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Study on Soil Salinization Characteristics of Farmlands Along West Trunk Canal in Ningxia Based on Redundancy Analysis

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Abstract. Based on the statistical analysis and redundancy analysis on the soil sampling points along West Trunk Canal in Ningxia of China, the spatial distribution characteristics and relations among total salt content, pH value and salt ions' composition at different depths are obtained. The correlation coefficients, eigenvalues and interpretation variances of salt ions in each soil layer are analyzed and discussed. According to the analysis, it can be concluded that the farmlands along West Trunk Canal is severely salinized, especially for the soil near the shallow surface. The redundancy analysis results show that in the 0-80cm soil layer, the angles between CO_3^{2-} and pH value and HCO_3^- and pH value, are smaller than other environmental factors, indicating that soil pH value is significantly affected by the content of CO_3^{2-} and HCO_3^-, and they are positively correlated. K^+ and Cl^- have the smaller and acute angle with total salt, indicating that total salt of the soil is significantly affected by the content of K^+ and Cl^- and they are also positively correlated. Different from others, in the 80-100cm soil layer, pH value is significantly affected by the content of Na^+ and the total salt of the soil is significantly affected by the content of Mg^{2+}, Cl^-, CO_3^{2-} and HCO_3^-.

Keywords. Salinization, redundancy analysis, total salt content, West Trunk Canal

1. Introduction

Soil salinization generally occurs in arid and semi-arid regions, and secondary salinization occurs periodically with seasonal rainfall and temperature. Due to the difference of land use in various areas, the salinization of cultivated land in different regions will show special characteristics in the long-term evolution process [1-3]. A comprehensive understanding of the general rules of soil salinization in irrigated areas is a necessary premise for preventing and controlling the further deterioration of salinization, and also provides a necessary basis for improving the salinization soil and scientifical use of land.

Some scholars have studied the distribution characteristics, salt composition, influencing factors and space-time variation of soil salinization. Shihaibin *et al*. [4] used descriptive statistics, surface clustering coefficient, geo-statistics and cluster analysis to systematically study the characteristics and spatial distribution of soil

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profile salinity before and after water-saving transformation. Wu *et al*. [5] analyzed the eight salt ions and pH values along West Trunk Canal by Pearson correlation analysis and principal component analysis, KZ Jadoon *et al*. [6] quantitatively estimated the distribution of soil salinity by using joint inversion of multicoil electromagnetic induction measurements. However, most of the above results consider the degree of soil salinization from a single index, and rarely consider the influence of different salt ions on soil salinization and alkalinization indexes and the characteristic factors dominated by regional soil salinization.

Ningxia Yellow River Diversion irrigation area is located in the northwest of China, with typical continental climate. It is one of the super large irrigation areas in China, and is also an important commodity grain base in China. Due to the influence of climate and irrigation and drainage conditions for many years, soil salinization is serious in this irrigated area. At present, the improvement of large area salinized soil in the Yellow River irrigation area of Ningxia still mainly depends on flushing and salt washing, and the water source is Yellow River. However, with the contradiction between supply and demand of water resources in Yellow River, above methods need to consume a large amount of water resources, which restricts the economic development of Ningxia to a certain extent and has affected high-quality and sustainable development of agriculture [7]. Thus, there is an urgent need to find a more effective way to improve soil salinization. The first step to improve salinized soil is to explore the composition of salt ions in soil and then accurately classify the types of salinized soil so as to better improve and utilize salinized soil. In view of the increasing interaction between the natural environment and human activities, ecogeographic zoning is increasingly required for environmental monitoring and management [8], while soil salinization characteristics of geographic zones require more accurate classification. Therefore, it is necessary and practical to ascertain the salinization status and salinization type in this area.

2. Methodology

2.1. The Studied Area

West Trunk Canal was built in the winter of 1959 and its irrigation area is 120 kilometers from the north to the south and 11 kilometers from the east to the west. It plays a very important role for farmland irrigation and flood control along the banks of the canal. The studied area has obvious continental climate characteristics of arid and semi-arid areas, with dry and windy spring, slightly more rainfall in summer, short autumn and dry and cold winter. The annual average temperature is 8.3°C, the annual average precipitation is 202mm, and the annual average evaporation is about 1800mm.

2.2. Research Methods

2.2.1. Typical Sampling Point Selection

In this study, 28 points are chosen for soil sampling. Total salt and pH value are taken as salinization indexes, and Na^+, Ca^{2+}, Mg^{2+}, K^+, SO_4^{2-}, Cl^-, HCO_3^- and CO_3^{2-} are taken as environmental variables. Firstly, detrended correspondence analysis are carried out on the research objects of each layer, and the results shows that the maximum gradient length of each ranking axis was less than 3, indicating that it is suitable for the redundancy analysis of linear corresponding model. Due to the dimensional inconsistency of research objects, error variance standardization should be carried out first, lg(x+1) conversion of data except pH value, and then redundancy analysis of salinization indexes and salt ions of each soil layer should be carried out [9]. In October 2020, using GPS positioning technology, the research group selected a total of 28 cultivated land sampling points along the banks of West Trunk Canal. The sampling depth is uniformly 0-100cm, which is respectively 0-20, 20-40, 40-60, 60-80 and 80-100cm. The spatial distribution of soil sampling positions is shown in figure 1.

Routine statistical analysis of soil salinity data in each layer was dealt with Microsoft Excel 2016 and JMP Pro14, and CANOCO 5.0 software was used for detrended correspondence analysis and redundancy analysis.

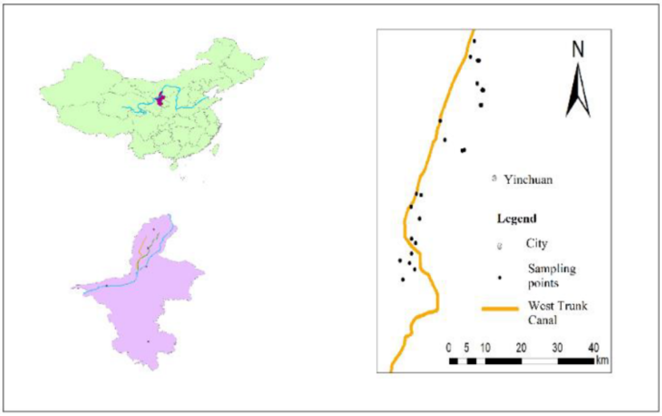


Figure 1. Distribution of sampling points.

2.2.2. Soil Sample Collection

The salt content of soil samples was measured according to *Soil Physical and Chemical Analysis* complied by Nanjing Institute of Soil Research. All the collected soil samples were air-dried in the room and passed through a 1mm sieve for later use. The contents of eight ions, namely, Na^{+}, Ca^{2+}, Mg^{2+}, K^{+}, SO_4^{2-}, Cl^{-}, HCO_3^{-} , CO_3^{2-} and pH value were measured by Ningxia Public Third Party Testing Cooperation, LTD.

2.2.3. Redundancy Analysis Method

Redundancy analysis is a multi-variable direct gradient analysis method, which is an extension of multiple linear regression and can reflect the correlation between response variables and explanatory variables [10]. By adopting the linear relationship model of two variable sets, the data matrix is obtained and the eigenvalues are decomposed, which can reflect the relationship between the indexes of soil salinization and the environmental factors such as salt ions [11]. To be specific, redundancy analysis is employed to analyze the causes of original variable variation through the correlation between original variables and typical variables. With the original variable as the dependent variable and the typical variable as the independent variable, the linear regression model is established, and the corresponding determination coefficient is equal to the square of the correlation coefficient between the dependent variable and the typical variable. It describes the proportion of the variation of the dependent variable in the total variation of the dependent variable. Finally, the sample points are projected onto a two-dimensional plane formed by two sorting axes, and the characteristics of the studied area are reflected by the scatter patterns and quadrants of the sample points.

3. Result and Analysis

3.1. Comparison of Total Salt Content among various Soil Layers

Total salt content is an important index to measure soil salinization, which directly reflects the degree of soil salinization. As can be seen from table 1, the total salt content (TS) of each soil layer in the study is greater than 1.5 g/kg, indicating that the soil in each soil layer within 0-100cm in this area is salinized, among which the average total salt content of the 0-20cm soil is 2.78g/kg, reaching a moderate salinization level, and the 0-100cm soil shows a downtrend with the increase of soil depth, which shows that soil salt in the cultivated land in the studied area have obvious gathered phenomenon in surface.

The coefficient of variation (CV) is an important index reflecting the degree of dispersion of variables, which reveals the spatial distribution characteristics of variables to a certain extent. The CV of each soil layer in the studied area ranges from 37.6% to 86.3%, and decreases with the increase of soil depth. Before October, as some crops have been harvested, soil irrigation is reduced, and there was no crop cover on the soil surface, resulting in a sharp increase in evaporation. The soil salt rise strongly with capillary water, and the salt migrated to the soil surface. However, some crops had not been harvested, hindering the upward migration of water, which caused the CV of total salt content of 0-20cm soil layer is the largest.

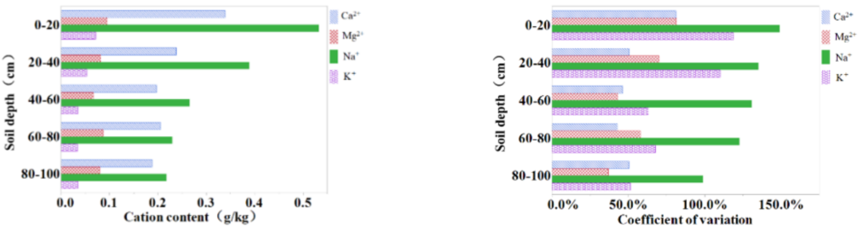
Table 1. Total salt content and vertical variation of various soil layers.

Soil depth / cm	Total salt content					
	Number of soil sample	Mean / (g/kg)	SD (Standard deviation)	MAX	MIN	CV / %
0-20	28	2.78	2.38	9.58	0.94	86.3
20-40	28	2.15	1.48	6.66	0.96	65.5
40-60	28	1.78	0.80	4.08	0.97	41.7
60-80	28	1.77	0.75	3.68	0.44	39.4
80-100	28	1.79	0.67	3.55	0.97	37.6

3.2. Comparison of Soil Salt Ions among various Soil Layers

Figure 2 shows the distribution of cations in each soil layer. The content of Na^+ accounts for 41.32%-51.35% of the total cations. The content of Ca^{2+} is next, accounting for 31.23%-36.89%; the proportion of Mg^{2+} ranges from 9.13% to 15.69%; the percentage of K^+ is the lowest, which only accounts for 6%-7%. The distribution trend of Ca^{2+}, Na^+ and K^+ contents in the profile are basically consistent with TS, showing that soil salt ions decrease with the increase of soil depth. The maximum contents of Ca^{2+}, Mg^{2+}, Na^{+} and K^{+} appears in the 0-20cm soil layer. The minimum content of Ca^{2+} and Na^{+} appears in 80-100cm soil layer. The minimum content of Mg^{2+} appears in the 40-60cm soil layer. The minimum content of K^{+} is found in the 60-80cm soil layer. In addition, the distribution trend of Mg^{2+} in the vertical profile of soil is relatively stable.

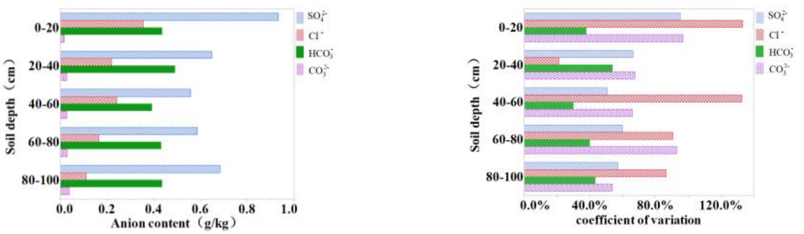
As shown in figure 2, the CV of Na^{+} and K^{+} are between 51.4% and 149.13%, showing medium-high spatial variability. The CV of Na^{+} and K^{+} generally shows a downward trend with the increase of soil depth, and the maximum value appears in the 0-20cm soil layer. The CV of Ca^{2+} shows a trend of high in the surface layer and bottom layer, and low in the middle layer. The maximum value appears in the 0-20cm soil layer, and the minimum value appears in the 60-80cm soil layer. The CV of Mg^{2+} shows an obvious increase in the 60-80cm soil layer.



(a) Distribution of cation content (b) Distribution of variation coefficient

Figure 2. Comparison of the major cations' content and their vertical variations among various soil layers.

The contents of major anions in each soil layer in the studied area are shown in figure 3. As shown in figure 3, the content of CO_3^{2-} in the soil of salinized farmland in the irrigated area is the lowest, and the content in each soil layer is less than 0.038g/kg, showing an increasing trend with the increase of soil depth. The content of SO_4^{2-} is the highest, accounting for more than 45% of the total anions in each soil layer. The content distribution trend is higher in the surface layer and bottom layer compared with the middle layer. The maximum value appears in the 0-20cm soil layer, and the minimum value appears in the 40-80cm soil layer. In the studied area, the content of HCO_3^- is second only to SO_4^{2-}, accounting for 25.1%-35.7%, and there is little difference in the content of HCO_3^- among different soil layers.

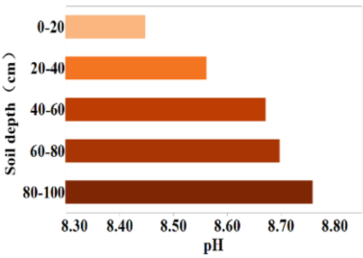


(a) Distribution of anion content (b) Distribution of variation coefficient

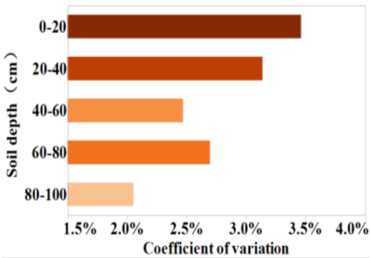
Figure 3. Comparison of the major anions' content and their vertical variation among various soil layers.

3.3. Comparison of Soil pH Value among various Soil Layers

PH value is usually used as an index to judge the occurrence of soil alkalinization and classify the level of alkalinization. As shown in figure 4, the change trend of pH in each soil layer is exactly opposite to TS, and the pH value rises with the increase of soil depth. The range of pH is between 8.45 and 8.76, which indicates that the soil of each layer has an obvious trend of alkalinization, and it is a medium strength alkalinization soil. The coefficient of variation of soil pH is very small, ranging from 2.1% to 3.5%, and its spatial distribution is very uniform at the same depth.



(a) Distribution of pH value



(b) Distribution of variation coefficient

Figure 4. Comparison of soil pH value and the vertical variation among various layers.

3.4. Redundancy Analysis of Salt Ion and Salinization Indexes

TS can be used to represent the degree of soil salinization, and pH value can be used to represent the degree of soil alkalization. The data of the above two indexes and soil salt ions cannot directly reflect the correlation between them. In this study, the redundancy analysis is used to deeply explore the characteristics of soil salinization in the area.

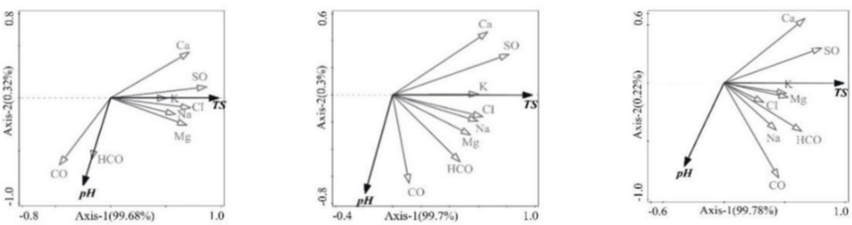
The redundancy analysis takes TS and pH value as response variables, and eight kinds of salt ions as environmental variables, and finds the relationship between soil salinization indexes in the longitudinal profile and soil salt ions in the two-dimensional ordination diagram. In the redundancy analysis ordering diagram, the solid arrows represent the response variables, namely total salt content and pH value; the hollow arrows represent the environmental variables, namely Na^+, Ca^{2+}, Mg^{2+}, K^+, SO_4^{2-}, Cl^-, HCO_3^- and CO_3^{2-}; the length of these lines represents the degree of influence from the environmental variables, and the cosine of the angle between the response variable and an environmental variable represents the degree of correlation between them [12].

According to figures 5(a)-5(d), in the 0-80cm soil layer, the angles between CO_3^{2-} and pH value, and between HCO_3^- and pH value, are smaller than other environmental factors, indicating that the pH value is affected by the content of CO_3^{2-} and HCO_3^-, and they are positively correlated. K^+ and Cl^- have the smaller and acute angle with TS, indicating that TS is affected by the content of K^+ and Cl^- and they are also positively correlated. Different from others, in the 80-100cm soil layer, pH value is affected by the content of Na^+ and the TS is affected by the content of Mg^{2+}, Cl^-, CO_3^{2-} and HCO_3^-.

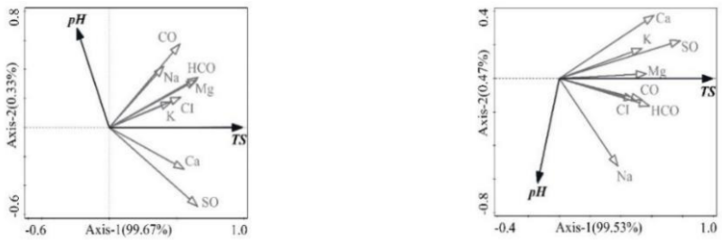
According to the *2020 Water Resources Bulletin* [13] reported by Ningxia Water Resources Department, the underground water level in October, January, February, March and April in 2020 in the irrigation area of the North in Yinchuan is slightly more than 2-m below the soil surface. The secondary salinization of soil is produced by the alternation of two opposite processes of salt accumulation and leaching. Soil salinization is mainly determined by the intensity and the possible height of soil capillary action. According Yuan's study [14], the height of capillary water in light soil of the whole section was 1.65m, and the soil of the studied area in 80-100cm layer is always within the range of the height of capillary water. Therefore, the salinity of groundwater has great influence on salt conditions in the 80-100cm soil layer.

By analyzing the controlled factors of response variables in different soil layers, the lengths of vectors of CO_3^{2-} and SO_4^{2-} in 0-20cm soil layer are relatively larger, which indicates that the spatial distribution of pH value and total salt are mainly affected by these salt ions; the lengths of vectors for CO_3^{2-}, SO_4^{2-} and Ca^{2+} in the soil layers of 20-40cm, 40-60cm and 60-80cm are approximately equal, which indicates that the contents of these ions equally affect the spatial distributions of soil pH value and TS. From figure 5, it can be found that the angle between the vectors for CO_3^{2-} and HCO_3^- is acute and relatively smaller, which suggests that the two ions are positively correlated. When soil depth increase, the angles between the vectors for CO_3^{2-}, pH value and HCO_3^-, pH value also increases gradually, so the correlation between them is decreasing. The increasing alkalinity of soil results in spatial heterogeneity of CO_3^{2-} and HCO_3^- contents.

The angle between Na^+ and Cl^- in 0-100cm soil layer is very small, which says that these two ions are in good correlation. Moreover, it can be found that the correlation between Na^+ and Cl^- is gradually weakening along downwards direction. K^+, Mg^{2+} and Na^+ are obviously correlated, and these three kinds of cations are easily soluble in the presence of SO_4^{2-}, the most abundant anion in soil. Moreover, the water and salt transport processes of these three kinds of cations are similar, resulting in strong correlation in the whole section. In addition, the climatic conditions for the occurrence of alkaline soils are usually arid and semi-arid areas where evapotranspiration exceeds rainfall, which is conducive to the retention and accumulation of exchangeable cations. The ratio of evaporation to precipitation in Ningxia Yellow River irrigation area is always more than 6, soil alkalinity is a function of calcium carbonate content in the bottom layer. Carbonate accumulates in carbonate-rich dust that is initially blown to the surface of the soil, and is also related to the chemical composition of soil parent materials. Precipitation combines with carbon dioxide in the atmosphere or soil to form weak carbonic acid. Ca^{2+} and HCO_3^- are released as a result of chemical reaction between calcium carbonate and carbonic acid in soil surface. Salt moves with water, that is, driven by soil water potential, mainly gravity potential, to the deeper soil profile. Under the condition of deep dry soil, the above chemical reaction will be in the reverse direction, the formation of secondary carbonate precipitation. Relevant studies have shown that the exchangeable cation of soil with high pH value is completely saturated, and there is free calcium carbonate in the soil.



(a) 0-20cm (b) 20-40cm (c) 40-60cm



(d) 60-80cm (e) 80-100cm

Figure 5. RDA through two-dimensional ordination diagram in various soil layers.

4. Conclusion

In this study, the redundancy analysis method is employed to analyze the soil sampling points along West Trunk Canal in Ningxia of China, and the spatial distribution and relations among TS, pH value and salt ions' composition are obtained. According to the method, the following conclusions can be obtained.

(1) The farmlands along West Trunk Canal are severely salinized, especially for the soil near the surface layer.

(2) In the 0-80cm soil layer, soil pH value is significantly affected by the content of CO_3^{2-} and HCO_3^-, and the TS is significantly affected by the content of K^+ and Cl^-.

(3) In the 80-100cm soil layer, the pH value is significantly affected by the content of Na^+ and the TS is significantly affected by the content of Mg^{2+}, Cl^-, CO_3^{2-} and HCO_3^-; in the 80-100cm soil layer, the salinity has great influence on the transport of water and salt.

(3) The major anion and cation in soil are SO_4^{2-} and Na^+ respectively. Except for HCO_3^-, the change trends of all ions content in each soil layer are similar to that of TS. The variation trend of pH in each soil layer is opposite to that of total salt yet.

(4) K^+ and Cl^- are the most strongly correlated with total salt content; HCO_3^- and Cl^- are the most strongly correlated with pH; SO_4^{2-} and Na^+ in anions and cations contribute the most to soil salinization; K^+ has the least influence on soil salinization yet; Cl^- decreases with the increase of soil depth.

(5) Compared with conventional statistical methods, the redundancy analysis can more intuitively display the characteristics of soil salinization in the studied area and the main factors affecting the degree and distribution of salinization. It is an effective method to analyze salinization information and can provide scientific basis for regional salinization evaluation, salinization soil management and land use management.

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Competing Interest

The authors declare that they have no competing interests.

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