Analysis of Soil Salinization and Fertility Characteristics Adjacent to Drainage Ditches in the Hetao Irrigation District, Inner Mongolia (Postprint)

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Date: 2021-03-02T17:00:01+00:00

Abstract

Rational improvement of saline-alkali land adjacent to drainage ditches in the Hetao Irrigation District can effectively promote ecological restoration of saline-alkali land and sustainable agricultural development in the irrigation district. Using methods of descriptive statistics and principal component analysis, the characteristics of soil salinization-alkalization and fertility of land adjacent to drainage ditches in the Urad Irrigation Subdistrict of the Hetao Irrigation District were analyzed. The results show that: (1) The soil in the study area belongs to severely chloride-type saline soil; Mg2+ is the key cation for high soil salinization, and excessively high Mg2+ content slows down the absorption rate of Na+ and exacerbates the soil alkalization process. (2) The soil alkalinity degree in the 0–40 cm soil layer ranges between 13.0% and 28.6%. The high soil alkalinity degree is attributed to two aspects: on the one hand, CaCO3 cannot prevent soil from adsorbing Na+, and on the other hand, Mg2+ in the soil cannot promote Na+ adsorption; there exists a positive correlation between soil pH and alkalinity degree, as well as total alkalinity. (3) Principal component analysis results indicate that soil salt content, Cl-, Ca2+, Mg2+, pH, total alkalinity, and alkalinity degree can be used as the main characteristic factors of soil salinization in the study area. (4) Soil potassium content in the study area is relatively high, while other nutrient elements are relatively low. The soil adjacent to drainage ditches belongs to composite saline-alkali land of chloride saline soil and alkaline soil, resulting in soil characteristics of particle dispersion, muddiness when wet, non-aeration, impermeability, hardening when dry, and extremely poor tillage properties; meanwhile, soil nutrients are relatively low, and other soil nutrient elements besides potassium should be supplemented in large quantities. This study plays an important role in analyzing saline-alkali

soil adjacent to drainage ditches in the Hetao Irrigation District, formulating rational land use policies and ecological improvement measures, and achieving regional sustainable development.

Full Text

Abstract

Reasonable improvement of saline-alkali soils adjacent to drainage ditches in the Hetao Irrigation Area can effectively promote ecological restoration and sustainable agricultural development in the region. This study analyzed the salinization and fertility characteristics of soils adjacent to drainage ditches in the Urad Irrigation District of the Hetao Irrigation Area using descriptive statistics and principal component analysis. The results indicate that: (1) The soils in the study area are classified as severely chloride-type saline soils. The Mg^{2+} content is the key cation determining soil salinization, and its excessive concentration slows the absorption rate of Na^{+} and intensifies soil alkalization. (2) The soil alkalization degree in the 0–40 cm layer ranges from 13.0% to 28.6%. High alkalization results from two factors: first, $CaCO_3$ cannot prevent soil from adsorbing Na^{+}; second, Mg^{2+} in the soil cannot promote Na^{+} adsorption. Soil pH shows a positive correlation with both alkalization degree and total alkalinity. (3) Principal component analysis reveals that soil salt content, Cl^{-}, Ca^{2+}, Mg^{2+}, pH, total alkalinity, and alkalization degree serve as the main characteristic factors of soil salinization. (4) The study area exhibits high potassium content but low levels of other nutrient elements. Soils adjacent to drainage ditches represent a compound saline-alkali land type combining chloride saline soil and alkaline soil, resulting in characteristics such as soil particle dispersion, muddy texture when wet, poor aeration and permeability, hard clods when dry, and extremely poor tillability. Concurrently, soil nutrients are low, requiring substantial supplementation of nutrient elements other than potassium. This research provides important insights for analyzing saline-alkali soils adjacent to drainage ditches in the Hetao Irrigation Area, formulating rational land use policies and ecological improvement measures, and achieving regional sustainable development.

Keywords: drainage ditch; salinization; salt ion; alkalization degree; principal component analysis; fertility; Inner Mongolia

Introduction

Soil salinization and alkalization are critical limiting factors in soil development and utilization, representing urgent challenges for improving cultivated land quality in arid and semi-arid regions. Throughout agricultural history, the importance of this issue has grown increasingly prominent. In many areas, rapid expansion of saline-alkali soils has led to significant declines in agricultural production. Soil salinization is primarily influenced by regional factors, with salt composition, accumulation, and leaching processes varying considerably due to differences in climate and geological conditions. In the Hetao Irrigation Area, the combination of special hydrogeological conditions and long-term irrational irrigation practices has resulted in severe land salinization and secondary salinization, with saline-alkali cultivated land covering approximately 39.4×10^4 hm^2, accounting for 68.65% of total cultivated land. This salinization causes difficulties in crop emergence and has forced large areas of cultivated land to be abandoned as saline wasteland, with wasteland area showing a yearly increasing trend. Consequently, soil salinization has become a primary constraint on land use in the Hetao Irrigation Area, limiting local agricultural economic sustainability.

Numerous scholars have conducted extensive research on the occurrence and evolution of soil salinization, its environmental impacts, and comprehensive management strategies, employing diverse analytical methods. Many researchers have used descriptive statistical analysis to classify the salinization and alkalization degrees of saline soils, while others have applied factor analysis and cluster analysis to evaluate saline-alkali land quality. Principal component analysis has been used to study salinization levels in the Hetao Irrigation Area, identifying soil salt content, Cl^-, Ca^{2+}, Mg^{2+}, pH, total alkalinity, and alkalization degree as the main factors characterizing soil salinity. Studies on ion variation trends in saline cultivated land have shown that soil salt composition changes over time, and research has also examined the spatial heterogeneity of key soil salinization parameters. Analyzing the characteristics of severely saline-alkali abandoned land in irrigation districts holds significant importance for local agricultural development.

Different types of saline-alkali soils require different improvement measures, making characteristic analysis particularly crucial. In the Hetao Irrigation Area of Inner Mongolia, severely saline-alkali soils are mainly distributed in low-lying areas along the main canals, main drainage ditches, and surrounding Wuliangsuhai Lake, characterized by high silt content that leads to slow water infiltration and year-round salt accumulation. Although considerable research exists on soil salinization in the Hetao Irrigation Area, the relationship between severely saline soils and drainage ditches remains unclear. To reveal the salinization characteristics of soils adjacent to drainage ditches in the Hetao Irrigation Area, this study focused on saline-alkali land adjacent to drainage ditches in Urad Front Banner, employing both descriptive and principal component analyses to elucidate soil salinization and fertility characteristics. This research provides a theoretical basis for rationally improving severely saline-alkali land adjacent to drainage ditches, expanding land resource utilization, and enhancing agricultural sustainability.

1. Materials and Methods

1.1 Study Area Overview

The study area is located in the Xishanzui Farm Fourth Division of Urad Front Banner, Bayannur City, Inner Mongolia, with geographical coordinates of 40°44′54″–40°45′49″N, 108°37′28″–108°39′49″E. The site comprises abandoned saline-alkali cultivated land covering an area of 10.54 hm^2. Situated in a mid-temperate continental climate zone, the region features dry and windy conditions, variable temperatures, abundant sunshine and light energy, low precipitation, strong evaporation, and a short frost-free period. The multi-year average temperature is 6–8°C, with extreme minimum and maximum temperatures of $-36.7°C$ and $36.4°C$, respectively. Precipitation is concentrated in June–August, with a multi-year average of 196–215 mm and a multi-year average evaporation of 2172.5 mm. The maximum frozen soil depth is 1.2 m. The physical properties of soils in the study area are presented in .

1.2 Sample Collection

Soil sampling points were selected considering soil texture and micro-topography factors, choosing representative spatial distribution points in the experimental area. Soil spatial variability was strong, with highly non-uniform soil properties. Soil profiles were collected at depths of 0–10 cm, 10–20 cm, and 20–40 cm, with 500 g samples taken from each layer. Two parallel rows of sampling points were established between the canal and the northern drainage ditch ([Figure 1: see original paper]), with a spacing of 20 m between rows and 10 m between points within each row. The distance between sampling points and the western drainage ditch was 5 m. A total of 40 soil samples were collected.

1.3 Measurement Items and Methods

Soil samples were air-dried indoors, sieved to remove impurities (plant residues, stones, bricks, etc.), spread on wooden boards, crushed with a wooden rod, and passed through a 1 mm sieve. The prepared samples were used to determine soluble salt ion content, total salt content, pH, electrical conductivity, and fertility indicators.

For soluble salt ion analysis, soil samples were weighed and mixed with distilled water at a 1:5 soil-water mass ratio, shaken for 3 minutes, and filtered. The filtrate was used to determine soluble salt ion content: Na^+ and K^+ by flame photometry; Ca^{2+} and Mg^{2+} by EDTA titration; Cl^- by $AgNO_3$ titration; SO_4^{2-} by EDTA indirect titration; and HCO_3^- by double-indicator hydrochloric acid neutralization titration. Total salt content was calculated as the sum of mass fractions of cations and anions. Soil pH and electrical conductivity were measured using a 1:5 soil-water suspension with a PHS-3C pH meter and a DDS-308A conductivity meter, respectively.

Total nitrogen was determined by Kjeldahl distillation using a Kjeldahl nitrogen analyzer; alkali-hydrolyzable nitrogen by alkali diffusion method; available phosphorus by sodium bicarbonate method using a UV spectrophotometer; readily available potassium by flame photometry; and soil organic matter by potassium dichromate external heating method.

1.4 Data Processing

Descriptive statistics and principal component analysis of soil salinization and fertility indicators were performed using SPSS 20.0. Pearson correlation coefficients characterized correlations among soil salt ions. Origin 2018 and Excel 2019 were used for chart preparation.

2. Results

2.1 Soil Salt Ion Characteristics

2.1.1 Distribution of Soil Salt Ions Soil salt ion content varied with depth ([Figure 2: see original paper]). The main anions were Cl^- and SO_4^{2-}, while Na^+ and Mg^{2+} dominated the cations. Soil salt content in the 0–10 cm, 10–20 cm, and 20–40 cm layers was 12.66 $g \cdot kg^{-1}$, 9.05 $g \cdot kg^{-1}$, and 7.88 $g \cdot kg^{-1}$, respectively, decreasing with depth and indicating severe surface salt accumulation and severe salinization. The anion content order was $Cl^- > SO_4^{2-} > HCO_3^-$, with Cl^- concentrations of 6.13 $g \cdot kg^{-1}$, 4.16 $g \cdot kg^{-1}$, and 3.79 $g \cdot kg^{-1}$ in the three layers. The cation content order was $Na^+ > Mg^{2+} > Ca^{2+} > K^+$, with Na^+ concentrations of 2.29 $g \cdot kg^{-1}$, 1.52 $g \cdot kg^{-1}$, and 1.41 $g \cdot kg^{-1}$, and Mg^{2+} concentrations of 2.08 $g \cdot kg^{-1}$, 1.86 $g \cdot kg^{-1}$, and 1.83 $g \cdot kg^{-1}$. The K^+ proportion was minimal, nearly zero. Cl^- content decreased significantly with depth, while Mg^{2+} decreased slightly and other ions remained relatively stable without obvious fluctuations. Salinization near drainage ditches results from two main factors: severe farmland salinization leading to high mineralization of agricultural drainage water that erodes adjacent soils, and reduced or dry drainage ditches during non-irrigation seasons where evaporation leaves salts in the surface soil, causing long-term cumulative diffusion and intensifying salinization.

2.1.2 Correlations Among Soil Salt Ions Correlation analysis () showed that Na^+ correlated most strongly with Cl^- ($r = 0.984$) and significantly with SO_4^{2-} ($r = 0.742$). Mg^{2+} showed extremely significant negative correlations with Ca^{2+} ($r = -0.686$). Soil salt content exhibited extremely significant positive correlations with all ions except K^+, with the strongest correlation with Cl^- ($r = 0.984$). Ca^{2+} showed extremely significant negative correlations with salt content, Na^+, Mg^{2+}, and Cl^-, with correlation coefficients of -0.592, -0.594, -0.686, and -0.528, respectively.

2.1.3 Relationship Between Soil Salt Content and Electrical Conductivity Regression analysis of all soil samples showed a linear relationship between soil salt content (y) and electrical conductivity (x): $y = 0.217x + 1.431$

($R^2 = 0.853$), significant at the $p < 0.01$ level ([Figure 3: see original paper]). This indicates that electrical conductivity can effectively represent soil salt content in this region.

2.2 Soil Alkalization Characteristics

2.2.1 Alkalization Index Features Descriptive statistics () showed that pH values were high across all layers: 8.09, 8.32, and 8.30 for 0–10 cm, 10–20 cm, and 20–40 cm, respectively. Alkalization degrees ranged from 13.0% to 28.6%, with surface soil at 20.3%, 21.3%, and 22.0% for the three layers, indicating severe alkalization. Total alkalinity values were 0.41, 0.66, and 0.56 $\text{cmol} \cdot \text{kg}^{-1}$, all exceeding the non-alkaline threshold (<0.3 $\text{cmol} \cdot \text{kg}^{-1}$), confirming alkaline characteristics. The CO_3^{2-} to HCO_3^- ratio exceeded 0.5 in all layers, with CO_3^{2-} accounting for over 50% of anions. When this ratio reaches approximately 0.5, it begins to inhibit crop growth, indicating substantial impacts on crop development in the study area.

2.2.2 Relationships Among pH, Alkalization Degree, and Total Alkalinity Analysis revealed linear relationships between pH and alkalization degree ($R^2 = 0.731$) and significant exponential relationships between total alkalinity and pH ($R^2 = 0.853$) ([Figure 4: see original paper]). Higher pH corresponds to higher alkalization degree. When total alkalinity is relatively low but pH remains high, soil alkalization has already occurred due to $Na_{2CO}3$ and $NaHCO_3$ presence, which enhances irreversibility of alkalization. High Na^+ content increases Na^+ exchange capacity, promoting OH^- production and elevating pH.

2.3 Dominant Factors of Soil Salinization-Alkalization

Correlation analysis demonstrated significant relationships among different salt ions and linear correlations among alkalization indices, indicating overlapping information among variables. Principal component analysis was applied to 40 soil samples, extracting factors with eigenvalues >1 and cumulative contribution >85%. The first two principal components had eigenvalues of 5.44 and 1.42, with variance contributions of 67.99% and 17.74%, respectively, reaching a cumulative contribution of 85.73% ().

The first principal component (F_1) showed strong positive loadings for soil salt content, Cl^-, Ca^{2+}, and Mg^{2+} (0.368, 0.382, 0.318, and 0.288, respectively), reflecting soil salinization status and confirming chloride-type salinization. Alkalization indices correlated negatively with F_1, with pH and total alkalinity showing strong loadings of −0.500 and −0.405. The second principal component (F_2) exhibited relatively high loadings for alkalization degree (0.375). Therefore, soil salt content, pH, total alkalinity, and alkalization degree can serve as the main characteristic factors. The principal component functions are:

$$F_1 = 0.368X_1+0.206X_2+0.288X_3+0.382X_4+0.318X_5-0.500X_6-0.305X_7-0.193X_8-0.405X_9$$

$$F_2 = 0.226X_1+0.280X_2+0.297X_3+0.037X_4-0.280X_5+0.375X_6+0.500X_7+0.305X_8+0.193X_9$$

where X_1–X_9 represent soil salt content, Cl^-, SO_4^{2-}, Na^+, Ca^{2+}, pH, alkalization degree, cation exchange capacity, and total alkalinity, respectively.

2.4 Soil Fertility Characteristics

Soil fertility indicators reflect the capacity to provide nutrients for crop growth. Descriptive statistics for 40 soil samples () showed high potassium content, with readily available potassium ranging from 101.5 to 287 mg·kg^{-1} across 0–40 cm. Total nitrogen ranged from 0.13 to 0.91 g·kg^{-1}, alkali-hydrolyzable nitrogen averaged 19.64, 17.96, and 17.00 mg·kg^{-1} for the three layers, available phosphorus was below 5.08 mg·kg^{-1} in all layers, and organic matter averaged 6.99, 6.47, and 6.27 g·kg^{-1}. According to national soil survey standards, total nitrogen and available phosphorus fertility levels were grade 5–6, alkali-hydrolyzable nitrogen was grade 6, readily available potassium was grade 1–2, and organic matter was grade 5–6 ([Figure 5: see original paper]), indicating low comprehensive fertility due to nutrient loss near drainage ditches. Variation coefficients ranged from 19% to 42%, showing moderate variability that decreased with depth.

3. Discussion

During irrigation periods, soil salts from adjacent cultivated land are leached by irrigation water and accumulate in abandoned land without irrigation. Soils adjacent to drainage ditches in the Hetao Irrigation Area exhibit high soluble salt content, high pH, and poor physical properties, consistent with previous findings. Saline-alkali soil types can be identified by the N_1/N_2 ratio, where N_1 represents $CO_3^{2-} + HCO_3^-$ and N_2 represents $Cl^- + SO_4^{2-}$. Ratios between 0.5–1.0 indicate chloride or sulfate-soda saline soils, while ratios <0.5 indicate chloride or sulfate saline soils. All samples in this study had N_1/N_2 ratios <0.5, confirming chloride saline soils.

$MgCl_2$ is a water-soluble salt that can be leached through repeated irrigation. However, at high salt concentrations, $MgCl_2$ has greater solubility than $MgSO_4$, and leaching efficiency for Mg^{2+} is lower than for Ca^{2+}. As Mg^{2+} and Ca^{2+} are equivalent cations, Ca^{2+} from desulfurization gypsum can replace Na^+ but only minimally replaces Mg^{2+}, making Mg^{2+} a key issue in salinization control. High Mg^{2+} content slows Na^+ absorption and intensifies alkalization. Correlation analysis showed Cl^- had the highest correlation with other cations, followed by SO_4^{2-}, consistent with the mobility sequence of chlorides > sulfates > carbonates during salt transport.

Due to poor permeability and severe salinization, direct leaching is inefficient for soils adjacent to drainage ditches. Improvement should combine physical property enhancement with subsurface drainage techniques. $NaHCO_3$ hydrolysis produces alkaline reactions, increasing exchangeable Na^+ and OH^- concentrations, which are important alkalization features. Severe alkalization results from high Na^+ content in irrigation water and continuous adsorption of Na^+ from drainage ditches, causing soil particle dispersion, poor aeration and permeability, and extremely poor tillability. Current improvement methods such as sand mixing and straw mulching can increase infiltration rates, but suitable measures for wasteland near drainage ditches require further investigation.

This study selected nine indicators (salt ions, salt content, pH, total alkalinity, etc.) as salinization parameters, comprehensively representing the overall situation. Principal component analysis provides more intuitive and efficient results than conventional statistical methods, identifying soil salt content, pH, total alkalinity, and alkalization degree as the main characteristic factors.

High alkalization degree correlates strongly with poor physical properties, affecting soil infiltration—a key reason for low permeability in the study area. This finding aligns with previous research in the Hetao Irrigation Area. High pH causes nitrogen loss through ammonia volatilization, contributing to low nitrogen content. Although available phosphorus is relatively stable in soil, its low surface content in this study relates to high pH, which reduces phosphorus availability. Therefore, improvement of severely salinized-alkalized soils adjacent to drainage ditches should address both salt-alkali problems and supplement nutrients other than potassium.

4. Conclusions

Using mathematical statistics and principal component analysis, this study examined salinization and fertility characteristics of saline-alkali soils adjacent to drainage ditches in the Hetao Irrigation Area. The main conclusions are:

1. Soil salt content in the 0–10 cm, 10–20 cm, and 20–40 cm layers was 12.66 $g \cdot kg^{-1}$, 9.05 $g \cdot kg^{-1}$, and 7.88 $g \cdot kg^{-1}$, respectively, decreasing with depth and indicating severe salinization. The salinization type is chloride saline soil. Soil salt content correlates significantly with electrical conductivity ($R^2 = 0.853$).
2. Soil alkalization degree ranged from 13.0% to 28.6% across layers, with severe alkalization causing soil particle dispersion, muddy texture when wet, poor aeration and permeability, and hard clods when dry. pH showed a linear relationship with alkalization degree ($R^2 = 0.731$), and total alkalinity showed a significant exponential relationship with pH ($R^2 = 0.853$).

3. Principal component analysis of salinization parameters showed the first two components cumulatively explained 85.73% of variance. The first component correlated positively with soil salt content, Cl^-, Ca^{2+}, and Mg^{2+}, while pH and total alkalinity correlated negatively. The second component showed high loading for alkalization degree. Therefore, soil salt content, pH, total alkalinity, and alkalization degree can serve as the main characteristic factors.

4. Soils in the study area are potassium-rich, with readily available potassium content of 101.5–287 $\text{mg} \cdot \text{kg}^{-1}$ (grade 1–2), while other fertility indicators are below grade 3, indicating low overall fertility. Variation coefficients of soil fertility indicators ranged from 19% to 42%, showing moderate variability.

References

[1] Zhang Jie, Chen Lixin, Kou Shiwei, et al. Characteristics and evaluation of salinization of different land use types of soils in Daqing City[J]. Journal of Soil and Water Conservation, 2011, 25(1): 171-175, 179.

[2] Lei Tingwu, Issac Shainberg, Yuan Pujin, et al. Strategic considerations of efficient irrigation and salinity control on Hetao plain in Inner Mongolia[J]. Transactions of the Chinese Society of Agricultural Engineering, 2001, 17(1): 48-52.

[3] Ding J L, Wu M C. Study on soil salinization information in arid region using remote sensing technique[J]. Agricultural Sciences in China, 2011, 10(3): 404-411.

[4] Acosta J A, Faz A. Assessment of salinity status in intensively cultivated soils under semiarid climate, Murcia, SE Spain[J]. Journal of Arid Environments, 2011, 75(11): 1056-1064.

[5] Martinez Sanchez M J, Perez Sirvent C. Monitoring salinization processes in soils by using a chemical degradation indicator[J]. Journal of Geochemical Exploration, 2011, 109(1-3): 1-7.

[6] Wang Heyun, Li Hongli, Dong Zhi, et, al. Salinization characteristics of afforested coastal saline soil as affected by species of trees used in afforestation[J]. Acta Pedologica Sinica, 2015, 52(3): 706-712.

[7] Zhang Xiaoguang, Huang Biao, Liang Zhengwei. et al. Study on salinization characteristics of surface soil in western Songnen plain[J]. Soils, 2013, 45(2): 332-338.

[8] Liu Taotao, Xiong Youcai, Yang Yan, et al. The characteristics of soil salinization in oasis desert ecotone of the lower reaches of manas river[J]. Journal of Shihezi University(Natural Science), 2012, 30(2): 186-192.

[9] Wang Zunqin, Zhu Shouquan, Yu Renpei. Saline Soil in China[M]. Beijing: Science Press, 1993.

[10] Huang Changyong. Pedology[M]. Beijing: China Agriculture Press, 2000.

[11] Li Xueyuan. Soil Chemistry[M]. Beijing: Higher Education Press, 2001.

[12] Wang Huimin, Hao Xiangyun, Zhu Zhongyuan. Drought assessment based on drought index and principal component analysis: A cased study in the Xilin River Basin [J]. Arid Zone Research, 2019, 36(1): 95-103.

[13] Zhang Renduo. Spatial Variation Theory and Its Application[M]. Beijing: Science Press, 2005.

[14] Li Liang, Shi Haibin, Jia Jinfeng, et al. Simulation of water and salt transport of uncultivated land in Hetao Irrigation District in Inner Mongolia[J]. Transactions of the Chinese Society of Agricultural Engineering, 2010, 26(1): 31-35.

[15] Song Nan, Yang Sicun, Liu Xuelu, et al. Distribution characteristics of soil salt ions in saline land relative to cultivation history[J]. Acta Pedologica Sinica, 2014, 51(3): 660-665.

[16] Jiang Ling, Li Peicheng, Hu Anyan, et al. The groundwater chemical characteristics in the Yaoba oasis of Alxa area, Inner Mongolia[J]. Journal of Arid Land Resources and Environment, 2009, 23(11): 105-110.

[17] Li Bin, Wang Zhichun. The alkalization parameters and their influential factors of saline sodic soil in the Songnen plain[J]. Journal of Arid Land Resources and Environment, 2006, 20(6): 183-191.

[18] Liu Yanfeng, Jin Menggui, Jin Yingchun. Principal component analysis of soil salinization in Yanqi Basin[J]. Agricultural Research in the Arid Areas, 2004, 22(1): 165-171.

[19] Bao Shidan. Study of Analysis of Soil and Agrochemistry[M]. Beijing: China Agriculture Press, 2000.

[20] Agricultural Chemistry Committee of Soil Society of China. Conventional Analytical Methods of Soil Agrochemistry[M]. Beijing: Science Press, 1983.

[21] Dou Xu, Shi Haibin, Miao Qingfeng, et al. Temporal and spatial variability analysis of soil water and salt and the influence of groundwater depth on salt in saline irrigation area[J]. Journal of Soil and Water Conservation, 2019, 33(3): 246-253.

[22] Kou Wei. Study on Spatial Variability of Soil Water and Salinity in Hetao District in Inner Mongolia, China[D]. Lanzhou: Northwest Normal University, 2008.

[23] Xue Rujun, Gao Tian, Ma Erdeng, et al. Effects of fertigation method and fertilizer amount on the growth, N, P, K utilization, and yield of flue cured tobacco[J]. Journal of Irrigation and Drainage, 2019, 38(8): 22-30.

[24] Xiao Kang, Sun Yaqiao, Ma Weiguo, et, al. Effects of biochar for abating salt stress and promoting seeding growth of winter wheat in a saline soil[J]. Journal of Irrigation and Drainage, 2019, 38(11): 22-27.

[25] Wang Shaoli, Xu Di, Yang Jianguo, et al. Chemical characteristics and its irrigation effect of drainage water in ditches of Yinbei Irrigation Districts[J]. Journal of Hydraulic Engineering, 2011, 42(2): 166-172.

Note: Figure translations are in progress. See original paper for figures.