

Article

Unraveling the Impact of Inter-Basin Water Transfer on Soil Salinity and Sodicty and the Crop Yield Response in the Karamay Irrigation District of China

Wei Liu, Xinwei Yin *, Meng Zhu *, Jutao Zhang , Wen Liu, Yingqing Su , Naying Chai and Yuhui Chen

State Key Laboratory of Ecological Safety and Sustainable Development in Arid Lands, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou 730000, China; weilu@lzb.ac.cn (W.L.); jutzhang@lzb.ac.cn (J.Z.); liuwen@lzb.ac.cn (W.L.); yingqingsu@nieer.ac.cn (Y.S.); 1073323020374@st.gsau.edu.cn (N.C.); chenyuhui@xjshzu.com (Y.C.)

* Correspondence: xinweiyin@lzb.ac.cn (X.Y.); zhuzheng@lzb.ac.cn (M.Z.)

Abstract: Large-scale inter-basin water transfer is an important means to alleviate the pressure on water resources in water shortage regions. However, the long-term impacts of inter-basin transfers on the regional water–salt balance and associated land productivity remain poorly understood, especially in salt-affected arid environments. To fill this gap, the core objective of this study was to reveal the implications of inter-basin water transfer on soil salinity and sodicty and the crop yield response under different irrigation practices. We conducted a case study on the Karamay irrigation district (KID), an artificial oasis with a 30-year history of inter-basin water transfer in northwestern China, using trend and correlation analyses, water–salt balance analyses, and salt-controlled yield reduction functions as well as field comprehensive measurements over 1996–2023. The results indicate that soil salinity and sodicty profiles, overall, exhibited a clear vertical stratification under both the early and late crop growing stages, and the degree of the soil salinization was decreasing, and the area of non-saline land was increasing significantly from 1996 to 2023 in the KID. Owing to the lack of salt-washing water and the poor irrigation water quality, the water-saving irrigated farmland was in the slight salt-aggregating state in the topsoil layer, while the other soil layers were in the salt-expelling or salt-equilibrating state in the KID. The profile distribution and exchange fluxes of soil salinity and sodicty are mainly characterized by climate, irrigation, and groundwater dynamics, as well as the plant salt tolerance, soil properties, and agronomic management which also influence the soil salt accumulation. With the transformation of irrigation schemes from traditional flood irrigation to modern water-saving irrigation during 1996–2023, the impact of soil salinity on relative crop yields has been substantially reduced in the KID, especially for salt-sensitive crops. This revealed that optimizing the drainage facilities, precise field irrigation and fertilization measures, and rational crop selection and agronomic practices are vital for high-quality development in the KID. Capitalizing on these research findings, we would provide effective directives for maintaining the sustainability of agricultural development in other similar inter-basin water transfer zones in the world.

Keywords: water transfer; irrigated agriculture; soil salinization; crop salt tolerance; sustainable development



Academic Editor: Belen Gallego-Elvira

Received: 2 May 2025
Revised: 31 May 2025
Accepted: 3 June 2025
Published: 5 June 2025

Citation: Liu, W.; Yin, X.; Zhu, M.; Zhang, J.; Liu, W.; Su, Y.; Chai, N.; Chen, Y. Unraveling the Impact of Inter-Basin Water Transfer on Soil Salinity and Sodicty and the Crop Yield Response in the Karamay Irrigation District of China. *Agronomy* **2025**, *15*, 1386. <https://doi.org/10.3390/agronomy15061386>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Water scarcity is a serious global issue affecting millions of people and ecosystems around the world, especially in drylands [1]. According to the United Nations

(www.unwater.org, accessed on 12 February 2025), approximately 40% of the world's population may face the risk of serious water scarcity by 2040. Existing assessments of future water scarcity suggest that increased global water demands related to population growth and economic development, combined with variations in water availability owing to altered hydrometeorological regimes, are exacerbating water scarcity issues globally [2,3]. Among many interventions to provide water supply security, inter-basin water transfer is a commonly used engineering approach to reduce the water deficit in water-stressed areas by directly transferring excess water from one water-surplus basin to another water-scarce basin [4]. The inter-basin water transfer has a long history worldwide, with the majority of schemes implemented in the early 1900s rising to a peak in the 1970s and 1980s and the average water transfer capacity per project increasing from 3.56 km³ per year up to 1980 to a projected 12.7 km³ per year in 2050, especially in arid and semi-arid areas (Figure 1) [5]. Nevertheless, inter-basin water transfers inevitably involve the redistribution of water resources in the relevant basins and may cause regional eco-environmental changes. Such changes involve both positive impacts, such as the promotion of the water cycle, the alleviation of ecological water scarcity, and the restoration of damaged ecosystems, and negative impacts, such as exacerbating regional soil salinization, deteriorating groundwater quality, and reductions in land productivity [6,7]. Therefore, it is crucial to reveal the long-term impacts of inter-basin water transfers on the regional soil and water environments.

Soil salinization is one of the major land degradation threats affecting soil stability, fertility, and biodiversity [8]. Worldwide, about 37% of arable land is categorized as sodic and 23% as saline, and nearly 50% of irrigated lands globally are considered to be significantly affected by soil salinization (Figure 1) [9]. Soil salinity refers to high concentrations of salt in the soil, while soil sodicity indicates a situation where sodium makes up a large portion of the total cations and is not necessarily accompanied by high salinity [10]. Both soil salinity and soil sodicity levels are spatially, vertically, and temporally dynamic, especially in arid environments, and are substantially influenced by governing climatic conditions and anthropogenic activities [8,11]. Generally, water is the primary driver of the salt transport through the soil, and seasonal changes in soil salinity and sodicity in the root zone occur as water enters and leaves the system. Also, precipitation regimes, irrigation management, and water quality can significantly affect root zone salinity and sodicity dynamics by controlling leaching and transpiration processes. Moreover, capillary upflow plays a dominant role in the dynamics of soil water and salts, which is strongly influenced by the shallow groundwater table and salinity. Furthermore, the plant salt tolerance and soil properties are important aspects of long-term root zone salt buildup, thereby controlling land productivity [12–15]. Nevertheless, the effect of inter-basin water transfer on the long-term dynamics of soil salinity and sodicity is poorly understood, especially under varying irrigation practices.

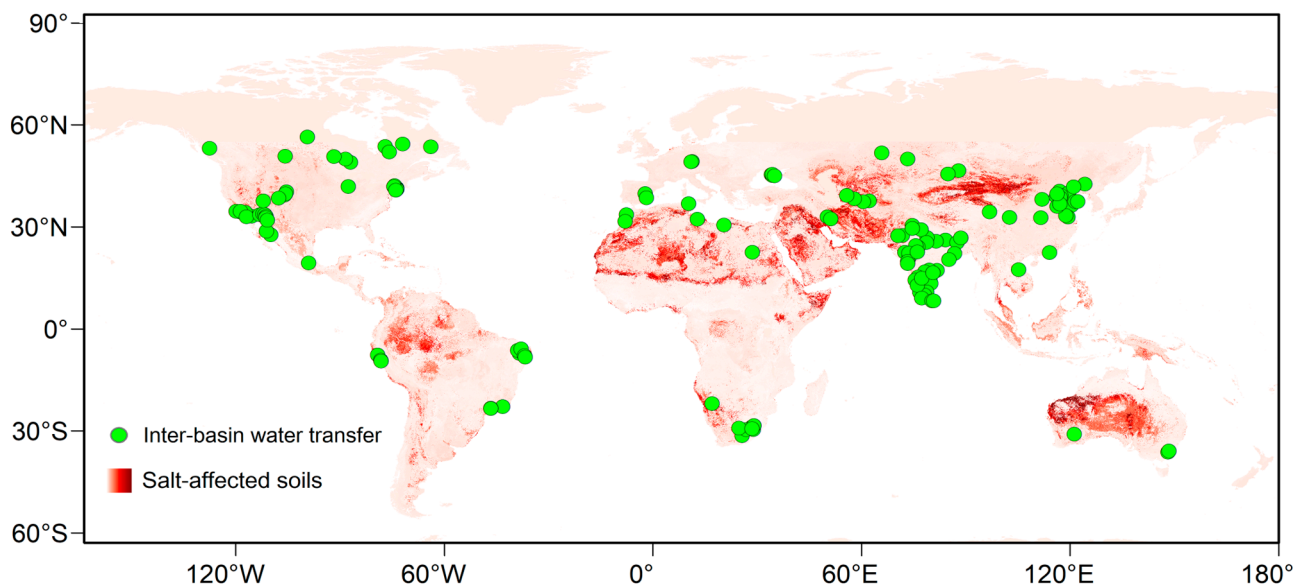


Figure 1. Global inter-basin water transfer systems [16] and a global distribution map of salt-affected soils in 2018 (excluding the frigid zones) [9].

The influence of salinization on crop production and concerns regarding its management have been the focus of agronomic research [10]. Salinization can reduce yields of many crops by 10~25%, and in severe cases, it can make crops completely uncultivable and lead to land desertification. Typically, soil salinity and sodicity directly affect healthy plant growth by affecting the plant water uptake, plant nutrient effectiveness, and imposing plant toxicity, as well as indirectly by the degradation of soil physical conditions [17]. For instance, the elevated osmotic pressure of the soil moisture can impede the water uptake by the roots, and nutrient imbalances, which conversely can result in toxicities and deficiencies, are the main reasons for the unfavorable effects of soil salinity and sodicity on plant growth [18]. Other unfavorable factors include poor soil physical regimes, such as a low permeability to water, which is induced by the clay swelling and dispersion related to complex interactions between sodicity and electrolyte concentrations [19]. Furthermore, soil salinity and sodicity can impose stress on agricultural crops, and when critical threshold ranges are exceeded, yields decrease [20]. In recent decades, plant response functions to various growth and environmental factors have been proposed and applied, with considerable attention concentrated on water and salinity [21]. At the same time, the response of crop yield reductions to soil salinity is often modeled using a threshold-type function [22] or a sigmoid (S-shaped) function [23]. Also, for most crops with different salt tolerances, this response function follows a sigmoidal relationship [24]. Hence, the plant response function to salinity is an effective tool to study the effect of salinity on crop yields in the inter-basin water transfer area.

The Karamay irrigation district is located in the northwestern edge of the Junggar Basin in Xinjiang, on the alluvial plains of the ancient Manas Lake, which is one of the most arid regions in the northwest of China with low precipitation, high evapotranspiration, and no surface runoff [25]. Since 2000, with the development of land for agricultural exploitation, there has been projected to be 260 million $\text{m}^3 \cdot \text{a}^{-1}$ of water transferred to the Karamay irrigation district, with 140 million $\text{m}^3 \cdot \text{a}^{-1}$ earmarked for agricultural use [6]. Initially, regional irrigation was dominated by flood irrigation. Since 2006, water-saving irrigation has been widely used on a large scale. By 2011, all irrigation districts had adopted water-saving irrigation [25]. Currently, extensive irrigation without adequate drainage has

caused rising groundwater levels and upset the original water–salt balance in the root zone and shallow aquifer in the Karamay irrigation district.

Here, to reveal the effect of inter-basin water transfer on soil salinity and sodicity and the associated vegetation dynamics under varying irrigation practices, the Karamay irrigation district of China was selected. Using field comprehensive measurements and meaningful modeling approaches, this study aims to achieve the following objectives: (1) investigating the effect of inter-basin water transfer on the spatio-temporal variations in soil salinity and sodicity dynamics, (2) revealing the soil salinity and sodicity exchange fluxes and their controlling factors in different soil layers, and (3) evaluating the long-term implications of soil salinity on yields for different salt-tolerant crops. Capitalizing on these research objectives, we would provide effective directives for maintaining the sustainability of soil and water environments in the inter-basin water transfer area in the face of ongoing and future global changes.

2. Materials and Methods

2.1. The Geographic Location and Characterization of the Study Area

The Karamay irrigation district (KID) is situated on the Lacustrine plain in the northwestern Junggar Basin of Xinjiang, China, and located 20 km from Kalamay city. The KID is located in the southeastern part of the Zaire Mountains and in the northwest of the Gurbantunggut Desert and covers an area of 194.3 km² (84°50′–85°20′ E, 45°22′–45°40′ N; 268–288 m) with a mean land surface slope of 0.26‰ from southwest to northeast (Figure 2). There are three main types of Quaternary sediments in the study area, with extensive lacustrine sediments (Q3) distributed in the center and north, alluvial sediments (Q3–4) of the Genghis Khan Mountains on the southwestern margin, and aeolian sand dunes (Q4) developing in the east–central part of the region [26]. Also, the zonal soils are mainly swampy soils developed from lake deposits and various types of salt soils formed from sedimentary deposits, in addition to a small amount of sandy and calcareous soils. Furthermore, according to 36 soil samples from 0 to 40 cm (21 locations—3 repetitions), the soil texture is heavy and dense, mainly sandy clay loam, with heavy salinization degree, low organic matter content, and poor soil nutrient status (Table 1).

The study area has a typical continental arid desert climate, with average annual rainfall of approximately 111 mm, and the rainfall period is concentrated from July to September every year; the annual potential evaporation is about 1000 mm, with an evaporation precipitation ratio of 10:1; the average annual air temperature is 8.5 °C, with a maximum of 42.9 °C in July and a minimum of −35.9 °C in January; the maximum wind speed is 49 m·s^{−1}; the annual sunshine time is 2734.6 h; and the frost-free period is 180–220 days [6]. Over the last 68 years (1956–2023), the mean annual temperature and precipitation in the KID have shown an increasing trend, with the overall trend being ‘warming and wetting’. Specifically, the mean temperature in the study area has increased by 0.19 °C per decade in the past 68 years, and the temperature has continued to be in the warming phase since 1968, with the maximum and minimum temperatures increasing by 0.11 °C and 0.38 °C per decade, respectively [26]. At the same time, the mean precipitation in the study area has increased by 8.0 mm per decade in the past 68 years, with a significant increase since 1972, especially the increase in extreme precipitation and extreme drought processes (Figure 3).

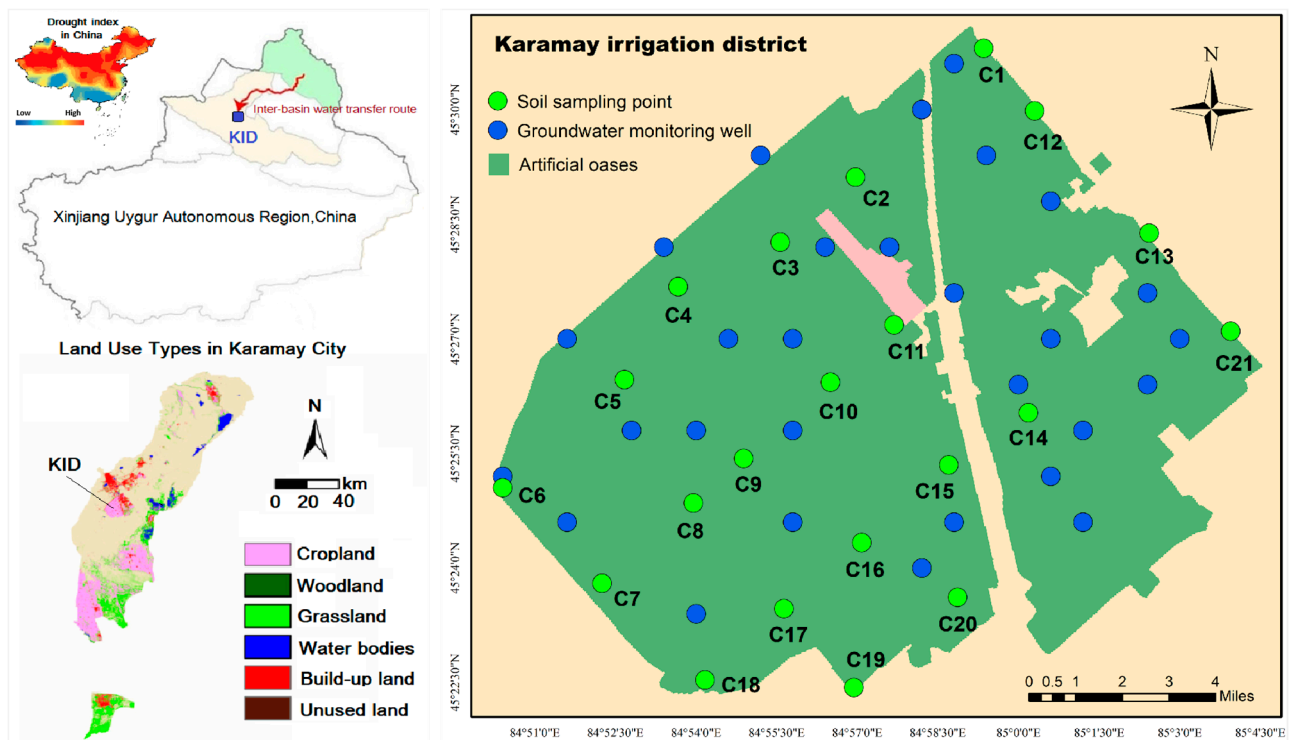


Figure 2. The location map of the Karamay irrigation district (KID) and the inter-basin water transfer, and the distribution of the soil sampling points (C1–C21) and groundwater monitoring wells.

Table 1. The basic properties of soil in the Karamay irrigation district.

Soil Index	SBD g·cm ⁻³	SOM g·kg ⁻¹	TN g·kg ⁻¹	TP g·kg ⁻¹	TK g·kg ⁻¹	ABN mg·kg ⁻¹	QCP mg·kg ⁻¹	QCK mg·kg ⁻¹	pH	SCC %	SSC %	SLC %	TSC g·kg ⁻¹	ESP %
Value	1.37	5.26	0.66	0.63	21.3	90.12	8.21	192.04	9.06	24.91	17.46	57.63	4.41	3.6

SBD: soil bulk density; SOM: soil organic matter; TN: total nitrogen; TP: total phosphorus; TK: Total Potassium; ABN: alkaline nitrogen oxide; QCP: quick-acting phosphorus; QCK: quick-acting potassium; SCC: soil clay content; SSC: soil sand content; SLC: soil silt content; TSC: total salt content; and ESP: exchangeable sodium percentage.

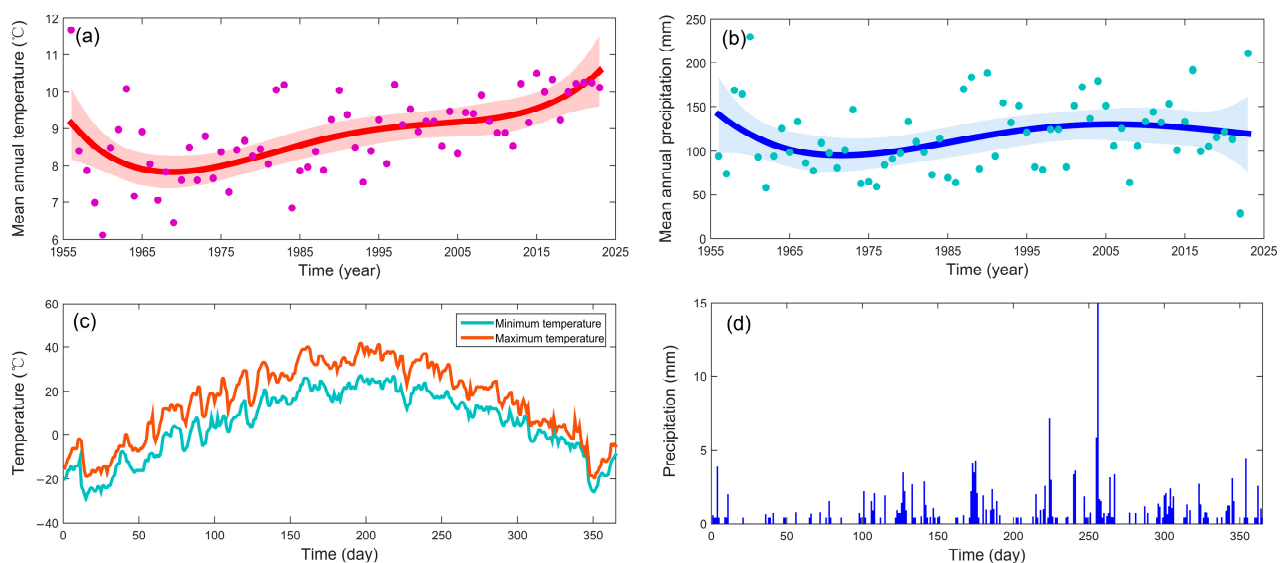


Figure 3. Changes in (a,b) the mean annual temperature and precipitation from 1956 to 2023 and (c,d) variations in the daily scale temperature and precipitation during 2023 in the Karamay irrigation district. Data were obtained from <https://www.msn.cn/zh-cn/weather/>, accessed on 12 February 2025.

The surface water and groundwater are extremely scarce in this study area; there has been no surface water flow through the area since the 1970s, yet only forming temporary floods in the adjacent Genghis Khan Mountains during heavy rainfall. Moreover, the groundwater in this area is not suitable for drinking, industrial, or agricultural use due to its small reserves, deep burial depths, and high mineralization (above $10 \text{ g}\cdot\text{L}^{-1}$ and up to $56 \text{ g}\cdot\text{L}^{-1}$), so water transfer from outside KID has and will continue to play a key role in meeting domestic, industrial, and agricultural water needs [27]. In 1997, this study area officially started the construction of the “Water Diversion from Irtysh River to Karamay” inter-basin water transfer project, which greatly increased the water resources in the KID, with $\sim 1.4 \times 10^8 \text{ m}^3$ being used for irrigated agriculture and $1.2 \times 10^8 \text{ m}^3$ for domestic and industrial uses, and as well, the water quality contents of EC , NO_3^- , CO_3^{2-} , HCO_3^- , Cl^- , SO_4^{2-} , Ca^{2+} , Mg^{2+} , K^+ , and Na^+ were $1160 \text{ us}\cdot\text{cm}^{-1}$, $0.794 \text{ mg}\cdot\text{L}^{-1}$, $0.010 \text{ g}\cdot\text{L}^{-1}$, $0.077 \text{ g}\cdot\text{L}^{-1}$, $0.888 \text{ g}\cdot\text{L}^{-1}$, $1.146 \text{ g}\cdot\text{L}^{-1}$, $0.159 \text{ g}\cdot\text{L}^{-1}$, $0.291 \text{ g}\cdot\text{L}^{-1}$, $0.006 \text{ g}\cdot\text{L}^{-1}$, and $0.199 \text{ g}\cdot\text{L}^{-1}$, respectively. Since the application of comprehensive agricultural developments in 2001, the cultivated land area has reached 10,043 hectares, and the main crops include cotton (*Gossypium hirsutum* L.), corn (*Zea mays*), alfalfa (*Medicago sativa* L.), sunflower (*Helianthus annuus* L.), and melon (*Cucumis melo* L.). Before 2006, the agricultural irrigation methods in the KID were traditional flood irrigation, but since 2006, water-saving irrigation has been widely used on a large scale. In 2011, all irrigation districts had adopted water-saving irrigation (Figure 4). Specifically, water-saving irrigation was dominated by film-mulched drip irrigation with “one film, two tubes, and six rows” in the study area.

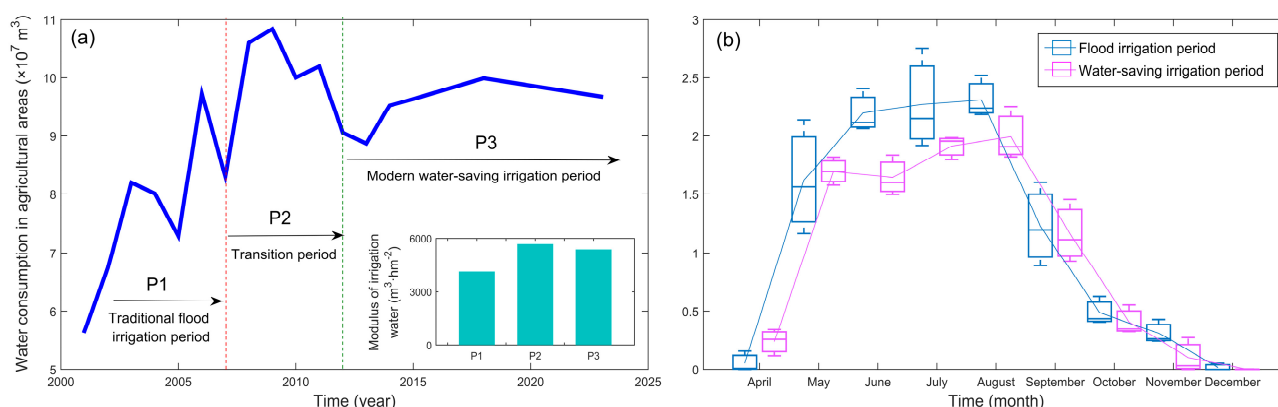


Figure 4. (a) Variations in irrigation patterns and the water consumption from 2001 to 2023 and (b) the monthly water consumption at different irrigation periods in the Karamay irrigation district.

With the increase in development intensity in the KID, the water consumption for agricultural irrigation has been rising. After 2006, the water consumption in agricultural areas was basically maintained at about $1 \times 10^8 \text{ m}^3$. Yet after 2011, the water consumption was reduced by adopting water-saving irrigation measures. And, water consumption in the study area is mostly concentrated from May to October each year during both the traditional flood irrigation and modern water-saving irrigation periods (Figure 4). At present, according to the average cultivated land area in the KID, the modulus of irrigation water is 540 mm , which is about 5 times of the mean annual precipitation for many years, indicating that the irrigation water consumption is on the high side. As a result, most of the irrigation water infiltrates into the ground to recharge groundwater, resulting in changes in the shallow groundwater regimes [6]. Since the large-scale reclamation of the irrigation area in 1996, the mean groundwater table depth (GTD) in the KID has increased significantly from 10.77 m in 1997 to 4.29 m in 2011. After the promotion of water-saving irrigation systems, the GTD was raised by 0.97 m from 2012 to 2023. At the same time, the GTD shows a decreasing trend from June to November 2023 (Figure 5a). In addition, from 1997

to 2023, the total dissolved solids (TDS) of shallow groundwater shows an increasing trend, and in 2023, the groundwater electrical conductivity was significantly higher in November than in June (Figure 5b).

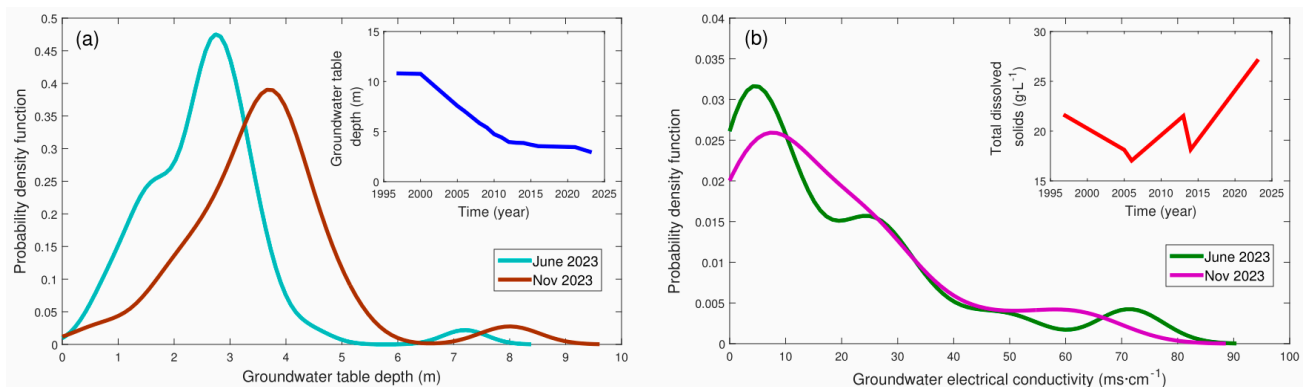


Figure 5. Changes in (a) the groundwater table depth and (b) groundwater electrical conductivity in June and November 2023 and from 1997 to 2023 in the Karamay irrigation district.

Due to the extreme climate, the hydrogeological conditions, and the development of irrigated agriculture, soil salinization has become a limiting factor for sustainable agricultural development in the KID. Furthermore, the average amount of salts brought into this study area by the water and fertilizer integrated pipe network was 2.54×10^4 tons per year; especially, the large application of nitrogen-containing chemical fertilizers (e.g., urea) and pesticides was another important reason for the increase in soil salinization and soil structural degradation [28].

2.2. Field Comprehensive Measurements

In order to investigate the spatial and temporal variability of soil salinity and sodicity under water-saving irrigation conditions during the crop growing season, as well as to comprehensively assess the evolution and causes of soil salinization in the KID, 21 soil sampling points were selected in the irrigation farmland and numbered consecutively as C1-C21 (Figure 1). Field measurements were performed on 1 June 2023 (i.e., the early crop growing stage, ECGS) and 1 November 2023 (i.e., the late crop growing stage, LCGS). Note that the ECGS and LCGS are basically the same for all crops in the KID. At each soil sampling point, soil samples were collected using a hand auger (5 cm in diameter); the total depth of soil sampling was 0–180 cm, and soil samples within 0–20 cm were obtained at 10 cm intervals, those within 20–100 cm at 20 cm intervals, and those within 100–180 cm at 40 cm intervals for each sampling point. In total, 1134 soil samples were collected (21 locations—3 repetitions—9 depths—2 periods) in the KID. Soil samples taken from each specific layer were divided into two portions: one portion was placed in an airtight aluminum container for measuring gravimetric soil water content by the oven-dry method (DHG-9000A, 24 h at 105 °C); another portion was sealed in a thickened valve bag, then it was air-dried and debris was removed and it was crushed and passed through a 2 mm mesh, and the soil electrical conductivity was measured in the paste extracts with soil/water ratio of 1:5 by a conductivity meter (FE-30; Mettler-Toledo International Inc., Greifensee, Switzerland). Conventional analysis methods were used to determine the content of soil ions, soil nutrients, and soil physicochemical properties (Table 1), and the determination method referred to Bao (2000) [29] for other variables included in the results section.

Furthermore, groundwater monitoring bores (total 28) were installed in the KID by the local water department government. Locations of the 28 wells are shown in Figure 1.

The buried depth of each groundwater well was determined during the soil sample collection period, and groundwater and surface water samples were collected for water quality determination, as described in Han [6]. Specifically, the groundwater electrical conductivity (GEC) was measured by a conductivity meter (FE-30; Mettler Toledo, Switzerland). The latitude, longitude, and elevation of each sampling point and monitoring well were determined using a handheld GPS receiver. The daily precipitation, air temperature, and other hydrometeorological data were obtained via a comprehensive weather station established in the KID by the local meteorological department. In addition, other data, such as irrigated agriculture data, soil environmental data, and groundwater data, before 2023 were derived from published or released literature and documents (e.g., [6,25]). Importantly, the exchangeable sodium percentage (ESP) was employed to characterize the soil sodicity, and the ESP was calculated after measurement of soluble and exchangeable cations of the original soil samples [18]:

$$ESP = \frac{100 \cdot \left[-0.0126 + 0.01475 \cdot \left(c_{Na^+} / \sqrt{(c_{Ca^{2+}} + c_{Mg^{2+}})/2} \right) \right]}{1 + \left[-0.0126 + 0.01475 \cdot \left(c_{Na^+} / \sqrt{(c_{Ca^{2+}} + c_{Mg^{2+}})/2} \right) \right]} \quad (1)$$

where c_{Na^+} , $c_{Mg^{2+}}$, and $c_{Ca^{2+}}$ are the concentration of Na^+ , Ca^{2+} , and Mg^{2+} in the soil water, respectively.

According to the classification standard of Xinjiang Soil Quality Geochemical Evaluation Specification, the soil salinity of farmland was divided into five categories according to the degree of soil salinization [25]: non-salinized soil ($<5.54 \text{ g} \cdot \text{kg}^{-1}$), no negative impact on crop; slightly salinized soil ($5.54 \sim 7.27 \text{ g} \cdot \text{kg}^{-1}$), yield reductions in vulnerable crops; moderately salinized soil ($7.27 \sim 8.66 \text{ g} \cdot \text{kg}^{-1}$), most crops have limited yields; severely salinized soil ($8.66 \sim 13.45 \text{ g/kg}$), only tolerant crops can produce satisfactory yield; and saline soil ($>13.45 \text{ g} \cdot \text{kg}^{-1}$), this may only be suitable for halophytes. Additionally, the log-linear fitting relationship between soil electrical conductivity ($EC_{1.5}$, $\mu\text{S} \cdot \text{cm}^{-1}$) and soil total salt content (TSC, $\text{g} \cdot \text{kg}^{-1}$) in the plowed layer of the study area was $\log TSC = 1.00089 \cdot \log EC_{1.5} - 2.33644$, $R^2 = 0.98$, and $p < 0.01$.

2.3. Modeling Salt-Controlled Crop Yields

To clarify the species-specific nature of crop yield response to salt stress, we propose a simple parameterization of the relation between relative crop yield, Y_r (i.e., the ratio of the actual to the potential yield) and root zone salt concentration, C_s , based on the proportionality between crop yield and transpiration (i.e., $Y_r = Y/Y_p = T/T_p = T_r$, where Y is crop yield, T is transpiration, T_r is relative transpiration, and the subscript p denotes potential) [20,21]. Following the fundamental assumptions of van Genuchten and Gupta [23] for the sigmoid (S-shaped) yield reduction function, by incorporating the level of crop salt tolerance, we described the relation between Y_r and C_s as a piecewise linear function [24]:

$$Y_r = \left[1 + \left(\frac{C_s}{C_{50}} \right)^3 \right]^{-1} \quad (2)$$

where the crop-specific salt tolerance parameter C_{50} is the solute concentration at which root water uptake is reduced by half. Van Genuchten and Gupta [23] found that fixing an index of 3 or using it as a fitting parameter did not have much impact on the sigmoid model fitting of relative yield data. A value of 3 has also been recommended for modeling crop yield reductions in response to soil salinity [24]. In this study, fixing the index is convenient

because the crop salt tolerance can be quantified with only one parameter, C_{50} . According to Ayers and Westcot [30], the C_{50} values are as follows: salt sensitive S (0~4.93 dS/m), moderately sensitive MS (4.93~9.54 dS/m), moderately tolerant MT (9.54~15 dS/m), and salt tolerant T (>15 dS/m).

In order to assess the depth persistence between soil salinity or sodicity in varying soil layers, we analyzed the data by using Spearman's rank correlation test [31]. Spearman's rank correlation coefficient, r_s , is calculated as

$$r_s = 1 - \frac{6 \sum_{i=1}^n (R_{ij} - R_{ik})}{n(n^2 - 1)} \quad (3)$$

where R_{ij} and R_{ik} are the ranks of the soil salinity or sodicity observed at location i in soil layers j and k , respectively, and n is the total number of observations. The r_s can take values between -1 and $+1$. When r_s is positive, it indicates a positive correlation between the two variables, while a negative value of r_s indicates a negative relationship.

2.4. Data Analysis

Exploratory analysis was performed in Microsoft Office Excel (Microsoft Corporation Inc., Redmond, WA, USA). Statistical analyses were performed using the IBM SPSS 21.0 (IBM Inc., Chicago, IL, USA) with least significant difference (LSD) post hoc test at $p < 0.05$. Mathematical calculation and charting were processed using MATLAB R2015a (The MathWorks Inc., Natick, MA, USA).

3. Results

3.1. Spatio-Temporal Dynamics of Soil Salinity and Sodicity

As presented in Figure 6, soil salinity and sodicity profiles at the 21 soil sampling sites exhibited a clear vertical stratification under both the early crop growing stage (ECGS) and late crop growing stage (LCGS) in the KID. The mean soil salinity profile under the ECGS was evidently greater than that under the LCGS among the 40~180 cm soil layer, and the higher soil salinity was mainly distributed in the deeper layer under the ECGS. The mean soil salinity increased from $465.63 \mu\text{S}\cdot\text{cm}^{-1}$ in the 0~20 cm layer to $731.75 \mu\text{S}\cdot\text{cm}^{-1}$ in the >20~100 cm layer and then decreased gradually to $791.49 \mu\text{S}\cdot\text{cm}^{-1}$ in the >100~140 cm layer under the ECGS. Yet, the soil salinity remained relatively stable (mean value of $550.92 \mu\text{S}\cdot\text{cm}^{-1}$), and two small salt deposits appeared at 20 cm and 100 cm under the LCGS. Moreover, the coefficient of variation (CV) of the soil salinity varied from 0.82 to 1.14 under the ECGS and from 1.06 to 1.32 under the LCGS among the layers (Figure 6a–d). At the same time, the mean soil sodicity displayed an increasing trend with the depth under both the ECGS and LCGS, and the mean soil sodicity profile under the ECGS (0.053) was evidently greater than that under the LCGS (0.048) among the >40~100 cm layer, whereas it was clearly greater under the LCGS (0.086) than under the ECGS (0.077) in the >100~180 cm layer. Furthermore, the CV of the soil sodicity increased from 0.5~0.7 for the 0~40 cm layer to 0.9~1.1 for the 100~180 cm layer under both stages (Figure 6e–h).

According to the profile distributions of the mean soil salinity, mean soil sodicity, and their coefficient of variation (CV) under both the ECGS and LCGS, the soil profile for both soil salinity and soil sodicity could be divided into three typical layers, i.e., 0~40, >40~100, and >100~180 cm. Except for the soil salinity of the LCGS, there were clear differences in both the soil salinity and soil sodicity for each typical soil layer in the Karamay irrigation district (Table 2).

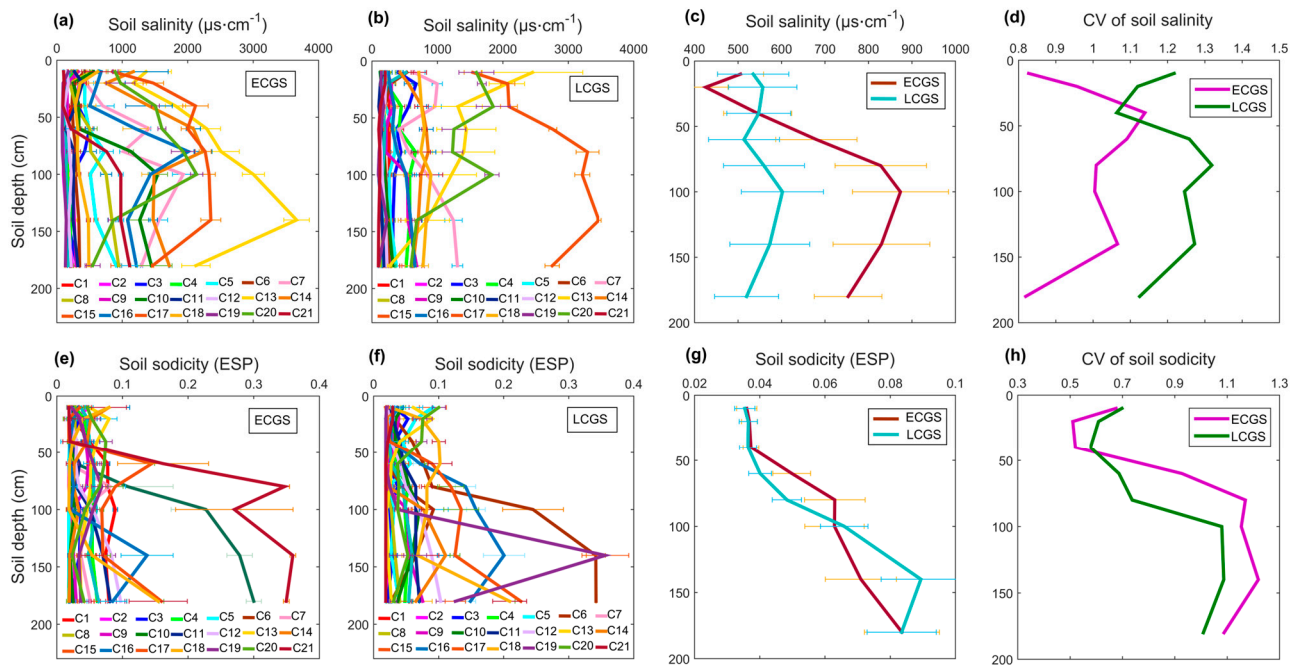


Figure 6. Variations in the (a,b) mean soil salinity with depth under the early crop growing stage (ECGS) and late crop growing stage (LCGS) during 2023 at 21 soil sampling sites (i.e., C1–C21) and (c,d) the comparison of soil salinity and its coefficient of variation (CV) between the ECGS and LCGS, and (e,f) the mean soil sodicity with depth under the ECGS and LCGS and (g,h) the comparison of soil sodicity and its CV between the ECGS and LCGS in the Karamay irrigation district. Error bars represent the standard error of the mean soil salinity or mean soil sodicity value.

Table 2. Soil salinity and sodicity at the three typical soil layers in the Karamay irrigation district.

Soil Index	Soil Salinity ($\mu\text{s}\cdot\text{cm}^{-1}$)			Soil Sodicity (ESP)		
Soil layer	0~40 cm	>40~100 cm	>100~180 cm	0~40 cm	>40~100 cm	>100~180 cm
ECGS	492.12 $\pm$ 56.51 a	793.97 $\pm$ 99.88 b	791.49 $\pm$ 92.01 b	0.037 $\pm$ 0.002 a	0.059 $\pm$ 0.007 b	0.077 $\pm$ 0.011 c
LCGS	546.44 $\pm$ 74.91 a	558.47 $\pm$ 88.37 a	546.33 $\pm$ 81.86 a	0.036 $\pm$ 0.002 a	0.051 $\pm$ 0.005 b	0.086 $\pm$ 0.012 c

ECGS: early crop growing stage (1 June 2023), LCGS: late crop growing stage (1 November 2023). Values represent mean $\pm$ standard error. Different lowercase letters in each row denote significant differences ($p < 0.05$) among soil layers for salinity and sodicity.

As illustrated in Figure 7, the degree of soil salinization is decreasing, and the area of non-saline land is increasing significantly from 1996 to 2023 in the Karamay irrigation district. Specifically, in 1996, there was no non-salinization land distribution in the study area, and the area of moderate and above salinization land accounted for 79% of the irrigation area. However, after 10 years of traditional flood irrigation and extensive field cultivation, the area of non-salinization land reached 47.07% in 2006, the area of moderate and severe salinization land decreased by 20.73%, and the area of saline land almost disappeared, but the area of mild salinization land increased by 15.12%. With the large-scale promotion of water-saving irrigation technology, the area of both moderate and non-salinization land showed an increasing trend in 2023, in which the non-salinization land area increased to 57.14%, whereas the area of both mild and severe salinization land exhibited a decreasing trend in this study area. Overall, soil salinization showed a pattern of first decreasing and then maintaining a relatively stable state from the traditional flood irrigation period (i.e., 1996–2006) to the modern water-saving irrigation period (i.e., 2011–present) in the study area.

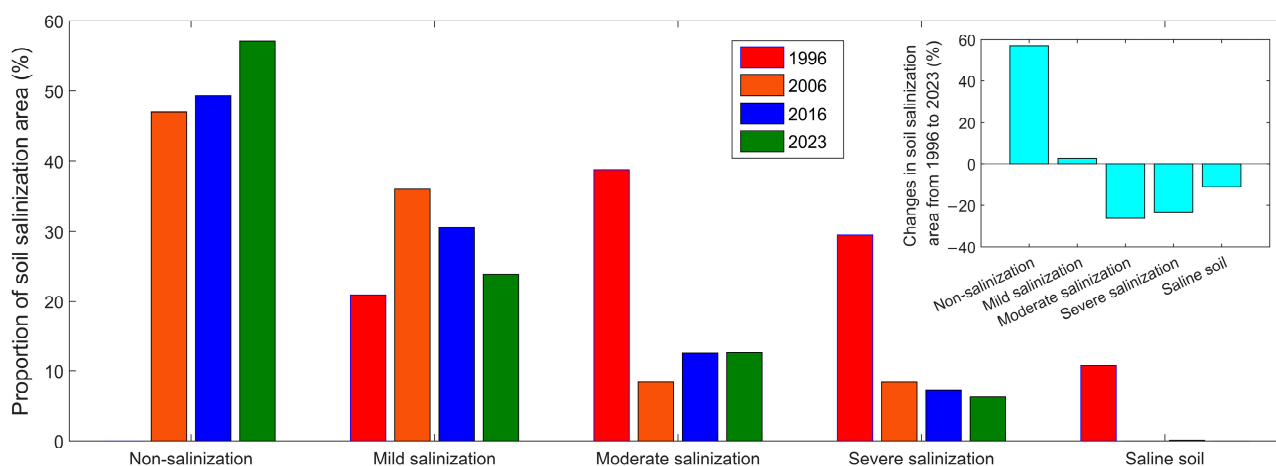


Figure 7. Changes in proportion of different grades of soil salinization area to total agricultural land area from 1996 to 2023 in the Karamay irrigation district. Data for 1996 and 2006 were provided by the Karamay Agricultural District Management Committee, and data for 2016 were obtained from [25].

3.2. Variations in Soil Salinity and Sodicity Exchange Fluxes

As illustrated in Figure 8, the average exchange flux of the soil salinity in the 0~40 cm, >40~100 cm, and >100~180 cm layers was 0.3376, -1.4634 , and -1.5234 $\text{g} \cdot \text{kg}^{-1}$, respectively, and the corresponding mean exchange flux of soil sodicity was -0.0006 , -0.0072 , and -0.0259 ESP, respectively, from the ECGS to the LCGS during 2023 in the Karamay irrigation district. For the soil salinity exchange flux (Figure 8(a1–a3)), at the 21 sampling sites, 42.86%, 66.67%, and 71.43% of the soil salinity exchange fluxes were negative (i.e., salt expelled from the soil layer) in the soil layers of 0~40 cm, 40~100 cm, and 100~180 cm, respectively. Furthermore, there was a significant positive correlation between the soil salinity exchange flux in the 40~100 cm and 100~180 cm soil layers ($r = 0.6929$, $p < 0.01$) in this study area.

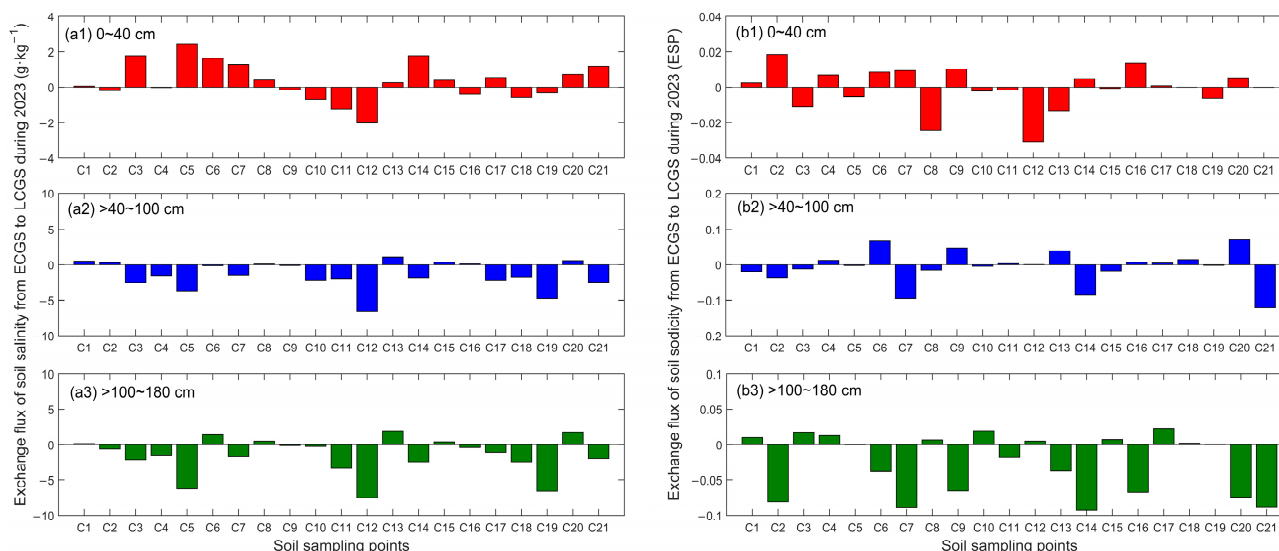


Figure 8. Exchange fluxes of (a1–a3) soil salinity and (b1–b3) soil sodicity from the early crop growing stage (ECGS) to the late crop growing stage (LCGS) during 2023 at the three typical soil layers (i.e., 0~40 cm, >40~100 cm, and >100~180 cm) at 21 soil sampling sites (i.e., C1–C21) in the Karamay irrigation district. Positive values denote upward fluxes.

For the soil sodicity exchange flux (Figure 8(b1–b3)), at the 21 sampling sites, 42.85%, 52.38%, and 52.38% of the soil sodicity exchange fluxes were negative (i.e., alkali discharged from the soil layer) in the soil layers of 0~40 cm, 40~100 cm, and 100~180 cm, respectively.

The results showed that the water-saving irrigated farmland in the KID was in a state of alkali aggregation in the 0~40 cm soil layer, while both the 40~100 cm and 100~180 cm soil layers were in a state of alkali equilibrium in the whole growing season. Meanwhile, the soil sodicity fluxes in the 40~100 cm and 100~180 cm soil layers showed a significant positive correlation ($r = 0.5061$, $p < 0.05$). By comparison, there is a certain synchronization between the soil salinity flux and the soil sodicity flux in each soil layer, but there may also be a certain lag in the study area. Altogether, the water-saving irrigated farmland was in the slight salt-aggregating state in the topsoil layer, while the other soil layers were in the salt-expelling or salt-equilibrating state in the study area.

3.3. Controlling Factors for Changes in Soil Salinity and Sodicity

In accordance with Figure 9, Spearman's rank correlation coefficients (r_s) identified an overall similarity in spatial patterns of both soil salinity and soil sodicity among the defined soil layers, especially between two adjacent layers, under both the ECGS and LCGS in the Karamay irrigation district. For soil salinity (Figure 9a), the overall similarity was higher under the ECGS, with the r_s ranging from 0.66 to 0.96 (mean r_s : 0.86), than under the ECGS, with the r_s ranging from 0.35 to 0.98 (mean r_s : 0.86). For soil sodicity (Figure 9b), the overall similarity was higher under the ECGS, with the r_s (absolute value) ranging from 0.01 to 0.91 (mean r_s : 0.51), than under the ECGS, with the r_s (absolute value) ranging from 0.66 to 0.96 (mean r_s : 0.36). The r_s between two adjacent layers for both soil salinity and soil sodicity under each stage were almost statistically significant ($p < 0.05$), suggesting that the spatial patterns of both soil salinity and soil sodicity between adjacent soil layers have a strong dependence. Furthermore, the r_s of both soil salinity and sodicity to the groundwater table depth (GTD) and groundwater electrical conductivity (GEC) were relatively low in all soil layers under both stages. Nevertheless, there was a significant correlation between the GTD and GEC in the study area.

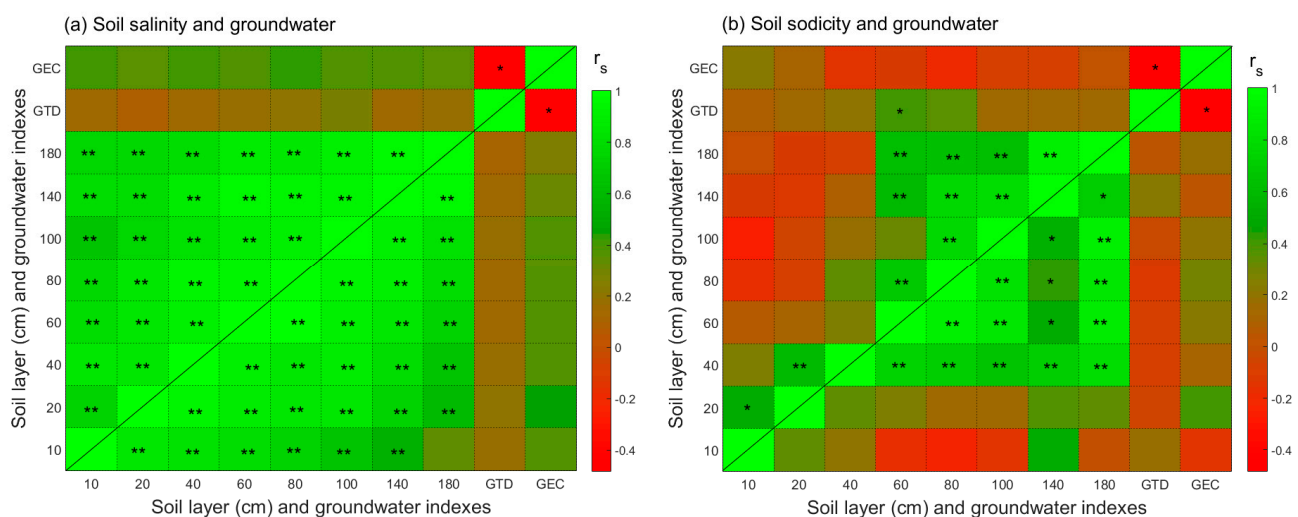


Figure 9. Spearman's rank correlation coefficients (r_s) between (a) the soil salinity among the various layers and the groundwater table depth (GTD) and groundwater electrical conductivity (GEC) and (b) the soil sodicity among the various layers and the GTD and GEC under the early crop growing stage (ECGS) and late crop growing stage (LCGS) in the Karamay irrigation district. The correlation coefficients of the ECGS are listed in the upper left triangle, and the corresponding LCGS is listed in the lower right triangle. ** significant at $p < 0.01$ level; * significant at $p < 0.05$ level.

The pre-existing soil moisture controls water fluxes in different soil layers under the interaction of precipitation and irrigation water as well as groundwater. As shown in Figure 10, there was a negative correlation between the soil water content and soil salinity,

while there was a positive correlation with soil sodicity during both the ECGS and LCGS in the Karamay irrigation district. In other words, as the soil water content increases, the soil salinity content gradually decreases; that is, “salt comes with water, and salt goes with water”. However, with the increase in the soil water content, the soil sodicity content of the soil gradually increases; that is, “alkali comes with water, and alkali stays with water loss”. The results showed that soil moisture dynamics are an important factor in regulating soil salinity and soil sodicity dynamics in water-saving irrigation farmland in the study area.

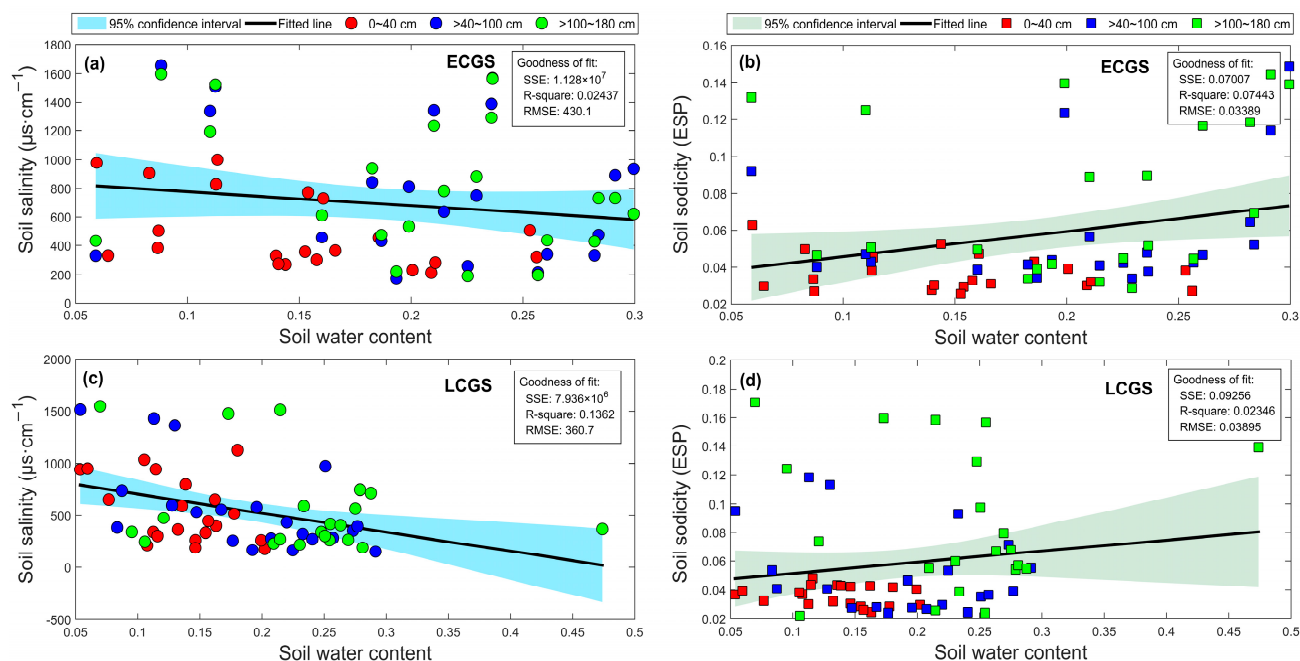


Figure 10. The effect of the soil water content on (a) soil salinity and (b) soil sodicity under the early crop growing stage (ECGS) and on (c) soil salinity and (d) soil sodicity under the late crop growing stage (LCGS) during 2023 at the three typical soil layers (i.e., 0~40 cm, >40~100 cm, and >100~180 cm) in the Karamay irrigation district.

Increased plant salt tolerance corresponds to a higher water use efficiency, lower values of the effective soil wilting point, and a greater potential to hinder leaching events and enhance soil salt accumulation [14]. As illustrated in Figure 11, changes in soil salinity during the growth period were $-196.06 \pm 149.27 \mu\text{s}\cdot\text{cm}^{-1}$, $-25.14 \pm 72.97 \mu\text{s}\cdot\text{cm}^{-1}$, $-69.72 \pm 70.21 \mu\text{s}\cdot\text{cm}^{-1}$, and $269 \pm 106.15 \mu\text{s}\cdot\text{cm}^{-1}$ for melons, cotton, maize, and sunflower, respectively, and the corresponding changes in soil sodicity during the growth period were -0.014 ± 0.005 , 0.003 ± 0.005 , -0.001 ± 0.006 , and -0.273 ± 0.016 , respectively. There were clear differences in soil salinity and soil alkalinity in the root zone of different salt-tolerant crops in the Karamay irrigation district. This suggests that crop salt tolerance is a crucial factor in controlling and limiting soil salinization and alkalization in water-saving irrigation farmland in the study area.

In addition, topography and geomorphology, which typically regulate the distribution of salts in soils by controlling the movement of the surface/subsurface runoff and the depth of the groundwater table, are two of the major factors affecting soil salt accumulation in this study area. Also, the soil texture in the study area (mainly silt, accounting for about three fifths of the particle composition, while the content of sand and clay accounted for about 20%, respectively) had a clear effect on the distribution of soil salinity and sodicity. In general, with the increase in the soil clay and silt content, the soil salt content increases, and with the increase in the sand content, the soil salt content decreases, because the surface area of clay and silt particles in the soil is larger, which is the active component of the soil,

and the sand particles are relatively inactive. Moreover, the water from the Xijiao Reservoir ($45^{\circ}34'22''$ N, $84^{\circ}51'25''$ E) was used for irrigation in the study area, and the mineralization was $1160 \mu\text{s}\cdot\text{cm}^{-1}$, although its value was small, but a large amount of salt was also carried into the study area and accumulated in the soil for many years of agricultural irrigation.

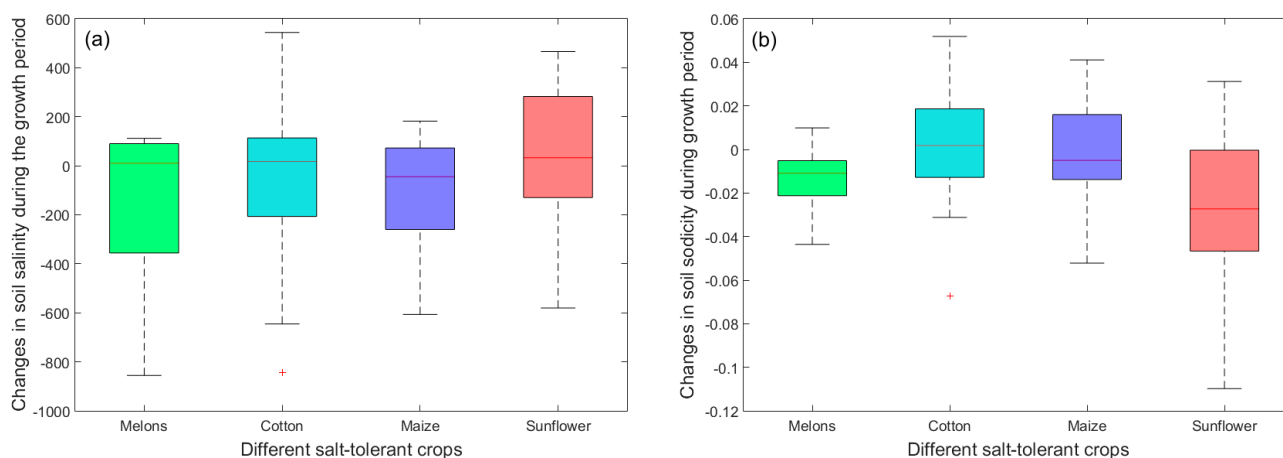


Figure 11. The effect of the crop salt tolerance (salt tolerance: cotton > sunflower > maize > melons) on (a) soil salinity and (b) soil sodicity in the root zone (0~80 cm) in the Karamay irrigation district. On each box, the central mark is the median, the edges are the 25th and 75th percentiles, and the outliers are plotted as points (+) individually.

Furthermore, the annual evaporation in the study area is 16.6 times of the annual rainfall, and under this arid climate, the leaching effect of the soil is weak, and the salts in the shallow groundwater and soil water are constantly transported to the surface under the strong evaporation and concentration effect, so that the both salinity and sodicity of the topsoil increased. Particularly, with the large-scale popularization and application of modern water-saving irrigation technology in this study area, the “bottom-up” soil salinization is reduced, but due to the small quota of single water-saving irrigation, the salt accumulated on the surface of the soil cannot be leached into the deep layer in time, and the new risk of “top-down” soil salinization appears, and the problem is more prominent when using brackish water for irrigation. In addition, the overapplication of nitrogen-containing fertilizers, especially urea, was also a major reason for the increase in soil salinity and sodicity in the implementation of the integrated irrigation of water and fertilizers in the study area.

3.4. Crop Yield Response for Given Soil Salinity and Salt Tolerance

As illustrated in Figure 12 and Table 3, the relative crop yield Y_r decreased significantly with the increasing root zone salinity C_s and the decreasing crop salt tolerance C_{50} in the Karamay irrigation district. In contrast, for salt-sensitive, moderately-salt-sensitive, moderately-salt-tolerant, and salt-tolerant crops, the average Y_r in 2013 was significantly higher than in 1996, while there was no significant difference between the average Y_r in 2023 and 2013. This indicates that the soil salinity in the study area is currently maintained within the lower limit of the threshold affecting the crop yield. In general, the effects of salt stress on different salt-tolerant crops are different, and excessive stress can reduce the yield of crops, and no more than a certain threshold can improve the quality of some crops. In reality, the crop response to soil salinity is affected by a number of factors besides root zone solute concentrations, such as climate, irrigation practices, soil fertility, and soil hydraulic conductivity. In the case of maize, for example, an irrigation water salt concentration of 3 g/L is the upper limit of the salt tolerance of maize seedlings, and when the irrigation

water salt concentration is lower than this value, the seedling growth is normal, and when it is higher than this value, the seedling growth is significantly inhibited. Therefore, the interaction effect of multiple factors should be considered in studying the response of the crop yield to soil salinity in future research practices.

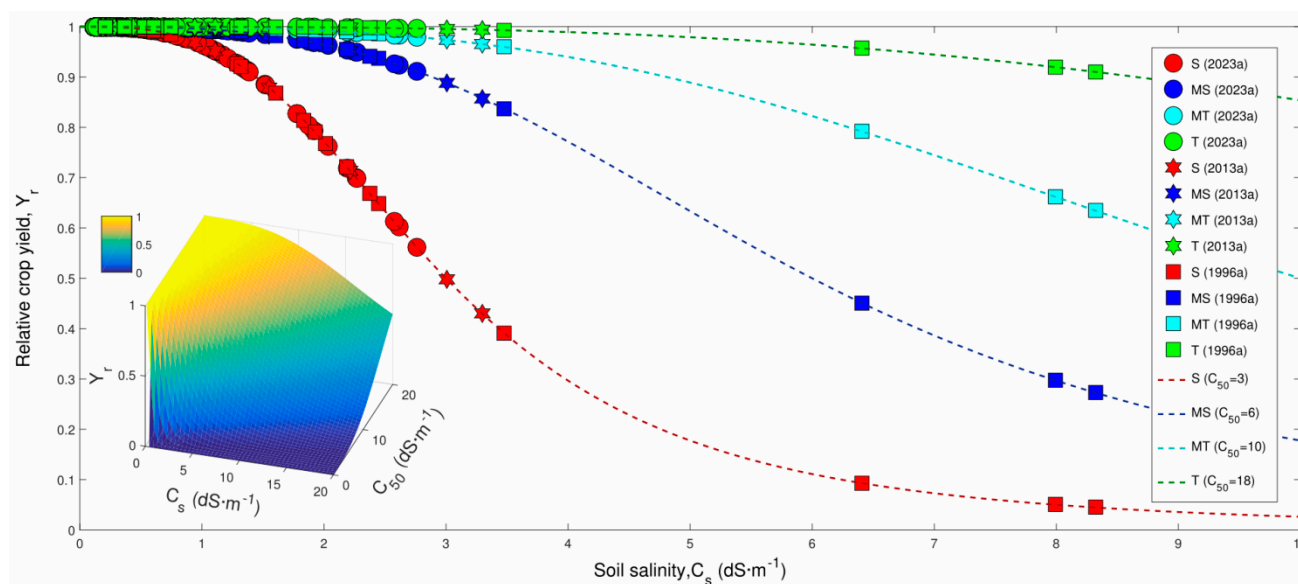


Figure 12. The effect of soil salinity (C_s) on the relative crop yield (Y_r) for different salt-tolerant crops (salt sensitive S, $C_{50} = 3 \text{ dS}\cdot\text{m}^{-1}$; moderately sensitive MS, $C_{50} = 6 \text{ dS}\cdot\text{m}^{-1}$; moderately tolerant MT, $C_{50} = 10 \text{ dS}\cdot\text{m}^{-1}$; and tolerant T, $C_{50} = 18 \text{ dS}\cdot\text{m}^{-1}$) during 1996, 2013, and 2023 in the Karamay irrigation district. The inset shows the response of Y_r to changes in the soil salinity and crop salt tolerance.

Table 3. Relative crop yields for diverse salt-tolerant crops during 1996, 2013, and 2023 in the KID.

Index	Salt-Sensitive Crop	Moderately Salt Sensitive	Moderately Salt Tolerant	Salt-Tolerant Crop
1996	$<0.843 \pm 0.061$	$0.843 \pm 0.061 \sim 0.943 \pm 0.028$	$0.943 \pm 0.028 \sim 0.981 \pm 0.009$	$>0.981 \pm 0.009$
2013	$<0.983 \pm 0.009$	$0.983 \pm 0.009 \sim 0.997 \pm 0.001$	$0.997 \pm 0.001 \sim 0.999 \pm 0.001$	$>0.999 \pm 0.001$
2023	$<0.989 \pm 0.002$	$0.989 \pm 0.002 \sim 0.998 \pm 0.001$	$0.998 \pm 0.001 \sim 0.999 \pm 0.001$	$>0.999 \pm 0.001$

The C_{50} values were $0 \sim 4.93$, $4.93 \sim 9.54$, $9.54 \sim 15$, and $>15 \text{ dS}\cdot\text{m}^{-1}$ for salt-sensitive, moderately-salt-sensitive, moderately-salt-tolerant, and salt-tolerant crops, respectively [30]. Values represent the mean $\pm$ standard error.

4. Discussion

Owing to limited precipitation but high potential evaporation and the absence of surface runoff in the KID, the inter-basin water transfer has substantially ensured the security of the regional water supply for irrigation, industrial, and domestic uses [6]. Nevertheless, when the region lacks a supporting drainage system or the drainage system is not properly designed, the inter-basin water transfer can lead to the accumulation and redistribution of salts in the soil once the groundwater level is higher than the critical depth of the groundwater. As a result, the soil structure is destroyed, nutrients are lost, and the water and salt balance is broken, which ultimately has a negative impact on the ecological environment and leads to a decrease in the crop yield in irrigated areas [7,32].

Since the large-scale agricultural development of the KID in 1997, the traditional flood irrigation method has been mostly used in the study area, and there is no drainage system, and the groundwater level has been rising year by year. By 2009, about two-thirds of the groundwater were buried to a depth of less than 4 m [6], and most areas of the KID were threatened by secondary soil salinization. The rising poor-quality groundwater and the soil salinization caused by it pose a serious challenge to the development of soil and water

resources in the study area. By 2010, 86.96% of the farmland in the study area was salinized to different degrees, and the soil salinity and sodicity of the cultivated layer and subsoil showed a negative correlation with the depth of the groundwater table. In order to inhibit the rise in the groundwater level and prevent secondary soil salinization, the farmland in the study area was switched from flood irrigation to drip irrigation in 2006. From 2011 to 2023, the change range of the groundwater depth in the study area tended to be flat, and the soil salinization showed a decreasing trend in the KID [25]. In general, under the background of inter-basin water transfer, from traditional flood irrigation to modern water-saving irrigation, soil salinization shows a decreasing trend due to declines in the shallow groundwater table.

Soil salinity and soil sodicity are dynamic in spatial, vertical, and temporal dimensions, and are substantially influenced by governing climatic conditions and anthropogenic activities, especially in arid environments [8]. The inter-basin water transfers have significant impacts on the hydrological regimes in the drylands [7]; thus, the hydrological regime change is an important factor affecting the spatial changes in soil salinity and sodicity. This may be attributed to the fact that the salts are transported and redistributed with the precipitation, soil water, irrigation water, and groundwater in the study area [33]. The distribution of salinity and sodicity in soil profiles of farmland are mainly characterized by climate, irrigation, crop, and groundwater dynamics. Similarly to Vico and Porporato [34], our results showed that irrigation schemes (i.e., traditional flood irrigation and water-saving irrigation) result in different soil salinity and sodicity profiles in the KID. In particular, the popularization and application of drip irrigation technology has improved the efficiency of water and fertilizer utilization and changed the mode of water and salt transport in farmland. On the one hand, the decline in the water table and the weakening of the connection between the soil water and groundwater have reduced the salts from shallow groundwater evaporation, reducing soil salinization; on the other hand, due to the lack of saline washing, the salt accumulated on the surface of the soil cannot be leached into the deep layer in time, and the salinization of the topsoil is aggravated, and the problem is more prominent when brackish water is used for irrigation [11,35].

Figure 8 indicates that throughout the growing season, the water-saving irrigated farmland in the study area was in the salt accumulation state in the 0~40 cm soil layer, while both the 40~100 cm and 100~180 cm soil layers were in the salt drainage state. Generally, the soil salinization under water-saving irrigation with marginal water is mainly caused by insufficient water leaching, so it may be necessary to irrigate with adequate low-salt water, at least once at the beginning of growing season, to facilitate salt leaching from the soil profile [13]. In addition, the plant salt tolerance, soil properties, and agronomic management also influences the salt accumulation in the soil profile in the KID. Perri [14] highlighted that the plant salt tolerance is a key factor in limiting the long-term soil salinization levels in salt-affected soils. Furthermore, sodicity negatively impacts the soil physical properties, reducing soil saturated hydraulic conductivity and indirectly affecting soil salt accumulation [9,19]. Thus, an integrated consideration of the interactive effects of multiple factors on soil salinity and sodicity is vital for controlling soil salinization and improving land productivity in the KID.

Dryland agricultural regions face significant challenges due to groundwater, soil, and irrigation water salinity, so gaining a comprehensive understanding of how groundwater, soil, and irrigation water salinity affect crop performance is crucial for implementing sustainable practices in dryland agriculture [36]. Often, soil salinity hinders crop growth, especially for salt-sensitive crops, by impeding water uptake, causing osmotic stress, and altering the nutrient availability. Similarly, the increased salinity in irrigation water and from the shallow groundwater capillary rise can directly affect the soil salt content. This

can lead to reduced crop yields, slower plant growth, reduced nutrient uptake, and greater susceptibility to pests and diseases, especially in arid and semi-arid saline soils [10]. Cumulatively, these factors may contribute to reduced agricultural yields and crop quality and ultimately jeopardize regional food security. In addition, salinity-induced soil degradation can lead to long-term environmental impacts, such as reduced soil fertility, increased soil erosion, and reduced biodiversity [36].

In our study area, under the background of inter-basin water transfer, with the transformation of irrigation methods from traditional flood irrigation to modern water-saving irrigation during 1996–2023, soil salinity has been effectively controlled, and the impact of soil salinity on crop yields has been greatly reduced. Hu [37] found that the total number of cotton roots under drip irrigation was 1.6 times that under flood irrigation, and the yield could be higher under drip irrigation with appropriate irrigation methods. Water-saving irrigation technology tremendously improves crop water productivity and crop yields; however, when brackish water is used for irrigation, soil salt accumulation is aggravated, which is prone to salt stress on crops [35]. In order to address the problems posed by the salinization of groundwater, soil, and irrigation water, the use of appropriate irrigation methods, such as precision irrigation, efficient water management techniques, and the use of high-quality irrigation water sources, is essential in the KID. In conclusion, further revealing the characteristics of soil water and salt transport and accumulation under drip irrigation conditions, formulating water and salt regulation programs for farmland, revealing the kinetic mechanism of coupled crop water and salt responses, determining the critical control threshold, constructing farmland drainage and regional salt disposal models, and optimizing salt-tolerant crop varieties are the keys to realizing the high-quality development of agro-ecosystems.

5. Conclusions and Implications

In this study, we presented an investigation of the spatio-temporal variability of soil salinity and sodicity dynamics and controlling factors and an evaluation of the effects of soil salinization on the yield of crops with diverse salt tolerances in an inter-basin water transfer area of northwestern China. The results revealed that soil salinity and sodicity profiles exhibited a clear vertical stratification under both the ECGS and LCGS in the KID. The degree of soil salinization has been decreasing and the area of non-saline land has been increasing significantly from 1996 to 2023 in the KID. Owing to the lack of salt-washing water and poor irrigation water quality, the water-saving irrigated farmland was in the slight salt-aggregating state in the topsoil layer, while the other soil layers were in the salt-expelling or salt-equilibrating state in the KID. The salinity and sodicity distribution are mainly characterized by climate, irrigation, and groundwater dynamics, and the plant salt tolerance, soil properties, and agronomic management also influence the soil salt accumulation. With the transformation of irrigation methods from traditional flood irrigation to modern water-saving irrigation during 1996–2023, the impact of soil salinity on the crop yield has been greatly reduced in the KID. Capitalizing on these research findings, we would provide effective directives for maintaining the sustainability of agricultural development in other similar inter-basin water transfer zones.

We conclude that inter-basin water transfer plays a key role in the high-quality development of agriculture in arid environments, yet irrational irrigation and drainage management may affect all aspects of local ecosystems. Future studies should optimize the drainage facilities according to the actual situation in the irrigation area to ensure that the groundwater level is within the ecological threshold in the irrigation area. At the same time, precise irrigation and fertilization measures should be fully implemented to prevent soil salinization caused by inadequate leaching and excessive fertilization. In addition, crop

selection and agronomic practices have a key role in minimizing the effect of soil salinity and sodicity, and farmers should plant salt-tolerant and low-water-consuming crops as well as use crop rotations to interrupt the salt cycle and improve soil fertility.

Author Contributions: Conceptualization, W.L. (Wei Liu), X.Y. and M.Z.; Data curation, W.L. (Wei Liu), X.Y., Y.S. and J.Z.; Formal analysis, X.Y., J.Z., Y.S. and W.L. (Wen Liu); Investigation, M.Z., X.Y. and N.C.; Methodology, J.Z., N.C., W.L. (Wen Liu), Y.S. and Y.C.; Writing—original draft, W.L. (Wen Liu), X.Y., W.L. (Wei Liu) and N.C.; Writing—review and editing, X.Y., M.Z. and W.L. (Wen Liu). All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Natural Science Foundation of China (grant number 32301671; U24A20178); the National Key Research and Development Program (grant number 2022YFF1303301); and the Gansu Provincial Natural Science Foundation Key Project (grant number 24JRR635); and the APC was funded by (grant number U24A20178).

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare that they have no conflicts of interest.

References

1. Mekonnen, M.M.; Hoekstra, A.Y. Four billion people facing severe water scarcity. *Sci. Adv.* **2016**, *2*, e1500323. [CrossRef] [PubMed]
2. Schlosser, C.A.; Strzepek, K.; Gao, X.; Fant, C.; Blanc, É.; Paltsev, S.; Jacoby, H.; Reilly, J.; Gueneau, A. The future of global water stress: An integrated assessment. *Earth's Future* **2014**, *2*, 341–361. [CrossRef]
3. Greve, P.; Kahil, T.; Mochizuki, J.; Schinko, T.; Satoh, Y.; Burek, P.; Fischer, G.; Tramberend, S.; Burtscher, R.; Langan, S.; et al. Global assessment of water challenges under uncertainty in water scarcity projections. *Nat. Sustain.* **2018**, *1*, 486–494. [CrossRef]
4. Sun, S.; Zhou, X.; Liu, H.X.; Jiang, Y.Z.; Zhou, H.C.; Zhang, C.; Fu, G.T. Unraveling the effect of inter-basin water transfer on reducing water scarcity and its inequality in China. *Water Res.* **2021**, *194*, 116931. [CrossRef]
5. Rollason, E.; Sinha, P.; Bracken, L.J. Interbasin water transfer in a changing world: A new conceptual model. *Prog. Phys. Geogr. Earth Env.* **2022**, *46*, 371–397. [CrossRef]
6. Han, D.M.; Song, X.F.; Currell, M.J.; Cao, G.L.; Zhang, Y.H.; Kang, Y.H. A survey of groundwater levels and hydrogeochemistry in irrigated fields in the Karamay Agricultural Development Area, northwest China: Implications for soil and groundwater salinity resulting from surface water transfer for irrigation. *J. Hydrol.* **2011**, *405*, 217–234. [CrossRef]
7. Wang, L.; Wei, W.; Sun, G.; Fu, B.J.; Chen, L.D.; Feng, X.M.; Ciais, P.; Mitra, B.; Wang, L.X. Effects of inter-basin transfers on watershed hydrology and vegetation greening in a large inland river basin. *J. Hydrol.* **2024**, *635*, 131234. [CrossRef]
8. Shokri, N.; Hassani, A.; Sahimi, M. Multi-scale soil salinization dynamics from global to pore scale: A review. *Rev. Geophys.* **2024**, *62*, e2023RG000804. [CrossRef]
9. Yin, X.W.; Feng, Q.; Liu, W.; Zhu, M.; Zhang, J.T.; Li, Y.G.; Yang, L.S.; Zhang, C.Q.; Cui, M.Q.; Zheng, X.J.; et al. Assessment and mechanism analysis of plant salt tolerance regulates soil moisture dynamics and controls root zone salinity and sodicity in seasonally irrigated agroecosystems. *J. Hydrol.* **2023**, *617*, 129138. [CrossRef]
10. Minhas, P.S.; Ramos, T.B.; Ben-Gal, A.; Pereira, L.S. Coping with salinity in irrigated agriculture: Crop evapotranspiration and water management issues. *Agric. Water Manag.* **2020**, *227*, 105832. [CrossRef]
11. Yin, X.W.; Feng, Q.; Li, Y.; Ravinesh, C.D.; Liu, W.; Zhu, M.; Zheng, X.J.; Liu, R. An interplay of soil salinization and groundwater degradation threatening coexistence of oasis-desert ecosystems. *Sci. Total Environ.* **2022**, *806*, 150599. [CrossRef] [PubMed]
12. Shah, S.H.H.; Vervoort, R.W.; Suweis, S.; Guswa, A.J.; Rinaldo, A.; van der Zee, S.E.A.T.M. Stochastic modeling of salt accumulation in the root zone due to capillary flux from brackish groundwater. *Water Resour. Res.* **2011**, *47*, W09506. [CrossRef]
13. Zhang, Z.; Hu, H.P.; Tian, F.Q.; Yao, X.; Sivapalan, M. Groundwater dynamics under water-saving irrigation and implications for sustainable water management in an oasis: Tarim River basin of western China. *Hydrol. Earth Syst. Sci.* **2014**, *18*, 3951–3967. [CrossRef]
14. Perri, S.; Suweis, S.; Entekhabi, D.; Molini, A. Vegetation controls on dryland salinity. *Geophys. Res. Lett.* **2018**, *45*, 11669–11682. [CrossRef]
15. Dai, L.; Miao, Q.; Shi, H.; Feng, Z.; Li, Y.; Liu, Y.; Xu, Y.; Xu, R.; Feng, W. Influence of Groundwater Depth on Salt Migration and Maize Growth in the Typical Irrigation Area. *Agronomy* **2025**, *15*, 1021. [CrossRef]
16. Lammers, R.B. Global Inter-Basin Hydrological Transfer Database. MSD-LIVE Data Repository. 2022. Available online: <https://data.msdlive.org/records/fkaan-vw036> (accessed on 12 February 2025).

17. Stavi, I.; Thevs, N.; Priori, S. Soil salinity and sodicity in drylands: A review of causes, effects, monitoring, and restoration measures. *Front. Environ. Sci.* **2021**, *9*, 712831. [\[CrossRef\]](#)
18. Mau, Y.; Porporato, A. A dynamical system approach to soil salinity and sodicity. *Adv. Water Res.* **2015**, *83*, 68–76. [\[CrossRef\]](#)
19. Agassi, M.; Shainberg, I.; Morin, J. Effect of electrolyte concentration and soil sodicity on infiltration rate and crust formation. *Soil. Sci. Soc. Am. J.* **1981**, *45*, 848–851. [\[CrossRef\]](#)
20. Shani, U.; Ben-Gal, A.; Tripler, E.; Dudley, L.M. Plant response to the soil environment: An analytical model integrating yield, water, soil type, and salinity. *Water Resour. Res.* **2007**, *43*, W08418. [\[CrossRef\]](#)
21. Ben-Gal, A.; Ityel, E.; Dudley, L.; Cohen, S.; Yermiyahu, U.; Presnov, E.; Zigmund, L.; Shani, U. Effect of irrigation water salinity on transpiration and on leaching requirements: A case study for bell peppers. *Agric. Water Manag.* **2008**, *95*, 587–597. [\[CrossRef\]](#)
22. Maas, E.V.; Hoffman, G.J. Crop salt tolerance-current assessment. *J. Irrig. Drain. Div. Am. Soc. Civ. Eng.* **1977**, *103*, 115–134. [\[CrossRef\]](#)
23. van Genuchten, M.T.; Gupta, S.K. A reassessment of the crop tolerance response function. *J. Indian. Soc. Soil. Sci.* **1993**, *41*, 730–737.
24. Skaggs, T.H.; Anderson, R.G.; Corwin, D.L.; Suarez, D.L. Analytical steady-state solutions for water-limited cropping systems using saline irrigation water. *Water Resour. Res.* **2014**, *50*, 9656–9674. [\[CrossRef\]](#)
25. Liu, G.H.; Tian, C.Y.; Mai, W.X.; Azeem, A.; Yang, J.G. Spatial and Temporal Variation in Soil Salinity and Correlation with Groundwater Depth in the Karamay Irrigation District of China. *Sustainability* **2023**, *15*, 15680. [\[CrossRef\]](#)
26. Qian, Y.B.; Jiang, J.; Wu, Z.N.; Wang, X.Q.; Zhao, C.J. Soil physical-chemical properties and agricultural sustainable development in exploitation area of Kelamayi. *J. Soil Water Conserv.* **2003**, 50–53+83. (In Chinese) [\[CrossRef\]](#)
27. Cui, D.; Liu, Z.Y.; Luo, Z.H.; Wen, J. *Hydrogeological Detailed Investigation Report of Ecological Agriculture Project in Karamay, Xinjiang*; Xinjiang Uygur Autonomous Region Water Resources and Hydropower Survey and Design Institute: Karamay, China, 1997; pp. 9–11.
28. Chen, Y.L.; Cheng, J.J.; Ma, Z.M. Analysis of soil water-salt movement and influence factor in Karamay agricultural development area. *J. Shihezi Univ.* **2016**, *34*, 222–231.
29. Bao, S.D. *Soil Agricultural Chemical Analysis*, 3rd ed.; China Agricultural Press: Beijing, China, 2000; pp. 265–267.
30. Ayers, R.S.; Westcot, D.W. *Water Quality for Agriculture, Irrigation and Drainage*; Paper No. 29; FAO: Rome, Italy, 1985.
31. Vachaud, G.; Passerat De Silans, A.; Balabanis, P.; Vauclin, M. Temporal stability of spatially measured soil water probability density function. *Soil. Sci. Soc. Am. J.* **1985**, *49*, 822–828. [\[CrossRef\]](#)
32. Liu, Y.; Xin, Z.H.; Sun, S.; Zhang, C.; Fu, G.T. Assessing environmental, economic, and social impacts of inter-basin water transfer in China. *J. Hydrol.* **2023**, *625*, 130008. [\[CrossRef\]](#)
33. Yin, X.W.; Feng, Q.; Zheng, X.J.; Zhu, M.; Wu, X.; Guo, Y.; Wu, M.; Li, Y. Spatio-temporal dynamics and eco-hydrological controls of water and salt migration within and among different land uses in an oasis-desert system. *Sci. Total Env.* **2021**, *772*, 145572. [\[CrossRef\]](#)
34. Vico, G.; Porporato, A. Traditional and microirrigation with stochastic soil moisture. *Water Resour. Res.* **2010**, *46*, W03509. [\[CrossRef\]](#)
35. Assouline, S.; Russo, D.; Silber, A.; Or, D. Balancing water scarcity and quality for sustainable irrigated agriculture. *Water Resour. Res.* **2015**, *51*, 3419–3436. [\[CrossRef\]](#)
36. Demo, A.H.; Gameda, M.K.; Abdo, D.R.; Guluma, T.N.; Adugna, D.B. Impact of soil salinity, sodicity, and irrigation water salinity on crop production and coping mechanism in areas of dryland farming. *Agrosyst. Geosci. Environ.* **2025**, *8*, e70072. [\[CrossRef\]](#)
37. Hu, H.C.; Zhang, Z.; Tian, F.Q.; Yang, P.J.; Ni, G.H.; Yao, X.H. Response of soil salinity and crop growth to irrigation methods in Xinjiang. *J. Tsinghua Univ.* **2016**, *56*, 373–380.

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.