Effects of Brackish Water Irrigation on Soil Salinity Balance and Crop Yield: Postprint

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Abstract

The Hebei Low Plain suffers from a shortage of freshwater resources but is rich in slightly saline water resources; the rational development and utilization of slightly saline water has become one of the important approaches to alleviating the water supply-demand conflict. This study was conducted from 2011 to 2015 at the Nanpi Eco-Agricultural Experimental Station, Chinese Academy of Sciences, in Cangzhou City, Hebei Province, using a winter wheat and summer maize double-cropping system as the research object to investigate the effects of implementing slightly saline water irrigation in the Hebei Low Plain on the yields of winter wheat and the subsequent summer maize crop, as well as the impact of irrigation on the annual balance of soil salinity. During the 2013–2014 winter wheat season, irrigation treatments included: rain-fed dryland treatment (CK), one freshwater irrigation at the jointing stage (F1), one irrigation with 2 $g \cdot L^{-1}$, 3 $g \cdot L^{-1}$, 4 $g \cdot L^{-1}$, or 5 $g \cdot L^{-1}$ slightly saline water at the jointing stage (B21, B31, B41, B51), freshwater irrigation at both jointing and grain-filling stages (F2), 3 $g \cdot L^{-1}$ slightly saline water at jointing stage plus freshwater at grain-filling stage (B31F1), freshwater at jointing stage plus 3 $g \cdot L^{-1}$ slightly saline water at grain-filling stage (F1B31), 3 $g \cdot L^{-1}$ slightly saline water at both jointing and grain-filling stages (B32), and freshwater irrigation at jointing, heading, and grain-filling stages (F3). In 2014–2015, based on the previous year' s results, the experimental treatments were simplified to: CK, F1, B31, B41, B51, and B42 (4 $g \cdot L^{-1}$ slightly saline water at both jointing and grain-filling stages). The results indicated that under normal annual conditions, two irrigations during the winter wheat growth period could achieve high and stable yields, with an average yield of 6,593.4 $kg \cdot hm^{-2}$. Using slightly saline water with salinity less than 5 $g \cdot L^{-1}$ for irrigation did not reduce winter wheat yield compared with freshwater irrigation; one slightly saline water irrigation increased yield by 10%-30% compared with the rain-fed treatment, indicating that slightly saline water could replace one freshwater irrigation. Under slightly saline water irrigation conditions, soil salinity accumulated by winter wheat harvest, with surface soil salinity exceeding 1 $g \cdot L^{-1}$, which affected the emergence and growth of the subsequent maize crop. However, applying 675-750 $m^3 \cdot hm^{-2}$ of freshwater irrigation after summer maize sowing could satisfy the salt leaching requirement of the tillage layer and reach the safety threshold for maize growth, resulting in no yield reduction compared with the freshwater irrigation treatment. Utilizing summer rainfall could leach soil salinity; when summer rainfall exceeded 300 mm, soil salinity under winter wheat slightly saline water irrigation reached annual balance. In the Cangzhou region, summer rainfall exceeds 300 mm in over 73% of years, creating conditions for soil salt leaching and ensuring the safety of replacing one freshwater irrigation with slightly saline water.

Full Text

Preamble

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Effect of Brackish Water Irrigation on Soil Salt Balance and Crop Yield

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Abstract

The Hebei low plain suffers from freshwater shortages but possesses abundant brackish water resources, making the rational development and utilization of brackish water an important approach to alleviating water supply-demand conflicts. This study was conducted at the Nanpi Eco-Agricultural Experimental Station of the Chinese Academy of Sciences in Cangzhou, Hebei Province from 2011-2015, focusing on a winter wheat-summer maize double cropping system to investigate the effects of brackish water irrigation on crop yields and annual soil salt balance in this region. During the 2013-2014 winter wheat season, irrigation treatments included: rainfed control (CK), one freshwater irrigation at jointing (F1), one brackish water irrigation (2, 3, 4, and 5 $g \cdot L^{-1}$) at jointing (B21, B31, B41, B51), two freshwater irrigations at jointing and grain-filling (F2), one 3 $g \cdot L^{-1}$ brackish water irrigation at jointing plus one freshwater irrigation at grain-filling (B31F1), one freshwater irrigation at jointing plus one 3 $g \cdot L^{-1}$ brackish water irrigation at grain-filling (F1B31), two 3 $g \cdot L^{-1}$ brackish water irrigations at jointing and grain-filling (B32), and three freshwater irrigations at jointing, heading, and grain-filling (F3). Based on the 2013-2014 results, treatments were streamlined in 2014-2015 to: CK, F1, B31, B41, B51, and B42 (two 4 $\mathrm{g \cdot L^{-1}}$ brackish water irrigations at jointing and grain-filling). Results showed that under typical conditions, two irrigations during winter wheat growth achieved high and stable yields, averaging $6,593.4\ \mathrm{kg \cdot hm^{-2}}$. Using brackish water with salinity less than 5 $\mathrm{g \cdot L^{-1}}$ did not reduce winter wheat yield compared to freshwater irrigation. A single brackish water irrigation increased yield by 10-30% over rainfed conditions, demonstrating that brackish water can substitute for one freshwater irrigation. However, brackish water irrigation caused soil salt accumulation, with topsoil salinity exceeding 1 $\mathrm{g \cdot L^{-1}}$ at winter wheat harvest, affecting summer maize germination and growth. Applying 675-750 $\mathrm{m^3 \cdot hm^{-2}}$ of freshwater irrigation after summer maize planting satisfied leaching requirements for the cultivated layer, bringing salinity below the safety threshold for maize growth without yield reduction. Summer rainfall enabled soil salt leaching; when summer rainfall exceeded 300 mm, annual soil salt balance was achieved. In the Cangzhou region, over 73% of years receive more than 300 mm of summer rainfall, creating favorable conditions for salt leaching and ensuring the safety of substituting one freshwater irrigation with brackish water during winter wheat growth.

Keywords: Brackish water irrigation; Soil; Winter wheat-summer maize double cropping system; Salt balance; Crop yield; Hebei low plain

Introduction

The Hebei low plain represents one of China' s important grain and cotton production bases, where agricultural production has long relied on deep groundwater extraction. This has caused severe groundwater level declines, creating the world' s largest groundwater funnel area and posing a serious threat to sustainable agricultural and socioeconomic development [1]. To protect groundwater resources, the government implemented groundwater overexploitation control measures in this region (including Cangzhou, Hengshui, Handan, and Xingtai cities in Hebei Province), essentially halting deep confined water extraction for all uses except domestic supply by 2017. Meanwhile, the region possesses substantial shallow saline groundwater resources. In the Heilonggang area alone, for example, brackish water with mineralization of 2-5 $\mathrm{g \cdot L^{-1}}$ covers 67% of the total area with reserves of approximately 2.3 billion $\mathrm{m^3}$, while current utilization is only 0.2 billion $\mathrm{m^3}$ [2]. Therefore, developing and utilizing brackish water resources represents an important measure to alleviate freshwater scarcity and increase grain production in regions with limited freshwater availability [3].

Compared with rainfed farming, brackish water irrigation demonstrates certain yield-increasing effects [4-6]. Research at the Hebei Academy of Agricultural Sciences' Dryland Water-saving Agriculture Experimental Station showed that winter wheat yields increased by 22.0%, 15.4%, and 0.1% when irrigated with 2, 4, and 6 $\mathrm{g \cdot L^{-1}}$ brackish water, respectively, compared to rainfed conditions [2]. Experiments in Nanpi County, Hebei Province, revealed that single irrigations of

2 and 4 $g \cdot L^{-1}$ brackish water at the jointing stage increased winter wheat yields by 32.8% and 22.1% compared to rainfed treatments [6]. Generally, brackish water irrigation produces yields comparable to or slightly lower than freshwater irrigation, with yield reduction increasing as irrigation water salinity increases. Shang et al. [7] analyzed 103 sets of experimental data on winter wheat irrigation with brackish water nationwide and found a negative correlation between irrigation water mineralization and relative wheat yield under full irrigation conditions. When irrigation water mineralization was 2-3 $g \cdot L^{-1}$, relative wheat yield was 0.87-0.93, representing only 7-13% yield reduction compared to freshwater irrigation. However, when using 3-5 $g \cdot L^{-1}$ saline water, wheat yield was more substantially affected due to severe salt stress, with yield reductions of approximately 13-24% compared to freshwater irrigation [7-8]. The impact of brackish water irrigation on crop yield depends not only on water salinity but also on irrigation amount. As salt input per unit area increases, relative wheat yield gradually decreases. Mao et al. [9] demonstrated at the Quzhou Experimental Station of China Agricultural University that summer maize yield was not significantly affected when soil solution electrical conductivity at 20-60 cm depth remained below 8 $mS \cdot cm^{-1}$, but yield decreased significantly when conductivity was maintained at 10-15 $mS \cdot cm^{-1}$ for extended periods with relatively low seasonal rainfall. When soil solution electrical conductivity at 20-60 cm depth was maintained at 12-15 $mS \cdot cm^{-1}$, salt stress caused approximately 10% winter wheat yield loss under high irrigation conditions. Previous brackish water irrigation research has primarily focused on full irrigation conditions and single-season crops. This study investigated the effects of brackish water irrigation on crop yields and soil salt dynamics in a winter wheat-summer maize double cropping system under limited irrigation conditions.

Previous research indicates that under monsoon climate conditions, pumping shallow brackish groundwater for irrigation during the dry spring season lowers the groundwater level before the rainy season, creating underground storage capacity and reducing shallow water evaporation, thereby preventing soil salinization. Rainfall recharge during the flood season increases infiltration, reduces surface runoff, and promotes shallow groundwater freshening, improving groundwater quality [10]. Extensive research on brackish water irrigation has been conducted domestically and internationally. Compared with rainfed farming, brackish water irrigation can increase yields to varying degrees [11-12], and under particularly dry conditions, it can reduce soil solution concentration and osmotic pressure, controlling root-zone solution concentration within crop physiological limits to meet crop water demands [13]. However, brackish water irrigation simultaneously increases salt input from irrigation water, causing soil salt accumulation [14-16]. Therefore, it is essential to balance meeting crop water requirements with controlling salt damage, maintaining root-zone soil salinity below crop salt tolerance thresholds; otherwise, crop growth will be affected and yields will decline with increasing salinity. Soil salt movement is strongly influenced by evaporation and rainfall, which are important factors affecting salt distribution in the soil profile. Salt accumulates during dry seasons with little rainfall and is leached by rainfall during rainy seasons [14]. This study investigated the effects of brackish water irrigation on crop yield and soil salt balance to provide a scientific basis for rational brackish water resource utilization and development, ensuring no crop yield reduction and no salt accumulation.

1.1 Experimental Design

Field experiments were conducted at the Nanpi Eco-Agricultural Experimental Station of the Chinese Academy of Sciences from 2013–2015. The station is located at 38°00′N, 116°40′E, at an elevation of 11 m in a warm temperate semi-humid monsoon climate zone with an average annual temperature of 12.3 °C and average annual precipitation of 480 mm. The 0–20 cm soil layer contained 104.8 $\mathrm{mg \cdot kg^{-1}}$ available potassium, 17.9 $\mathrm{mg \cdot kg^{-1}}$ available phosphorus, 88.9 $\mathrm{mg \cdot kg^{-1}}$ available nitrogen, and 14.0–19.0 $\mathrm{g \cdot kg^{-1}}$ organic matter, with a soil bulk density of 1.45 $\mathrm{g \cdot cm^{-3}}$ and an average bulk density of 1.427 $\mathrm{g \cdot cm^{-3}}$ for the 0–100 cm profile. Field water capacity was 24.1% (W/W). Initial soil salinity levels are shown in ; the experimental soil was slightly saline. Shallow groundwater was brackish, while deep groundwater was fresh.

The cropping system was winter wheat-summer maize double cropping. Since winter wheat has a higher salt tolerance threshold than summer maize, different irrigation frequencies and salinities were applied during the winter wheat growth period, while summer maize received only freshwater irrigation to investigate effects on winter wheat yield, subsequent summer maize yield, and soil salt balance. Winter wheat irrigation treatments varied by frequency (rainfed, one, two, or three irrigations) and brackish water salinity (2, 3, 4, and 5 $\mathrm{g \cdot L^{-1}}$) for one or two applications. In 2013–2014, ten treatments were established: CK (rainfed), F1 (one freshwater irrigation), B21 (one 2 $\mathrm{g \cdot L^{-1}}$ brackish water irrigation), B31 (one 3 $\mathrm{g \cdot L^{-1}}$ brackish water irrigation), B41 (one 4 $\mathrm{g \cdot L^{-1}}$ brackish water irrigation), B51 (one 5 $\mathrm{g \cdot L^{-1}}$ brackish water irrigation), F2 (two freshwater irrigations), B32 (two 3 $\mathrm{g \cdot L^{-1}}$ brackish water irrigations), F1B31 (one freshwater + one 3 $\mathrm{g \cdot L^{-1}}$ brackish water irrigation), B31F1 (one 3 $\mathrm{g \cdot L^{-1}}$ brackish water + one freshwater irrigation), and F3 (three freshwater irrigations). In 2014–2015, treatments were streamlined to six: CK, F1, B31, B41, B51, and B42 (two 4 $\mathrm{g \cdot L^{-1}}$ brackish water irrigations). All treatments were flat-planted. Single irrigation treatments were applied at jointing; two irrigation treatments at jointing and grain-filling; and three irrigation treatments at jointing, heading, and grain-filling. Plot size was 5 m × 7 m with four replications in a randomized arrangement. Freshwater irrigation used deep well water with mineralization of 1.05 $\mathrm{g \cdot L^{-1}}$. Brackish water of different salinities was prepared by mixing shallow well water with coarse salt (purchased natural coarse salt from Huanghua City, Hebei Province) in storage tanks.

Winter wheat was planted in 15 cm row spacing. Varieties were 'Shixin 828' in 2013–2014 and 'Shixin 688' in 2014–2015, with sowing dates of October 13, 2013 and October 11, 2014, respectively. Seeding rate was 225 $\mathrm{kg \cdot hm^{-2}}$, with harvest dates of June 6, 2014 and June 10, 2015. Basal fertilizer application before sowing consisted of 450 $kg \cdot hm^{-2}$ diammonium phosphate (KH_2PO_4, 98%) and 150 $kg \cdot hm^{-2}$ urea (N: 46.4%). At jointing, 375 $kg \cdot hm^{-2}$ urea was topdressed. Summer maize variety 'Zhengdan 958' was mechanically planted in 60 cm rows at a density of $52,500$-$60,000$ $plants \cdot hm^{-2}$ immediately after wheat harvest, with harvest on September 30.

1.2 Observation Items and Methods

Soil salinity: Soil samples were collected after wheat harvest (June) and maize harvest (September) each year using soil augers at depths of 0-20, 20-40, 40-60, 60-80, and 80-100 cm, with three replicates per treatment. After air-drying, soil total salt content and eight major salt ions (Ca^{2+}, Mg^{2+}, HCO_3^-, Cl^-, SO_4^{2-}, $Na^+ + K^+$) were determined using complexometric titration.

Winter wheat yield: Forty wheat spikes were randomly selected from each plot for yield component analysis, including spike number, kernels per spike, and thousand-kernel weight.

Summer maize yield: Plot harvest was conducted to determine plant density, with ten random ears selected for kernel number and thousand-kernel weight measurements.

1.3 Data Processing Methods

Experimental data were analyzed and graphed using SPSS Ver. 16.0 software and Microsoft Excel.

2.1.1 Effects on Winter Wheat Yield and Yield Components

Results from 2013-2014 (Table 2) showed no significant difference in winter wheat yield between one freshwater irrigation and one brackish water irrigation (2-4 $g \cdot L^{-1}$). Similarly, no significant differences were observed among two freshwater irrigations, two brackish water irrigations, or alternating freshwater and brackish water irrigations. When one of two winter wheat irrigations used 3 $g \cdot L^{-1}$ brackish water, yield did not differ significantly from two freshwater irrigations. Two 3 $g \cdot L^{-1}$ brackish water irrigations also showed no significant yield difference compared to two freshwater irrigations. Therefore, substituting one freshwater irrigation with 2-4 $g \cdot L^{-1}$ brackish water during winter wheat growth did not reduce yield. Compared to rainfed conditions, one brackish or freshwater irrigation increased yield by an average of 13.4%, while two brackish water irrigations increased yield by 22.6%. Alternating one brackish and one freshwater irrigation increased yield by 8.5% compared to one freshwater irrigation.

In 2014-2015, based on previous results, higher salinity brackish water irrigation experiments were conducted. Results showed no significant yield difference between one irrigation of 3-5 $g \cdot L^{-1}$ brackish water and one freshwater irrigation. Two 4 $g \cdot L^{-1}$ brackish water irrigations also showed no significant yield difference compared to two freshwater irrigations, indicating that 3-5 $g \cdot L^{-1}$ brackish water irrigation did not reduce winter wheat yield (Table 2).

Combined results from both years demonstrated that one brackish water irrigation increased winter wheat yield by 10-30% over rainfed conditions. A single jointing-stage irrigation with 2-5 $g \cdot L^{-1}$ brackish water showed no significant yield difference compared to freshwater irrigation, indicating that brackish water can substitute for one freshwater irrigation without affecting yield. Two brackish water irrigations during winter wheat growth increased yield by over 40% compared to no irrigation, and two irrigations with 2-5 $g \cdot L^{-1}$ brackish water at jointing and grain-filling stages showed no significant yield difference from two freshwater irrigations, suggesting that brackish water can replace two freshwater irrigations.

2.1.2 Effects on Summer Maize Yield

Brackish water irrigation introduces both water and salt into the soil, and accumulated salt can affect subsequent crop growth. In winter wheat-summer maize double cropping systems, summer maize has lower salt tolerance than winter wheat, so salt remaining in the soil from winter wheat brackish water irrigation can impact the following summer maize crop. Therefore, the impact on subsequent crops must be considered when implementing brackish water irrigation for winter wheat.

Table 3 shows the effect of previous winter wheat brackish water irrigation on summer maize yield. All summer maize plots received one freshwater irrigation after sowing to reduce salt effects on germination and seedling growth. Results indicated that winter wheat brackish water irrigation had some impact on subsequent summer maize yield. In 2014, one 2-4 $g \cdot L^{-1}$ brackish water irrigation during winter wheat growth reduced summer maize yield by an average of 15.9% compared to one freshwater irrigation. Two 3 $g \cdot L^{-1}$ brackish water irrigations reduced summer maize yield by 11.17% compared to two freshwater irrigations. Under two irrigation events, replacing one freshwater irrigation with 3 $g \cdot L^{-1}$ brackish water reduced summer maize yield by an average of 2.19%. Specifically, when 3 $g \cdot L^{-1}$ brackish water was applied at jointing and freshwater at grain-filling, summer maize yield did not differ from two freshwater irrigations. However, when freshwater was applied at jointing and brackish water at grain-filling, summer maize yield decreased by 4.6% compared to two freshwater irrigations.

In 2015, summer maize yield trends were similar to 2014. One 3-5 $g \cdot L^{-1}$ brackish water irrigation during winter wheat growth reduced summer maize yield by an average of 9.5% compared to one freshwater irrigation. Summer maize yield under two brackish water irrigations did not differ significantly from two freshwater irrigations.

2.2 Effects of Different Salinity Levels on Soil Salt Balance

After brackish water irrigation at winter wheat jointing stage, soil salt moved upward with evaporating water as temperatures rose, increasing topsoil salinity. Figure 1 [Figure 1: see original paper] shows soil salt content after three years of brackish water irrigation (2013-2015) at winter wheat and summer maize harvest. Figure 1a indicates that 0-60 cm soil salinity was higher than pre-sowing levels, increasing with irrigation water salinity. Salinity in the 60-100 cm layer changed little, while two brackish water irrigations resulted in higher average soil salinity than one irrigation. At summer maize harvest (Figure 1b), topsoil (0-20 cm) salinity in brackish water treatments decreased compared to winter wheat harvest, with salt accumulating mainly in the 40-80 cm layer.

Soil salt changes in 2014-2015 are shown in Figures 1c and 1d. Soil salinity under rainfed winter wheat represented pre-sowing conditions. Soil salinity under rainfed and one-two freshwater irrigations was essentially consistent at winter wheat harvest, averaging 1.0 $g \cdot kg^{-1}$ in the 0-60 cm layer—lower than rainfed conditions—indicating that one-two freshwater irrigations leached soil salt. Soil salinity in the 0-60 cm layer increased significantly under 3-5 $g \cdot L^{-1}$ brackish water irrigation, averaging 1.4 $g \cdot kg^{-1}$, with the highest salinity in the 0-20 cm topsoil reaching 1.6 $g \cdot kg^{-1}$.

One freshwater irrigation after summer maize sowing leached salt below the 20 cm layer, and subsequent concentrated summer rainfall further leached salt. By summer maize harvest, the 0-80 cm layer was in a desalinization state. Salinity in all treatments decreased, with average 0-100 cm and 0-60 cm salinity of 1.0 $g \cdot kg^{-1}$ and 0.9 $g \cdot kg^{-1}$, respectively—both lower than pre-sowing levels.

Results differed substantially between the two years due to different rainfall amounts. Summer maize season rainfall (June-September) was 155.9 mm in 2014 and 451.3 mm in 2015 (Figure 6 [Figure 6: see original paper]). The 2014 drought resulted in minimal salt leaching and salt accumulation, while the 451.3 mm of concentrated rainfall in 2015 leached more salt than accumulated, resulting in substantial desalinization.

2.3 Effects of Irrigation and Rainfall on Soil Salt Balance

In winter wheat-summer maize double cropping systems, brackish water irrigation at winter wheat jointing stage causes salt accumulation in the topsoil through later evaporation, often exceeding summer maize salt tolerance thresholds and affecting normal germination and seedling growth, resulting in yield reduction. Mitigating salt accumulation effects on summer maize emergence is crucial for safe and efficient brackish water utilization. Rainfall and increased irrigation leaching can reduce topsoil salinity and alleviate impacts on subsequent crops (Figure 3 [Figure 3: see original paper]).

Figure 4 [Figure 4: see original paper] shows the effect of different irrigation amounts on 0-20 cm soil salinity after winter wheat harvest. Results indicated that with 70 mm surface irrigation, topsoil salinity decreased below the safe threshold for maize growth (1.0 $g \cdot kg^{-1}$) within five days. Localized irrigation measures could further reduce water requirements.

Figure 5 [Figure 5: see original paper] shows pre-sowing soil salinity in 0–100 cm depth for 2013, 2014, and 2015. Average 0–100 cm salinity was 0.93, 1.12, and 0.96 $g \cdot kg^{-1}$, respectively, while 0–60 cm salinity was 0.89, 1.12, and 0.84 $g \cdot kg^{-1}$. Pre-sowing 0–100 cm salinity was below 1.0 $g \cdot kg^{-1}$ in 2013 and 2015 but exceeded 1.0 $g \cdot kg^{-1}$ in 2014. Figure 6 [Figure 6: see original paper] shows summer maize season rainfall for the three years: 543.7 mm in 2013, 155.9 mm in 2014, and 451.3 mm in 2015. The low rainfall in 2014 caused salt accumulation in the soil.

The 0–20 cm layer is strongly affected by crop growth and field management, showing large salt content fluctuations. Soil salinity at winter wheat harvest was higher than at maize harvest because intense soil evaporation during late winter wheat growth moved salt upward. Subsequent summer maize season rainfall then leached the accumulated salt downward, reducing 0–20 cm salinity. This cycle repeated annually. The 2015 rainy season had more rainfall than 2014, resulting in stronger salt leaching. Compared with the 0–20 cm layer, 0–100 cm soil salinity changes were more stable.

2.4 Winter Wheat Irrigation System Research

In the winter wheat-summer maize double cropping system of the Hebei low plain, winter wheat grows during the dry winter-spring season when rainfall cannot meet normal growth requirements, making supplemental irrigation essential for yield. However, severe groundwater overexploitation and government control measures have limited freshwater availability, making brackish water the primary irrigation source. Research shows winter wheat has higher brackish water irrigation thresholds than summer maize, and crops have different salt tolerances at different growth stages. Dividing winter wheat growth into sowing-regreening, regreening-jointing, jointing-heading, and heading-maturity stages, the salt impact indices are 0.1426, 0.3270, 0.0265, and 0.012, respectively. Salt sensitivity is higher before and after regreening (low salt tolerance stage) and lower after jointing (salt-tolerant stage, suitable for brackish water irrigation) [17].

This study found that brackish water irrigation with salinity less than 5 $g \cdot L^{-1}$ at winter wheat jointing stage significantly increased yield, indicating that one jointing-stage brackish water irrigation can substitute for freshwater irrigation while ensuring high winter wheat yields. These results align with other reports on brackish water irrigation effects on winter wheat [18–19].

However, soil salt accumulation from winter wheat brackish water irrigation negatively affected the subsequent maize crop, reducing summer maize yield. Findings from Ma et al. [1] and Pang et al. [3] in Hebei Province are consistent with this study. This research further demonstrated that approximately 70 mm of freshwater irrigation after summer maize sowing could reduce 0-20 cm soil salinity below summer maize thresholds, mitigating yield reduction caused by winter wheat brackish water irrigation. This aligns with local agricultural management needs because intense soil evaporation and crop transpiration during late winter wheat growth deplete soil moisture, requiring irrigation after summer maize sowing to ensure germination and seedling growth. This freshwater irrigation thus satisfies both water requirements and salt leaching needs.

Chen et al. [20] showed that in Cangzhou, Hebei, soil salt accumulation from brackish water irrigation is primarily leached by concentrated summer rainfall, with leaching effectiveness depending on total summer rainfall and individual rainfall events. Generally, single rainfall events exceeding 25 mm provide leaching effects, and rainfall greater than 300 mm during June-September essentially ensures soil salt balance. Analysis of rainfall patterns in Nanpi County, Hebei from 1996-2014 (Figure 8 [Figure 8: see original paper]) shows average annual rainfall of 533.4 mm and average summer rainfall of 395.3 mm, with summer rainfall exceeding 300 mm in 73% of years and 400 mm in over 57% of years, creating favorable conditions for soil salt leaching and desalinization.

Conclusion

Developing and utilizing brackish water resources for irrigation can alleviate freshwater scarcity to some extent, but brackish water irrigation can cause soil salinization. Therefore, ensuring the safety of brackish water irrigation for crops and the environment is crucial for sustainable agricultural development. Based on this research, the following conclusions are drawn:

In the winter wheat-summer maize double cropping system of the Hebei low plain, two irrigations at jointing and heading-flowering stages generally achieve stable, high yields. Using brackish water with salinity not exceeding 5 $g \cdot L^{-1}$ to replace one freshwater irrigation maintains crop yields without reduction, with jointing-stage irrigation being more effective than heading-flowering stage irrigation. After winter wheat brackish water irrigation, high water consumption during growth causes obvious salt accumulation in the topsoil, exceeding the salt tolerance threshold of the subsequent summer maize crop. Applying 675-750 $m^3 \cdot hm^{-2}$ of freshwater irrigation after summer maize sowing can leach salt to below the safety threshold without affecting maize seedling growth. The summer maize growth period coincides with the rainy season; when summer rainfall is less than 300 mm, salt accumulates, but when rainfall exceeds 300 mm, leaching effects achieve annual salt balance and soil desalinization [16], providing technical support for safe brackish water irrigation and grain yield increases. However, long-term monitoring is needed to assess the long-term impacts of brackish water irrigation on soil and the environment.

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