Spatiotemporal variability of soil salinity and the driving factors of cultivated land in Xinjiang, China

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Abstract: Soil salinization poses a major challenge to agricultural production, food security, and sustainability in arid and semi-arid regions worldwide. Effectively addressing this issue requires a thorough understanding of the spatiotemporal variations in soil salinity and its driving factors. This study investigates soil salinity in Xinjiang, China, using geostatistical methods to analyze its spatial distribution in cultivated lands across the region and its southern and northern sub-regions in 2021. Additionally, it examines the spatiotemporal changes in soil salinity from 2011 to 2021 in Bachu County (southern Xinjiang) and Nileke County (northern Xinjiang), which serve as representative areas. The results showed that in 2021, soil salinity across Xinjiang ranged from 0.1 to 27.7 g/kg, with an average of 2.8 g/kg and a coefficient of variation of 130.4%, indicating significant variability. Soil salinity levels were higher in southern Xinjiang (3.8 g/kg) compared to northern Xinjiang (2.0 g/kg), showing a spatial trend of "increasing salinity from north to south." Key drivers of spatial variation included available potassium, mean annual precipitation, alkali-hydrolyzable nitrogen, elevation, and soil pH. Between 2011 and 2021, soil salinity in cultivated lands increased significantly by 2.0 g/kg in Bachu County, while it decreased by 4.2 g/kg in Nileke County, with these changes mainly influenced by climatic factors such as precipitation, evapotranspiration, and surface temperature. These findings provide critical insights and data support for monitoring and managing soil salinization in Xinjiang, offering valuable guidance for improving agricultural sustainability in the region.

Keywords: soil salinization, spatial-temporal variation, driving factors, Xinjiang
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1 Introduction

Soil salinization and alkalinization pose a substantial global challenge that significantly impedes the sustainable development of agriculture worldwide[1]. Currently, approximately 1 billion hm^2 of land globally are affected by soil salinization and alkalinization, distributed across more than 100 countries and regions, with soil salinization levels continuing to increase[2]. In China, the total area of saline-alkaline land is approximately 36 million hm^2, with saline-alkaline cultivated land encompassing around 9.21 million hm^2, representing 6.62% of the country's total cultivated land[3,4]. The pervasive occurrence of saline-alkaline land poses a considerable risk to soil quality, crop growth, and the long-term sustainability of agricultural practices[5]. Elevated salt concentrations in soil can lead to the deterioration of its physical structure, a reduction in microbial activity, the formation of soil compaction, decreased water retention, and diminished soil fertility. These factors have a detrimental impact on crop nutrient and water uptake, impeding normal physiological processes and stunting crop growth[6]. Therefore, considering the increasing demands arising from population growth and cultivated land expansion, monitoring and scientifically managing soil salinization and alkalinization is crucial

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for sustainable agricultural development.

The processes of soil salinization and alkalinization are the result of a complex interplay between natural and human-induced factors. The combined effects of natural factors, including parent material, climate, topography, irrigation, and cultivation, as well as human activities, contribute to the development of these soil conditions. As a result, the distribution of soil salinity exhibits distinct regional characteristics[6]. A substantial body of research has been undertaken to investigate the spatiotemporal variations and driving factors of soil salinity under varying environmental conditions. These studies have been conducted across a variety of geographical areas, including regions[7], watersheds[8-10], mountainous areas[11], plains[12], basins[13], and oases[14]. These studies encompass various geographical scales, including national[15], provincial[16], municipal[17], county[18], and cultivated land levels[7]. The findings indicate that soil salinity in cultivated land exhibits varying characteristics based on the research scale, the prevailing environmental conditions, and the temporal and spatial contexts under consideration. The impact of natural and human factors can vary significantly based on the specific conditions under which they occur. Even within the same region, the dynamics of soil salinity and its driving factors can vary over time[19]. Therefore, it is imperative to understand the spatiotemporal variations and driving factors of soil salinity in different regions to effectively manage saline-alkaline land, improve soil quality, and enhance crop yields.

Xinjiang (XJ), situated at the center of the Eurasian continent, is a crucial agricultural production base in western China and one of the principal regions where saline-alkaline cultivated land is concentrated. Over one-third of the region's total cultivated land is affected by salinization, rendering soil salinization a significant issue[20]. In light of a growing population and increasing demand for cultivated land, it is imperative to understand the spatial distribution patterns of soil salinity in XJ's cultivated land and identify the driving factors to enhance the prevention and control of soil salinization. Currently, most research on soil salinization in cultivated land predominantly focuses on field or small-scale studies, with a notable lack of large-scale analyses. This study addresses this gap by focusing on the entire XJ region, employing geostatistical methods, the Boruta algorithm, and geographical detectors to analyze the spatial distribution patterns and key driving factors of soil salinity in cultivated land. Additionally, it analyzes the spatiotemporal evolution of soil salinity in representative areas of southern Xinjiang (S-XJ) and northern Xinjiang (N-XJ). The objectives of this study were: 1) to elucidate the spatial distribution of soil salinity across XJ's cultivated land; 2) to analyze the spatiotemporal evolution of soil salinity in representative areas of S-XJ and N-XJ; 3) to identify the primary driving factors of spatiotemporal variation in soil salinity in XJ, providing support for enhancing cultivated land quality and preventing soil salinization.

2 Materials and methods

2.1 Study area

Xinjiang Uygur Autonomous Region is located in the western part of China and is a large region with complex geographical, climatic, and ecological characteristics. Situated inland, Xinjiang is surrounded by mountains, deserts, and grasslands, covering a total area of approximately 1.66 million km^2, which accounts for about one-sixth of China's total area, making it the largest provincial-level administrative region in China. Its geographical coordinates are 73°33′-96°23′E and 34°25′-49°10′N (Figure 1). Xinjiang's natural geography is diverse, with the Altai Mountains in the north, the Tianshan Mountains in the center, and the Kunlun Mountains in the south. The north is home to the Junggar Basin, while the south features the Tarim Basin, forming a unique "three mountains and two basins" terrain. Xinjiang has a typical continental climate, with significant climatic differences across regions. The average annual temperature in southern Xinjiang is around 14°C[21,22], with annual precipitation usually below 100 mm, and annual evapotranspiration reaching over 2000 mm. In northern Xinjiang, the average annual temperature is about 5°C, with annual precipitation around 250 mm and evapotranspiration around 1200 mm, resulting in a relatively humid climate[23]. Due to the scarcity of rainfall and uneven distribution of water resources, Xinjiang faces serious soil salinization problems[24]. The area of salinized soil is extensive, impacting agricultural production. The ecological environment of Xinjiang is facing significant challenges due to both natural conditions and human activities, especially issues related to water resource shortages and land degradation, which have become key concerns for the region's sustainable development.

Bachu County (77°22′E-79°56′E, 38°47′N-40°17′N), located in the southwestern part of Xinjiang and governed by Kashgar Prefecture, lies at the intersection of the southern Tianshan Mountains and the northwestern edge of the Tarim Basin. The county is bordered by mountain ranges to the south, west, and north, while the Taklamakan Desert lies to the east. The region experiences a temperate continental arid climate, with dry conditions, low rainfall, and high evaporation rates. The multi-year average annual temperature is approximately 11.0°C-12.5°C, and most precipitation occurs during the summer months, averaging around 60 mm per year. Evaporation is significantly higher than rainfall, reaching 40 to 50 times the amount of precipitation, which is a key factor contributing to the severe soil salinization in Bachu County.

Nileke County (81°85′E-84°58′E, 43°25′N-44°17′N) is located in the western part of Xinjiang, within the western section of the Tianshan Mountains and the northeastern area of the Ili region, near the upper reaches of the Ili River. The county has an elongated shape stretching from east to west, with an average elevation of around 1750 m. Nileke County experiences a continental temperate climate, with abundant sunlight, and its annual sunshine duration can exceed 4000 h. The frost-free period lasts approximately 100 days each year, and the average annual temperature is about 6.0°C. The area receives substantial precipitation, averaging around 500 mm annually, making it one of the most humid regions in the Ili River Valley.

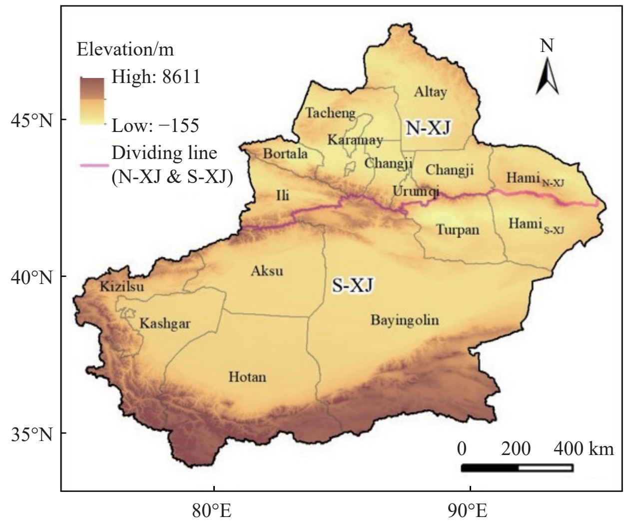


Figure 1 Geographic location and topographic map of Xinjiang

2.2 Data sources

Soil salt content data for cultivated land in XJ in 2021, encompassing 7936 sampling points (Figure 2), as well as soil property data (including soil type and nutrient content), and soil salt content data for cultivated land in Bachu County in 2011 (67 sampling points) and 2021 (93 sampling points), and Nileke County in 2011 (105 sampling points) and 2021 (76 sampling points), were sourced from the XJ Soil Fertilizer Station. Soil salinity was quantified by the conductivity method, alkali-hydrolyzable nitrogen (AN) content was determined through the alkali dissolution diffusion method, available potassium (AK) content was assessed using the atomic absorption spectrophotometer method, and available phosphorus (AP) content was measured using the sodium bicarbonate method. Fertilizer application data were obtained from the Xinjiang Uygur Autonomous Region Bureau of Statistics (https://tjj.xinjiang.gov.cn/tjj/index.shtml). The DEM used in this study was obtained from the Shuttle Radar Topography Mission (SRTM) data provided by NASA (https://earthdata.nasa.gov/). Land use data were sourced from CLCD (https://zenodo.org/record/5210928#.YcZ_nWBByUk), a 30-meter resolution dataset for China covering 1990-2022, developed by Professors Jie Yang and Xin Huang[25] from Wuhan University. Fractional vegetation cover (FVC) data for 2021 were provided by the National Tibetan Plateau Data Center (TPDC) at a resolution of 250 m (https://data.tpdc.ac.cn/). Mean annual rainfall (MAP) data for 2021 were from the CHIRPS dataset, mean annual surface temperature (MAST) data were from the ERA5 dataset, and mean annual evapotranspiration (MAE) data were derived from MODIS. All meteorological data were accessed via the Google Earth Engine platform (https://code.earthengine.google.com/). All datasets were uniformly resampled to 30 m×30 m for subsequent processing and application.

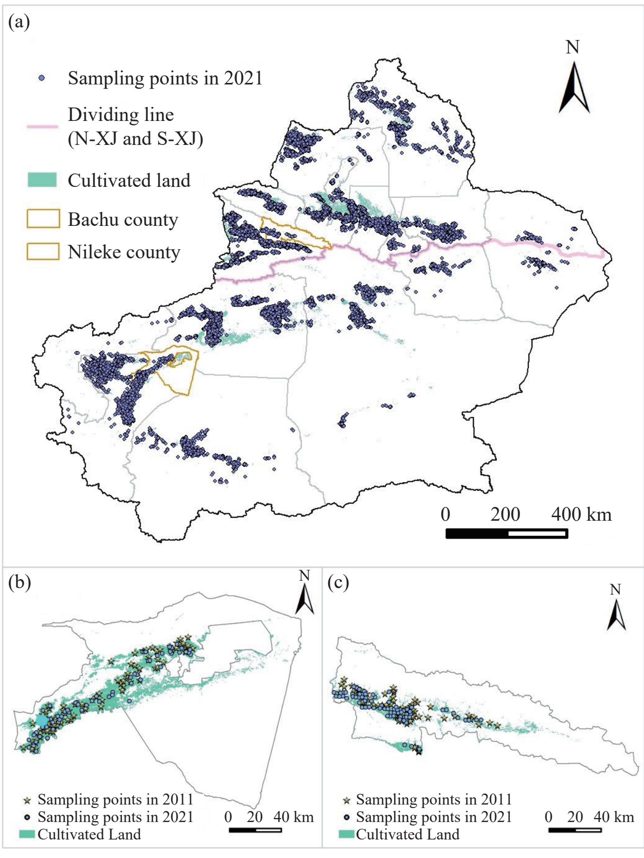


Figure 2 Distribution of sampling points in Xinjiang (2021, a) and point distribution in Bachu County (2011 and 2021, b) and Nileke County (2011 and 2021, c)

2.3 Data analysis

Normality tests, basic statistical procedures, analysis of variance (ANOVA), and *t*-tests for soil salinity data were carried out with the help of Excel 2021 (Microsoft, United States) and SPSS 26.0 software (IBM Corp, United States). A logarithmic transformation was performed on the soil salinity data to approximate a normal distribution. The best semivariogram model for XJ cultivated land soil salinity was fitted using GS+ 9.0 software (Gamma Design Software, United States). Spatial interpolation analysis and mapping of soil salinity were carried out using the inverse distance weighting interpolation method in the geostatistical analysis module of ArcGIS 10.8 software (Esri Inc, United States). Feature importance evaluation was conducted using R 4.3.3 software (R Core Team, Austria) with the Boruta package, and geographical detector analysis was performed using R 4.3.3 software with the GD package.

2.4 Methods

2.4.1 Semivariogram

In geostatistics, the semivariogram is a key concept used to analyze spatial variability. This study employs the semivariogram, based on the theory of regionalized variables, with the variogram as the main analytical method. This study's focus is on the spatial variation of soil salinity in cultivated lands, which exhibits notable spatial correlation and dependency. This study also investigates the mechanisms that drive these spatial variations. The semivariogram formula is expressed as follows[26]:

$$\gamma(h)=\frac{1}{2N(h)}\sum_{i=1}^{N(h)}[Z(x_i)-Z(x_i+h)] \quad (1)$$

where, $\gamma(h)$ represents the semivariogram value for all points separated by a spatial distance h; h denotes the spatial step size or interval distance between sample points; and $N(h)$ is the logarithm of the number of points at distance h. $Z(x_i)$ and $Z(x_i+h)$ represent the values of the variable Z at spatial locations x_i and (x_i+h), respectively[27].

2.4.2 Independent samples *t*-test

The independent samples *t*-test is a statistical technique used to assess whether there is a significant difference between the means of two separate samples, and by extension, between the populations they represent. The formula is as follows:

$$t=\frac{\omega_1-\omega_2}{\sqrt{\frac{(n_1-1)S_1^2+(n_2-1)S_2^2}{n_1+n_2-2}\left(\frac{1}{n_1}+\frac{1}{n_2}\right)}} \quad (2)$$

where, ω_1 and ω_2 represent the means of the two samples; S_1^2 and S_2^2 denote the variances of the two samples; n_1 and n_2 are the sample sizes of the two groups[28].

2.4.3 Geographical detector

The geographical detector is a tool for exploring spatial differentiation, measuring spatial heterogeneity, detecting explanatory factors, and analyzing interactions between variables. The factor contribution rate to the spatio-temporal variation of soil salinization is measured by the *q*-value; a higher *q*-value indicates a greater influence of the factor[29]. The formula is as follows:

$$q=1-\frac{\sum_{h=1}^{L}N_h\sigma_h^2}{N\sigma^2} \quad (3)$$

where, q is the indicator for measuring the spatial and temporal distribution of carbon storage changes, with a range of 0 to 1; L is the total number of zones; N_h and N represent the sample sizes for zone *h* and the entire region, respectively; and σ^2 denote the sample variances for zone *h* and the entire region, respectively[30].

2.4.4 Feature importance evaluation

The Boruta algorithm is a feature selection method based on the Random Forest model. It generates a set of "shadow features" by randomly permuting the values of the original input variables, creating features that have no relationship with the target variable. It then assesses the relative importance of the original features in comparison to the shadow features. In the event that the importance of a variable is less than the maximum score assigned to a shadow feature, it is classified as unimportant and discarded; otherwise, it is retained[31] The algorithm is capable of identifying crucial variables associated with the target variable from a multitude of feature variables, subsequently providing a ranking of feature importance. This approach is well-suited to the assessment of the importance of soil salinity features[32].

In this study, four aspects were selected for analysis based on previous research and the availability of data: geographical factors, natural factors, soil properties, and crop factors. The variables considered include elevation, slope, mean annual precipitation (MAP), mean annual evapotranspiration (MAE), mean annual surface temperature (MAST), available potassium (AK), alkali-hydrolyzable nitrogen (AN), available phosphorus (AP), soil organic matter (SOM) content, soil pH, soil type, and fractional vegetation cover (FVC), as detailed in Table 1.

2.4.5 Soil salinization classification

In this study, saline cultivated land was classified into five classes: non-salinization, mild salinization, moderate salinization, severe salinization, and saline soil according to the criteria in Table 2[33].

Table 1 Main driving factors of soil salinization in cultivated land of Xinjiang

Factor	Indicator	Explanation
Geographical factors	Elevation	The elevation corresponding to a specific point, m.
	Slope	The degree of steepness of the surface unit, °.
Natural factors	MAP	The average precipitation in the study area for the year 2021, mm.
	MAE	The average evapotranspiration in the study area for the year 2021, mm.
	MAST	The average surface temperature in the study area for the year 2021, °C.
Soil properties	AK	Potassium available for plant uptake in the soil, mg·kg^{-1}.
	AN	Nitrogen available for plant uptake in the soil, mg·kg^{-1}.
	AP	Phosphorus available for plant uptake in the soil, mg·kg^{-1}.
	SOM	All forms of carbon-containing organic matter present in the soil, g·kg^{-1}.
	pH	A general term for soil acidity and alkalinity. Often used to measure the strength of the soil's acid-base reaction.
	Soil type	Different categories of soil based on their formation, properties, and distribution.
Crop factors	FVC	The percentage of the ground area covered by the vertical projection of vegetation (including leaves, stems, and branches), %.

Table 2 Soil salinization classification standards

Salinization	Non-salinization	Mild salinization	Moderate salinization	Severe salinization	Saline soil
Soil salinity/g·kg^{-1}	<2.5	2.5-6	6-12	12-20	≥20

2.4.6 Technical roadmap

The technical roadmap of this study is shown in Figure 3.

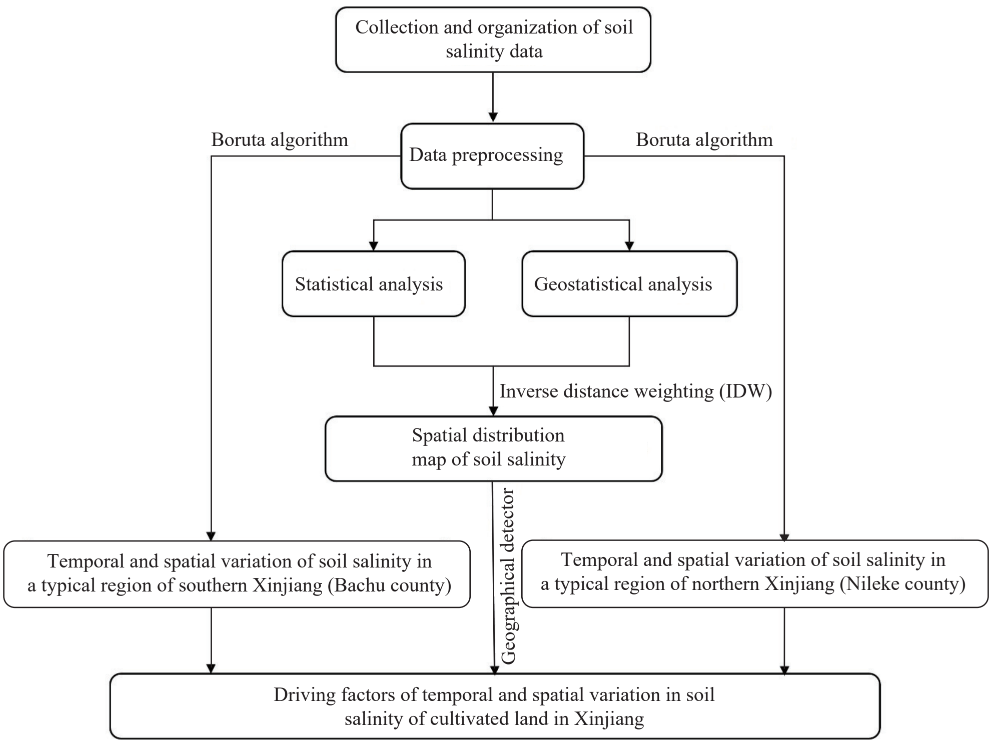


Figure 3 Schematic diagram of the technical roadmap

3 Results

3.1 Descriptive statistics of soil salinity in cultivated land

As listed in Table 3, in 2021, soil salinity in cultivated land in XJ ranged from 0.1 to 27.7 g/kg, with a mean value of 2.8 g/kg. In N-XJ, soil salinity ranged from 0.1 to 27.2 g/kg, with a mean value of 2.0 g/kg, whereas in S-XJ, soil salinity ranged from 0.2 to 27.7 g/kg, with a mean value of 3.8 g/kg, which is significantly higher than that of N-XJ (p<0.05). Overall, the spatial distribution pattern of soil salinity in cultivated land in XJ exhibits "increasing salinity from north to south."

The soil salinity of cultivated land in various cities and prefectures across XJ exhibits considerable variation. In the Bayingolin Mongol Autonomous Prefecture (Bayingolin), the average soil salinity is 4.71 g/kg, representing the highest levels observed across the region. In contrast, the soil salinity in Hotan Prefecture is notably lower, with an average of 1.4 g/kg. Among N-XJ's regions, the soil salinity of cultivated land in Bortala Mongol Autonomous Prefecture (Bortala) is markedly higher than that of other regions (p<0.05). With the exception of Bortala, the soil salinity in cultivated land of other northern regions is less than 4.0 g/kg. In S-XJ, the soil salinity in Hotan Prefecture is significantly lower than that of other regions (p<0.05). With the exception of Hotan, the soil salinity in cultivated land in other southern regions is greater than 2.0 g/kg.

Table 3 Descriptive statistics of soil salinity in cultivated land across different regions of Xinjiang

Region	City	Samples	Min/g·kg^{-1}	Max/g·kg^{-1}	Mean±Std*/g·kg^{-1}	CV/%
N-XJ	Altay	635	0.1	22.5	2.2±2.8^{gh}	128.0
	Bortala	294	0.6	22.3	4.0±4.8^{abc}	117.9
	Changji	1032	0.1	7.8	1.5±1.2^{h}	77.8
	Urumqi	124	0.7	25.2	2.7±3.2^{fg}	117.0
	Karamay	70	0.5	21.1	3.5±4.0^{def}	115.1
	Ili	1041	0.2	16.4	1.4±1.7^{h}	119.8
	Tacheng	1244	0.1	27.2	2.2±3.0^{gh}	138.8
	Hami $_{N\text{-}XJ}$	67	0.9	16.3	3.2±4.1^{def}	126.2
	Total $_{N\text{-}XJ}$	4506	0.1	27.2	2.0±2.7^{gh}	134.3
S-XJ	Aksu	1124	0.4	27.7	3.6±4.5^{cde}	123.6
	Turpan	135	0.4	26.6	2.7±4.1^{fg}	151.4
	Bayingolin	572	0.4	25.3	4.7±3.8^{a}	81.4
	Hotan	344	0.5	20.0	1.4±1.3^{h}	97.1
	Kashgar	1071	0.2	27.5	4.5±4.8^{ab}	106.9
	Kizilsu	97	0.6	15.1	3.3±3.7^{def}	112.5
	Hami $_{S\text{-}XJ}$	86	1.0	23.2	4.5±5.0^{abc}	111.0
	Total $_{S\text{-}XJ}$	3430	0.2	27.7	3.8±4.4^{bcd}	115.0
XJ	Total	7936	0.1	27.7	2.8±3.6^{efg}	130.4

Note: *: Different letters for data in the same column indicate significant differences (p<0.05), and the same letter indicates non-significant differences (p>0.05).

The coefficient of variation (CV) is a statistical measure that indicates the extent of data dispersion[34]. In this study, the CV of soil salinity in cultivated land in XJ was found to be 130.4%, indicating strong spatial variability according to Nielsen's classification criteria[35]. The CV in N-XJ was 134.3%, slightly higher than that in S-XJ at 115.0%. This suggests that soil salinity in N-XJ exhibits greater spatial variability than in S-XJ.

3.2 Spatial distribution patterns of soil salinity in cultivated land

3.2.1 Semivariogram analysis of soil salinity in cultivated land

GS+ 9.0 software was employed to determine the optimal semivariogram models for the soil salinity data of Xinjiang (XJ) and its subregions, N-XJ and S-XJ, for the year 2021 (Table 4). As shown in Table 4, the exponential model was identified as the optimal semivariogram model across all three spatial scales, with residual sums of squares approaching zero and R^2 values exceeding 0.75, indicating a strong goodness of fit[36].

Table 4 Optimal semivariogram models for soil salinity in cultivated land of Xinjiang

Region	Optimal model	Nugget variance (C_0)	Sill (C_0+C)	Structural variance [C_0/(C_0+C)]/%	Range (A_0)/ km	R^2	RSS
XJ	Exponential	0.3	0.7	43.6	47.0	0.86	5.99×10^{-3}
N-XJ	Exponential	0.3	0.6	49.9	22.1	0.80	2.80×10^{-3}
S-XJ	Exponential	0.3	0.8	32.4	39.8	0.79	1.46×10^{-2}

3.2.2 Spatial distribution of soil salinity in cultivated land

Kriging interpolation is one of the most commonly used spatial interpolation techniques. However, it often results in a smoothing effect[37]. To accurately and intuitively represent the spatial distribution of soil salinity in cultivated land across XJ, this study utilized the widely accepted inverse distance weighting (IDW) interpolation method for the 2021 soil salinity data. Subsequently, the data were classified into five categories (Table 2): non-salinization, mild salinization, moderate salinization, severe salinization, and saline soil (Figure 4).

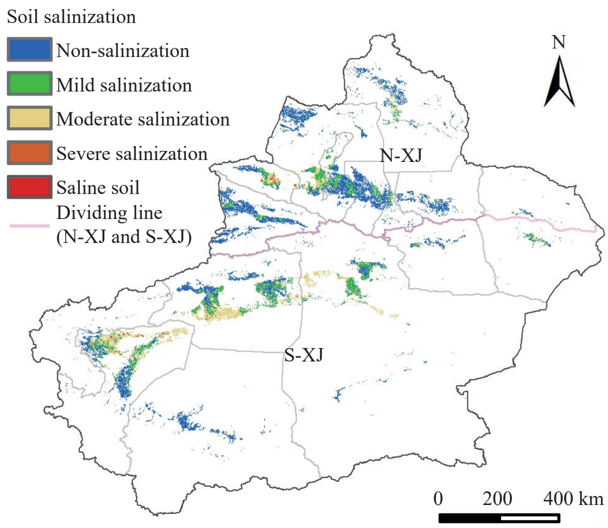


Figure 4 Spatial distribution pattern of soil salinity in cultivated land in Xinjiang

Analysis indicates that most cultivated land in XJ is classified as non-salinized or slightly salinized. Overall, soil salinity in cultivated land in S-XJ is higher than in N-XJ, demonstrating a spatial distribution pattern of "increasing salinity from north to south." This pattern may be attributed to the region's distinct climate, geographical characteristics, and agricultural management practices. Soil salinity in cultivated land in N-XJ is generally lower, with higher salinity areas sporadically occurring in the eastern portion of Bortala, the southern region of Tacheng, and a few locations in Altay, Turpan, and Hami $_{N\text{-}XJ}$. In S-XJ, soil salinity shows a spatial distribution pattern of "higher in the northwest, lower in the southeast." Areas with higher soil salinity are concentrated in regions adjacent to Kashgar and Aksu, as well as those bordering Bayingolin and Aksu. In contrast, other regions generally display lower soil salinity.

To gain a clearer understanding of the extent of soil salinization in cultivated land across XJ, this study subjected the proportions of different salinization levels in XJ, N-XJ, and S-XJ to statistical analysis (Figure 5). The analysis reveals that soil salinization poses a significant challenge in XJ, with approximately 46.45% of cultivated land showing signs of salinization. Among these, the most prevalent form of salinization is mild, accounting for 26.68% of the total, followed by moderate salinization at 17.95%. The proportions of land affected by severe salinization and saline soil are relatively small, at 1.78% and 0.03%, respectively. A notable discrepancy exists in the extent of land affected by varying degrees of salinization between N-XJ and S-XJ. In N-XJ, the proportion of

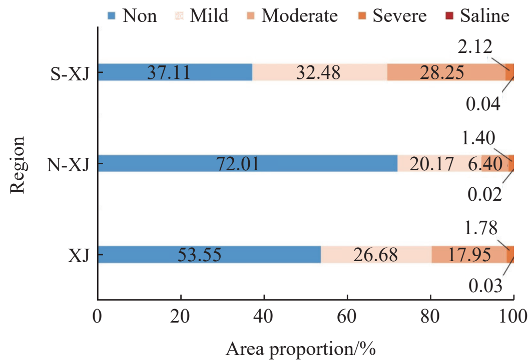


Figure 5 Statistics on the area share of cultivated land with different degrees of salinization in Xinjiang

non-salinized land is highest at 72.01%. The proportion of land with moderate or higher salinization is relatively low, comprising only 7.46% of the total cultivated area. In contrast, non-salinized land in S-XJ constitutes only 37.11% of the cultivated area, with similar proportions of mild (32.48%) and moderate (28.25%) salinization. The prevalence of severe salinization and saline soil in S-XJ is 2.12% and 0.04%, respectively, comparable to the figures observed in N-XJ. In summary, soil salinization poses a significant challenge in XJ. S-XJ faces more pronounced salinization issues compared to N-XJ. The primary distinction is in the distribution of mildly and moderately salinized land, with minor discrepancies observed in the prevalence of severe salinization and saline soil.

3.2.3 Main driving factors of spatial distribution of soil salinity in cultivated land

To investigate the driving factors of soil salinity in cultivated land across XJ, this study references previous research findings and considers the ease of data acquisition. A total of 12 indicators were selected across four aspects: geographical factors, natural factors, soil properties, and crop factors (Table 1). The Boruta algorithm is employed to assess the importance of all features related to the target variable in the dataset, enabling the selection of significant features while removing redundant ones, thus effectively evaluating variable importance[38]. Based on the selected 12 indicators, the Boruta algorithm was used to calculate and rank the Z-scores of potential driving factors affecting soil salinity in the cultivated lands of XJ, N-XJ, and S-XJ. For clarity, the calculated Z-scores were converted into relative importance, as illustrated in Figure 6.

The analysis reveals that the primary driving factor for soil salinity in cultivated lands across XJ is AK, with a relative importance of 16.2%. This is followed by MAP, AN, elevation, and pH, each exhibiting a relative importance exceeding 10%. The influence of AP, FVC, and Slope on soil salinity in XJ is limited, with Slope having the least impact, showing a relative importance of only 1.5%.

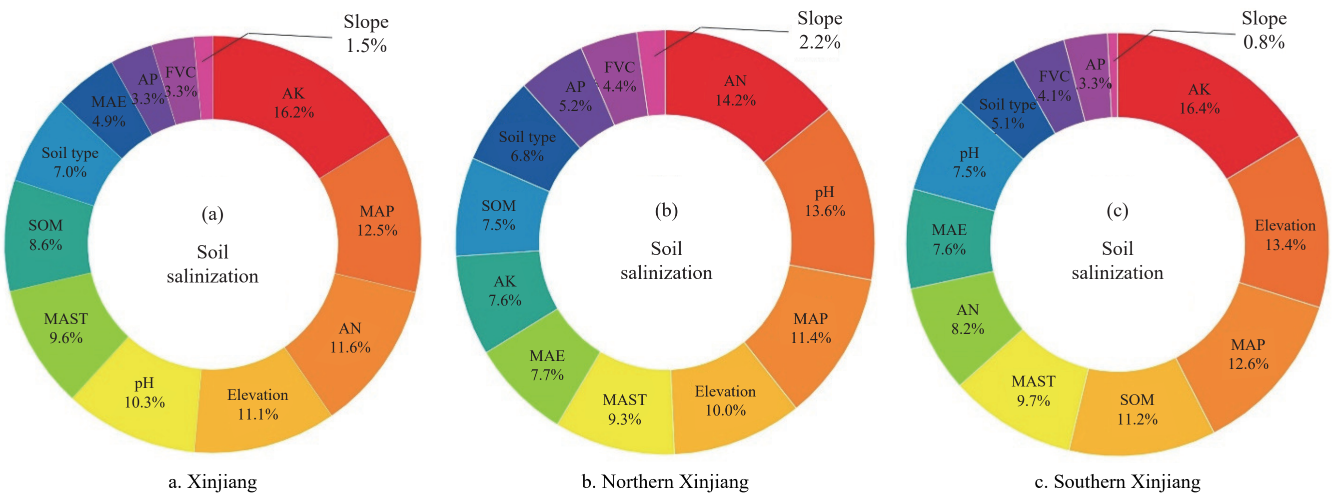


Figure 6 Driving factors of soil salinity in cultivated land

In the various regions of XJ, the principal factors influencing soil salinity in cultivated lands of N-XJ, in descending order of importance, are: AN>pH>MAP>Elevation>MAST>MAE>AK>SOM>Soil type>AP>FVC>Slope. In contrast, the ranking of the driving factors in S-XJ is as follows: AK>Elevation>MAP>SOM>MAST>AN>MAE>pH>Soil type>FVC>AP>Slope.

Notable discrepancies exist in the primary driving factors between N-XJ and S-XJ. In N-XJ, the main factors are AN and pH, with relative importances of 14.2% and 13.6%, respectively. In contrast, in S-XJ, their relative importances are only 8.2% and 7.5%, ranking sixth and eighth, respectively. Conversely, AK, the most significant factor in S-XJ, is ranked only seventh in N-XJ. However, in both regions, Slope has the least significant impact on soil salinity in cultivated lands.

3.3 Spatiotemporal variation characteristics and driving factors of soil salinity in cultivated land in typical areas

3.3.1 Spatial and temporal variability of soil salinity

To investigate the differences in spatiotemporal evolution of soil salinity between S-XJ and N-XJ, regions with significant variations in climate, terrain, and other factors, Nileke County in Ili Kazakh Autonomous Prefecture (Ili, N-XJ) and Bachu County in Kashgar (S-XJ) were selected as representative areas. Statistical methods and IDW interpolation were used to analyze spatiotemporal variation. Descriptive statistics for soil salinity in these regions during different periods are listed in Table 5. In 2011, the average soil salinity in Nileke and Bachu was 5.20 g/kg and 4.90 g/kg, respectively, indicating severe salinization in both areas. An independent samples *t*-test yielded a significance level of 0.712, showing no significant difference in soil salinity between the counties at that time. By 2021, the average soil salinity in Nileke had decreased to 1.03 g/kg, while Bachu's average increased to 6.89 g/kg. The 2021 *t*-test revealed a significant difference in soil salinity between the two counties (p<0.01).

To investigate the spatiotemporal evolution of soil salinity in cultivated land in typical areas of S-XJ and N-XJ, IDW interpolation was employed to analyze soil salinity in Nileke

County and Bachu County for two distinct periods (Figure 7). The analysis indicates that, in 2011, soil salinization in Nileke County was predominantly mild, with non-salinized cultivated land primarily concentrated in the southwestern part. Moderate to high levels of salinization were predominantly observed in the western regions, with isolated instances also noted in the central area. In Bachu County, the predominant soil salinization level was moderate, with virtually no non-salinized land. The areas of moderate salinization were primarily concentrated in the southwestern corner of Bachu County, exhibiting a contiguous distribution pattern. In 2021, soil salinity in cultivated land in Nileke County remained generally low, exerting minimal impact on agricultural productivity. In contrast, soil salinization in Bachu County predominantly remained mild; however, the degree of salinization in the majority of the northeastern region exhibited a notable shift towards moderate or even severe levels, indicating a tendency for contiguous distribution. The southwestern region of the county continues to demonstrate elevated levels of soil salinity, with a discernible tendency to expand towards the northeastern area. Over the past decade, soil salinity in the majority of cultivated land in Nileke County has exhibited a downward trend, with changes ranging from –4.5 to 0 g/kg. In the western region of the county, some areas have even experienced a decrease in soil salinity of more than 8.5 g/kg. The occurrence of cultivated land experiencing an increase in salinity is virtually non-existent. In Bachu County, the majority of the central and southwestern regions exhibited a decline in soil salinity, although isolated instances of increases were observed. In contrast, the northeastern region of Bachu County has exhibited a notable increase in soil salinity, with numerous areas displaying salinity levels exceeding 6.5 g/kg.

Table 5 Descriptive statistics of soil salinity in cultivated land in Nileke County and Bachu County at different periods

County	2011			2021			Change in soil salinity content/ $g\cdot kg^{-1}$	q-value of t-test
	Samples	Mean±Std/ $g\cdot kg^{-1}$	CV/ %	Samples	Mean±Std/ $g\cdot kg^{-1}$	CV/ %		
Nileke	105	5.2±7.9	152.70	76	1.0±1.2	114.63	–4.2	0.000**
Bachu	67	4.9±2.1	43.45	93	6.9±5.3	77.17	2.0	0.001**
q-value of t-test	-	0.712	-	-	0.000**	-	-	-

Note: ** Correlation is significant at the 0.01 level (2-tailed).

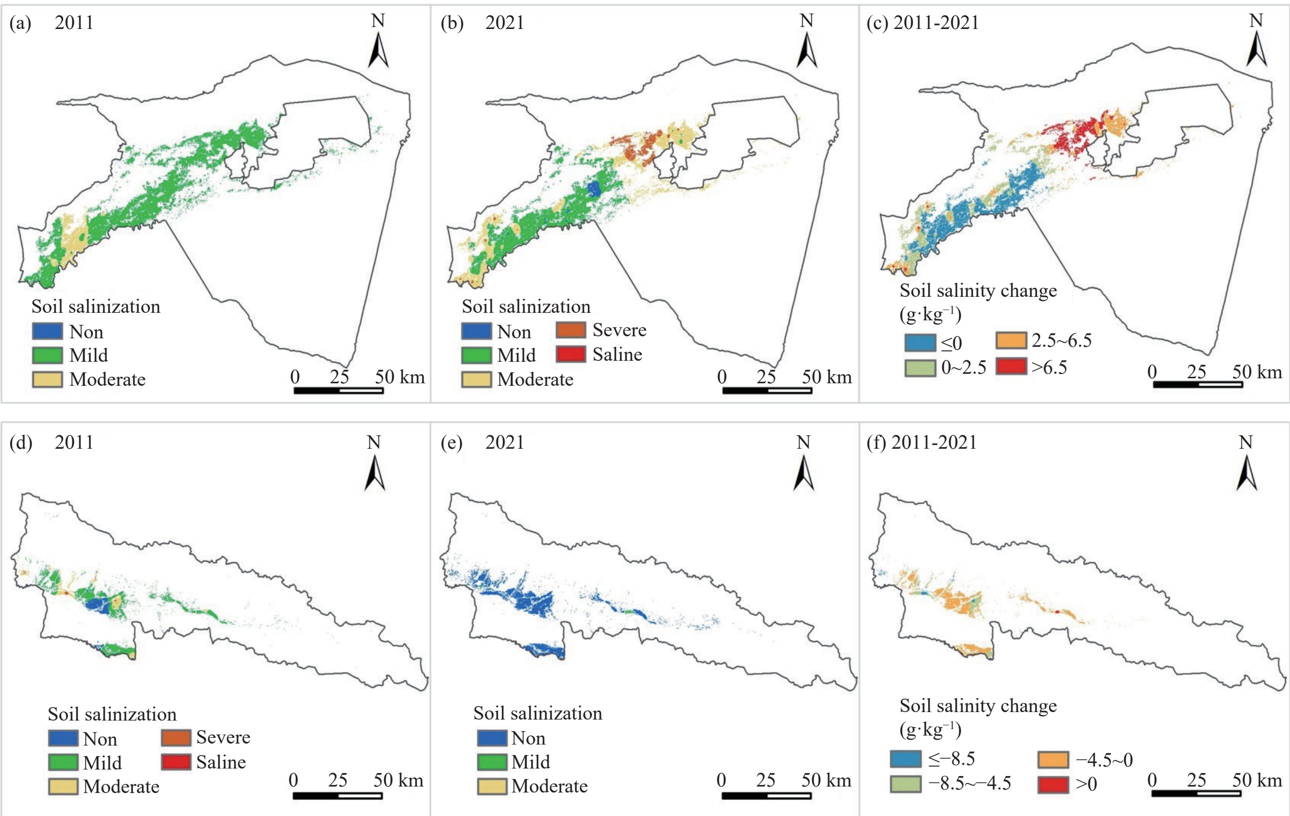
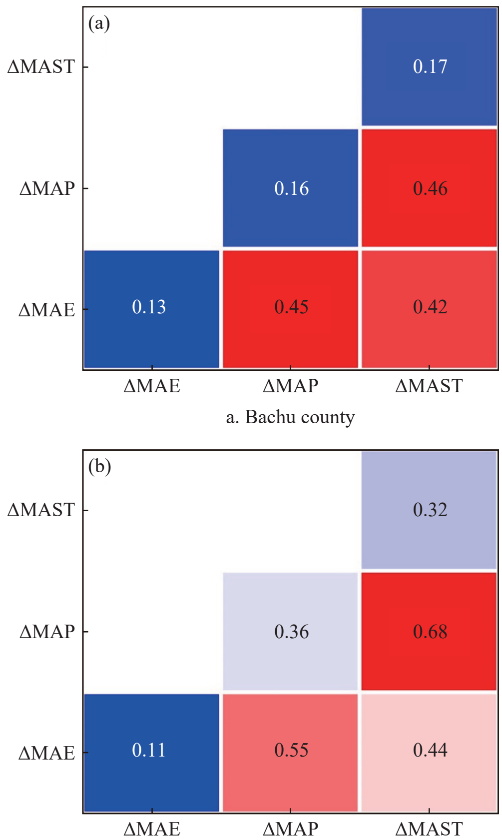


Figure 7 Spatiotemporal variation of soil salinity content in cultivated land in Bachu County and Nileke County from 2011 to 2021

3.3.2 Driving factors of soil salinity changes

To explore the primary factors affecting the temporal and spatial changes in soil salinity of cultivated land in Nileke County and Bachu County, this study selected three influencing factors: the changes in mean annual precipitation (ΔMAP), mean annual evapotranspiration (ΔMAE), and mean annual surface temperature (ΔMAST) from 2011 to 2021. Using the geographic detector method, the explanatory power (q-value) of each factor on soil salinity variation in Nileke and Bachu Counties between 2011 and 2021, as well as their interactions, were analyzed (Figure 8). A larger q-value indicates a stronger explanatory power of the factor regarding spatial and temporal changes in soil salinity. The results indicate that climatic factors significantly impact soil salinity changes. In Nileke County, the q-values of the factors, in descending order, were ΔMAP (0.36), ΔMAST (0.32), and ΔMAE (0.11), with ΔMAP serving as the dominant factor influencing the spatial-temporal variation of soil salinity. In Bachu County, the q-values were ΔMAST (0.17), ΔMAP (0.16), and ΔMAE (0.13), with ΔMAST serving as the primary factor influencing changes in soil salinity. The lower q-values for the three climatic factors in Bachu County, compared to those in Nileke County, suggest that the temporal and spatial changes in soil salinity in Bachu County are influenced more by other factors.

The results of interaction detection indicated that, for Bachu and Nileke Counties, any combination of two influencing factors enhanced the effects on soil salinity changes, suggesting that the interaction of factors better explains the spatial and temporal changes in soil salinity in cultivated land than a single factor. In terms of q-values, the interaction q-values of the factors in Nileke County were as follows: ΔMAP∩ΔMAST (0.68)>ΔMAP∩ΔMAE (0.55)>ΔMAE∩ΔMAST (0.44). In contrast, the interaction q-values of the factors in Bachu County were: ΔMAP∩ΔMAST (0.46)> ΔMAP∩ΔMAE (0.45)>ΔMAE∩ΔMAST (0.42). This indicates that rainfall and surface temperature among the climatic factors are more significant for soil salinization in both S-XJ and N-XJ. Additionally, the q-values of the interactions among factors in Bachu County are lower than those in Nileke County, further demonstrating that the influencing factors of soil salinization are more diversified in S-XJ. In conclusion, when managing soil salinization, changes in climatic factors must be fully considered to optimize management strategies and establish a scientific mechanism for controlling soil salinization.



a. Bachu county

b. Nileke county

Figure 8 Univariate and interaction analysis of factors influencing temporal changes in soil salinity in cultivated land

4 Discussion

4.1 Analysis of temporal and spatial variability of soil salinity

Soil salinization can lead to soil compaction and a decline in fertility, severely limiting crop growth and often resulting in yield reduction or even crop failure. A comprehensive analysis of the spatial distribution patterns and influencing factors of soil salinity facilitates the monitoring of the current status and future trends of soil salinization, thereby enabling the development of localized and scientifically sound prevention and control measures. The findings of this study indicate that, in 2021, the soil salinity level in cultivated land across XJ was relatively high, averaging 2.8 g/kg. Soil salinity in cultivated land in S-XJ (3.8 g/kg) was significantly higher than that in N-XJ (2.0 g/kg), exhibiting a distinct "increasing salinity from north to south" spatial distribution pattern, consistent with previous research findings[39]. This phenomenon is likely attributable to the Tianshan Mountains, which act as a barrier across central XJ, impeding the southward movement of warm, moist air masses and resulting in notable climatic disparities between N-XJ and S-XJ[40]. The relatively humid climate of N-XJ, characterized by higher precipitation levels, facilitates the leaching of salts from the surface soil and their subsequent movement into deeper layers. This process effectively limits the increase in soil salinity in this region[23]. In contrast, S-XJ experiences a dry climate with scarce rainfall and high evaporation, resulting in the transport of soil salts to the surface through capillary action, thereby exacerbating soil salinization[6,41]. Furthermore, human activities, such as irrigation and fertilization, exert a significant influence on the spatial distribution of soil salinity in cultivated lands.

In XJ, areas with relatively high soil salinity are primarily concentrated in the cultivated lands of Kashgar, Aksu, and parts of Bayingolin in S-XJ. In N-XJ, elevated soil salinity is observed solely in the eastern region of Bortala, aligning with the findings of Zhuang et al.[39]. This pattern may be influenced by several factors, including climate, topography, fertilization, and irrigation practices. The cities of Kashgar, Aksu, and Bayingolin are located in S-XJ, a region characterized by arid conditions. As indicated by the study conducted by Yan et al.[42], the cultivated lands at the juncture of these regions exhibit relatively elevated levels of AK. Despite the greater precipitation in N-XJ, Fei et al.[43] also verified elevated AK levels in cultivated soils within this region. This study identifies AK content as the primary factor influencing soil salinity in cultivated lands across XJ, which may explain the high levels of soil salinity observed in these regions.

Due to the concentration of sampling points in S-XJ in 2011, which did not meet the requirements for geostatistical analysis, and considering the unique geographical characteristics of XJ that complicate data collection, this study selected Nileke County in N-XJ and Bachu County in S-XJ as representative areas for a comprehensive and accurate investigation into the spatiotemporal evolution of soil salinity. The research findings indicate that in 2021, the average soil salinity in cultivated land was 1.03 g/kg in Nileke County and 6.89 g/kg in Bachu County. Cultivated land in Nileke County is largely free from the threat of salinization, whereas soil salinization poses a significant concern in Bachu County. Over the past decade, a notable decline in soil salinity has occurred in cultivated land in Nileke County, with a reduction of 4.17 g/kg (p<0.01). Conversely, in Bachu County, soil salinity has exhibited a marked increase of 1.99 g/kg (p<0.01). This phenomenon can primarily be attributed to the significant climatic differences between the two regions. Bachu County is located on the periphery of the Taklamakan Desert, characterized by an arid climate with low precipitation and intense evaporation. The annual evaporation rate in this region can reach up to 50 to 60 times that of the annual precipitation[43], contributing to the significant salinity levels observed in the soil[44]. Consequently, the leaching effect of rainfall on soluble salts in the soil is minimal, and the arid climate facilitates the accumulation of salts in the surface soil. In contrast, Nileke County, located in the northeastern part of the Ili River Valley and upstream of the Ili River, receives abundant precipitation and possesses rich water resources[10]. The soils in the agricultural areas primarily consist of black calcareous soil, chestnut calcareous soil, and gray calcareous soil. These fertile soils possess good water retention, making them less conducive to salt accumulation and resulting in lower soil salinity levels[45].

4.2 Analysis of driving factors for temporal and spatial variability of soil salinity

This study found that the primary driving factor for the spatial distribution of soil salinity in cultivated land in XJ is AK, followed by MAP, AN, elevation, and pH, all of which exhibit relative importance greater than 10%. In contrast, the effects of MAST, SOM, soil type, AP, and FVC on soil salinity are moderate, with relative importance ranging from 3% to 10%. The effect of slope on soil salinity is relatively weak, with relative importance of less than 3%. Research conducted by Li et al.[10] in the Ili River Basin also confirms that topography and the levels of readily available soil nutrients are important driving factors for soil salinization.

Topography plays a pivotal role in influencing soil salinity, as its variations affect the redistribution of soil water, nutrients, and thermal resources, thereby impacting the distribution of salts both horizontally and vertically. This facilitates the accumulation of salts at the surface, as evidenced by references [10] and [45]. Moreover, climatic conditions serve as a principal intrinsic driver of soil salinization. XJ, located at the center of the Eurasian continent, exhibits a distinctive temperate continental climate characterized by aridity, limited precipitation, and elevated evaporation rates. The annual evaporation rate can reach between 7 and 20 times the annual precipitation rate[41]. The combination of elevated temperatures, high evaporation rates, and low precipitation results in weak leaching processes in the soil. Consequently, soluble salts in the groundwater can accumulate at the surface through capillary action; the drier the climate, the more pronounced the trend of surface salt accumulation[45]. Additionally, these conditions facilitate weathering processes, resulting in the concentration of exchangeable cations at the soil surface, which increases salt saturation and exacerbates soil salinization issues[46].

Climate change is a primary factor influencing variations in soil salinity levels in typical regions of both S-XJ and N-XJ. A review of relevant studies indicates that over the past three decades, the climate in XJ has exhibited a trend toward warming and increased humidity[47,48]; however, S-XJ has generally experienced higher temperatures and evaporation rates compared to N-XJ, while receiving significantly less rainfall. This discrepancy in climatic conditions may significantly contribute to the observed differences in soil salinity levels between these two regions.

Human activities, particularly fertilization management, significantly contribute to the notable changes in surface soil salinity levels[49]. This study finds that AK and AN are the primary driving factors influencing soil salinity in XJ. A clear correlation exists between soil salinity and higher levels of AK and AN. In contrast, the impact of AP on soil salinity is relatively minor, consistent with previous research findings[50]. When soil AK concentrations reach excessive levels, K^+ that plants cannot absorb tends to accumulate. Extensive research has established a pronounced positive correlation between K^+ levels and soil salinity, confirming K^+ as a pivotal factor influencing soil salinity[49,51,52]. Additionally, Chen et al.[53] observed that the amount of K^+ absorbed by crops diminishes as soil salinity rises, thereby exacerbating soil salinization. Generally, the conversion of inorganic nitrogen in the soil increases with higher levels of nitrogen fertilizer application[54]. Nitrogen fertilizer application can intensify nitrification processes, accelerating the release of basic cations and directly affecting soil salinity distribution[55].

Table 6 summarizes the fertilizer application rates per unit area of cultivated land in XJ for 2011 and 2021. The analysis reveals that the spatial distribution of fertilizer application in XJ is highly imbalanced, with the application rate in S-XJ being approximately twice that of N-XJ. Over the past decade, the fertilizer application rate per unit area of cultivated land in XJ has increased by approximately 1.2 times, with varying increases in the application of nitrogen, phosphorus, and potassium fertilizers. In N-XJ, the application rate has increased by a factor of 1.3, while in S-XJ, it has increased by a factor of 1.1. In summary, although the growth in fertilizer application per unit area in S-XJ was less pronounced, the total amount remains significantly higher than that in N-XJ. The increase in fertilizer application has led to a rapid accumulation of readily available soil nutrients, influencing the extent of soil salinization and, consequently, the spatiotemporal variations in soil salinity across cultivated land in XJ.

Table 6 Fertilizer application per unit area in cultivated land in Xinjiang for 2011 and 2021

Period	Region	Fertilizer application/ $kg \cdot hm^{-2}$	N fertilizer application/ $kg \cdot hm^{-2}$	P fertilizer application/ $kg \cdot hm^{-2}$	K fertilizer application/ $kg \cdot hm^{-2}$
2011	N-XJ	136.8	62.4	32.2	8.5
	S-XJ	314.8	149.0	98.0	17.5
	XJ	217.0	101.4	61.9	12.5
2021	N-XJ	180.0	75.3	43.9	18.9
	S-XJ	348.5	146.4	102.2	26.7
	XJ	255.9	107.4	70.2	22.4

4.3 Comprehensive management measures for soil salinization

1) It is recommended that irrigation practices be optimized. It is advised that the drainage and canal systems within the irrigation area be renovated and upgraded, anti-seepage treatments for channels be enhanced, and a scientific and effective irrigation-drainage system be established to improve water use efficiency[56]. It is essential to improve irrigation techniques to circumvent excessive flood irrigation. Furthermore, there is a critical need to promote the widespread adoption of advanced water-saving irrigation technologies, including drip, sprinkler, and furrow irrigation. This will prevent an increase in groundwater levels and thereby mitigate secondary soil salinization[1].

2) In response to national initiatives, the adoption of soil testing and formulated fertilization techniques is encouraged. Based on regional soil nutrient content, tailored and scientifically sound fertilizer formulations and application rates should be developed to prevent both under-fertilization, which can hinder crop growth, and over-fertilization, which may lead to soil salinization. Applying a balanced mix of fertilizers, particularly organic fertilizers, is essential for stimulating soil microbial activity and enhancing soil conditions. Existing research indicates that the active adoption of soil testing and formulated fertilization techniques can effectively reduce soil salinity[57].

3) Optimize field management practices by implementing measures such as straw incorporation, plastic film mulching, deep plowing, loosening, and land leveling to mitigate soil salinization. Straw incorporation creates a barrier layer beneath the plow layer that blocks soil capillaries and prevents surface salt accumulation, thereby achieving water retention and salt reduction[58]. Furthermore, research indicates that straw incorporation significantly increases soil organic matter content and enhances soil quality[59]. Plastic film mulching effectively reduces evaporation, aiding in moisture and

warmth retention while decreasing soil salinity[60]. Deep plowing, loosening, and land leveling enhance soil aeration through conservation tillage practices, prevent soil compaction, and improve soil quality[61].

In conclusion, this study analyzed the spatial distribution patterns of soil salinity in cultivated land across XJ in 2021 and identified its primary driving factors. The research focused on the differences in spatial distribution and key driving factors of soil salinity between S-XJ and N-XJ. A typical region from both S-XJ and N-XJ was selected to analyze the spatiotemporal variation of soil salinity over the past decade, aiming to provide theoretical support for remote sensing monitoring and scientific management of soil salinization in XJ. Due to limitations in data availability and distribution, the spatiotemporal variation analysis was conducted using only one county each from S-XJ and N-XJ, which, while somewhat representative, may not fully capture the trends in both regions. Furthermore, the analysis of factors influencing temporal changes in soil salinity was limited to climatic factors due to data constraints, which made it less comprehensive. Additionally, the time period selected for the study was relatively short, making it challenging to reflect the long-term dynamics of soil salinity in cultivated land across XJ. Therefore, in future work, more extensive and long-term data on soil salinity and related factors in XJ is planned to be collected, with the aim of conducting deeper and more comprehensive research.

5 Conclusions

This study utilizes geostatistical methods to analyze the spatial distribution characteristics of soil salinity in cultivated land across various geographical regions of XJ in 2021. The study focuses on representative areas, specifically Bachu County in S-XJ and Nileke County in N-XJ, examining the spatiotemporal variation of soil salinity from 2011 to 2021. The Boruta algorithm was employed to identify the primary driving factors, while the geographic detector model further investigated the key determinants. The findings reveal that: 1) In 2021, the mean soil salinity for cultivated land in XJ was 2.8 g/kg, significantly higher in S-XJ compared to N-XJ, demonstrating a spatial distribution pattern of "increasing salinity from north to south." The results of the semi-variance function analysis indicate that soil salt content is influenced by both natural and anthropogenic factors. 2) The results of the characteristic importance assessment indicated that the spatial distribution pattern of soil salinity in cultivated land in XJ in 2021 was primarily influenced by the following factors: AK, MAP, AN, elevation, and soil pH. Furthermore, the temporal changes in soil salinity were closely associated with fluctuations in meteorological variables, including rainfall, evapotranspiration, and surface temperature. 3) Between 2011 and 2021, the soil salinity of cultivated land in Nileke County, a region representative of N-XJ, decreased significantly by 4.2 g/kg. In contrast, the soil salinity of cultivated land in Bachu County, a region representative of S-XJ, increased significantly by 1.99 g/kg. The causes of this phenomenon may be attributed to both natural factors, such as meteorology and topography, and field management practices, including irrigation and fertilization, in the two counties.

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