Postprint: Soil pH Inversion in Southern Xinjiang Cotton Fields Based on Electromagnetic Induction Data

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Abstract

Soil salinization is one of the primary factors limiting agricultural development in Xinjiang. Accurate acquisition of soil salinization information is conducive to reconciling the conflict between substantial agricultural irrigation water demand and relatively scarce freshwater resources, and holds significant importance for enhancing agricultural production and environmental sustainability. This study employed soil pH in nine cotton fields within the Alar Reclamation Area of southern Xinjiang as the research indicator, utilizing cotton field soil apparent electrical conductivity data acquired by the EM38-MK2 electromagnetic induction sensor alongside laboratory-measured soil pH as data sources. Linear regression models between soil profile pH and soil apparent electrical conductivity were constructed using two modeling approaches: whole-region and zonal methods, with geostatistical software employed for spatial analysis of soil profile pH. The results demonstrated that: (1) Under zonal conditions, the correlation coefficient between soil apparent electrical conductivity and soil profile pH ranged from 0.60 to 0.95; under whole-region conditions, the correlation coefficient ranged from 0.28 to 0.46, all exhibiting extremely significant negative correlations, thereby indicating that the EM38-MK2 electromagnetic induction sensor can be utilized for soil pH determination. (2) Zonal models achieved $0.74 \leq R^2 \leq 0.93$, $2.00 \leq RPD \leq 3.50$, and lower RMSE values, all superior to whole-region models, demonstrating that zonal model accuracy surpasses that of whole-region models, and that model inversion accuracy is correspondingly higher in cotton fields with elevated soil salt content. (3) Spatial analysis results revealed that due to influences from winter irrigation, cotton root systems, and cotton residues, deep soil pH in cotton fields exceeds surface soil pH. These findings can provide insights for rapid soil pH measurement and guidance for scientific management of soil salinization.

Full Text

Abstract

Soil salinization is a major factor limiting agricultural development in Xinjiang. Accurate acquisition of soil salinization information helps regulate the contradiction between large agricultural irrigation water demand and relatively scarce freshwater resources, which is of great significance for improving agricultural production and environmental sustainability. This study focused on cotton field soil pH in the Alar Reclamation Area of southern Xinjiang, using apparent electrical conductivity data obtained by the EM38-MK2 geodetic conductivity meter as the research indicator. With 486 soil profile samples as the data source, two modeling approaches—global and zonal—were adopted to construct linear regression models between soil profile pH and soil apparent conductivity. Geostatistical software was used to conduct spatial analysis of soil profile pH. The results showed that: (1) Under both global and zonal conditions, the correlation coefficients between soil apparent conductivity and soil profile pH ranged from 0.28 to 0.46 and 0.60 to 0.95 respectively, both showing extremely significant negative correlations, indicating that the EM38-MK2 geodetic conductivity meter can be used for soil pH determination. (2) Zonal models showed smaller RMSE values (0.01-0.12) and higher R^2 (0.74–0.93) and RPD (2.00–3.50) values than global models, demonstrating that zonal model accuracy is superior to global models, and that cotton fields with higher soil salt content also exhibit higher model inversion accuracy. (3) Spatial analysis results revealed that due to the influence of winter irrigation, cotton root systems, and cotton litter, deep soil pH in cotton fields was higher than surface soil pH. These findings provide ideas for rapid determination of soil pH and guidance for scientific management of soil salinization.

Keywords: soil pH; soil apparent conductivity; inversion model; cotton field; spatial distribution; southern Xinjiang

1.1 Study Area Overview

The Alar Reclamation Area is located in the hinterland of the Eurasian continent [Figure 1: see original paper], with geographic coordinates of 80°30 –81°58 E and 40°22 –40°57 N. The terrain slopes from high in the north and west to low in the south and east. The area has an average annual precipitation of less than 50 mm and an average annual evaporation exceeding 1992 mm, with an evaporation-to-precipitation ratio of 40, making it a typical extremely arid region in China. The Reclamation Area is rich in light and heat resources, suitable for cultivating economic crops such as cotton, and represents the largest cotton production base in Xinjiang. Cotton is cultivated using plastic film mulching with flood irrigation in spring and winter, and drip irrigation under film during the cotton growth period, primarily using water from the Tarim River. The northern part of the Reclamation Area borders desert regions with high soil salinization levels. Improving saline soils requires large amounts of freshwater, exacerbating the conflict between ecological and agricultural water use. The special geographic location, extreme climatic conditions, and irrational irrigation practices have led to frequent soil salinization and secondary salinization, making this a typical salinization region in China.

1.2 EM38-MK2 Structure

The EM38-MK2 geodetic conductivity meter [Figure 2: see original paper] is the primary instrument for obtaining soil property data. It contains one transmitting coil and two receiving coils, with vertical and horizontal measurement modes. In horizontal mode, it can measure apparent conductivity of soil depths of 0–0.375 m (ECh0.375) and 0–0.75 m (ECh0.75). In vertical mode, it can measure apparent conductivity of soil depths of 0–0.75 m (ECv0.75) and 0–1.0 m (ECv1.0).

1.3 Data Acquisition and Processing

Soil apparent conductivity data were obtained as follows: In each 100 m × 100 m cotton field plot, EM38-MK2 manual measurement mode was used with an acquisition frequency of one reading per second. Measurements were taken at 20 m intervals along rows, collecting both horizontal and vertical apparent conductivity data [Figure 3: see original paper]. Data collection occurred in late March 2020. Based on the soil apparent conductivity data obtained from the EM38-MK2 handheld device, gradient-based sampling was conducted, with 54 soil profile column samples collected from each plot at measurement points. Soil apparent conductivity data and GPS coordinates were simultaneously recorded. Soil column samples were collected using a Rhino S1 soil sampler [Figure 4: see original paper] with 1.0 m long sampling tubes. The collected column samples were sealed and transported to the laboratory, where they were sectioned at 0.375 m, 0.75 m, and 1.00 m depths to obtain soil profile samples from the 0–0.375 m, 0.375–0.75 m, and 0.75–1.00 m layers. Soil pH was measured at a 1:2.5 soil-to-water ratio, and soil electrical conductivity was measured at a 1:5 soil-to-water ratio. Microsoft Excel 2019 was used for linear fitting between soil apparent conductivity and soil pH, and ArcGIS 10.7 geostatistical software was used for spatial analysis.

1.4 Model Construction and Accuracy Validation

Two modeling approaches were adopted: global modeling and zonal modeling. The global model combined all 486 soil profile data and divided them into calibration (70%) and validation (30%) sets for modeling and validation. The zonal model used data from each plot separately, with 70% of data from each plot for modeling and 30% for validation. Multiple linear regression was employed as the modeling method. Model accuracy was evaluated using coefficient of determination (R^2), root mean square error (RMSE), and residual prediction deviation (RPD). Model accuracy evaluation followed methods described in the literature.

2.1 Descriptive Statistical Analysis of Sample Soil pH

The descriptive statistical characteristics of soil profile pH in the study area are shown in Table 1. Soil pH ranged from 6.5 to 9.5, with values $ $7.5 indicating alkaline soil. Across the 0-1.00 m profile, pH gradually increased with soil depth, and most soils in the study area were alkaline. Analyzing each soil layer separately, the 0-0.375 m layer had the highest mean pH, while the minimum value occurred in the 0.375-0.75 m layer, with a difference of 3.0 pH units between extremes. Standard deviation reflects the dispersion degree of a dataset. Table 1 shows that the 0.75-1.00 m layer had the lowest dispersion, while the 0-0.375 m layer showed high dispersion, indicating significant differences in pH among different plots.

2.2 Correlation Analysis Between Soil pH and Soil Apparent Conductivity

Before correlating soil pH with apparent conductivity, the reliability of apparent conductivity data must be analyzed. The comprehensive analysis of all samples showed that the coefficient of variation for apparent conductivity in the 0-1.00 m layer was less than 15%, indicating low variability. Correlation analysis between pH data from three soil layers and multi-mode apparent conductivity data revealed extremely significant negative correlations ($P < 0.01$) in both global and zonal approaches. Global correlation coefficients ranged from 0.28 to 0.46, while zonal coefficients ranged from 0.60 to 0.95 , demonstrating that apparent conductivity data are reliable for model construction.

Analyzing each plot separately [Figure 4: see original paper], the correlation coefficients between soil pH and apparent conductivity varied significantly among plots but were all higher than global correlations. For the 0-0.375 m layer, the highest correlation was with ECh0.375 ($r = 0.85$). For the 0.375-0.75 m layer, the highest correlation was with ECh0.75 and ECv0.75 ($r = 0.81$). For the 0.75-1.00 m layer, the highest correlation was with ECv0.75 ($r = 0.78$). These results indicate strong correlations between soil pH and both horizontal and vertical modes of EM38-MK2 measurements.

2.3 Determination of Modeling Factors

Given the extremely significant correlations between soil pH and apparent conductivity, linear regression models were constructed using apparent conductivity data. Modeling factor selection fully considered the non-linear response function of EM38-MK2, as different measurement modes exhibit varying sensitivity to soil depth. Based on the instrument' s response range, six data combinations were tested as modeling factors. Model accuracy is shown in Table 4.

The results show that model R^2 first decreased then increased with soil depth. For the 0-0.375 m layer, using ECh0.375 + ECh0.75 as modeling factors yielded the highest R^2. For the 0.375-0.75 m layer, ECh0.75 + ECv0.75 performed best. For the 0.75-1.00 m layer, ECv0.75 + ECv1.0 was optimal. The non-linear response function of EM38-MK2 indicates that 85% of the response occurs above 60 cm depth, which aligns with our findings that R^2 was lowest in the 0.375-0.75 m layer.

2.4 Comparison of Global and Zonal Model Accuracy

Global model accuracy is presented in Table 5. The global model showed R^2 values of 0.28-0.46, RMSE of 0.08-0.15, and RPD of 1.00-1.35, indicating poor predictive capability according to established evaluation standards.

Zonal model accuracy is shown in Table 6. Zonal models achieved R^2 of 0.74-0.93, RMSE of 0.01-0.12, and RPD of 2.00-3.50, all superior to global model values. This demonstrates that zonal models have excellent predictive capability. In summary, zonal model accuracy surpasses global models, and all subsequent predictions and interpolations were based on zonal models.

2.5 Spatial Distribution Characteristics of Soil pH in Different Profiles

Kriging interpolation was used to simulate the spatial distribution of soil pH in six plots using ArcGIS 10.7. To further analyze soil pH variation across the study area, three representative plots were selected: Plot 1 (high-yield cotton area), Plot 5 (wetland area), and Plot 9 (area surrounded by drainage ditches). Interpolation results are shown in [Figure 5: see original paper].

The results indicate that soil pH in typical plots showed significant spatial heterogeneity. The high-yield cotton area (Plot 1) had the lowest pH range (7.5-8.3 units) across 0-1.00 m depth. The area surrounded by drainage ditches (Plot 9) showed the largest pH range, differing by 2.0 units, with higher pH values concentrated in the eastern and northern regions. All plots demonstrated increasing pH with depth. The spatial patterns may be related to winter irrigation, cotton root distribution, and litter decomposition. Winter irrigation leaches salts to deeper layers, while roots and litter affect surface pH through organic acid secretion and decomposition.

3 Discussion

This study rapidly obtained soil apparent conductivity data from different cotton field areas in the Alar Reclamation Area using electromagnetic induction technology. Analysis of 486 soil profile samples revealed that the 0.375-0.75 m layer showed the largest pH variation, likely related to winter irrigation practices. After winter irrigation, soil salts accumulate below 40 cm depth. With low temperatures and minimal evaporation in March, insufficient upward salt migration leaves most salts accumulated in the 0.375–0.75 m layer and below. Previous research has shown that with increasing years of drip irrigation under film, soil salts continuously accumulate and migrate upward, altering surface soil pH. Although winter irrigation leaches salts below the tillage layer, the legacy of salt accumulation affects pH distribution.

Zonal models demonstrated higher accuracy than global models, possibly due to soil texture, fertilization practices, and cotton litter decomposition. First, EM38-MK2 measurements reflect the content of free-state electrolytes within the soil volume. Within a single plot, soil properties are relatively stable, resulting in small differences among apparent conductivity data points, which enhances zonal model prediction capability and stability. In contrast, global models combine data from all plots, where different management practices (fertilization, irrigation) cause dramatic variations in soil properties, reducing model accuracy. Second, during data collection, fields were in an unplowed state with cotton litter covering the surface and roots remaining in the soil. Root exudates and decomposing litter directly influence soil pH mechanisms.

The "salt effect zero point" theory explains how soil salinity affects pH. This theory proposes that for variable-charge soils, a net charge zero point exists where pH is unaffected by salt concentration. Most variable-charge soils have salt effect zero points at pH 3.5–5.0. Since the Reclamation Area soils have pH $ $7.5, they are far from the zero point and thus significantly affected by salt concentration. Miller' s investigations found that for a given soil, higher salt concentrations exert greater influence on pH. Additionally, this study found a highly significant negative correlation between apparent conductivity and pH, while Zhao Changwei' s research in Jilin Province found a positive correlation. This discrepancy may be attributed to differences in soil texture and ion types.

This study used soil electrical conductivity as a medium to construct linear regression models between apparent conductivity and pH, enabling pH determination. Future research should focus on improving global model accuracy and expanding the scope of EM38-MK2 applications for large-scale pH measurement.

4 Conclusions

Using EM38-MK2 geodetic conductivity meter horizontal and vertical modes, apparent conductivity data were obtained from nine cotton fields in the Alar Reclamation Area. Global and zonal modeling approaches were employed to construct inversion models between apparent conductivity and soil pH. The main conclusions are:

1) Linear fitting between soil measured electrical conductivity and apparent conductivity showed correlation coefficients as high as 0.93. Correlation tests between soil pH and measured electrical conductivity revealed extremely significant negative correlations ($P < 0.01$) across all layers (0–0.375 m, 0.375–0.75 m, 0.75–1.00 m), with coefficients ranging from 0.66 to 0.85. Apparent conductivity, electrical conductivity, and pH showed

consistent correlation patterns. Zonal correlation coefficients (0.60–0.95) were higher than global coefficients (0.28–0.46), all showing extremely significant negative correlations, confirming that EM38-MK2 can be used for soil pH determination.

2) Using both horizontal and vertical mode data from EM38-MK2 as modeling factors significantly improved model accuracy. Zonal models achieved R^2 of 0.74–0.93, RMSE of 0.01–0.12, and RPD of 2.00–3.50, with higher accuracy than global models. Cotton fields with higher salt content showed higher model accuracy.

3) Spatial analysis results demonstrated that due to winter irrigation, cotton root systems, and litter, soil pH in all plots was higher in deep layers than surface layers. This study provides a methodological basis for rapid soil pH determination and scientific management of soil salinization in cotton fields.

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