Postprint: Spatial Variability of Soil Apparent Electrical Conductivity in Soda-Salinized Dryland of Songnen Plain

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Abstract

In the western Songnen Plain, Leshang Township, Da' an City, Jilin Province, a typical salinized dryland plot with heterogeneous salinity-alkalinity levels and an area of 4.8 hm^2 was selected as the study site on April 20, 2013. Using EM38 electromagnetic induction sensor measurements combined with field fixed-point sampling, and employing a combination of classical statistics and geostatistics, the spatial variability characteristics of apparent electrical conductivity in salinized dryland soils were investigated, and the relationship between apparent electrical conductivity and soil salinity-alkalinity indicators was analyzed. The results indicated that the horizontal apparent electrical conductivity (ECh) of salinized dryland soil exhibited strong spatial autocorrelation after logarithmic transformation, with its variability characteristics primarily associated with structural factors such as topography and hydrological conditions. The vertical apparent electrical conductivity (ECv) displayed moderate spatial autocorrelation after logarithmic transformation, with its variability characteristics influenced by both structural and random factors. The optimal semivariogram models for ECh and ECv were the spherical model and exponential model, respectively. Pearson correlation analysis revealed that soil apparent electrical conductivity (ECh and ECv>) was positively correlated with soil salinity-alkalinity indicators including EC1:5, pH1:5, SAR, SC, Na , CO ^{2} , and HCO ($P < 0.05$), with correlation coefficients between ECh and soil salinity-alkalinity indicators all greater than those for ECv. In practical applications, EC>h> can be used to indicate soil salinity-alkalinity levels. Regression analysis demonstrated that soil apparent electrical conductivity (ECh and ECv) was linearly correlated with soil salinity-alkalinity indicators, and the coefficients of determination for ECh regression models were all greater than those for ECv regression models, enabling the use of horizontal apparent electrical conductivity (ECh>) to calculate soil salinity-alkalinity indicators for rapid assessment of soil salinization.

Full Text

Spatial Variations of Apparent Soil Electrical Conductivity in Saline-Sodic Upland Soil of the Songnen Plain

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Abstract

This study investigated a representative saline-sodic upland field measuring 4.8 hm^2 with heterogeneous salinity-alkalinity levels in Leshang Town, Da' an City, western Jilin Province of the Songnen Plain on April 20, 2013. Apparent soil electrical conductivity was measured using an EM38 electromagnetic induction device combined with GPS positioning and field sampling. The spatial variability characteristics of saline-sodic upland soil apparent electrical conductivity were analyzed using integrated classical statistics and geostatistics. After logarithmic transformation, the horizontal apparent electrical conductivity (EC) showed strong spatial autocorrelation, while the vertical apparent electrical conductivity (EC) exhibited moderate spatial autocorrelation. The optimal semivariogram models were spherical for EC and exponential for EC . Correlation analysis revealed significant positive relationships ($p < 0.05$) between soil apparent electrical conductivity and salinity-alkalinity indicators. Regression analysis demonstrated that both EC and EC were linearly correlated with soil salinity-alkalinity parameters including EC : , pH : , SAR, SC, and Na , with EC showing higher correlation coefficients than EC . The determination coefficients of regression models using EC were greater than those using EC . In practical applications, horizontal apparent soil electrical conductivity (EC) can be used to calculate soil salinity-alkalinity indicators and rapidly assess soil salinization.

Keywords: apparent soil electrical conductivity; spatial variation; saline-sodic upland soil; EM38; Songnen Plain

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Introduction

The Songnen Plain contains approximately 3.7 million hectares of saline-sodic upland soil, predominantly lightly to moderately salinized, with significant spatial heterogeneity in salinization degree [1]. This spatial heterogeneity leads to substantial variation in crop yields across saline-sodic upland fields and creates saline patches with higher salinity-alkalinity levels, increasing the difficulty of farmland cultivation and crop planting. For years, this non-uniformity has seriously affected local agricultural production and greatly limited large-scale utilization and mechanized management of saline-sodic upland fields, representing a major obstacle to high crop yields in the region [2]. Therefore, analyzing the spatial variability of soil salinization in soda saline-sodic upland fields, achieving rapid diagnosis of salinization degree, and evaluating spatial heterogeneity are theoretically and practically significant for proposing targeted improvement and management measures to enhance local grain production and maintain sustainable agricultural development.

The goal of saline-sodic upland soil improvement is to bring topsoil salinization indicators within the range suitable for normal crop growth. For specific fields or regions, addressing the spatial heterogeneity of topsoil salinization is essential to achieve high-yield and high-efficiency agriculture on a large scale of saline-alkali land. Many scholars have conducted research on the spatial variability of soil salinization properties [3-5] and proposed targeted management techniques based on spatial differences in soil properties [6-8]. Soil apparent electrical conductivity is closely related to salinization degree and other physicochemical properties and has been used to indicate spatial variability of soil properties [9-10]. As a non-destructive, simple, and real-time field measurement parameter, soil apparent electrical conductivity has gradually become an important tool in precision agriculture research [4, 11]. Establishing relationships between soil apparent electrical conductivity and soil salinity-alkalinity properties, and integrating spatial distribution characteristics of salinization with agronomic techniques such as field soil improvement and water-fertilizer management to form precision management technologies, represents an international research hotspot [7, 9]. However, previous studies have mainly focused on chloride salinized soil areas [12]. Since the soil characteristics of chloride salinized soils are completely different from those of soda saline-sodic soils, the salinity-alkalinity indicators reflected by apparent electrical conductivity also differ completely. Reports on spatial variability studies of soda saline-sodic upland soils are limited.

Some studies have used classical statistical methods to investigate field-scale spatial variability [13], but this approach has considerable randomness for spatial variation research. A key question for precision management of saline-sodic upland soils is how to quantitatively characterize the spatial heterogeneity of salinization in soda saline-sodic upland soils through convenient measurement of soil apparent electrical conductivity. This study employed electromagnetic induction conductivity meters (EM38) to monitor apparent soil electrical conductivity in typical soda saline-sodic upland fields, established equations relating apparent electrical conductivity to soil salinization-alkalization indicators, and combined spatial variation theory with saline-alkali land improvement practice to implement localized removal or reduction of soil salinity-alkalinity hazards.

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1. Study Area and Methods

1.1 Study Area Overview The study area is located in Leshang Town, Da'an City, western Jilin Province of the Songnen Plain (123°21 31 –123°40 58 E, 45°26 28 –45°29 27 N). Situated in a mid-temperate continental monsoon zone with an average annual precipitation of 413 mm and higher evaporation, the region has a mean annual temperature of 4.3°C. Saline-sodic soils are widely distributed in this area, belonging to inland soda saline-sodic soils with sodium carbonate (Na CO) and sodium bicarbonate (NaHCO) as the main salt components. Soil types are loam and clay loam, representing typical distribution areas of low-yield, lightly and moderately salinized upland fields in the Songnen Plain.

1.2 Methods and Experimental Design A typical saline-sodic upland plot with heterogeneous salinity-alkalinity levels was selected as the study site, measuring 300 m × 160 m (4.8 hm^2). The study area was divided into a grid with 20 m × 20 m cells, with grid nodes established as observation points for apparent soil electrical conductivity measurement. The EM38 electromagnetic induction device (Geonics) was used in combination with GPS. Based on electromagnetic induction principles, this device enables non-contact, rapid, and accurate measurement of soil electrical conductivity. It has two detection modes: vertical dipole mode with a detection depth of 1.5 m and horizontal dipole mode with a detection depth of 0.75 m [15]. Accordingly, measured apparent soil electrical conductivity is divided into vertical and horizontal components.

Within the survey area, 144 sampling points were arranged considering the spatial distribution of different soil apparent electrical conductivity values and the principle of rational spatial distribution. Soil samples were collected at depths of 0–30 cm. Soil salinity-alkalinity indicators were measured, including soluble salt ions (Na , HCO , SO ^{2} , Cl), electrical conductivity of 1:5 soil-water extracts (EC :), pH of 1:5 extracts (pH :), sodium adsorption ratio (SAR), and total soluble salt content (SC). SAR was calculated as the ratio of Na concentration to the square root of the average Ca^2 and Mg^2 concentrations, with ion concentrations expressed in mmol_c/L.

1.3 Data Processing Methods Descriptive statistical analysis was performed using SPSS 11.5 software. The Kolmogorov-Smirnov (K-S) test was used to check for normal distribution. Data not following normal distribution were log-transformed in GS+ for Windows 5.3b software. Semivariogram calculations and Kriging interpolation were performed using Surfer software to generate two-dimensional spatial distribution maps.

2. Results

2.1 Statistical Characteristics of Apparent Soil Electrical Conductivity EC and EC represent apparent soil electrical conductivity measured in horizontal and vertical directions, respectively. The horizontal mode shows highest sensitivity at the surface, decreasing with depth, while the vertical mode shows very low sensitivity near the surface, increasing with depth. The ratio EC /EC reflects differences in near-surface sensitivity: if EC /EC > 1, surface soil salinity-alkalinity exceeds that of deeper layers; if readings are similar, soil profile salinity-alkalinity is relatively uniform.

The maximum EC value was 74 mS/m, while the maximum EC was 64 mS/m. Mean values were 15.9 mS/m for EC and 23.5 mS/m for EC , indicating that deep soil electrical conductivity exceeded surface conductivity. The coefficient of variation (CV) reflects relative variability (discrete degree of random variables). Previous research classifies spatial variation as weak (CV 0.1), moderate ($0.1 < CV < 1$), or strong (CV 1). In this study area, CVs for EC and EC were 0.31 and 0.24 respectively ($0.1 < CV < 1$), indicating moderate spatial variation. The CV for EC was smaller than for EC , suggesting greater spatial variation in surface soil salinization than in deep soil salinization.

Survey plot apparent electrical conductivity statistical characteristics

2.2 Geostatistical Analysis of Spatial Variability in Saline-Sodic Upland Soil

2.2.1 Semivariogram Analysis of Apparent Electrical Conductivity Geostatistical methods require normally distributed data. Kolmogorov-Smirnov tests showed that both horizontal and vertical apparent electrical conductivity data were not normally distributed ($p < 0.05$, two-tailed). Logarithmic transformation of EC and EC yielded normal distributions ($p = 0.338$ and $p = 0.119$, respectively), meeting geostatistical analysis requirements. All subsequent semivariogram calculations used log-transformed data.

During semivariogram model fitting, the optimal model requires minimal residual sum of squares (RSS) and maximal coefficient of determination. Considering these indicators comprehensively, the spherical model was optimal for EC , while the exponential model was optimal for EC . Both models had small nugget values, indicating minimal influence from experimental error and random factors.

For EC , the effective range was 91.9 m, meaning observations were independent beyond 91.9 m but showed spatial autocorrelation within this distance. For EC , the effective range was 198.9 m. The nugget-to-sill ratio indicates spatial dependence: ratios $< 25\%$ indicate strong spatial autocorrelation, 25–75% indicate moderate autocorrelation, and $> 75\%$ indicate weak autocorrelation [19]. The EC semivariogram had a nugget-to-sill ratio of 6.5% ($< 25\%$), indicating strong spatial autocorrelation primarily caused by structural factors such as topography and hydrology. The EC semivariogram had a ratio of 47.8% (25–75%), indicating moderate spatial autocorrelation influenced by both structural and random factors.

Therefore, for assessing salinization degree in upland soils, horizontal apparent electrical conductivity (EC) should be selected as the evaluation indicator to study spatial variability characteristics of salinization and analyze relationships between structural factors (topography, hydrology) and soil salinization, enabling targeted improvement of saline-sodic upland fields.

K-S test for normal distribution of apparent soil electrical conductivity Semivariogram parameters of log-transformed apparent soil electrical conductivity (n = 144)

2.2.2 Spatial Distribution Based on Kriging Interpolation

Based on semivariogram models, Kriging interpolation was applied to generate spatial distribution maps of log-transformed apparent electrical conductivity. The spatial distributions of EC and EC were very similar, showing strip or patchy mosaic distributions of different conductivity levels. Both horizontal and vertical directions exhibited large strip-shaped high salinity-alkalinity zones in the northwest and southern parts of the plot, smaller high salinity zones in the northeast and north-central areas, and patchy low salinity-alkalinity zones in the central and southeastern parts.

Saline-sodic upland soils exhibit microtopographic features: severely saline-alkali areas have slightly higher elevation with no crop growth; slightly lower areas have moderate salinity with lower crop yields; the lowest areas are lightly salinized or non-salinized with normal crop growth. Thus, different salinization degrees directly affect crop growth, resulting in highly uneven crop yields.

[Figure 1: see original paper] Spatial distribution characteristics of log-transformed apparent soil electrical conductivity in the experimental plot

2.3 Correlation Analysis Between Apparent Electrical Conductivity and Soil Salinity-Alkalinity Indicators

Pearson correlation analysis was conducted between horizontal/vertical apparent electrical conductivity and soil salinity-alkalinity indicators (soluble salt ions, EC : , pH : , SAR, SC). Both EC and EC showed extremely significant correlations with these indicators ($p < 0.01$). Correlation coefficients between EC and soil salinity-alkalinity indicators were higher than those for EC . This result is consistent with other studies [20]. Since the horizontal mode has highest sensitivity at the surface, EC correlates better with near-surface (0–30 cm) soil salinity-alkalinity indicators. For monitoring soda saline-sodic soils in the Songnen Plain, horizontal apparent electrical conductivity alone can effectively indicate soil salinity-alkalinity degree.

Pearson correlation analysis between apparent soil electrical conductivity and salinization parameters

2.4 Regression Analysis Between Apparent Electrical Conductivity and Related Factors Stepwise regression analysis was performed to further investigate relationships between apparent electrical conductivity and soil salinity-alkalinity indicators. Both EC and EC showed linear relationships with EC : , pH : , SAR, and SC, with good simulation effects. Determination coefficients (R^2) ranged from 0.60 to 0.82 for EC models and 0.52 to 0.70 for EC models. All EC regression models had higher R^2 values than corresponding EC models.

In practical applications, EC can be used to calculate surface soil (0–30 cm) salinity-alkalinity indicators and assess soil salinization degree.

Regression models between EC and soil salinity-alkalinity parameters

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3. Discussion and Conclusions

3.1 Discussion Soil apparent electrical conductivity exhibits spatial variability, manifested as strip or patchy mosaic distributions of different conductivity values, reflecting the spatial distribution pattern of salinization in upland soils. Most saline-sodic upland fields in the Songnen Plain were reclaimed from degraded grasslands, exhibiting microtopographic differences that affect water and salt movement. Micro-high terrain features have both vertical and lateral moisture gradients. According to capillary water movement principles (from high to low moisture zones), micro-high areas receive both upward and lateral capillary water flow. As soil water moves upward and from lower to higher micro-slope positions, salts migrate and accumulate at the surface through evaporation, creating severely salinized areas [21-22]. The lowest areas remain lightly salinized or non-salinized.

Spatial heterogeneity of salinization in Songnen Plain upland soils poses serious challenges for soil improvement, large-scale utilization, and crop production. Identifying the area and proportion requiring improvement is key to efficient use of saline-sodic upland soils. Integrating soil salinity spatial variation theory with saline-alkali land improvement practice and using horizontal apparent electrical conductivity for rapid assessment facilitates fast, low-cost improvement of saline-sodic upland fields.

Different crops have varying salinity-alkalinity tolerance thresholds. For fields with lower and less variable salinization, apparent electrical conductivity can indicate crop tolerance thresholds, enabling planting of appropriate crops—a crucial approach for rational saline soil utilization. For severely salinized areas where salt-tolerant crops cannot survive, localized improvement is necessary. In heavy saline patches, large amounts of exchangeable Na cause soil clay dispersion, poor permeability, and deteriorating soil properties. The best improvement method is applying amendments containing divalent cations to replace exchangeable Na . Amendment requirements vary with crop type and salinization degree.

Classical statistical analysis showed moderate spatial variation for both EC and EC . Geostatistical analysis revealed that log-transformed EC had strong spatial autocorrelation, while log-transformed EC had moderate spatial autocorrelation. EC variability was primarily caused by structural factors such as topography and hydrology, whereas EC variability was influenced by both structural and random factors. The optimal semivariogram models were spherical for EC and exponential for EC .

3.2 Conclusions Both correlation and regression analyses demonstrated significant positive and linear relationships between soil apparent electrical conductivity and salinity-alkalinity indicators ($p < 0.05$). In practice, EC effectively reflects soil salinity-alkalinity conditions, with better performance than EC . Horizontal apparent electrical conductivity (EC) can be used to calculate soil salinity-alkalinity indicators in soda saline-sodic upland fields and guide salinization assessment.

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