Chemical properties and fertility analysis of dredger-fill silt during soil formation: The tianjin dredge–fill project

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Dredger-fill silt has been used in the port of Tianjin, China to reclaim land; however, the dredger-fill silt has no soil ecological function. Translating the silt into soil rapidly and accelerating the soil-forming process are key to solving the ecological problems of the Dredge–Fill project. This study measured 15 chemical properties of the dredger-fill silt for 8 years of the soil forming process to explore fertility changes and the critical factors affecting soil formation. The results showed that: (1) the salinity of silt changed from severe to mild with a reduction in Na^+ and Cl^- concentration. Other ion concentrations changed slightly. (2) Effective nutrients significantly decreased during soil formation. Soil organic matter (SOM) , the nitrate-nitrogen, available phosphorus (A-P) and available potassium (A-K) decreased by 26.22%, 86.23%, 45.92%, 33.61% respectively, indicating severe nutrients loss. (3) Principal component analysis showed that silt fertility decreased significantly and the total soil fertility loss was severe. This study has significance for the artificial improvement of silt.

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Chemical Properties and Fertility Analysis of Dredger-fill silt During Soil Formation: The Tianjin Dredge–Fill Project

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Abstract: Dredger-fill silt has been used in the port of Tianjin, China to reclaim land; however, the dredger-fill silt has no soil ecological function. Translating the silt into soil rapidly and accelerating the soil-forming process are key to solving the ecological problems of the Dredge–Fill project. This study measured 15 chemical properties of the dredger-fill silt for 8 years of the soil forming process to explore fertility changes and the critical factors affecting soil formation. The results showed that: (1) the salinity of silt changed from severe to mild with a reduction in Na^+ and Cl^- concentration. Other ion concentrations changed slightly. (2) Effective nutrients significantly decreased during soil formation. Soil organic matter (SOM) ， the nitrate-nitrogen, available phosphorus (A-P) and available potassium (A-K) decreased by 26.22%, 86.23%, 45.92%, 33.61% respectively, indicating severe nutrients loss. (3) Principal component analysis showed that silt fertility decreased significantly and the total soil fertility loss was severe. This study has significance for the artificial improvement of silt.

Key words: chemical properties; dredger-fill silt; fertility; Principal component analysis

Introduction

The Tianjin Port is located in the lower reaches of the Haihe River, at the western end of Bohai Bay (38°59′08″N, 117°42′05″E). The Tianjin beach is a typical silt coast (Sun Lian-cheng, 2011). Siltation phenomenon was so severe that it restricted the initial development of the port. Presently the Tianjin Port requires silt to be extracted from the seabed to dredge the channel every year, and the silt is used for land reclamation to increase the area of the port (L Zhao, 2015). However, vegetation does not grow well on the reclaimed land because of the high salt and alkali content of the silt (salinity>1%, pH>8.0) (Thorup JT, 1969; Tuteja N, 2007 ;Waśkiewicz A et al., 2013). The area of reclaimed land is increasing every year, but the area has become wasteland due to the poor ecological function of the soil. Understanding how to develop the silt into soil rapidly is the key to improving the land quality.

Since the commencement of the dredger-fill project in 2000, many scholars have made efforts to improve the quality of dredger-fill silt in many ways. In terms of physical and chemical properties, some scholars filled the waste into the silt to improve it, such as gypsum, bran, sand

and so on(Zhang Wan-jun et al,. 2001a, 2002b; Guo Hongyu et al,. 2005；Wang Guoqiang et al,. 2011；Jin Cong, 2013; Tian miao et al,. 2014;). In the perspective of bioremediation, some scholars proposed planting halophytes can improve the silt quality (Zou Guimei et al,. 2010). Although these measures have some good effects in a short period of time, the long-term effect is not well, and the cost of manpower and material resources is enormous, so the practicability still needs to be studied. In view of the current research, most scholars hope to improve silt quality directly through external means, but they ignore the silt can transform into soil in a natural long evolution. Therefore, this study suggests that the combination of the natural evolution and artificial modification can be used to improve the silt quality. Artificial improvement could be guided by the study of various natural factors changes in the evolution process of silt. At the same time, the use of artificial improvement means can conform to the natural evolution trend, guiding and accelerating the dredger-fill silt to change into soil.

Under natural conditions, soil formation takes million years and is impacted by various factors, while manual intervention is expected to shorten the time of soil formation. After extracted into the terrestrial ecosystem and exposed to natural environment, silt tend to evolve into soil with ecology function, which was affected by geological processes and multi－factors process (air, microorganisms, temperature, humidity, and other factors). In this study, 15 chemical properties of the dredger-fill silt are determined. Principal component analysis is used to evaluate the changes in soil over time, indicating the change of dredger-fill silt fertility during the period of soil formation. Exploring the natural evolution process of silt has guiding significance for the artificial improvement of silt.

1 Materials and Methods

1.1 Soil collection

Soil samples were selected from the Tianjin Port area in 2016. The soil formation time is different at every sampling point (Figure 1). As the sampling took place all in the same year, dredger filling time represents the soil formation time, including soil formation for year 0 (S0), year 1 (S1), year 4 (S4), year 6 (S6), year 7 (S7), and year 8 (S8). As the sampling sites for year 2 (S2), year 3 (S3), and year 5 (S5) have been covered by construction, soil was not collected. At each soil sampling point, the topsoil (0–30 cm) was selected for the chemical properties study. Three replicate experiments were performed on each soil sample. Each soil sample was collected from multiple sites, mixed uniformly, then packed into plastic bags and taken to the laboratory. The soil samples were divided into two groups; a fresh sample was preserved at -20°C and the other sample was air dried after impurities such as gravel were removed, and sieved through two different sieve sizes (0.025 and 0.015 mm). In this study, we quoted the soil chemical properties of eight farmland sampling points from the literature (Wenmei Ma, 2011) that are located close to the silt sampling points , and every parameter was determined by the same method used in this study. The farmland sampling points are shown in Figure 1. The farmlands are located in the New Coastal Region of Tianjin; the soil has a near neutral pH and exhibits mild or moderate soil salinization. The mean value of the eight-farmland sampling points was used in order to ensure the accuracy of the data.

1.2 Analysis of the chemical properties of silt

The chemical properties of silt were determined by the conventional method(**Table 1**). The data were averaged over three replicates.

1.3 Principal component analysis

In this paper, 15 chemical properties were evaluated by principal component analysis (Jolliffe IT, 1986; Wold S et al., 1987 ； Liu XJ, 2010; Zhang SQ, 2011 ； Xie LW et al., 2015;). The comprehensive score was used to evaluate the silt fertility of each sample(Li B, 1992; Qin Z, 2015). As each variable represents a single index of silt fertility, the comprehensive score can represent the overall level of dredger-fill silt fertility. In addition, this study used Sigmaplot 12.5 and SPSS17.0 to analyze the data.

2 Results and discussion

2.1 Salinity and alkalinity of silt during the soil formation

With increased soil-forming time, the electrical conductivity (EC) and salinity of the dredger-fill silt first increased, then decreased (**Figure 2a and Fig 2b**). The EC of the soil samples positively correlate with salinity; both can be used to evaluate the degree of soil salinization. EC increased by 61.39% from S0 to S4 and then decreased by 36.20% from S4 to S8. The salinity of the dredger-fill silt increased slightly by 15% from S0 to S4 and then declined dramatically by 69% from S4 to S8. The silt underwent severe salinization from S0 to S4(Chinese Academy of Science, 1991). The level of salinization decreased significantly from S4 to S8. That indicates, salinization degree of silt had a reducing trend. In addition, the dredger-fill silt was strongly alkaline during soil formation; the pH values were 8.7–8.9 throughout the experiment and had no significant differences(**Figure 2c**).

At S0 , the silt maintained the high salinity and strong alkalinity of the marine environment, which were major limiting factors of soil formation. However, the salinity reduced with time improving conditions for soil formation. The alkalinity did not change with time and continued to inhibit soil formation.

With increasing soil formation time, the Na^+ and Cl^- content changed sharply, and the other ions changed slightly (**Figure 3**). Tests of significance showed that the K^+, HCO_3^-, and SO_4^{2-} content of the soil did not exhibit significant differences ($P > 0.05$), indicating that over the eight years the content remained stable. The content changes of Na^+, Cl^-, Ca^{2+}, Mg^{2+} exhibited significant difference ($P<0.05$), indicating that these ions had significant differences over eight years.

In S4, the Na^+, Cl^-, Mg^{2+}, and Ca^{2+} content of the silt increased 3 g/kg, 0.1 g/kg, 0.014 g/kg, and 0.043 g/kg respectively. From S4 to S8, the Na^+ content declined significantly by 17 g/kg. Compared with S0, the Na^+, Cl^-, Mg^{2+}, and Ca^{2+} contents of the silt declined by 14 g/kg (72%), 0.2 g/kg, 0.014 g/kg, and 0.04 g/kg, respectively. From S0–S8, the Na^+ and Cl^- content showed a declining trend, Mg^{2+} and Ca^{2+} content remained stable.

Sodium constitutes >90% of the salt in the silt. The Na^+ and Cl^- content are the main ions of salinity and had the most significant change with time (**Figure 3 and Figure4**); consistent with the marine characteristics of silt. In the marine environment, Na^+ and Cl^- account for the largest proportion of seawater salt. It indicates that the silt retained the high salinity marine characteristics in the initial stages of soil forming. However, salinity showed a decreasing trend and had a positive impact on the soil formation, which is consistent with Liu YJ (Liu YJ, 2010).

The salinity of silt in S8 decreased to 7.3 g/kg, less than the salinity of the farmland in Tianjin New Coastal Region (13.36 g/kg), which shows that salinity had reached the level of farmland. However, the pH did not significantly improve, retaining a strong alkali signature. The comparison with the nearly neutral pH of farmland (7.45) indicates that measures should be taken to reduce the pH in the dredger-fill silt. The K^+ content of the silt did not change significantly in the soil-forming process; the mean value was about 0.03 g/kg, far below that of farmland soil (1.604 g/kg). The low K^+ content inhibits soil formation and cannot be improved under natural soil-forming conditions. The Na^+ content showed a decreased trend, and the minimum value was 7 g/kg, less than that of farmland soil (11.364 g/kg). The decrease in Na^+ content has a positive impact on soil formation. The Cl^- content of silt had a decreasing trend, and the minimum value was 0.078 g/kg, slightly higher than that of the farmland (0.053 g/kg), but the difference narrowed with time, which is positive to the formation of soil. The Mg^{2+} content of silt 0.04 g/kg (mean value) throughout the eight years, and is concordant with the farmland soil values (0.037 g/kg), whichaccorded with the requirement of Mg^{2+} of soil. The Ca^{2+} content of silt was stable from S0-S8 with a mean value of 0.08 g/kg, lower than the farmland values (0.16 g/kg). The HCO_3^- content of the silt did not change significantly with soil formation time; the mean value was 0.44 g/kg, higher than the farmland soil value (0.029 g/kg). The SO_4^{2-} content of silt did not change significantly with the soil formation time, the mean value was 0.2 g/kg, higher than that of farmland (0.108 g/kg). The Ca^{2+}, HCO_3^-, and the SO_4^{2-} concentration cannot be improved under natural conditions and has a negative impact on soil formation. The natural change of salinity, Na^+ and Mg^{2+} content was positive to soil formation, while natural regulations of the other ions were negative to soil formation, which need artificial improvement urgently.

2.2 Effective nutrients during the soil forming process

The SOM, A-P, A-K, and nitrate-N content of the dredger-fill silt reduced linearly with increased time, while the content of ammonia-N showed a stable trend first and then increased significantly (Figure 4). The SOM, A-P, A-K, and nitrate-N content of the dredger-fill silt reduced by 3.75 g/kg, 5.97 mg/kg, 0.4 mg/kg, and 7.14 mg/kg, respectively, within eight years. Compared with S1, the SOM, A-P, A-K, and nitrate-N content of the dredger-fill silt reduced by 26.22%, 45.92%, 33.61%, and 86.23%, respectively.

The ammonia-N content was maintained from S0 to S6 and then increased by 84.31%, from 0.24 mg/kg (S6) to 1.53 mg/kg (S8). With increasing soil formation time, the nitrate-N content decreased and the content of ammonia-N increased (**Figure 3d and 3e**), indicating that some nitrate-N was converted to ammonia-N. The total inorganic nitrogen content showed a downward trend.

The analysis of the nutrients showed that the maximum organic matter content of the silt was 14.30 g/kg, which is less than farmland soil (23.6 g/kg). The SOM content of the silt decreased with increasing soil formation time, negatively influencing the soil forming process. The A-K content of the silt declined with increasing soil formation time to a minimum of 0.79 mg/kg during S8, more than that in farmland (0.47 mg/kg). Distinction of A-K content has a narrowing tendency between silt and farmland , which was positive for the soil formation. The nitrate-N content decreased with increasing of soil formation time and reached a minimum in S8 (1.14 mg/kg), much lower than the farmland soil value (290 mg/kg). The nitrate-N is more suitable for artificial improvement due to the large gap between the farmland and silt soil values. The maximum content of ammonia-N was 1.53 mg/kg, lower than the farmland soil (4.5 mg/kg), but it increased naturally with time. Overall, apart from the change of ammonia–N, which was favorable to soil formation, the loss of the other effective nutrients was severe within the eight years and limited soil formation.

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2.3 Comprehensive fertility evaluation based on principal component analysis

Principal component analysis (PCA) was used to analyze 15 chemical properties that represent the fertility level of silt, three principal components were extracted, and the accumulative contribution rate was 91.834%(**Table 2**). Due to the indicators in this experiment had different dimension and order of magnitude, data standardization processing needs to be applied, to eliminate the influence of dimension and order of magnitude on the evaluation results and ensure the objectivity and accuracy of evaluation, which was completed by SPSS software automatically. The standardized variables for each sample are denoted as Z1 to Z15.

The principal component is a linear combination of all the standardized indexes, and the weight is the component score coefficients of each index (**Table 2**), so the linear combination of the three principal components and the 15 original indexes can be obtained as follows:

$$F1=-0.022\times Z1+0.107\times Z2-0.085\times Z3+0.101\times Z4+0.086\times Z5+0.091\times Z6-0.008\times Z7-0.106\times Z8-0.014\times Z9+0.101\times Z10+0.12\times Z11+0.14\times Z12-0.065\times Z13+0.15\times Z14-0.095\times Z15$$

$$F2=0.160\times Z1+0.045\times Z2-0.065\times Z3+0.112\times Z4-0.157\times Z5+0.127\times Z6+0.186\times Z7-0.122\times Z8+0.046\times Z9-0.111\times Z10-0.103\times Z11-0.034\times Z12+0.155\times Z13+0.028\times Z14+0.101\times Z15$$

$$F3=0.229\times Z1+0.292\times Z2-0.335\times Z3-0.216\times Z4+0.012\times Z5+0.137\times Z6-0.016\times Z7+0.121\times Z8+0.121\times Z9-0.217\times Z10+0.158\times Z11-0.079\times Z12+0.008\times Z13-0.087\times Z14-0.114\times Z15$$

By substituting the standardized data into the above formula, the scores of 6 samples on three principal components can be obtained.

In this study, the comprehensive fertility of 6 samples was represented by comprehensive scores of principal component analysis. The comprehensive score formula is $F=0.43\times F1+0.34\times F2+0.15\times F3$, the coefficients are the principal component contribution rates. The principal component scores and comprehensive scores of each sample are shown in **Table 3**.

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The comprehensive fertility of the silt showed a downward trend, and the loss of soil fertility was severe which was consistent with the above results, which further verified the serious fertility loss in the process of soil formation over the eight-year soil formation time (**Figure 5**).

2.4 Discussion on improvement methods of dredger-fill silt

Artificial improvement and manual regulation of the silt is needed to adjust the pH values to improve the strong alkaline environment. The pH values can be adjusted by adding calcium reagent and acidic substances(Rhoades JD and Loveday J, 1990), and adding industrial waste (e.g., fly ash)(Xiuzhen Z and Jiang W, 1990; Xun Z et al., 2011; Nan C, 2012; Wen Z et al,. 2013). Reducing the salinity and alkaline can be achieved by irrigation and drainage engineering (Wang X et al,. 2013). Organic nutrients, like organic matter, A-K, A-P, and nitrate-N should be added manually. Artificial intervention should be performed in the early stages of soil formation to reduce the loss of silt fertility. The application of organic fertilizer and eutrophic sludge(Jihong Z et al., 1986; Li G et al., 2002 ; Bo F et al., 2012; Liang Z et al., 2014; Liangquan W et al., 2015) can be used for soil reclamation. Ions (K^+,Ca^{2+}, HCO_3^-, SO_4^{2-}, etc.) were added to the dredger-fill silt to increase the concentrations to reach the farmland ion content level. In addition, plants and other biological methods are feasible ways to improve the silt fertility (Cui J et al., 2012; Pinho RC et al., 2012; Li X et al., 2015).

3 Conclusion

(1) The dredger-fill silt changed from severe to mild salinization during the eight years of soil formation. Na^+ and Cl^- were the most abundant ions and showed the greatest change; the other ions were present in lower concentration and changed slightly. The pH value of the silt was >8.5 and did not vary during the study period.

(2) The silt effective nutrient loss was severe. The concentration of organic matter, nitrate-N, A-P, and A-K decreased by 3.75 g/kg, 7.14 g/kg, 5.97 g/kg and 0.4 g/kg respectively, indicating that effective nutrients loss was severe.

(3) Using the principal component analysis method, the comprehensive fertility of the silt was evaluated. The results showed that silt fertility decreased significantly and the total fertility loss was severe.

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Figure 1

Experimental sampling area and distribution map of Tianjin Port

Black triangles: Sampling sites of cropland New Coastal Region of Tianjin（Wenmei Ma, 2011）; Black box: Silt sampling area in Tianjin(Supported by Tianjin Port Gulf Landscaping Limited Company). ①:Silt extracted in 2016, soil formation time was 0 years (S0). ②: Silt extracted in 2015, soil formation time was 1 year (S1). ③:Silt extracted in 2010, soil formation time was 6 years (S6). ④: Silt extracted in 2009, soil formation time was 7 years (S7). ⑤: Silt extracted in 2008, soil formation time was 8 years (S8). ⑥: Silt extracted in 2012, soil formation time was 4 years (S4).

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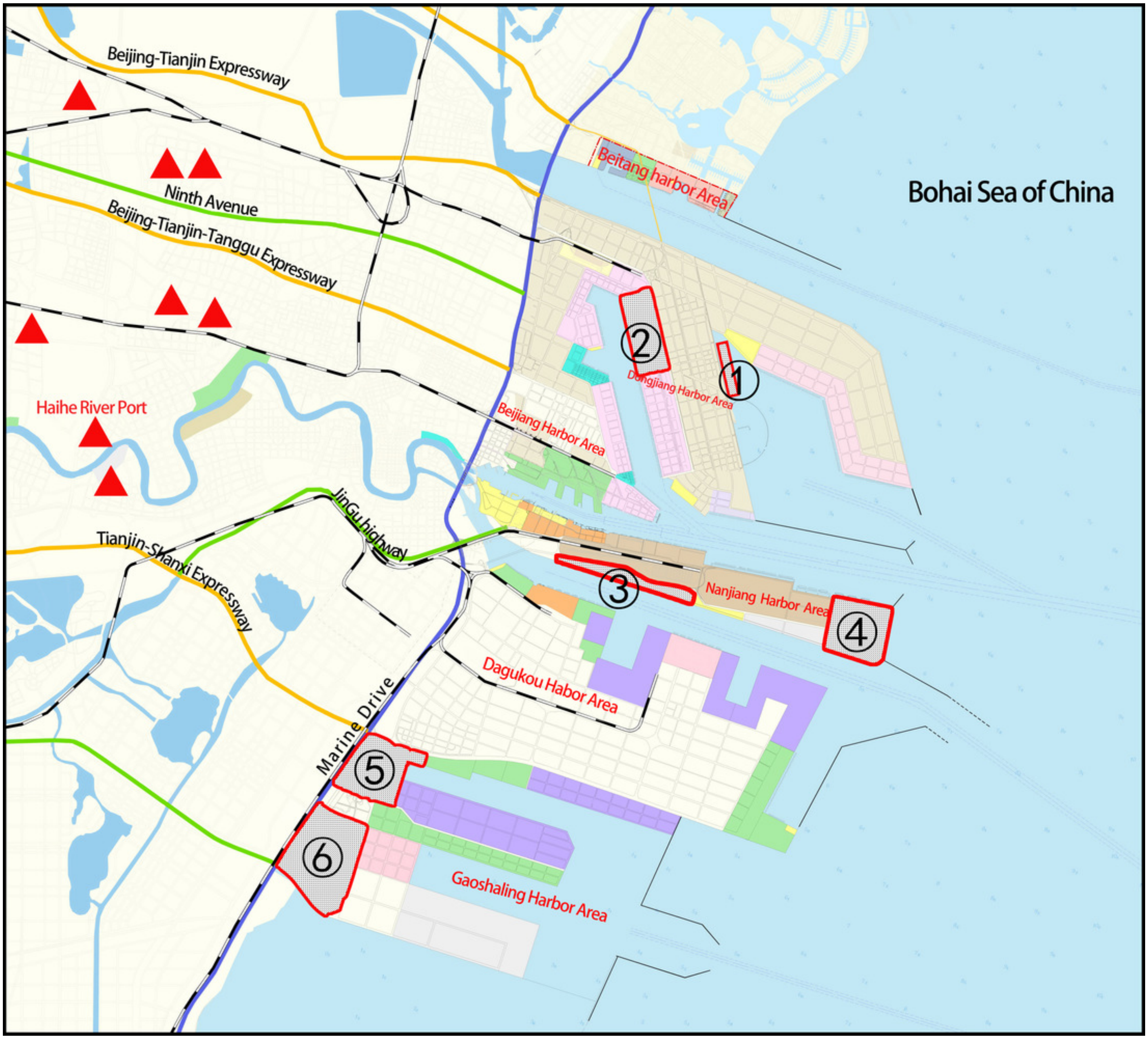
Beijing-Tianjin Expressway
Bohai Sea of China
Beitang harbor Area
Ninth Avenue
Beijing-Tianjin-Tanggu Expressway
Dongjiang Harbor Area
Haihe River Port
Beijiang Harbor Area
JinGu highway
Tianjin-Shanxi Expressway
Nanjiang Harbor Area
Dagukou Habor Area
Marine Drive
Gaoshaling Harbor Area
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④
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Figure 2

Change of salinity and alkalinity in the process of dredger-fill silt soil-forming.

R-value of every fitting curve is shown in the top left corner of figure. Vertical bars indicate ± SE.

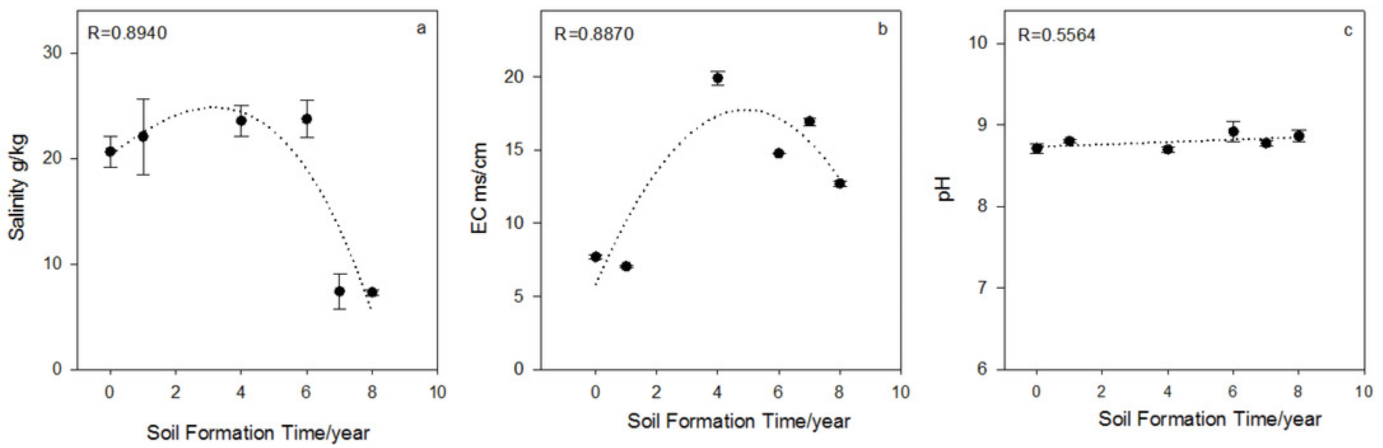

Figure 3

Change in water-soluble ion content and comparison with cropland.

R-value of every fitting curve is shown in the top left corner of the figure. Vertical bars indicate ± SE. The last picture is the water-soluble ions content of farmland in the New Coastal Region of Tianjin from the literature(Wenmei Ma, 2011). The mean value of eight samples is shown.

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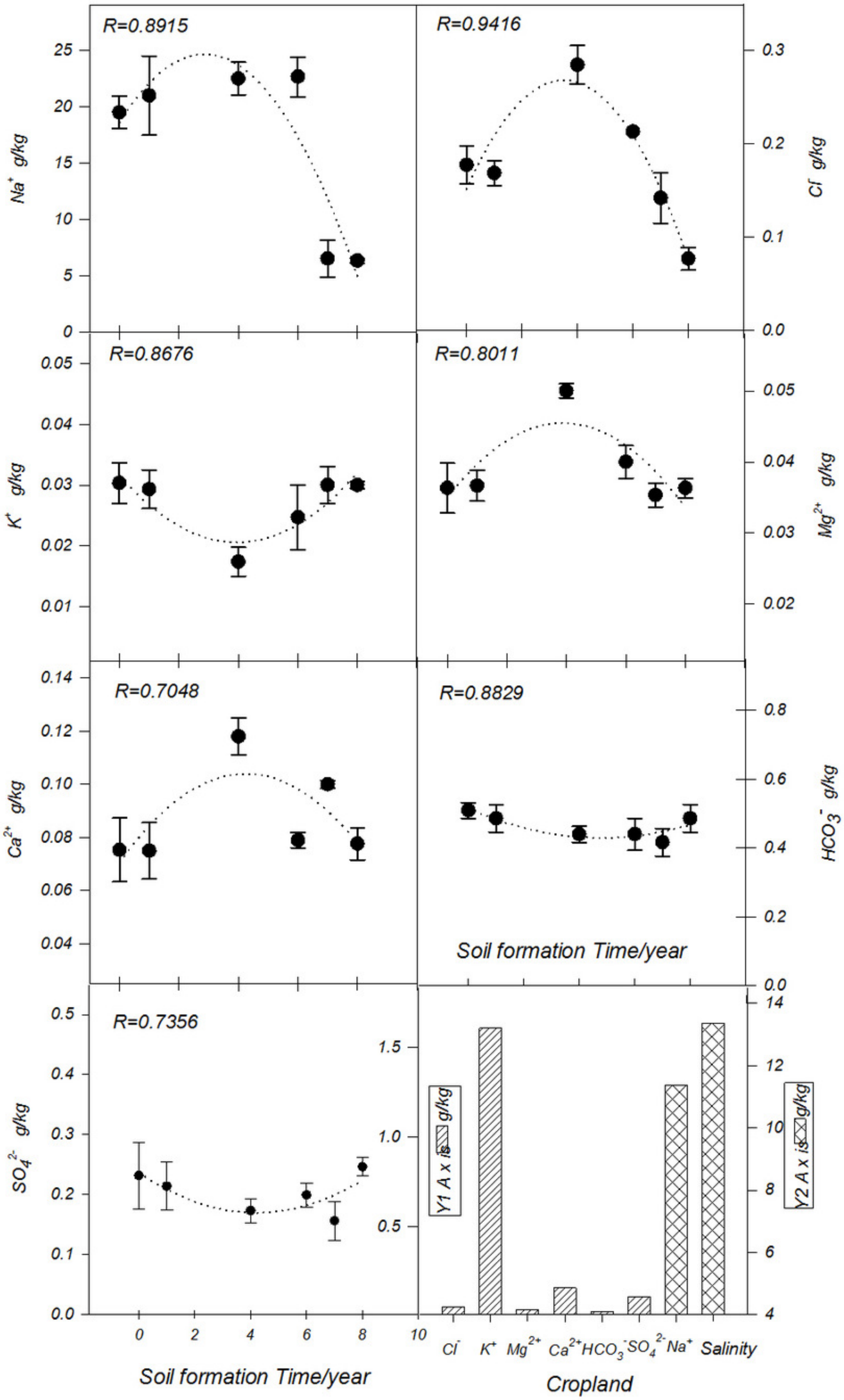
R=0.8915
Na+ g/kg
R=0.9416
Cl- g/kg
R=0.8676
K+ g/kg
R=0.8011
Mg2+ g/kg
R=0.7048
Ca2+ g/kg
R=0.8829
HCO3- g/kg
Soil formation Time/year
R=0.7356
SO42- g/kg
Soil formation Time/year
Y1 A x is g/kg
Y2 A x is g/kg
Cl- K+ Mg2+ Ca2+ HCO3- SO42- Na+ Salinity
Cropland

Figure 4

Change of effective nutrients and comparison with cropland (a f).

R-value of every fitting curve is shown in the top left corner of figure. Vertical bars indicate mean ± SE; (f) The concentration of effective nutrients in cropland in New Coastal Region of Tianjin. All data comes from literature, which were mean values of eight samples.

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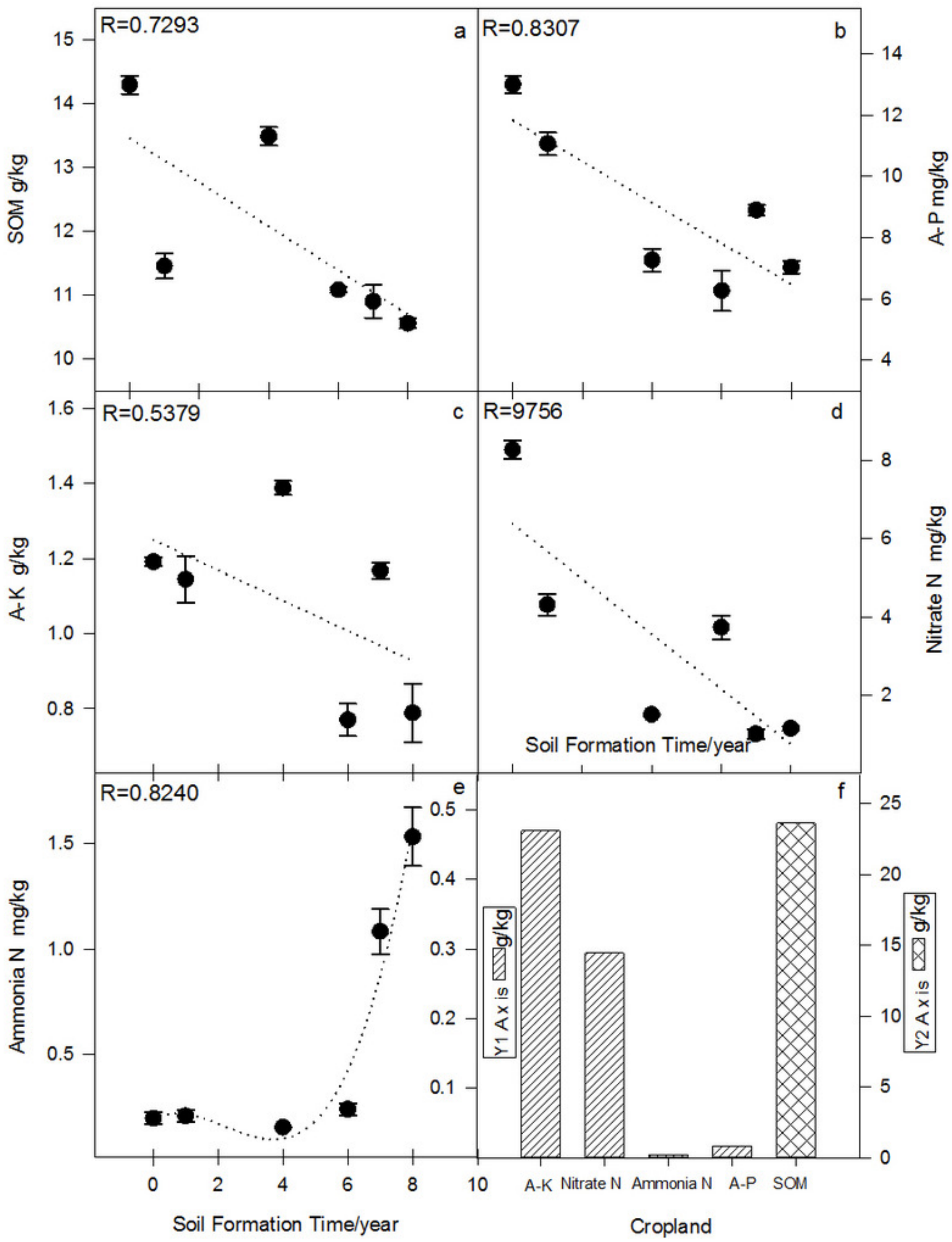
R=0.7293
a
R=0.8307
b
SOM g/kg
A-P mg/kg
R=0.5379
c
R=9756
d
A-K g/kg
Nitrate N mg/kg
Soil Formation Time/year
R=0.8240
e
f
Ammonia N mg/kg
Y1 Axis is g/kg
Y2 Axis is g/kg
A-K
Nitrate N
Ammonia N
A-P
SOM
Soil Formation Time/year
Cropland

Figure 5

Change in silt fertility during soil formation.

The comprehensive fertility of silt is characterized by the comprehensive score of the principal component analysis, and the comprehensive scores fit a curve, showing the change in fertility level. The R-value of the curve is shown in the top left corner of the figure.

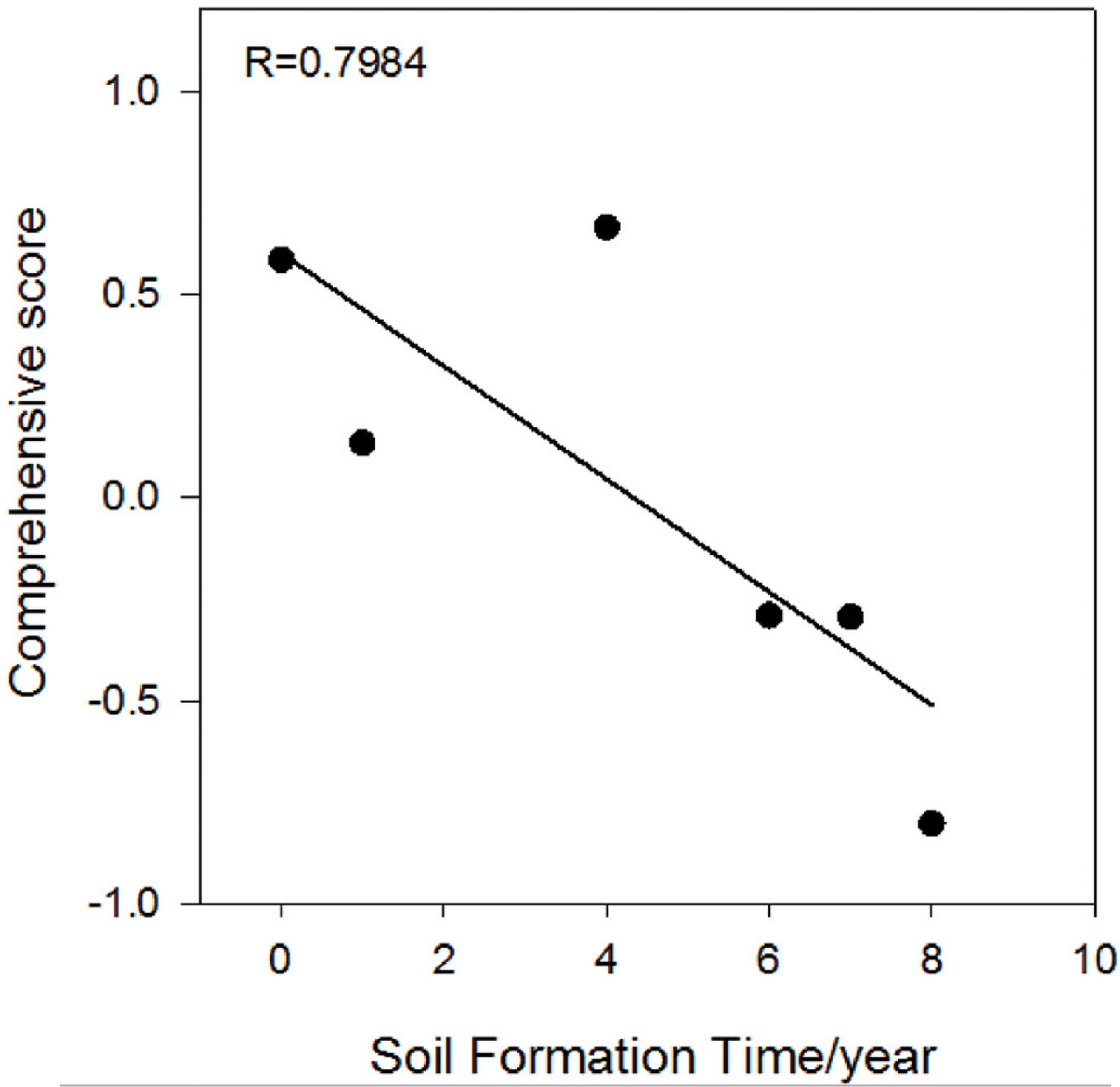

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Table 1 (on next page)

Chemical Properties and Fertility Analysis of Dredger-fill silt During Soil Formation: The Tianjin Dredge–Fill Project Measured methods of chemical properties

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Chemical properties	Measured methods
pH	Potentiometry (Fanggong S and Junliang L, 2004)
A-K	ammonium acetate extraction and the flame photometric method (Fanggong S and Junliang L, 2004)
A-P	molybdenum blue colorimetric method(Fanggong S and Junliang L, 2004)
SOM	potassium dichromate method (Fanggong S and Junliang L, 2004)
EC	FE3-type METTLER TOLEDO conductivity meter
K^+	flame photometry(Shitan Bao, 2000)
Na^+	flame photometry(Shitan Bao, 2000)
Ca^{2+}	atomic absorption spectrophotometry(422.7nm) (Shitan Bao, 2000)
Mg^{2+}	atomic absorption spectrophotometry(285.2nm) (Shitan Bao, 2000)
Cl^-	silver nitrate titration(Shitan Bao, 2000)
SO_4^{2-}	EDTA Indirect Complex metric titration(Shitan Bao, 2000)
Salinity	sum of the eight major ions(Shitan Bao, 2000)
Nitrate-N	continuous flow analyzer (dissolution in potassium chloride)
Ammonia-N	continuous flow analyzer (dissolution in potassium chloride)
HCO_3^-	Double Indicator - Neutralization Titration (Shitan Bao, 2000)

Table 2 (on next page)

Chemical Properties and Fertility Analysis of Dredger-fill silt During Soil Formation: The Tianjin Dredge–Fill Project Principal component analysis of chemical properties of silt.

	Properties	Component scoring coefficient			Components	eigenvalues of the correlation matrix		
		f1	f2	f3		Eigenvalue	Proportion %	Cumulative%
Z1	HCO_3^-	0.163	0.022	0.034	f1	6.42	42.801	42.801
Z2	Nitrate-N	0.156	0.089	0.05	f2	5.102	34.015	76.817
Z3	SO_4^{2-}	0.144	0.044	-0.099	f3	2.253	15.018	91.834
Z4	A-P	0.131	-0.068	0.238				
Z5	K^+	0.112	-0.142	0.058				
Z6	Salinity	0.044	0.241	-0.097				
Z7	SOM	0.044	0.046	0.198				
Z8	Na^+	0.043	0.241	-0.097				
Z9	pH	0.014	0.095	-0.338				
Z10	A-K	-0.041	-0.066	0.304				
Z11	Ammonia-N	-0.044	-0.197	0.012				
Z12	Cl^-	-0.06	0.166	0.001				
Z13	Mg^{2+}	-0.104	0.125	-0.018				
Z14	Ca^{2+}	-0.161	-0.052	0.146				
Z15	EC	-0.178	-0.019	-0.009				

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Table 3(on next page)

Chemical Properties and Fertility Analysis of Dredger-fill silt During Soil Formation: The Tianjin Dredge–Fill Project Principal component score and comprehensive score of samples

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Samples	F1	F2	F3	Comprehensive scores
S0	-0.12713	1.59001	0.6613	0.585133
S1	-0.24588	0.79137	-0.19104	0.134681
S4	1.78421	-0.38973	0.20062	0.664795
S6	0.11665	-0.23146	-1.74199	-0.28984
S7	-0.23516	-1.0934	1.19805	-0.29317
S8	-1.2927	-0.66679	-0.12694	-0.80161

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