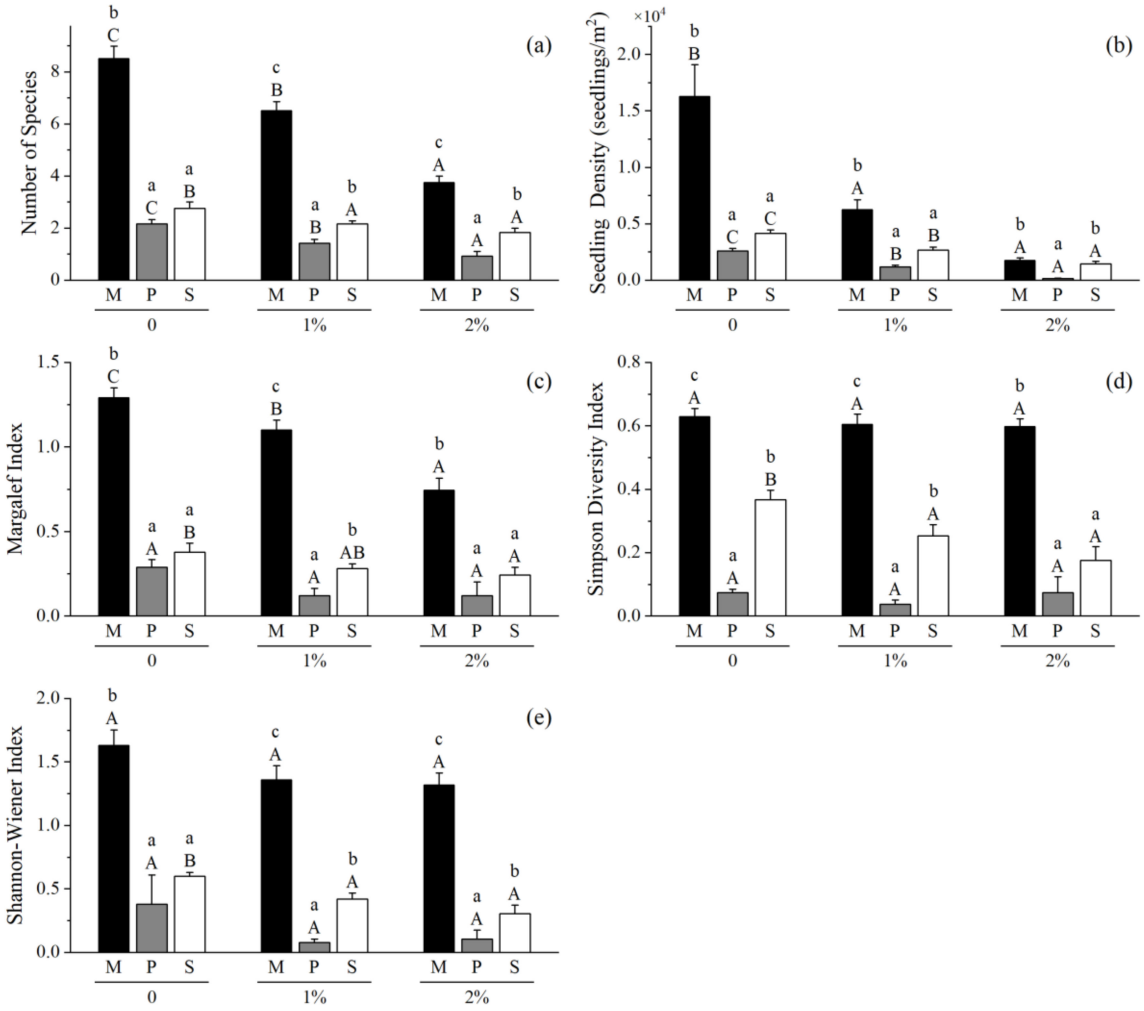

Figure 1. Effects of salinity on the seed germination of the three dominant communities in the YRD. (**a**–**e**) are the different parameters to describe the seed germination characteristics under different salinity. The columns are the mean values of the parameters, and the error bars are the standard error of the values, N = 4, $p = 0.05$. M: Multi-species community; P: *Phragmites australis* community; S: *Phragmites australis*–*Suaeda glauca* community. The 0%, 1% and 2% refers to the different soil salinities; a, b and c are used to describe the significance of the differences among the three communities under the same soil salinity; A, B and C are used to describe the differences among the three soil salinities under the same community type.

The effect of salinity on seed germination was further analyzed at the community level (Figure 1). It can be concluded from the analysis that the number of germinated species, seedling density, and the species diversity of the seed bank in the multi-species community are the highest in the three dominant vegetation communities under the same soil salinity. In addition, the adaptive ability of the *P. australis*–*S. glauca* community to soil salinity is better than that of the *P. australis* community (Figure 1). With the increase in soil salinity, the number of germinated species, seedling numbers, and species diversity of

the three vegetation communities all show a decreasing trend; the number of germinated species and the seedling numbers have significant differences among the three dominant vegetation communities (Figure 1a,b). At the same time, the effects of salinity and diesel on seedling numbers of specific species were also analyzed using a three-way ANOVA (Table 6). The result proved that the seedling numbers of *P. australis*, *S. glauca*, *S. arvensis*, *T. orientalis*, *A. patens*, *A. mongolica*, *S. viridis*, *A. fauriei*, *S. salsa* and *C. virgata* had significant difference among the three vegetation communities (Table 5). The seedling numbers of *P. australis*, *S. glauca*, *S. arvensis*, *T. orientalis*, *A. patens*, *A. mongolica*, *S. viridis*, and *A. fauriei* were significantly higher than *S. salsa*, *C. virgata*, *Cirsium arvense*, and *Ixeris polycephala* (Table 3). There existed a significant interaction effect between the vegetation community type and the soil salinity on the seedling numbers of *T. orientalis*, *A. mongolica*, *S. viridis*, *A. fauriei*, and *Cirsium arvense* (Table 6).

Table 5. Three-way ANOVA analysis of vegetation community types, salinity, and diesel concentration on the germination and diversity of soil seed banks in the YRD.

	Number of Germinated Species		**Seedling Number**		**Margalef Index**		**Simpson Index**		**Shannon–Wiener Index**	
	F	**P**	**F**	**P**	**F**	**P**	**F**	**P**	**F**	**P**
C	282.060	0.000	36.253	0.000	159.960	0.000	206.764	0.000	110.522	0.000
S	57.070	0.000	33.251	0.000	20.161	0.000	5.499	0.006	5.207	0.007
D	0.169	0.845	0.627	0.537	0.338	0.714	1.586	0.211	0.348	0.707
C × S	17.517	0.000	11.959	0.000	4.507	0.002	1.892	0.119	0.137	0.968
C × D	0.938	0.446	0.293	0.882	1.662	0.166	0.440	0.779	0.300	0.877
S × D	0.548	0.701	0.389	0.816	0.342	0.849	0.347	0.845	1.949	0.109
C × S × D	0.488	0.862	0.516	0.841	0.428	0.901	0.303	0.963	0.742	0.655

Notes: C: vegetation community types; S: soil salinity; D: diesel concentration; $N = 4$.

Table 6. Three-way ANOVA of the effects of community type, salinity, and diesel concentration on the seedling numbers of the dominant species in the YRD.

Species Name	**C**	**S**	**D**	**C × S**	**C × D**	**S × D**	**C × S × D**
Phragmites australis	0.000	0.000	0.262	0.067	0.114	0.326	0.609
Suaeda glauca	0.000	0.031	0.750	0.055	0.769	0.650	0.802
Sonchus arvensis	0.038	0.000	0.346	0.070	0.421	0.292	0.671
Typha orientalis	0.003	0.000	0.256	0.001	0.380	0.339	0.566
Atriplex patens	0.022	0.003	0.730	0.168	0.851	0.837	0.633
Artemisia mongolica	0.000	0.000	0.579	0.000	0.712	0.886	0.972
Setaria viridis	0.000	0.001	0.920	0.000	0.988	0.915	0.984
Artemisia fauriei	0.001	0.001	0.353	0.000	0.401	0.384	0.426
Suaeda salsa	0.000	0.701	0.919	0.804	0.996	0.992	0.999
Chloris virgata	0.025	0.257	0.304	0.263	0.330	0.808	0.925
Cirsium arvense	0.059	0.054	0.453	0.025	0.545	0.529	0.626
Ixeris polycephala	0.014	0.222	0.222	0.214	0.214	0.551	0.654

Notes: Only the species' with seedling numbers greater than 20 were included. C: Community type; S: Salinity; D: Diesel concentration, $N = 4$, $p = 0.05$.

4. Discussion

4.1. The Species Diversity of Above-Ground and Under-Ground Vegetation in the YRD

The wetlands in the YRD region are typical saline wetlands, and the dominant vegetation species are mainly salt-tolerant species such as *S. salsa*, *S. glauca*, and *P. australis* [24]. *S. salsa* and *S. glauca* are the two common *Suaeda* species that coexist in the YRD. *S. salsa* is mainly distributed near the muddy tidal flat and high tide line of the coast, whereas *S. glauca* mainly exists in the inland close to the sea [25]. *P. australis* is another most important and widespread wetland plant species [26]. There is about 2600 ha of *P. australis* wetlands

that form monodominant communities or mix with other plant species such as *Triarrhena lutarioriparia*, *Typha orientalis*, *Sonchus arvensis*, and *S. salsa* [27]. The species of vegetation are usually low in the low-nutrient and high-salinity coastal wetlands. In the present study, there were only 14 species found from the investigation of the soil seed banks, and the above-ground species were fewer than the species of the seed banks (Table 3). *P. australis* was always the dominant species in the multi-species community, *P. australis* community, and the *P. australis*–*S. glauca* community. A previous study on the above-ground vegetation and soil seed banks of the new Yellow River course (NYR) and the abandoned Yellow River course (OYR) in the YRD wetlands had similar results. There were only 17 plant species across both sites, 9 species were in OYR, and 16 species were in the NYR [28].

4.2. Effects of Soil Salinity and Diesel Contamination on the Germination of Seeds

Soil salinity is an important environmental factor affecting the physiological conditions of plants. High salinity can inhibit the germination of seeds and the elongation of leaves [29], reduce the photosynthetic rate [30], and decrease the root uptake capacity [31], thereby affecting the composition of vegetation communities [32,33]. In the present study, soil salinity significantly inhibits the number of species, seedling numbers, and the species biodiversity of the soil seed banks (Table 5, Figure 1). However, the reactions of specific species to salinity are different; *P. australis*, *S. glauca*, *S. arvensis*, *T. orientalis*, *A. patens*, *A. mongolica*, *S. viridis*, and *A. fauriei* are more tolerant of soil salinity, especially *P. australis*, *S. glauca*, *A. mongolica* and *S. viridis* (Tables 3 and 6). *P. australis* is one of the dominant species in the YRD, and its habitats span from freshwater swamps to salt marshes with a salinity ranging from 0 to 20% [22]. However, a soil salinity of 10% significantly decreases the growth of *P. australis* [32]. Moreover, the density and species richness of the seed banks are also significantly lower under saline-alkaline stresses [34]. *S. glauca* is a succulent halophyte that is highly resistant to salt and alkali stresses [25,35]. The seedlings of *S. glauca* do not show significant symptoms of injury after imposing 5.85–17.55% of NaCl stress, and the low concentration of NaCl (5.85%) even promoted its growth [36]. Increasing shoot–root ratio, maintaining leaf succulence and relying on proline and metal ions as osmotic regulators are regarded as the main regulation strategies of *Suaeda* species to adapt to high salinity environment conditions.

Diesel oil is a complex mixture produced by the distillation of crude oil. It consists of hydrocarbons with carbon numbers in the range of C_9–C_{38} [37]. Diesel is more toxic than crude oil due to the easy uptake and bioavailability of lower molecular weight over higher molecular weight compounds [38]. The research of Adam and Duncan (2002) shows that diesel oil postpones the germination time, but it has no significant inhibitory effect on the germination rate of seeds [20]. The hard seed coat is the main barrier to resisting the damage of oil penetration; therefore, the embryo of the seed cannot easily be injured or killed. The inhibitory effect of diesel fuel on seed germination is due to its water repellent property, the film of diesel fuel around the seeds may prevent or reduce both water and oxygen from entering the seeds; therefore, the lag phase preceding germination is increased many times [20,39]. Furthermore, the germination rates vary greatly with plant species when affected by hydrocarbons. Zhu et al. evaluated the seed germination rates of 65 grass species in North Dakota affected by crude oil [15]. The results showed that the germination rate of all species reduced from 4.3 to 100% under the inhibition of crude oil, 28 were tolerant species, 29 were moderately tolerant species, 6 were moderately sensitive species, and 2 were sensitive species. The pot experiment carried out by Wei et al., shows that crude oil has a negative effect on the germination rate, plant height, and biomass of six indigenous plant species in the semi-arid loess area, and 2% is the crucial level that has a significant inhibitory effect on the growth of plants [39]. The above studies are inconsistent with the results of our present study on soil seed banks.

4.3. Potential of Soil Seed Banks for the Restoration of the Degraded Coastal Wetland

The wetlands in China account for 5.58% of the whole national territorial area, which plays an important role in maintaining the ecosystem function [4]. Although the wetlands have been severely disturbed due to multiple influencing factors, such as urbanization, oil exploitation, agriculture activities, etc., soil seed banks are a germplasm reservoir that can directly affect the species composition and plant community structure. It is considered an important method in wetland restoration [26]. Guan et al. (2019), studied the above-ground vegetation and soil seed banks of the NYR course and the abandoned OYR course in the YRD wetlands; there were 17 species with a seed density of $2.06 \pm 1.25 \times 10^3$ seeds m^{-2} [28]. In the present study, we found similar results; there were 14 species found in the three common vegetation communities altogether, the seed density ranged from $3.01 \pm 0.55 \times 10^3$ to $19.60 \pm 5.90 \times 10^3$ seeds m^{-2}. The multi-species vegetation community had the highest seed bank storage, species richness, and diversity. Moreover, the species number of the seed banks was closely related to its above-ground vegetation. The species number of the multi-species vegetation community was also the highest in the three vegetation communities (Tables 3 and 5).

The ultimate goal of wetland restoration is to create a self-supporting ecosystem that can resist perturbation without further assistance [17]. In the present study, soil salinity was identified as an important factor that influences the number of germinated species, seedling density, and the species diversity of the vegetation communities in the YRD (Tables 5 and 6). The multi-species vegetation community was mainly distributed in the low salinity soil, while the *P. australis* community and the *P. australis*–*S. glauca* communities were more suitable to living in the high salinity soil. Diesel has no significant inhibitory effect on seed germination under 2% concentration (Tables 5 and 6). Therefore, soil salinity should be one of the most important factors to consider prior to wetland restoration using topsoil transplantation. The *P. australis* community and *P. australis*–*S. glauca* communities can be used in degraded wetlands with 1–2% soil salinity and 0–2% oil contamination, while multi-species communities are more suitable for the restoration of wetlands with 0–1% salinity and 0–2% oil contamination.

5. Conclusions

The soil seed banks and above-ground vegetation of three dominant vegetation communities (multi-species community, *P. australis* community, and *P. australis*–*S. glauca* community) in the coastal wetlands of the YRD were investigated. The number of above-ground species was fewer than the species of seed banks, and *P. australis* was the most dominant species among the 14 species in the soil seed banks. The tolerance of different plant species to salinity and diesel is species-specific, and the inhibitory effect of salinity is more significant than diesel. The seed coat can resist the penetration of diesel but cannot resist the stress of salt, and the inhibition starts in the initial stage of germination. Therefore, soil salinity is considered a more important factor than diesel for wetland restoration in the YRD. To facilitate improved germination and growth, it is recommended that soil seed banks are transplanted into the soil conditions for which they are better adapted. The soil seed banks of the *P. australis* and *P. australis*–*S. glauca* communities are suitable to be used in degraded wetlands with a soil salinity of between 1% and 2%, while multi-species communities are more suitable for use in a soil salinity of between 0% and 1%.

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