Postprint of Study on Salinity Threshold for Long-term Saline Water Irrigation of Winter Wheat in the Hebei Low Plain

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Abstract

In the process of studying the effects of saline water irrigation on soil and crops, monitoring soil salinity is relatively difficult, whereas monitoring the salinity of irrigation water is simpler and more feasible; however, the salinity threshold for irrigating crops with saline water at different growth stages is difficult to determine. Based on long-term saline water irrigation experiment data conducted at the Hengshui Dryland Farming and Water-saving Experimental Station in Hebei Province from 2007 to 2015 (the irrigation water was set at five salinity levels: 1 $g \cdot L^{-1}$, 2 $g \cdot L^{-1}$, 4 $g \cdot L^{-1}$, 6 $g \cdot L^{-1}$, and 8 $g \cdot L^{-1}$; water was applied three times during the winter wheat growing season), and using 1 $g \cdot L^{-1}$ irrigation water as the fresh water control, this study investigated crop growth, yield, and environmental change indicators such as relative emergence rate, relative grain yield, and soil salinity under different treatments, and analyzed the salinity threshold and its influencing factors for multi-year saline water irrigation of 'Shijiazhuang 8' winter wheat using the FAO piecewise function method. The results showed that under 4 $g \cdot L^{-1}$ and 6 $g \cdot L^{-1}$ saline water irrigation, the multi-year average wheat emergence rate was equivalent to 93.8% ($P>0.05$) and 70.4% ($P<0.05$) of that under fresh water, respectively, and the multi-year average yield was equivalent to 86.0% ($P<0.05$) and 65.3% ($P<0.05$) of that under fresh water irrigation. When using saline water with salinity less than 4 $g \cdot L^{-1}$ for irrigation, grain yield (with yield change less than 15%) and emergence rate were not limiting factors affecting the salinity threshold for saline water irrigation. The calculated salinity threshold for multi-year saline water irrigation of winter wheat was 2.14–3.95 $g \cdot L^{-1}$, with an average value of 3.19 $g \cdot L^{-1}$ and a coefficient of variation of 21.1%. Considering both yield and soil salinity accumulation risks, the salinity threshold for long-term saline water irrigation of winter wheat in the low plain area of Hebei was determined to be 2.47 $g \cdot L^{-1}$. The salinity threshold had a certain negative correlation with pre-sowing soil salinity in the 1 m soil profile (correlation coefficient -0.587) and a certain positive correlation with fresh water irrigation yield (correlation coefficient 0.516). Soil salinity accumulation risk analysis results indicated that, according to predictions from an exponential equation fitted between irrigation water salinity and average soil salinity, using 2.47 $g \cdot L^{-1}$ saline water for continuous 9-year irrigation, the 0–20 cm tillage layer soil did not reach salinization level (predicted average soil salinity 0.98 $g \cdot kg^{-1}$), while the 1 m soil profile exhibited mild salinization (predicted average salinity content 1.17 $g \cdot kg^{-1}$). Soil salinity accumulated slightly but did not cause significant impact on winter wheat yield. From this perspective, the risk of severe soil salinization caused by long-term irrigation with 2.47 $g \cdot L^{-1}$ saline water is relatively small.

Full Text

Salinity Threshold of Long-Term Saline Water Irrigation for Winter Wheat in Hebei Lowland Plain

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Abstract

Monitoring soil salt content under saline water irrigation is relatively difficult, whereas monitoring irrigation water salinity is simpler and more practical. However, determining the salinity threshold for irrigation water at different crop growth stages remains challenging. Based on long-term saline water irrigation experiments conducted from 2007 to 2015 at the Hengshui Dry-land Farming Station in Hebei Province, this study investigated the effects of saline water with five salinity levels (1 $g \cdot L^{-1}$, 2 $g \cdot L^{-1}$, 4 $g \cdot L^{-1}$, 6 $g \cdot L^{-1}$, and 8 $g \cdot L^{-1}$) on winter wheat growth. With freshwater irrigation (1 $g \cdot L^{-1}$) as the control, we examined relative seedling emergence rate, relative grain yield, and soil salinity changes using the FAO piecewise linear model to analyze the salinity threshold and its influencing factors for 'Shijiazhuang 8' winter wheat under long-term saline irrigation. Results showed that irrigation with 4 $g \cdot L^{-1}$ and 6 $g \cdot L^{-1}$ saline water produced multi-year average emergence rates equivalent to 93.8% ($P>0.05$) and 70.4% ($P<0.05$) of freshwater, respectively, while grain yields were 86.0% ($P<0.05$) and 65.3% ($P<0.05$) of freshwater levels. When using saline water below 4 $g \cdot L^{-1}$, neither grain yield (with variation <15%) nor emergence rate limited the salinity threshold. The calculated salinity threshold for long-term winter wheat irrigation ranged from 2.14 to 3.95 $g \cdot L^{-1}$, averaging 3.19 $g \cdot L^{-1}$ with a coefficient of variation of 21.1%. Considering both yield and soil salt accumulation risks, the recommended salinity threshold for long-term winter wheat irrigation in Hebei Lowland Plain is 2.47 $g \cdot L^{-1}$. The threshold showed a negative correlation with pre-sowing soil salt content in the 0–100 cm profile (r = -0.587) and a positive correlation with freshwater-irrigated yield (r = 0.516). Risk analysis indicated that continuous 9-year irrigation with 2.47 $g \cdot L^{-1}$ saline water would result in 0–20 cm topsoil remaining non-salinized (predicted average soil salt 0.98 $g \cdot kg^{-1}$), while the 0–100 cm profile would experience mild salinization (predicted average salt content 1.17 $g \cdot kg^{-1}$). Although slight salt accumulation occurred, no significant yield reduction was observed, suggesting low risk of severe soil salinization from long-term irrigation at this threshold.

Keywords Hebei Lowland Plain; Winter wheat; Saline water; Long-term irrigation; Salinity threshold

1. Materials and Methods

1.1 Experimental Site Description

The study was conducted at the Hengshui Dry-land Farming Station of Hebei Academy of Agriculture and Forestry Sciences, where saline water irrigation experiments began in October 2006. Located in the Hebei Lowland Plain, the station features flat terrain at 21 m elevation with a groundwater table depth of approximately 7 m. The region has a mean annual temperature of 12.8°C, 2,509.4 h of sunshine, a frost-free period of 188 days, and mean annual precipitation of 512.5 mm (with about 70% falling during June–August). Annual evaporation reaches 1,785.4 mm. The soil is a clay loam desalinized soil. Initial soil conditions in 2006 showed organic matter content of 12.8 $g \cdot kg^{-1}$, alkali-hydrolyzable nitrogen of 65.5 $mg \cdot kg^{-1}$, available phosphorus of 17.6 $mg \cdot kg^{-1}$, available potassium of 134 $mg \cdot kg^{-1}$, topsoil (0–20 cm) salt content of 0.437 $g \cdot kg^{-1}$, and 0–100 cm profile salt content of 0.657 $g \cdot kg^{-1}$.

1.2 Experimental Design

The experiment employed continuous multi-year irrigation with saline water at five salinity levels: 1 $g \cdot L^{-1}$ (control), 2 $g \cdot L^{-1}$, 4 $g \cdot L^{-1}$, 6 $g \cdot L^{-1}$, and 8 $g \cdot L^{-1}$. The randomized complete block design included three replications. The cropping system was winter wheat–summer maize rotation. Winter wheat cultivar 'Shijiazhuang 8' , a dominant local variety, was planted in plots of 57 m^2 (9.5 m × 6 m) with 50 cm isolation strips between plots.

Winter wheat typically received 2–3 irrigations during the growing season: pre-sowing irrigation (omitted if 0–20 cm soil moisture exceeded 70% of field capacity), jointing-stage irrigation, and flowering-stage irrigation. Saline water of different salinities was prepared by mixing freshwater with industrial salt (ion composition shown in). Each irrigation applied 60 mm of water measured by flow meters. Pre-sowing tillage involved two rotary tillage operations at 12–15 cm depth without maize straw incorporation. Conventional fertilization included basal application of diammonium phosphate (525 $kg \cdot hm^{-2}$ containing

46% P_2O_5 and 18% N) before wheat sowing, and topdressing with urea (375 kg · hm^{-2} containing 46% N) during the first spring irrigation. Wheat was sown between October 12-23 at 195-225 kg · hm^{-2} and harvested between June 10-15 using 15 cm row spacing. Seasonal precipitation during wheat growth is shown in .

1.3 Measurements and Methods

Relative seedling emergence rate: Three weeks after sowing, seedling counts were taken at three points per plot (1 m double rows). Relative emergence rate was calculated as:

$$\text{Relative emergence rate (\%)} = \frac{N_t}{N_{CK}} \times 100 \quad (1)$$

where N_t is the seedling number for each treatment ($×10^{4}$ plants · hm^{-2}) and N_{CK} is the seedling number for freshwater control ($×10^{4}$ plants · hm^{-2}).

Relative biomass: At maturity, 3 m^2 was harvested from each plot, air-dried, and weighed to calculate biomass per unit area. Relative biomass was calculated as:

$$\text{Relative biomass (\%)} = \frac{M_t}{M_{CK}} \times 100 \quad (2)$$

where M_t is the biomass for each treatment (kg · hm^{-2}) and M_{CK} is the biomass for freshwater control (kg · hm^{-2}).

Relative grain yield: At maturity, 3 m^2 was harvested, threshed manually, and air-dried to calculate grain yield. Relative grain yield was calculated as:

$$\text{Relative grain yield (\%)} = \frac{Y_t}{Y_{CK}} \times 100 \quad (3)$$

where Y_t is the grain yield for each treatment (kg · hm^{-2}) and Y_{CK} is the grain yield for freshwater control (kg · hm^{-2}).

Soil salinity: Soil samples were collected before sowing and after harvest at 20 cm intervals to 1 m depth. Three sampling points per plot were mixed, air-dried, ground, and sieved. Soil salt content was measured using a DDS-11A conductivity meter at a 1:5 soil-water ratio.

Threshold calculation: The FAO piecewise linear model was used to calculate the salinity threshold of irrigation water based on annual relative yields under different saline water treatments:

$$Y_r = \begin{cases} 100 & \text{if } x \leq x_0 \\ 100 - b(x - x_0) & \text{if } x > x_0 \end{cases}$$

where Y_r is relative yield, b is the yield reduction rate per unit salinity beyond the threshold, x_0 is the salinity threshold of irrigation water, and x is irrigation water salinity (see [Figure 1: see original paper]).

Statistical analysis was performed using SX software, with Microsoft Excel used for graphing and simulation.

2. Results and Analysis

2.1 Effects of Saline Water Irrigation on Winter Wheat Emergence

Crop seed germination and emergence are particularly sensitive to salt stress. shows relative emergence rates of 'Shijiazhuang 8' winter wheat from 2007/2008 to 2014/2015. Emergence rate decreased significantly with increasing irrigation water salinity. The 2 $g \cdot L^{-1}$ and 4 $g \cdot L^{-1}$ treatments achieved 99.8% and 93.8% of freshwater emergence rates, respectively, without significant differences from the control. The 6 $g \cdot L^{-1}$ treatment reduced emergence to 70.4% of freshwater, significantly lower than both freshwater and 4 $g \cdot L^{-1}$ treatments. The 8 $g \cdot L^{-1}$ treatment further reduced emergence to 35.5% of freshwater, significantly different from the 6 $g \cdot L^{-1}$ treatment. These results indicate that irrigation water salinity above 4 $g \cdot L^{-1}$ significantly inhibits emergence, while salinity below 4 $g \cdot L^{-1}$ has minimal impact on 'Shijiazhuang 8' emergence. Notably, the 8 $g \cdot L^{-1}$ treatment showed an accelerating decline in emergence over time. During the first four years (2007/2008-2010/2011), emergence remained relatively stable at 49.6-69.8% of freshwater, but dropped sharply to 23.7% in the fifth year, then fell below 20% in subsequent years, with some years showing virtually no emergence.

2.2 Effects of Saline Water Irrigation on Winter Wheat Yield and Threshold Values

presents relative yields across eight wheat growing seasons from 2007/2008 to 2014/2015. Grain yield decreased with increasing irrigation water salinity. The 2 $g \cdot L^{-1}$ treatment showed only 1.0% yield reduction compared to freshwater, with no significant difference. The 4 $g \cdot L^{-1}$ treatment yielded 86.0% of freshwater (14.0% reduction), significantly different from both freshwater and 2 $g \cdot L^{-1}$ treatments. The 6 $g \cdot L^{-1}$ treatment yielded 65.3% of freshwater (34.7% reduction), significantly different from freshwater and 4 $g \cdot L^{-1}$ treatments. The 8 $g \cdot L^{-1}$ treatment yielded only 29.3% of freshwater (70.7% reduction), significantly different from freshwater and 6 $g \cdot L^{-1}$ treatments, with some years experiencing total crop failure. Yield reduction relative to freshwater increased rapidly with salinity: 1.0%, 14.0%, 34.7%, and 70.7% for 2, 4, 6, and 8 $g \cdot L^{-1}$ treatments, respectively. Irrigation with saline water below 4 $g \cdot L^{-1}$ maintained yield loss within 15% of freshwater levels, while 6 $g \cdot L^{-1}$ irrigation still achieved 65% of freshwater yield.

The piecewise function model calculated annual salinity thresholds ranging from 2.14 to 3.95 $g \cdot L^{-1}$, with a mean of (3.19$±0.7)$g\cdot L^{\{-1\}.Thedifferencebetweenmaximumandminimumannualthresholdswas}$ 1}, $withacoefficientofvariationof21.1^{\{-1\}, and87.5}${-1}$ (). This suggests that 2.14 $g \cdot L^{-1}$ saline water irrigation would not significantly reduce yield compared to freshwater in Hebei Lowland Plain, while 2.47 $g \cdot L^{-1}$ irrigation carries a 12.5% risk (one in eight years) of yield reduction. Further analysis using the 2014 threshold of 2.14 $g \cdot L^{-1}$ indicated that applying 2.47 $g \cdot L^{-1}$ saline water (exceeding the threshold by 0.33 $g \cdot L^{-1}$) would reduce yield by only 3.9% compared to freshwater. Therefore, 2.47 $g \cdot L^{-1}$ can be adopted as the salinity threshold for 'Shijiazhuang 8' winter wheat in Hebei Lowland Plain.

2.3 Factors Influencing Salinity Threshold for Winter Wheat Irrigation

To identify factors causing inter-annual variation in the salinity threshold, we analyzed correlations between the threshold and rainfall, freshwater-irrigated control yield, and pre-sowing soil salinity in both 0–20 cm and 0–100 cm layers. Results showed that under irrigation conditions, the salinity threshold was positively correlated with growing-season precipitation (r = 0.141, not significant), negatively correlated with pre-sowing 0–20 cm topsoil salinity (r = -0.213, not significant), and more strongly negatively correlated with pre-sowing 0–100 cm profile salinity (r = -0.587, not significant). The threshold also showed a positive correlation with freshwater control yield (r = 0.516, not significant) (). These relationships indicate that accumulated soil salts reduce wheat salt tolerance, while environmental conditions favoring higher yields can enhance salt tolerance. Pre-sowing soil salinity in the 1 m profile had greater influence on the threshold than topsoil salinity, likely because pre-sowing irrigation effectively leaches salts from the surface layer downward. Consequently, pre-sowing 0–20 cm salinity had less impact than the 0–100 cm profile. This also demonstrates that salt accumulation in the soil profile from saline irrigation affects salt tolerance thresholds and appropriate irrigation salinity levels.

2.4 Risk Analysis of Soil Salt Accumulation Under Long-Term Threshold-Based Saline Irrigation

Saline irrigation causes soil salt accumulation, and the 1 m soil profile salinity negatively affected the threshold. Therefore, soil salt accumulation risk must be considered when applying threshold-based long-term saline irrigation. presents average soil salt contents and inter-annual variation coefficients for different saline water treatments from 2007–2015. Higher irrigation water salinity caused greater soil salt accumulation with larger inter-annual variation, while lower salinity irrigation resulted in smaller accumulation and variation. Multi-year averages for 0–20 cm topsoil salt content were 0.66, 0.88, 1.39, 2.80, and 4.48 $g \cdot kg^{-1}$ for 1, 2, 4, 6, and 8 $g \cdot L^{-1}$ treatments, respectively, with variation coefficients of 30.8%, 42.1%, 55.8%, 64.1%, and 56.0%. Although all treatments increased topsoil salinity, the 2 $g \cdot L^{-1}$ treatment maintained topsoil salt below 1 $g \cdot kg^{-1}$ (non-salinized according to classification standards). The 4 $g \cdot L^{-1}$ treatment resulted in 1-2 $g \cdot kg^{-1}$ topsoil salinity (mildly salinized), while 6 $g \cdot L^{-1}$ and higher treatments exceeded 2 $g \cdot kg^{-1}$ (salinized). Average 0–100 cm profile salt contents were 0.87, 1.08, 1.60, 2.35, and 3.37 $g \cdot kg^{-1}$, with variation coefficients of 19.4%, 26.8%, 34.6%, 44.2%, and 40.9%, respectively. According to salinization standards, 2 $g \cdot L^{-1}$ and 4 $g \cdot L^{-1}$ treatments caused mild salinization (1-2 $g \cdot kg^{-1}$) in the 1 m profile.

To assess long-term environmental risk, we evaluated the relationship between irrigation water salinity and soil salt content using regression analysis. shows that both 0–20 cm and 0–100 cm soil salinity had strong linear relationships with irrigation water salinity (R^2 = 0.94 and 0.97, respectively). However, exponential models better described salt accumulation, with R^2 values of 0.99 for 0–20 cm and 0.999 for 0–100 cm, improving upon linear models by 5.5 and 2.4 percentage points, respectively. Exponential models more accurately reflect the characteristic of minimal salt accumulation at low salinities followed by rapid exponential increase at higher salinities, rather than the constant proportional increase assumed by linear models. Using the exponential model, the 2.47 $g \cdot L^{-1}$ threshold corresponds to predicted average soil salt contents of 0.98 $g \cdot kg^{-1}$ in the 0–20 cm layer (non-salinized) and 1.17 $g \cdot kg^{-1}$ in the 0–100 cm profile (mildly salinized). Analysis of long-term saline irrigation data indicates low risk of soil salinization when applying the 2.47 $g \cdot L^{-1}$ threshold in Hebei Lowland Plain. Therefore, this salinity level is suitable as a long-term irrigation threshold for winter wheat in the region, considering both yield and soil salt accumulation.

This 9-year study with eight wheat seasons and five salinity gradients revealed substantial inter-annual threshold variation (2.14-3.95 $g \cdot L^{-1}$, mean 3.19 $g \cdot L^{-1}$, CV = 21.1%), a finding difficult to obtain from short-term studies. The threshold determined through multi-year yield analysis was 3.19 $g \cdot L^{-1}$, while risk analysis refined this to 2.47 $g \cdot L^{-1}$—23.5% higher than the current 2 $g \cdot L^{-1}$ standard for blended saline-fresh water irrigation. The FAO-reported wheat irrigation threshold of 4 $dS \cdot cm^{-1}$ corresponds to approximately 2.56 $g \cdot L^{-1}$, closely matching our value. Wu et al. (2008) identified 3 $g \cdot L^{-1}$ as the maximum concentration for wheat irrigation in Nanpi, Hebei, similar to our multi-year average threshold.

Key factors influencing inter-annual threshold variation were pre-sowing 1 m profile soil salinity and freshwater control yield. The positive correlation between threshold and control yield suggests that saline-irrigated wheat is more sensitive to adverse environmental conditions than freshwater-irrigated wheat, and that improved management practices can enhance salt tolerance. The stronger influence of 1 m profile salinity over topsoil salinity reflects effective salt leaching by pre-sowing irrigation.

Theoretically, the salinity threshold represents the maximum irrigation water salt content that does not significantly reduce yield compared to freshwater.

Practical considerations include: (1) This threshold applies well to blended or pure saline irrigation, but alternate saline-fresh irrigation during specific growth stages may tolerate higher concentrations since crops show varying salt sensitivity across developmental stages, and freshwater leaching conditions may allow higher thresholds; (2) Irrigation with water above this threshold may cause yield reduction compared to freshwater but can still substantially increase yield over rainfed conditions, as demonstrated by studies showing significant production increases with >3 $g \cdot L^{-1}$ saline water compared to dryland farming.

While this long-term study revealed greater threshold variability than most previous short-term research, no significant factors explaining this fluctuation were identified among those examined. Further research should investigate these complex influences more thoroughly.

Conclusion

The multi-year salinity threshold for ‘Shijiazhuang 8’ winter wheat in Hebei Lowland Plain ranged from 2.14 to 3.95 $g \cdot L^{-1}$, averaging 3.19 $g \cdot L^{-1}$ with significant inter-annual variation (CV = 21.1%). The final recommended threshold, considering both yield and soil salt accumulation, is 2.47 $g \cdot L^{-1}$.

Primary factors causing inter-annual threshold variation were pre-sowing 1 m profile soil salinity (negative correlation, r = -0.587) and freshwater control yield (positive correlation, r = 0.516).

Continuous 9-year irrigation with 2.47 $g \cdot L^{-1}$ saline water maintained 0–20 cm topsoil below salinization levels (0.98 $g \cdot kg^{-1}$) while causing mild salinization in the 1 m profile (1.17 $g \cdot kg^{-1}$). Despite slight salt accumulation, no significant yield reduction occurred, indicating low risk of severe soil salinization.

References

[1] Wang H J. Research of Comprehensive Grain Production Capacity in Hebei Province[M]. Shijiazhuang: Hebei Science and Technology Press, 2010

[2] Tao P J, Wang N, Zhou Z J, et al. Water-saving technology in agriculture and analysis of choice in Heilonggang Region of Hebei Province[J]. Management of Agricultural Science and Technology, 2008, 27(2): 34–37

[3] Zhang G H, Fei Y H, Liu C H, et al. Adaptation between irrigation intensity and groundwater carrying capacity in North China Plain[J]. Transactions of the CSAE, 2013, 29(1):

[4] Zhang G H, Liu Z P, Fei Y H, et al. The relationship between the distribution of irrigated crops and the supply capability of regional water resources in North China Plain[J]. Acta Geoscientica Sinica, 2010, 31(1): 17–22

[5] Liu Z P, Zhang G H, Yan M J, et al. Impact of fertilization and high grain production on groundwater exploitation in Shijiazhuang Plain[J]. Chinese Journal of Eco-Agriculture, 2012, 20(1): 111–115

[6] Chen W H. The Groundwater in Hebei[M]. Beijing: Earthquake Press, 1999

[7] Zhang Y Z, Shen J M, Wang Y, et al. The distribution and utilization of underground (slightly) saline water in Hebei Lowplain[J]. Agro-Environment & Development, 2009, 26(6): 29-33

[8] Tanji K K, Kielen N C. Agricultural Drainage Water Management in Arid and Semiarid Areas. FAO Irrigation and Drainage Paper 61[M]. Rome: Food and Agriculture Organization of the United Nations, 2002

[9] Guo Y C. Study on irrigation with saline water in Heilonggang Region[J]. Journal of Irrigation and Drainage, 1992, 11(4): 14-19

[10] Zhang M X, Wang Y R, Wang Z X. Yield response function of wheat and cotton to soil in Sushui Basin in Shanxi Province[J]. Journal of Soil Erosion and Soil and Water Conservation, 1999, 5(6): 123-126

[11] Rhoades J D, Kandiah A, Mashali A M. The Use of Saline Waters for Crop Production –FAO Irrigation and Drainage Paper 48[M]. Rome: Food and Agriculture Organization of the United Nations, 1992

[12] Wang Y Y. A brief discussion about the blending irrigation of saline and fresh water[J]. Ground Water, 2004, 26(3): 210-211

[13] Hebei Provincial Administration of Quality and Technical Supervision. DB13/T 928–2008 Technical Specification of Irrigation Engineering Mixed with Saline Water and Fresh Water[S]. Beijing: Chinese Publishing House, 2008

[14] Pang H C, Yang J S, Yan H J. Effects of irrigation with saline water on soil salinity and crop yield[J]. Plant Nutrition and Fertilizer Science, 2004, 10(6): 599-603

[15] Zhang Y B, Shi H. Field test study on salt water irrigation systems in the high yielding cultivation of winter wheat[J]. Transactions of the CSAE, 2000, 16(1): 44-47

[16] Hu W M. Experimental study on effect of crop growth with light-saline water irrigation[J]. Journal of Irrigation and Drainage, 2007, 26(1): 86-88

[17] Wu Z D, Wang Q J. Effects of blending irrigation with brackish water on soil physico-chemical properties and winter wheat yield[J]. Transactions of the CSAE, 2008, 24(6): 69-73

[18] Guo H R, Jin M G, Gao Y F. Experiments on irrigation with brackish groundwater and management of soil salt in winter wheat fields[J]. Geological Science and Technology Information, 2002, 21(1): 61-65

[19] Li Q C. Effect on brackish water irrigation to wheat and corn crop[J]. Journal of Anqing Teachers College: Natural Science, 2003, 9(2): 37-40

[20] Mao Z Q, Yu Z R, Ma Y L. Influence of brackish water on the soil salt regime and yield of winter wheat and summer maize[J]. Journal of China Agricultural University, 2003, 8(S):

[21] Wu Z D, Wang Q J. Effect of saline water continuous irrigation on winter wheat yield and soil physicochemical property[J]. Transactions of the Chinese Society of Agricultural Machinery, 2010, 41(9): 36-43

[22] Shao Y C, Li Y, Sheng F K, et al. Safety of winter wheat and soil using brackish water irrigation[J]. Ecology and Environment, 2006, 15(6): 1241-1245

[23] Ye H Y, Wang Q J, Liu X J. Slight saline water irrigation systems for winter wheat[J]. Transactions of the CSAE, 2005, 21(9): 27-32

[24] Xiao Z H, Wan H F, Zheng L F. Effect of irrigation water quality on

soil chemical characteristics and crop growth[J]. Acta Pedologica Sinica, 1997, 34(3): 272–285

[25] Feng D, Zhang J P, Sun C T, et al. Effects of long-term irrigation with saline water on soil physical-chemical properties and activities of soil enzyme[J]. Journal of Soil and Water Conservation, 2014, 28(3): 171-176

[26] Qiao Y H, Yu Z R. Effect of brackish water on soil environment in saline area of Quzhou of Hebei Province[J]. Transactions of the CSAE, 2003, 19(2): 75-79

[27] Maas E V, Hoffman G J. Crop salt tolerance —Current assessment[J]. Journal of the Irrigation and Drainage Division, 1977, 103: 115-134

[28] Wang Z Q, Zhu S Q, Yu R P. The Saline Soil in China[M]. Beijing: Science Press, 1993

[29] Ayers R S, Westcot D W. Water Quality for Agriculture[R]. FAO Irrigation and Drainage Paper. Rome: Food and Agriculture Organization of the United Nations, 1985

[30] FAO. Irrigation scheduling: From theory to practice[C]//Proceedings of the ICID/FAO Workshop on Irrigation Scheduling. Rome, Italy: FAO, 1995

[31] Chen S Y, Zhang X Y, Shao L W, et al. Effect of deficit irrigation with brackish water on growth and yield of winter wheat and summer maize[J]. Chinese Journal of Eco-Agriculture, 2011, 19(3): 579—585

[32] Zhang Y L, Shao Y C, Yan Y D, et al. Practices of improving brackish water irrigated crops growth[J]. Journal of Agro-Environment Science, 2006, 25(S): 295—300

[33] Qadir M, Oster J D. Crop and irrigation management strategies for saline-sodic soils and waters aimed at environmentally sustainable agriculture[J]. Science of The Total Environment, 2004, 323(1/3): 1—19

[34] Chen L J, Feng Q, Wang Y, et al. Water and salt movement under saline water irrigation in soil with clay interlayer[J]. Transactions of the CSAE, 2012, 28(8): 44-51

[35] Chen D M, Yu R P. Studies on relative salt tolerance of crops: . Salt tolerance of some main crop species[J]. Acta Pedologica Sinica, 1996, 33(2): 121-128

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