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Remote Sensing Monitoring and Spatiotemporal Analysis of Soil Salinization in the Alar Reclamation Area (Postprint)

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Abstract

Timely and accurate monitoring of regional soil salinization information is of great significance for saline soil management and sustainable development of land use. Using Landsat 7 ETM+/8 OLI imagery of the Aral Reclamation Area as the data source, a remote sensing salinity monitoring index (Salinization detection index, SDI) model was developed employing the Salinity Index (SI) and Normalized Difference Vegetation Index (NDVI) to retrieve soil salinization in the Aral Reclamation Area and analyze the spatial distribution characteristics of soil salinization in the reclamation area over the past decade. The results indicate that the SDI model exhibits a coefficient of determination R^2=0.7579 with measured soil electrical conductivity, demonstrating its capability to retrieve soil salinity in the Aral Reclamation Area. From 2011 to 2021, the areas of non-salinized soil and lightly salinized soil increased by 318.22 km^2 and 0.80 km^2, respectively, while the areas of moderately and severely salinized soil decreased by 229.87 km^2, and the area of saline soil increased by 68.61 km^2. The degree of soil salinization in the northern and southern regions of the Aral Reclamation Area was significantly alleviated, whereas the degree of soil salinization in the central and eastern regions intensified, with the overall soil salinization in the reclamation area showing significant improvement. The SDI model can effectively retrieve the spatiotemporal characteristics of soil salinization in the Aral Reclamation Area and can provide a valuable reference for the economic and social development of the region.

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Full Text

Remote Sensing Monitoring and Temporal-Spatial Characteristics Analysis of Soil Salinization in Aral Reclamation Area

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Abstract

Timely and accurate acquisition of regional soil salinization information is of great significance for saline soil management and sustainable land use development. Using Landsat 7 ETM+ and Landsat 8 OLI imagery of the Aral Reclamation Area as data sources, this study constructed a remote sensing salinization detection index (SDI) model based on the salinity index (SI) and normalized difference vegetation index (NDVI) to invert soil salinization and analyze its spatial distribution characteristics from 2011 to 2021. The results show that the SDI model achieved a fitting degree of $R^2 = 0.7579$ with measured soil electrical conductivity, demonstrating its capability to invert soil salinity in the Aral Reclamation Area. From 2011 to 2021, the areas of non-salinized and lightly salinized soils increased by 318.22 km^2 and 0.80 km^2, respectively; moderately and severely salinized areas decreased by 229.87 km^2; and saline soil area increased by 68.61 km^2. The degree of soil salinization in the northern and southern parts of the Aral Reclamation Area improved significantly, while the central and eastern regions experienced intensified salinization. Overall, soil salinization in the reclamation area showed favorable improvement. The SDI model can effectively characterize the spatiotemporal patterns of soil salinization in the Aral Reclamation Area, providing valuable reference for regional economic and social development.

Keywords: soil salinization; saline soil; remote sensing salinization detection index (SDI); salinity index-normalized difference vegetation index (SI-NDVI); Aral Reclamation Area

1. Introduction

Soil salinization not only affects regional agricultural economic development but also poses serious threats to the ecological environment [1]. Utilizing scientific techniques to timely and accurately grasp soil salinization information and prevent secondary salinization holds practical scientific significance for regional development [2]. Soil salinization in China predominantly occurs in arid, semi-arid, and coastal regions, with hotspot areas mainly located in the Hetao Irrigation District [3], Yellow River Delta [4], Xinjiang Uygur Autonomous Region [5], and other locations. Current research typically employs soil spectral characteristics or indirect features (vegetation growth, soil elements, land cover types, etc.) for investigation [6]. The development of remote sensing technology from multispectral to hyperspectral and then to microwave remote sensing has remained a research focus among scholars worldwide. Remote sensing technology, with its advantages of rapidity, timeliness, accuracy, and efficiency, is widely applied in soil salinization research [7]. Among these, spectral indices in multispectral remote sensing are convenient and easy to obtain, becoming one of the research hotspots. Common indices include NDVI, modified soil-adjusted vegetation index (MSAVI), and salinity index (SI) [8].

Early international research focused on soil salt-sensitive bands. Dwivedi and Rao [9] proposed that blue, red, and mid-infrared bands synthesized images provided optimal information for salinized soils. After the 21st century, soil salinization research expanded beyond sensitive band studies, with constructing relevant parameters or models for qualitative and quantitative research becoming contemporary hotspots. Sidike et al. [10] applied normalized difference vegetation index (NDVI) and soil brightness index as parameters in soil salinity inversion models to improve accuracy. El Horiny [11] studied the relationship between electrical conductivity and spectral indices, demonstrating that salinity indicators correlated highly with electrical conductivity. Liu et al. [12] established two-dimensional feature spaces and constructed remote sensing salinization detection index (SDI) models, representing an advanced method for soil salinization monitoring. Wang et al. [13] built MSAVI-SI feature spaces and constructed modified salinization detection index (MSDI) models to invert salinity in the Hetao Irrigation District with high reliability. Wang et al. [14] confirmed that NDVI-SI feature space models could accurately invert surface soil salinity in the Yutian Oasis of southern Tarim. Constructing two-dimensional feature spaces offers tremendous potential for developing quantitative methods and indicators for salinization remote sensing monitoring [15].

The Aral Reclamation Area is a typical oasis farmland severely affected by soil salinization, with widespread distribution [16]. As an important grain and cotton production base in Xinjiang and a key deployment area for the Xinjiang Production and Construction Corps' southward development, the reclamation area holds a core strategic position. However, previous research has been limited to salinization studies in cotton fields or partial experimental plots, with few systematic investigations of the entire reclamation area' s spatiotemporal distribution. Therefore, to further understand the distribution of soil salinization and improve precise management and prevention, this study selected Landsat imagery to establish two-dimensional feature spaces and construct SDI models. The inversion results can serve as a reference for salinization management and hold practical significance for promoting economic and social development.

1.1 Study Area Overview

The Aral Reclamation Area is located in southern Xinjiang (40°22 ~40°57 N, 80°30 ~81°58 E), belonging to the alluvial fine soil plain of the Tarim River, with dry climate conditions and fragile ecological environment. Adjacent to the Tarim River, the terrain slopes from northwest to southeast. The reclamation area governs seven regiments (7th to 14th) and covers an area of 4197.58 km^2, with an elevation of 12-15 m. The region experiences strong surface evaporation, with an annual average temperature of 4-20°C, annual precipitation of 40.1-82.5 mm, and annual evaporation of 1876.6-2558.9 mm. The main crops are cotton, while fruit trees include jujube, walnut, and pear. Agricultural irrigation primarily combines winter-spring flood irrigation for salt leaching with drip irrigation under plastic film (Figure 1). The reclamation area contains three major reservoirs: Duolang, Shengli, and Shangyou.

1.2 Data Sources

Imagery data were obtained from the Geospatial Data Cloud (http://www.gscloud.cn), selecting Landsat 7 ETM+ and Landsat 8 OLI images with cloud cover less than 10% for the Aral Reclamation Area (path/row: 146/32). The imagery has a pixel resolution of 30 m × 30 m. The 2011 Landsat ETM+ imagery suffered from stripe loss, which was addressed using the landsat_{gapfill} plugin in ENVI 5.3 [17].

Field soil samples were collected from the 0-10 cm surface layer in October 2011 and 2021. A total of 139 sampling points were established, distributed randomly and uniformly from the 7th to 14th regiments to satisfy the principle of uniform distribution. Each sampling point followed the triangular sampling method, collecting three samples that were placed in aluminum boxes. After weighing in the field, samples were oven-dried at 105°C. The three samples from each point were uniformly mixed, ground, and sieved through a 2 mm mesh to remove plant roots and stones. A 5:1 water-to-soil extract was prepared by fully mixing and stirring, then standing and filtering. The filtrate' s electrical conductivity was measured using a Shanghai Keyou DDS-11A conductivity meter. Geographic coordinates were recorded at each sampling point.

1.3 Methods

1.3.1 Data Processing Original remote sensing imagery underwent geometric correction, radiometric calibration, atmospheric correction, and other preprocessing steps before being clipped to the study area extent.

1.3.2 Remote Sensing Spectral Indices Normalized Difference Vegetation Index (NDVI): Although vegetation cover alters soil spectral response, vegetation growth status is largely affected and controlled by salinity, making it an effective indirect indicator of soil salinization. NDVI is inversely proportional to soil salinization degree—higher salinity suppresses vegetation growth

[18]. NDVI is calculated using red and near-infrared bands:

NDVI = nir - nir + landsat ETM+/OLI

Salinity Index (SI): Calculated from blue and red bands, research shows these bands are sensitive to soil salinity [9]:

SI = blue × landsat ETM+/OLI

1.3.3 Masking Processing The Aral Reclamation Area borders the Taklamakan Desert and contains water bodies including the Duolang, Shengli, and Shangyou reservoirs and the Tarim River. To avoid interference from water bodies and sandy land in soil salinization information extraction, the Normalized Difference Moisture Index (NDMI) was used to mask and remove water bodies and unvegetated sandy land (Figure 2):

NDMI = nir - nir + landsat ETM+/OLI swir1 swir1 swir1

1.3.4 Normalization Processing Due to different dimensions among indices, normalization was applied to eliminate differences before model construction:

SI - SImin SImax - SImin

NDVI = NDVI - NDVImin NDVImax - NDVImin

where SImin and SImax are the minimum and maximum values of the salinity index, and NDVImin and NDVImax are the minimum and maximum values of the normalized difference vegetation index.

2. Results and Analysis

2.1 Remote Sensing Salinization Detection Index Model

Using May remote sensing imagery data from the Aral Reclamation Area, SI-NDVI two-dimensional scatter plots were established with SI as the x-axis and NDVI as the y-axis [19]. Fitting models for the two-dimensional scatter points were calculated (Table 1). All models achieved $R^2 > 0.7$, suitable for constructing SDI models to invert soil salinization information in the Aral Reclamation Area at a macro scale.

The SDI model calculation formula is:

SDI = SI +(NDVI - 1)

where SI is the normalized salinity index and NDVI is the normalized vegetation index.

2.2 Soil Salinization Spatial Distribution and Area Statistics

2.2.1 Model Accuracy Analysis Using electrical conductivity data from 139 field soil sample points, the SDI model was validated for accuracy (Figure 4). The fitting degree R^2 between measured soil electrical conductivity and the SDI model reached 0.7579, indicating good performance and demonstrating that the model can invert soil salinization information across large areas of the Aral Reclamation Area.

2.2.2 Spatial Distribution Characteristics Based on the soil salinization grade standard corresponding to electrical conductivity values from the U.S. Salinity Laboratory [36], soil salinization in the Aral Reclamation Area was classified into five categories using the SDI model (Table 2). The spatial distribution maps were generated (Figure 5) and area statistics calculated (Table 3).

In 2011, non-salinized soil in the Aral Reclamation Area covered 972.98 km^2 (29.37% of the study area), scattered in the northwest, northeast, and west. Light salinized soil was mainly distributed near the Tarim River channel and reservoirs in the south. Moderate and severe salinized soils were primarily located in the northeast and southeast regions.

By 2021, non-salinized soil area expanded significantly to 1291.20 km^2, distributed in the west, north, and east. Light salinized soil was mainly in the west and north. Moderate salinized soil occurred in central and northeast regions. Severe salinized soil was primarily in the northeast, with reduced distribution in the southeast. Saline soil distribution remained similar to 2011.

From 2011 to 2021, the areas of non-salinized and light salinized soils increased by 318.22 km^2 and 0.80 km^2 respectively, while moderate and severe salinized soils decreased by 229.87 km^2. Saline soil area increased by 68.61 km^2, mainly in the northeast.

2.2.3 Temporal Dynamic Change Analysis Using ArcGIS 10.3, soil salinization area transfer matrices (Table 4) and dynamic change maps (Figure 6) were generated for 2011-2021. Areas showing significant improvement were mainly distributed in the north and south, where non-salinized soil primarily converted from moderate and severe salinized soils (87.83 km^2 and 60.40 km^2 respectively). Light salinized soil mainly converted from non-salinized and severe salinized soils (183.29 km^2 and 155.89 km^2), scattered in the west and northeast.

Areas with deteriorating salinization were mainly in central and eastern regions, where severe salinized soil converted from moderate salinized soil and saline soil (105.19 km^2 and 70.42 km^2 respectively). Saline soil primarily converted from severe salinized soil (140.02 km^2 and 94.15 km^2).

According to field data, sample quantities followed the relationship: non-salinized > light > moderate > severe > saline soils, with non-salinized samples accounting for 32.70% of total samples. Combined with OvitalMap analysis, the 2021 spatial pattern showed that inverted non-salinized areas were mainly farmland, light and moderate salinized soils were scattered in farmland or near the Tarim River, while severe salinized soils and saline soils were mostly distributed near deserts, consistent with actual survey conditions and previous research [23,35].

3. Discussion

3.1 Model Selection

The SDI model achieved an inversion accuracy of $R^2 = 0.7579$ for soil salinization in the Aral Reclamation Area, consistent with Wang et al. [14] who used the same model in the southern Tarim Basin, indicating the model' s suitability for this region. Numerous SDI models exist, but their applicability to the Aral Reclamation Area requires further experimental verification. Different study areas have varying natural conditions and socioeconomic factors. The unique climate and geographical location of southern Xinjiang cause SDI models developed for inland regions to have different accuracies. Therefore, geographical location and other factors should be fully considered when selecting the most appropriate spectral indices to construct SDI models, yielding more scientific and reasonable salinization information.

3.2 Vegetation Index and Soil Salinity

Plant growth status is closely correlated with soil salinity. When soil salt content exceeds certain thresholds, it affects vegetation physiological parameters and changes corresponding spectral reflectance. Consequently, many scholars agree that vegetation indices can indirectly reflect soil salinization [13,15,24-25]. The NDVI values calculated in this study show strong similarity with soil salinization distribution patterns. Lower SDI-inverted salinization grades correspond to higher NDVI values, with an inverse relationship between vegetation and salinity —as soil salinity increases, NDVI values decrease [13,15,24-25]. While NDVI is the most commonly used index, the accuracy of other vegetation indices for soil salinity inversion in the reclamation area requires further verification. Additionally, vegetation in southern Xinjiang' s arid region mainly grows from April to October, requiring consideration of other spectral indices for salinity research during other periods.

3.3 Driving Factors of Soil Salinization Changes in Recent Decades

Soil salinization distribution is influenced by natural and anthropogenic factors [37]. The Aral Reclamation Area is located in an arid region of southern Xinjiang with low rainfall, long sunshine duration, strong light, and high evaporation. Farmland is dominated by non-salinized and light salinized soils, consistent with Wu [38] who studied cotton field salinization in the reclamation area.

Farmland employs flood irrigation for salt leaching in spring/winter and drip irrigation under plastic film during crop growth. With increasing cultivation years, salts are rapidly leached downward, significantly reducing surface soil salinity [39]. However, large agricultural water demand and relatively limited Tarim River water input cause strong evaporation in riverbeds and grasslands after irrigation, where soil moisture carries salts upward to accumulate at the surface [40], resulting in moderate and severe salinization. In desertified areas near the Taklamakan Desert, long-term water shortage and intense sunlight cause salts to concentrate as salt patches on the surface with almost no vegetation growth. Local areas in farmland also experience varying salinization degrees due to hydrogeological units, vegetation types, irrigation water quality, and drip tape quality.

To analyze driving factors, data were obtained from the Ministry of Agriculture's Facility Agriculture Research Institute Greenhouse Data Sharing Platform (http://data.sheshiyuanyi.com/) and the Xinjiang Production and Construction Corps Yearbook [41]. Analysis of average annual temperature, precipitation, and effective irrigation area shows temperature fluctuations of 1-2°C, precipitation variations of 20-100 mm, and irrigation area fluctuations of 0.5×10^{4} km^2. The overall trend shows rising temperature, decreasing precipitation, and increasing irrigation area. Combined with the area change trend of "increase, increase, decrease, decrease, increase" for non-salinized, light, moderate, severe, and saline soils, climate factors have minor impacts while anthropogenic factors, particularly irrigation area, are the main drivers of soil salinization changes.

4. Conclusions

1) Farmland in the Aral Reclamation Area is dominated by non-salinized and light salinized soils. The Tarim River channel, grasslands, and forest belts are mainly moderately and severely salinized, while desertified areas near the desert are primarily saline soils.

2) From 2011 to 2021, the area changes of non-salinized, light, moderate, severe, and saline soils in the Aral Reclamation Area followed the trend of "increase, increase, decrease, decrease, increase." Overall, soil salinization improved significantly over the past decade.

3) Areas with significant salinization improvement were mainly in the north and south, where non-salinized soil primarily converted from moderate and severe salinized soils. Central and eastern regions experienced intensified salinization, dominated by conversion between severe salinized soils and saline soils.

4) The SDI model based on Landsat ETM+/OLI data can effectively monitor soil salinization in the Aral Reclamation Area. However, due to the 30 m resolution, it can only invert large-scale patterns. Higher-resolution imagery should be considered for precise small-scale inversion.

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