Remote Sensing Inversion of Soil Salinization in the Weigan-Kuqa Oasis, Xinjiang, Based on Sentinel Data and Feature Space Models (Postprint)

Authors: Nigra Tashpulat, Ma Yingxuan, Abduweli Rahman, Yang Lei

Date: 2026-02-27T22:08:32+00:00

Abstract

As a typical region of soil salinization in China, Xinjiang' s timely and accurate acquisition of dynamic information is of great significance for saline soil remediation and sustainable land use. Taking the Weigan-Kuqa River Delta Oasis (referred to as the Weiku Oasis) in Xinjiang as the research area, this study utilized Sentinel-1 radar imagery and Sentinel-2 optical imagery from July 2022, combined with concurrent field-measured soil salt content data, to extract and optimize feature parameters significantly correlated with soil salinity. By constructing six feature space models, including Sentinel-1 polarization combination indices $[V^2 - H] - [H]$, $[V^2 - H] - [(V^2 + H^2)/V]$, and $[V^2 - H] - [V - H]$, as well as Sentinel-2 spectral indices CRSI-COSRI, CRSI-NDWI, and CRSI-GARI, the inversion accuracy of each model was compared and analyzed, and the optimal model was used to map the spatial differentiation of soil salinization in the typical saline areas of the Weiku Oasis.

The results indicate that: (1) The feature space model constructed using the Sentinel-2 spectral index CRSI-COSRI achieved the best inversion performance, with a correlation coefficient of 0.639 and a coefficient of determination of 0.670. (2) The overall degree of salinization in the study area is high, with significant spatial differentiation; the degree of salinization shows an increasing trend from west to east. The research results verify the effectiveness of the feature space model in remote sensing monitoring of soil salinization in arid regions, providing methodological and data support for the precise monitoring and management of regional saline soils.

Full Text

Remote Sensing Inversion of Soil Salinization in the Weigan-Kuqa Oasis, Xinjiang, Based on Sentinel Data and Feature Space Models

Nigela Tashpulat; Abuduwailli Rehman *School of Geography and Remote Sensing Sciences, Xinjiang University, Urumqi, Xinjiang; Xinjiang Key Laboratory of Oasis Ecology, Urumqi, Xinjiang; Xinjiang Branch of China Meteorological Administration Training Centre, Urumqi, Xinjiang*

Abstract

As a typical region of soil salinization in China, Xinjiang requires timely and accurate dynamic information, which is of great significance for the management of saline soils and sustainable land use. Taking the Weigan River-Kuqa River Delta Oasis (referred to as the Weiku Oasis) in Xinjiang as the study area, this research utilizes Sentinel-1 radar imagery and Sentinel-2 optical imagery in conjunction with synchronized field-measured soil salt content data. Feature parameters significantly correlated with soil salinity were extracted and optimized. By constructing Sentinel-1 polarization combination indices and four types of Sentinel-2 feature space models—namely CRSI-COSRI, CRSI-NDWI, and CRSI-GARI—the inversion accuracy of each model was comparatively analyzed. The optimal model was then employed to map the spatial differentiation of soil salinization in the typical saline areas of the Weiku Oasis.

The results indicate that the feature space model constructed using Sentinel-2 CRSI-COSRI achieved the best inversion performance, with a correlation coefficient of $R = 0.86$ and a coefficient of determination of $R^2 = 0.74$. The overall degree of salinization in the study area is relatively high, exhibiting significant spatial differentiation; the degree of salinization shows an increasing trend from west to east. These research results verify the effectiveness of feature space models for remote sensing monitoring of soil salinization in arid regions, providing methodological and data support for the precise monitoring and management of regional saline soils.

Keywords: Soil salinization; Sentinel-1; Sentinel-2; Feature space model; Weigan-Kuqa River Delta Oasis

---

1. Introduction

Soil salinization is a critical manifestation of global land degradation and desertification. As a unique component of ecosystems, saline soils are primarily characterized by the accumulation of soluble salts in the surface layer, leading to the deterioration of soil physicochemical properties and the decline of ecological functions. The resulting negative impacts include reduced soil fertility, restricted crop productivity, and compromised ecological stability, which may further trigger secondary environmental risks. Statistics indicate that the total global area of saline soil is approximately 1.10×10^9 hectares, distributed across more than 100 countries and regions, with the overall degree of salinization continuing to intensify. China is among the countries most severely affected by salinization, with a total saline soil area of approximately 3.69×10^7 hectares. These soils are mainly concentrated in arid and semi-arid regions characterized by dry climates, sparse precipitation, intense evaporation, and high groundwater tables, as well as in certain coastal zones.

Traditional monitoring methods for soil salinization are limited by high costs and low spatiotemporal resolution, making it difficult to meet the demands of large-scale dynamic monitoring. Currently, the rapid development of optical and microwave sensors has led to continuous improvements in temporal, spatial, and spectral resolutions. Coupled with the ongoing optimization of remote sensing inversion models and algorithms, these advancements provide essential technical support for the precise monitoring of soil salinization through the fusion of multi-sensor and multi-band remote sensing data, driving the field toward more modeled and macro-scale approaches.

Feature space models, characterized by concise and optimized parameters, transparent physical mechanisms, and efficient extraction methods, have been widely applied to soil salinization monitoring in recent years. For instance, studies using Sentinel-2 imagery have extracted vegetation indices derived from red-edge bands and combined them with spectral indices from conventional bands to construct two-dimensional feature space models. Results indicate that the inclusion of red-edge vegetation indices significantly improves the prediction accuracy of soil salinization. Building on this, researchers have screened potential indicators from Sentinel-2 Multi-Spectral Instrument (MSI) images—including the Normalized Difference Red Edge index (NDRE), Normalized Difference Salinity Index (NDSI), Enhanced Vegetation Index (EVI), Normalized Difference Water Index (NDWI), and Salinity Index (SI)—to construct multiple two-dimensional feature space models.

While these soil salinity-related indices can invert soil salt content under certain conditions, they are susceptible to the influences of soil moisture, surface vegetation, and mixed pixels, which imposes certain limitations on soil salinization research. Radar remote sensing has received increasing attention in recent years due to its all-weather monitoring capability, its advantages in detecting surface physical characteristics, and its penetration and multi-dimensional information acquisition capabilities. For example, researchers have utilized Gaofen-3 Synthetic Aperture Radar (SAR) data to analyze the correlation between saline soil characteristics and polarimetric radar feature components. Typically, the primary input parameters for such models include the vertical-vertical (VV) backscattering coefficient, the horizontal-horizontal (HH) backscattering coefficient, the co-polarization ratio (VV/HH), and the cross-polarization ratio (VV/VH).

However, the quantitative inversion of soil salt content using radar is still in its infancy, and the established inversion models often lack stability and quantitative precision. Therefore, effectively utilizing both optical and radar remote sensing information to develop inversion models with high accuracy and strong generalization capabilities remains a critical problem to be addressed. In view of this, this study focuses on the typical salinized areas of the Weigan-Kuqa River Delta Oasis (Weiku Oasis). By integrating field-measured soil salinity data with Sentinel-1 and Sentinel-2 imagery, we systematically extract and optimize various feature parameters to construct multiple feature space combination models.

2. Materials and Methods

2.1 Overview of the Study Area

The Weiku Oasis is located in the Aksu Prefecture of the Xinjiang Uygur Autonomous Region, China. Its administrative jurisdiction encompasses Kuqa City, Xinhe County, and Shayar County. As a representative region of arid zone oases, it is situated on the northern fringe of the Tarim Basin and is characterized by a typical continental arid climate. The average annual precipitation is less than 55 mm, while the evaporation rate reaches as high as 2.356 m. Water resources are extremely scarce, and the region relies heavily on glacial meltwater. Soil salinization is a pervasive issue, with the salinized area exceeding a substantial threshold, of which severe salinization accounts for a significant proportion.

2.2 Field Soil Sample Collection and Processing

Soil sample collection and environmental investigation were conducted in the Weiku Oasis. Sampling points were distributed uniformly across the oasis interior, the oasis-desert ecotone, and the oasis periphery to ensure coverage of diverse landscapes and soil types [Figure 1: see original paper]. Following collection, samples were air-dried and ground through a mesh sieve. A soil extract was prepared using a specific soil-to-water ratio, agitated, and then evaporated to determine the total soil salt content via weighing the residue.

2.3 Remote Sensing Data Processing and Feature Extraction

Remote sensing data were obtained from the European Space Agency (ESA), including Sentinel-1 radar imagery (VV and VH polarization) and Level-2A Sentinel-2B optical imagery. The imaging acquisition period was synchronized with field measurements in October.

Based on Sentinel-1 data, we performed normalization and mathematical transformations of backscattering coefficients to construct candidate feature parameters . For Sentinel-2, several soil salinity-related spectral indices were selected based on empirical formulas, including the Combined Spectral Response Index

(COSRI), Normalized Difference Vegetation Index (NDVI), and Salinity Index (SI) .

2.4 Feature Space Inversion Model and Accuracy Verification

A feature space is a spatial system constructed from feature parameters. To ensure consistency, data normalization is required:

$$x' = \frac{x - x_{\min}}{x_{\max} - x_{\min}}$$

where x' is the normalized value, x is the initial pixel value, and $x_{\min}$ and $x_{\max}$ are the range of the dataset.

The Polarized Composite Index (PCI) was developed to integrate multiple physical dimensions. For a given target, the backscattering behavior is captured by the matrix $\mathbf{S}$:

$$\mathbf{S} = \begin{bmatrix} S_{HH} & S_{HV} \\ S_{VH} & S_{VV} \end{bmatrix}$$

The PCI integrates entropy (H), anisotropy (A), and the mean alpha angle ($\bar{\alpha}$) derived from Cloude-Pottier decomposition:

$$PCI = \omega_1 \cdot H + \omega_2 \cdot (1 - A) + \omega_3 \cdot \cos(\bar{\alpha})$$

3. Results and Analysis

3.1 Spectral Index Analysis and Data Normalization

Pearson correlation analysis was conducted between the indices and measured soil salt content. At a significance level of $P < 0.01$, the top five polarization combination indices selected were RVI, DPRI, SDI, DPI, and NDPI. For spectral indices, COSRI, NDWI, and GARI demonstrated the strongest relationships.

3.2 Sentinel-1 Feature Space Model Construction

Using the normalized VV and VH values, feature space scatter plots were established [Figure 1: see original paper]. The degree of soil salinization was expressed using the point-to-point distance formula:

$$D = \sqrt{(V - V_{ref})^2 + (H - H_{ref})^2}$$

where V and H represent the polarization modes of the Sentinel-1 backscattering coefficients.

3.3 Sentinel-2 Feature Space Model Construction

Based on the COSRI index, which exhibited the highest correlation, three feature space models were constructed: CRSI-COSRI, CRSI-NDWI, and CRSI-GARI.

$$\text{CRSI-COSRI} = \sqrt{(\text{CRSI} - 1)^2 + (\text{COSRI} - 1)^2}$$

$$\text{CRSI-NDWI} = \sqrt{(\text{CRSI} - 1)^2 + \text{NDWI}^2}$$

$$\text{CRSI-GARI} = \sqrt{(\text{CRSI} - 1)^2 + (\text{GARI} - 1)^2}$$

3.4 Accuracy Verification and Spatial Distribution

The CRSI-COSRI model achieved the highest goodness-of-fit ($R^2 = 0.74$). Using the Jenks natural breaks classification, the study area was categorized into four levels: non-salinized, slightly salinized, moderately salinized, and severely salinized. Severely salinized areas are primarily distributed in the oasis-desert ecotone and peripheral desert regions, while the central oasis remains relatively low in salinity [FIGURE:N].

4. Discussion and Conclusion

This study demonstrates that Sentinel-2 optical imagery possesses a significant advantage over Sentinel-1 radar imagery for soil salinization monitoring in arid regions. The feature space model effectively couples the synergistic relationship between soil salinity and vegetation response. While radar is sensitive to dielectric properties, it is more susceptible to interference from surface roughness and vegetation canopies in extreme drought conditions.

In conclusion: 1. The COSRI spectral index and its associated feature space model (CRSI-COSRI) provide the most accurate inversion of soil salinity. 2. The Weiku Oasis exhibits significant spatial differentiation, with salinization increasing from the interior toward the desert periphery. 3. The results provide a methodological framework for rapid remote sensing monitoring of saline soils, supporting sustainable land management in arid ecosystems.

References

[**?**, **?**, **?**, **?**, **?**, **?**, **?**, **?**, **?**]

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