Remote Sensing-Based Risk Assessment of Soil Salinization and Its Evolution Pattern Postprint

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Abstract

Risk assessment and monitoring of soil salinization are of great significance for precise management of saline soils and ensuring sustainable agricultural and ecological development. This study takes Dali County as the research area, and based on the driving mechanisms and processes of soil salinity, combined with the characterization status of soil salinity, constructs comprehensive salinity index, comprehensive soil index, comprehensive vegetation index, and comprehensive geographic index using the CRITIC weighting method, and establishes a soil salinization risk assessment model using the AHP-entropy weight method combined weighting approach. Monitoring reveals that soil salinization risk in Dali County is primarily mild, with 2021 exhibiting a relatively high salinization risk level, where the total area of moderate and above salinization risk reached the maximum value in recent 4 years, accounting for approximately 50%. From 2020 to 2023, the variation characteristics of soil salinization risk levels are dominated by risk escalation types, and the stability of soil salinization risk levels in the Yellow River basin area in the east is relatively poor. Cropland is the main land cover type in the early warning zones and restoration zones within the management partitions, primarily distributed in the eastern part of Dali County. Through correlation verification, it is found that there is a significant strong correlation between the soil salinization risk assessment results and the measured soil electrical conductivity sample points during the same period, and the soil salinization risk assessment model can effectively characterize the spatiotemporal evolution characteristics of soil salinization in Dali County. Furthermore, the intensification of soil salinization risk is mainly influenced by multiple factors including concentrated heavy rainfall, rising temperatures, elevated groundwater levels, increased surface evapotranspiration, and agricultural production. Therefore, the soil salinization risk assessment in Dali County can provide scientific theoretical basis and data support for precise and efficient management of saline soils, effectively promoting agricultural production structure

adjustment and ecological sustainable development.

Full Text

Remote Sensing-Based Risk Assessment of Soil Salinization and Its Evolutionary Patterns

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Abstract

Soil salinization risk assessment and monitoring are crucial for the precise management of saline soils and for ensuring sustainable agricultural and ecological development. This study focuses on Dali County, where we constructed comprehensive indices for salt, soil, vegetation, and geography using the CRITIC weighting method, based on the driving mechanisms and processes of soil salinity combined with the characterized state of soil salt content. We then employed the Analytic Hierarchy Process (AHP)-entropy weight method to build a soil salinization risk assessment model. Monitoring results revealed that soil salinization risk in Dali County was predominantly mild, though 2021 exhibited relatively high risk levels. The total area under moderate or higher salinization risk reached its maximum value over the four-year period, accounting for approximately 50% of the total area. From 2020 to 2023, changes in soil salinization risk levels were primarily characterized by risk escalation, and the stability of risk levels around the Yellow River Basin in the eastern region was relatively poor. Cultivated land was the primary land cover type in the warning and restoration zones of the management classification, mainly distributed in the eastern part of Dali County. Correlation analysis demonstrated a significant strong correlation between the soil salinization risk assessment results and measured soil electrical conductivity samples from the same period, confirming that the assessment model can effectively characterize the spatiotemporal evolution of soil salinization in Dali County. Furthermore, increased soil salinization risk is mainly influenced by multiple factors including concentrated heavy rainfall, rising temperatures, elevated groundwater levels, increased surface evapotranspiration, and agricultural production activities. Therefore, the soil salinization risk assessment for Dali County can provide scientific theoretical foundations and data support for precise and efficient saline soil management, effectively promoting agricultural production structure adjustment and ecological sustainability.

Keywords: soil salinization; remote sensing; Dali County; information evolution map; combined weight method

1. Introduction

Soil salinization, caused by natural processes or human activities, leads to land abandonment, declining cultivated land quality, and grassland degradation, directly threatening human survival and development [?]. Currently, the total area of saline soil in China is approximately 9.913×10^{7} hm^{2}, with saline areas in cultivated land reaching 7.6×10^{6} hm^{2}, accounting for about 4.9% of the nation’s total cultivated area. Dali County, located on the western bank of the Yellow River, features highly variable land, shallow groundwater tables, and high mineralization, making it highly susceptible to saline soil formation and consequently affecting its agricultural production and economic development.

Traditional salinization monitoring requires field collection of soil salinity information, with spatial interpolation used to reflect the distribution of soil salt content. While this method can accurately obtain soil salinity information around sampling points, it is time-consuming, labor-intensive, and difficult to implement for large-area, long-term monitoring [?]. Remote sensing technology, with its macroscopic, rapid, and dynamic characteristics, has become the primary means for large-scale spatiotemporal monitoring of soil salinization.

Elnagga et al. [?] utilized Landsat imagery and decision tree classification to extract salinized areas in Oregon’ s arid regions, achieving 98.8% accuracy. Wang et al. [?] monitored spatiotemporal changes in salinized soils in China’ s semi-arid regions from 1992 to 2011 using Landsat imagery, finding that salinized soil area increased at a rate of 0.28% annually. Kabiraj et al. [?] employed Sentinel-2 imagery to monitor soil salinization distribution in India’ s Thoothukdu region, achieving over 90% accuracy. Hong et al. [?] used Sentinel-2 imagery to monitor the spatial patterns of soil salinization in cotton fields of Xinjiang' s Aral Reclamation Area, with validation precision reaching $R^2 = 0.93$. These studies demonstrate that remote sensing technology can effectively identify the spatiotemporal patterns of salinized soils and enable precise monitoring of soil salinization degrees based on its causes, mechanisms, and processes.

Machine learning methods for building soil salinization assessment models can monitor salinization levels but require extensive training samples of measured saline soil data, posing challenges for sample-scarce regions or long-term, large-scale monitoring [?]. Consequently, scholars have developed theoretical models using evaluation indicators to construct soil salinization assessment models, primarily including subjective and objective weighting methods.

Seydehmet et al. [?] used elevation, normalized difference vegetation index (NDVI), and evapotranspiration as indicators with the Analytic Hierarchy Process (AHP) to construct a soil salinization risk assessment model for the Keriya Oasis in Xinjiang. De et al. [?] used relief, NDVI, and population density as 13 evaluation indicators with AHP to build a soil salinization risk assessment model for the Yinchuan Plain in Ningxia. Subjective weighting methods primarily rely on prior knowledge, which can affect the objectivity and accuracy of assessment results [?]. Ilyas et al. [?] used ground elevation, surface albedo, and NDVI as indicators with grey correlation analysis to construct a salinization risk evaluation model for the Keriya Oasis. Wang et al. [?] used vegetation senescence reflectance index, NDVI, and slope as 11 evaluation indicators with correlation coefficient analysis to build soil salinization risk assessment models for dry and rainy seasons in the Ebinur Lake Wetland National Nature Reserve. While objective weighting methods follow objective scientific data, they may neglect the actual influence of evaluation factors in real-world scenarios [?]. Therefore, combining subjective and objective methods can overcome the limitations of individual weighting methods, accurately evaluate the actual importance of each factor in soil salinization monitoring, and achieve precise long-term, large-scale monitoring.

Accordingly, this study, based on the driving mechanisms and processes of soil salt content combined with the characterized state of soil salinity, uses 10 m resolution Sentinel-2 remote sensing data integrated with meteorological, topographic, and human activity intensity data. We employ the AHP-entropy combined weighting method to construct a soil salinization risk assessment model for Dali County, analyze the spatial distribution and evolution patterns of soil salinization risk from 2020 to 2023, and propose scientific management zones for saline soils to provide reliable theoretical foundations for agricultural production, economic development, and ecological sustainability in Dali County.

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1.1 Study Area Overview

Dali County is located in the eastern part of Guanzhong, southern Shaanxi Province (34°36 -35°02 N, 109°43 -110°19 E), at the confluence of the Yellow, Wei, and Luo Rivers (Fig. [Figure 1: see original paper]). The total area is 1,776 km^2, with elevations ranging from 329 to 534 m. The region has a warm temperate semi-humid and semi-arid monsoon climate, with an average annual temperature of 14.4°C and annual precipitation of 514 mm concentrated in summer. In 2021, the county experienced the strongest rainfall since 1961, with annual precipitation exceeding the normal level and reaching 726.2 mm. The terrain generally slopes from high in the northwest to low in the southeast, featuring four geomorphic types: Loess tableland, Wei River terraces, Luo River sandy land, and Yellow River floodplain. The Yellow River floodplain, located in the eastern and southern parts of the county, is highly variable due to post-flood sedimentation and channel changes. Soil types are primarily loam, aeolian sandy soil, loess, alluvial soil, and saline soil, with saline soil accounting for about 4.9% of the county' s total soil area. Surface soils are mainly silt loam with low organic matter, nitrogen, phosphorus, and potassium content, and poor water and nutrient retention. Cultivated land is the main land use type, with irrigated land being the primary category, accounting for 94.5% of cultivated land. The cropping system involves wheat-corn rotation, with irrigation using sprinkler, drip, and micro-irrigation methods from surface river water and groundwater. Shallow groundwater with high mineralization makes Dali County prone to soil salinization.

1.2 Data Sources

We used Sentinel-2 imagery from 2020 to 2023 (same period each year) as the remote sensing data source, obtained from the European Space Agency (https://scihub.copernicus.eu/). Precipitation data were derived from daily precipitation records at 11 national meteorological stations, with spatial interpolation using the Kriging method to obtain annual cumulative precipitation data at 10 m resolution for Dali County. The data were sourced from the National Oceanic and Atmospheric Administration (www.ncei.noaa.gov). The Digital Elevation Model (DEM) was the ASTER GDEM V3 product with 30 m resolution from the Japan Aerospace Exploration Agency (https://www.eorc.jaxa.jp). The Human Activity Intensity of Land Surface (HAILS) index, which characterizes human activity intensity, was estimated based on the ChinaCover land cover dataset [**?**].

We collected shallow soil samples (0–20 cm depth) across Dali County using a high-precision handheld GPS (G138BD) and measured soil electrical conductivity following the HJ 802-2016 standard [**?**] to obtain measured soil conductivity data for validation (spatial distribution shown in Fig. [Figure 2: see original paper]).

2. Methods

2.1 Soil Salinization Risk Assessment Model

2.1.1 Model Theory Based on the driving mechanisms and processes of soil salt content [?], combined with the characterized state of soil salinity, we constructed a theoretical framework comprising four layers: the target layer (soil salinization risk assessment), the criterion layer (soil texture, vegetation growth status, soil salt content, and geographical environment), the evaluation factor layer (corresponding indicators), and the comment collection layer (risk levels). Using the AHP-entropy combined weighting method, we built a soil salinization risk assessment model. We divided the comment collection layer into five risk levels: no risk, mild risk, moderate risk, severe risk, and extreme risk (Fig. [Figure 2: see original paper]).

2.1.2 Model Indicators Based on the theoretical framework, we selected 10 indicators to construct evaluation factor layer indices: comprehensive salt index, comprehensive soil index, comprehensive vegetation index, and comprehensive geographical index. The comprehensive salt index used 13 soil salinity indices, the comprehensive soil index used 3 soil texture indices, the comprehensive vegetation index used 10 vegetation indices, and the comprehensive geographical index used 3 indicators: Slope, precipitation, and HAILS. All data were resampled to 10 m resolution (Table).

2.1.3 Model Construction Methods **CRITIC Weighting Method.** We used the CRITIC method to weight the four comprehensive indices (comprehensive salt index, comprehensive soil index, comprehensive vegetation index, and comprehensive geographical index). This objective weighting method evaluates indicators based on contrast intensity and conflict [?]. The formulas are:

$$C_i = \sigma_i \sum_{j=1}^{n} (1 - r_{ij})$$

$$W_i = \frac{C_i}{\sum_{i=1}^{n} C_i}$$

where C_i represents the information content of indicator i (greater information content yields greater weight), and W_i represents the weight of indicator i.

AHP-Entropy Combined Weighting Method. We used the AHP-entropy combined weighting method to construct the soil salinization risk assessment model. AHP is a subjective decision-making method that calculates subjective weights by comparing the relative importance of indicator pairs [?]. The entropy method objectively reflects indicator weights based on data variability, where greater differences in indicator values indicate greater importance in comprehensive evaluation [?]. AHP alone cannot avoid personal bias, while entropy weighting alone may assign low weights to actually important factors. Combining them addresses these limitations [?]. The formulas are:

$$\omega_i = \frac{P_i \times E_i}{\sum_{i=1}^{n}(P_i \times E_i)}$$

where P_i is the AHP weight for evaluation factor i, E_i is the entropy weight, and ω_i is the combined weight.

The soil salinization risk assessment model is:

$$SSR' = \sum_{i=1}^{n} \omega_i Y_i$$

$$SSR = \frac{SSR' - \min(SSR')}{\max(SSR') - \min(SSR')}$$

where ω_i is the combined weight of driving factor i, Y_i is the value of driving factor i, SSR' is the initial assessment result, and SSR is the final soil salinization risk assessment result.

Using the natural breaks method and assessment results for Dali County, we classified risk levels as: no risk (0-0.2), mild risk (0.2-0.4), moderate risk (0.4-0.6), severe risk (0.6-0.8), and extreme risk (0.8-1.0).

2.2 Soil Salinization Risk Evolution Map

We used information evolution mapping [?] to analyze evolution patterns. Using coding methods, we obtained conversion codes for the five risk levels in the comment collection layer:

$$SSR_i = 10^y \times C_{i,y} + 10^{y-1} \times C_{i,y-1} + ... + 10^0 \times C_{i,0}$$

where SSR_i is the conversion code for comment collection layer C_i, y is the monitoring end year, and $C_{i,y}$ is the code for year y (assigned 1 if belonging to risk level C_i, otherwise 0). Based on these codes, we categorized changes into five conversion types (Table).

By superimposing the conversion types of each comment collection layer C_i, we obtained the soil salinization risk evolution map:

$$SR = 10^4 \times SSR_{none} + 10^3 \times SSR_{mild} + 10^2 \times SSR_{moderate} + 10^1 \times SSR_{severe} + SSR_{extreme}$$

where SSR_{none}, SSR_{mild}, $SSR_{moderate}$, SSR_{severe}, and $SSR_{extreme}$ represent conversion codes for each risk level, and SR is the final evolution map divided into four change characteristic zones (Table).

We also calculated the number of risk level changes from 2020 to 2023 to create a stability evolution map for analyzing salinization risk stability.

2.3 Saline Soil Management Zoning

Based on the risk evolution map and stability map, we constructed saline soil management zones through spatial overlay (Table). The **Optimization Zone** (long-term stable, never changed) indicates stable soil conditions suitable for optimization. The **Protection Zone** (fluctuating stable, 1-2 changes) requires appropriate management measures. The **Warning Zone** (risk-decreasing type, ~2 changes) had higher previous risk levels with poor stability, needing enhanced monitoring. The **Restoration Zone** (risk-increasing type, $ $2 changes) faces rising risk levels with the poorest stability, requiring urgent management.

3. Results

3.1 Spatial-Temporal Distribution Patterns of Soil Salinization Risk

We validated model accuracy using Pearson correlation analysis between measured soil conductivity and assessment results. Since soil water-soluble salts are strong electrolytes with conductive solutions, electrical conductivity effectively reflects salinization degree [?]. Results showed a significant strong correlation ($R = 0.648$, $p < 0.001$) (Fig. [Figure 3: see original paper]), confirming the model’ s effectiveness.

From 2020 to 2023, mild risk dominated across Dali County, primarily dispersed in cultivated land. Moderate risk was mainly distributed in the upper and middle reaches of the Yellow River in the northeast and Zhaodu Town in the southeast (Fig. [Figure 4: see original paper]). In 2021, the risk level increased significantly, with moderate risk area expanding dramatically to its maximum (934.846 km^2, 52.613% of total area). Severe and extreme risks also appeared prominently. Except for 2021, mild risk area exceeded 45% in other years. The total area of no risk and mild risk combined was 84.491% in 2020 but only 53.921% in 2021, decreasing by 224.157 km^2 and 30.124% respectively. The total area of moderate or higher risk was smallest in 2020 (<10%) but reached 52.613% in 2021, decreasing to 20.423% in 2022 and 18.653% in 2023 (Table).

3.2 Evolution Patterns of Soil Salinization Risk

From 2020 to 2023, no risk areas showed mainly decreasing conversion types, while other levels showed mainly fluctuating stable types. Risk-increasing conversion types (escalation and fluctuating escalation) and risk-decreasing types (de-escalation and fluctuating de-escalation) were compared by area. No risk and mild risk levels had smaller risk-increasing areas than risk-decreasing areas, while moderate, severe, and extreme risk levels showed the opposite pattern. Among risk-increasing conversions, moderate risk had the largest area; among risk-decreasing conversions, no risk had the largest area.

The evolution map (Fig. [Figure 5: see original paper]) shows western and northern Dali County primarily had continuous mild risk (22.313% of total area). The southern area mainly showed conversion from mild, moderate, severe, or extreme risk to no risk. The northeastern area primarily showed conversion from mild risk to moderate, severe, or extreme risk. Areas around the upper Yellow River mainly showed conversion from no risk to mild, moderate, or severe risk, while downstream areas showed continuous no risk. Statistical analysis indicated that areas with two evolutions accounted for the largest proportion (32.103%), followed by three evolutions (26.932%), one evolution (18.653%), and zero evolutions (22.313%) (Fig. [Figure 6: see original paper]).

The stability map (Fig. [Figure 7: see original paper]) shows western Dali County had primarily 0–1 evolutions (good stability), while areas around the eastern Yellow River had poor stability, with 2 evolutions in the northeast and 3 evolutions in the southeast.

Integrating the evolution and stability maps yielded the saline soil management zoning (Fig. [Figure 8: see original paper]). The **Optimization Zone** covered 430.675 km^2 (26.932%), mainly in northern areas away from the Yellow River. The **Protection Zone** was largest at 497.216 km^2 (31.093%), mainly in southern marginal areas. The **Warning Zone** was smallest at 326.594 km^2 (20.423%). The **Restoration Zone** covered 344.658 km^2 (21.553%). Warning and restoration zones were dominated by cultivated land in the upper Yellow River region in eastern Dali County.

Risk escalation was the dominant change characteristic (36.777% of area), while risk de-escalation was minimal (8.438%). Long-term stable and fluctuating stable types had similar proportions. Among long-term stable patterns, continuous mild risk had the largest area of all evolution patterns. Among fluctuating stable patterns, mutual conversion between mild risk and moderate, severe, or extreme risk was largest (291.067 km^2). Among risk de-escalation patterns, conversion from mild, moderate, severe, or extreme risk to no risk was largest (100.259 km^2), about half the area of the fluctuating stable pattern (Table).

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4. Discussion

4.1 Model Applicability Analysis

Remote sensing technology is now widely applied in soil salinization research. Many scholars have used remote sensing indices to construct soil salt inversion models that can accurately characterize spatiotemporal patterns [?]. Our correlation analysis showed significant strong correlation ($R = 0.648$, $p < 0.001$) with measured soil conductivity, validating the model’s effectiveness.

The AHP-entropy combined weighting method has been successfully applied in various ecological assessment models. Jia et al. [?] used it to monitor long-term ecological vulnerability in the Tarim River Basin from 1990 to 2020. Liu et al. [?] applied it to evaluate short-term ecological changes in the Weihe River Basin from 2000 to 2020. Wang et al. [?] used it to assess the health of protection forests in the upper Yangtze River from 2000 to 2015. These studies demonstrate that this method can effectively analyze both long-term and short-term ecological changes.

Input data resolution affects assessment results. We used 10 m Sentinel-2 imagery as the primary data source, overlaid with 30 m ASTER GDEM and 10 m precipitation data interpolated from 11 national meteorological stations. While resampling to uniform resolution, high-resolution data can be affected by low-resolution data, reducing information content and potentially increasing uncertainty for 10–30 m features [?]. However, using 11 stations with Kriging interpolation [?] adequately characterized Dali County’s precipitation spatial pattern while avoiding uneven spatial distribution from station selection bias.

Soil salt content is a key factor limiting crop yield, with generally lower yields in high-salinization areas [?]. According to Weinan City statistical yearbooks, total grain production (wheat, rice, corn, and soybeans) and per-unit yield showed a decreasing then increasing trend from 2020 to 2022, corresponding to the salinization risk pattern (Fig. [Figure 9: see original paper]). In 2021, when salinization was most severe with moderate or higher risk approaching 50% of the area, grain yield reached its lowest point. In 2022, despite a 6.961% increase in moderate or higher risk area compared to 2020, total grain production decreased by 0.060$×10^{4}$ t. Grain yield is also affected by precipitation, temperature, radiation, cultivated area, multiple cropping, and extreme weather events [?].

4.2 Driving Factors of Soil Salinization Evolution

Soil salinization involves the accumulation of soluble salts, primarily influenced by natural factors (rainfall [?], temperature [?], evapotranspiration [?], groundwater level [?]) and human disturbances (agricultural production [?], agricultural policies [?]).

Increased salinization risk in Dali County is mainly affected by concentrated heavy rainfall, rising temperatures, elevated groundwater levels, increased evapotranspiration, and agricultural production. The county' s shallow, high-mineralization groundwater and strong long-term evaporation cause salts from deep soil and shallow groundwater to accumulate at the surface. Concentrated heavy rainfall can rapidly raise groundwater levels. Combined with rising temperatures and increased evapotranspiration, this elevates groundwater, moves deep soil salts upward, and deposits them at the surface, worsening salinization [?]. Additionally, outdated drainage facilities, shallow and silted channels, and traditional flood irrigation exacerbate salinization [?]. In mid-August 2021, concentrated heavy rainfall in Dali County, combined with shallow, blocked drainage channels, prevented timely water removal, increasing salinization risk. Monitoring showed significantly elevated risk in 2021, with large areas shifting from mild to moderate risk.

Rising annual temperatures have increased evapotranspiration, causing a slow upward trend in salinization risk, with moderate risk area increasing by 6.502% in 2022 and 15.941% in 2023 compared to 2020. However, proactive agricultural management measures such as water-saving irrigation, improved water systems, and better drainage conditions can effectively mitigate salinization risk [?]. Since 2022, Dali County has implemented agricultural management measures to reduce salinization, including high-standard farmland construction ensuring effective drainage systems [?]. After heavy rainfall in 2021, the government implemented farmland drainage restoration projects, dredging and renovating channels to prevent sustained groundwater level rise and salinization [?]. The county also promoted sprinkler, drip, and micro-irrigation to control or lower groundwater levels and maintain surface soil water-salt balance [?]. Monitoring results showed significantly reduced risk in 2023, with moderate or higher risk area decreasing by 29.757% compared to 2021, while no risk area increased by 1.402% and mild risk area increased by 2.693%. This demonstrates that human interventions such as water-saving irrigation, improved water systems, and better drainage can effectively control or lower groundwater levels and prevent salinization worsening.

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5. Conclusions

Escalating soil salinization risk severely hinders agricultural production and economic development. Understanding its spatial distribution and evolution patterns provides reliable data support for precise management and treatment. Based on soil salt driving mechanisms and processes combined with characterized salt states, we constructed a soil salinization risk assessment model for Dali County using Sentinel-2 data, ASTER GDEM, HAILS index, and national meteorological station data with the AHP-entropy combined weighting method. Using information evolution mapping, we analyzed spatiotemporal patterns and change characteristics from 2020 to 2023 and proposed scientific management zones. The main conclusions are:

1) Soil salinization risk in Dali County is predominantly mild and mainly dispersed in cultivated land, hindering agricultural production and economic development to some extent. In 2021, risk levels increased significantly, with moderate risk area expanding dramatically and prominent severe and extreme risks appearing. The total area of moderate or higher risk increased by 36.718% compared to 2020, severely impacting crop growth. By 2023, risk levels decreased significantly, with moderate or higher risk area reducing by 29.757% compared to 2021, gradually improving cultivated land conditions and weakening salinization impacts on crops.
2) From 2020 to 2023, change characteristics were dominated by risk escalation (36.777% of area), particularly in the northeastern and downstream Yellow River areas. Stability around the Yellow River Basin was poor, mainly with two evolutions, while western areas showed better stability. Warning and restoration zones requiring urgent management are dominated by cultivated land in the eastern Yellow River region, necessitating intensified treatment and timely land improvement to reduce agricultural impacts.
3) Validation showed significant strong correlation between assessment results and measured soil conductivity, confirming the model' s effectiveness. Increased salinization risk is mainly influenced by concentrated heavy rainfall, rising temperatures, elevated groundwater levels, increased evapotranspiration, and agricultural production. Human interventions such as water-saving irrigation, improved water systems, and better drainage are needed to control groundwater levels and prevent salinization worsening.

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