Response Analysis and Modeling of Microwave Dielectric Properties of Typical Saline Soils in Xinjiang: Postprint

Authors: Zhao Shuang

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Abstract

Soil salinization exerts negative impacts on regional economic and ecological sustainable development. Microwave dielectric constant is a key factor in microwave remote sensing detection of soil; however, the relationship between dielectric constant and salinity remains unclear. To analyze the effects of salt type and salinity content on soil dielectric constant, the dielectric constants of two typical saline soil types in Xinjiang (sulfate-chloride type: Na2SO4-NaCl; chloride-sulfate type: NaCl-Na2SO4) were measured at frequencies of 0.3~20.0 GHz, and the influences of water content, salinity content, salt type, and texture on soil dielectric properties were investigated. The results indicate that: (1) Salinity content affects both the real part (′) and imaginary part (″) of the complex dielectric constant of moist soil and dry loam. (2) For the two types of moist saline soils at the same level at 0.3 GHz frequency, overall ″Na2SO4-NaCl > ″NaCl-Na2SO4. (3) The electrical modulus of the imaginary part (M″) is more closely related to salinity content, and 0.3~5.0 GHz is an important frequency range. The research results can provide scientific support for microwave remote sensing monitoring of soil salinization under complex underlying surfaces.

Full Text

Preamble

Response Analysis and Modeling of Microwave Dielectric Properties of Typical Saline Soil in Xinjiang

ZHAO Shuang[1,2,3], DING Jianli[1,2,3], HAN Lijing[1,2,3], HUANG Shuai , GE Xiangyu[1,2,3]
[1]College of Geography and Remote Sensing Sciences, Xinjiang University, Urumqi 830046, China
[2]Xinjiang Key Laboratory of Oasis Ecology, Xinjiang University, Urumqi

830046, China
[3]Key Laboratory of Smart City and Environment Modelling of Higher Education Institute, Xinjiang University, Urumqi 830046, China
College of Geography and Environment, Liaocheng University, Liaocheng 252000, China

Abstract: Soil salinization negatively impacts regional economic and ecological sustainable development. The microwave dielectric constant is a key factor for microwave remote sensing detection of soil, yet the relationship between dielectric constant and salt content remains unclear. To analyze the influence of salt type and salinity on soil dielectric constant, this study measured the dielectric constants of two typical saline soil types from Xinjiang (sulfate-chloride type: NaCl-Na SO ; chloride-sulfate type: Na SO -NaCl) across frequencies from 0.3 to 20.0 GHz. The effects of water content, salt content, salt type, and soil texture on dielectric properties were investigated. Results show that: (1) Salt content significantly affects both the real and imaginary parts of the complex dielectric constant of wet soil and dry silty loam. (2) The imaginary part of the dielectric modulus (M'') shows a stronger relationship with salt content, and for moist saline soils of the same class, ε'' of Na SO -NaCl $>$ ε'' of NaCl-Na SO at 0.3 GHz. (3) Machine learning analysis indicates that the 0.3–5.0 GHz frequency range is most important for predicting soil salinity. This research provides scientific support for microwave remote sensing monitoring of soil salinization over complex underlying surfaces.

Keywords: microwave dielectric constant; soil salinization; machine learning; microwave remote sensing

1. Introduction

Soil salinization represents a primary form of land degradation in arid and semi-arid regions, directly causing crop yield losses of 18%–43% and severely hindering regional economic and ecological sustainable development. It is estimated that by 2050, soil salinization will continue to intensify worldwide, with over half of all arable land potentially becoming salinized. Currently, China has the largest distribution area of saline soils globally. In Xinjiang, located in northwestern China, approximately one-third of cultivated land is threatened by salinization due to unique climatic conditions, with numerous and widely distributed saline soil types.

Compared with traditional optical remote sensing, microwave remote sensing is less affected by underlying surface conditions, offering greater advantages for monitoring salinization in desert regions, areas with complex terrain, and coastal zones. The effective backscattering coefficient of radar imagery is closely related to soil complex dielectric constant, which is the key to microwave remote sensing of soil properties. As a lossy medium, the real part of soil complex dielectric constant is associated with electromagnetic wave scattering and transmission at the soil surface, while the imaginary part relates to electromagnetic wave attenuation in soil.

Extensive research has been conducted on soil moisture monitoring using microwave remote sensing, and scholars have proposed models describing the relationship between dielectric constant and soil moisture. However, these models lack consideration of soil salinity effects. For saline soils, salt effects on dielectric constant may be significant. Studies have shown that ignoring salinization effects in soil moisture retrieval from microwave remote sensing (L-band) can reduce accuracy. Moreover, directly establishing relationship models between radar backscatter coefficients and soil salinity remains difficult. Therefore, developing dielectric models for saline soils is essential.

Previous studies have analyzed dielectric characteristics of saline soils, showing that salt significantly affects the imaginary part of dielectric constant at frequencies below 5.0 GHz. However, natural soils contain mixed salt types, and most studies have only considered single salt effects, with limited research on how different saline soil types influence dielectric properties. The key to addressing these issues lies in clarifying the response relationships among salt content, salt type, soil texture, and soil dielectric characteristics, which would facilitate mechanism verification and development of dielectric models for saline soils, providing theoretical support for soil salinity retrieval.

This study aims to: (1) Configure soil samples with different water contents, salinity levels, and salt types, and measure microwave dielectric constants across 0.3–20.0 GHz; (2) Investigate the response relationships between soil complex dielectric constant real part (ε'), imaginary part (ε''), and dielectric modulus (M', M'') with salinity; and (3) Develop a saline soil dielectric model using Random Forest (RF) and identify frequency bands sensitive to salinity.

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2. Study Area and Methods

2.1 Study Area Overview

To investigate the effect of soil texture on dielectric constant, soil samples were collected from two regions to obtain different textures (Fig. 1). The Weigan-Kuqa Oasis lies between the Weigan and Kuqa Rivers (82°10 –83°50 E, 41°06 – 41°40 N) at an elevation of 892–1100 m. This region has a continental warm temperate arid climate with mean annual precipitation of 55.5 mm, mean annual temperature of 10.5–14.4°C, and an evaporation-to-precipitation ratio of about 65. Soil types are primarily fluvo-aquic and meadow soils, with widespread distribution of bog soils and saline soils. High groundwater levels cause continuous salt migration to the surface, expanding salinization areas and threatening the oasis ecosystem and agricultural production. Salts are mainly composed of chlorides and sulfates.

The Ebinur Lake Wetland Nature Reserve is located in Bortala Mongolian Autonomous Prefecture (79°53 –85°02 E, 43°38 –45°52 N). This complex mountain-oasis-desert ecosystem has mean annual evaporation of 3627 mm. Soil types are mainly calcic, alpine, and desert soils. Both regions have mixed salt compositions in saline soils.

2.2 Experimental Methods

Three soil textures were selected and labeled as Soil No. 1, No. 2, and No. 3. Laboratory preprocessing included air-drying and grinding. Soil No. 1 and No. 2 were collected from the Weigan-Kuqa Oasis at 30 cm depth in October 2020. Soil No. 3 was collected from the Ebinur Lake area in October 2021.

Soil salinity was measured using a Cond 7310 conductivity meter (WTW GmbH, Germany) with a 1:5 soil-water ratio. The relationship between soil extract electrical conductivity (k, μS · cm ^{1}) and salt content is: Salt = 127.45 × k, with soil salinity ranging 3.01–4.50 g · kg ^{1}. Particle size distribution was measured using a MICROTRAC S3500 laser particle size analyzer (Microtrac Inc., USA) following USDA soil texture classification standards.

To analyze salt type effects on dielectric properties, NaCl and Na SO were used to prepare different salinity levels. After pretreatment, soils were oven-dried at 105°C to remove moisture before preparing samples with different water and salt contents. Sample preparation involved: (1) calculating and weighing required water for target water content; (2) calculating and weighing required salt; (3) mixing salt and water to prepare solution; (4) spraying the solution onto soil samples. Prepared samples were sealed in aluminum boxes for dielectric constant measurement.

Each soil texture was prepared with 4 water content levels and 5 salinity levels, totaling 20 samples per texture and 60 samples overall.

2.3 Soil Dielectric Constant Measurement

A Keysight PNA-N5232A network analyzer with an 85070E dielectric probe was used to measure soil complex dielectric constant (real part ε' and imaginary part ε''). The frequency range was 0.3–20.0 GHz with 500 sampling points. The network analyzer was preheated for 30 minutes and calibrated using air, short-circuit standard, and deionized water at room temperature before each measurement. The probe was pressed firmly against the sample surface during measurement.

The dielectric modulus is often used to analyze measured media and is defined as the reciprocal of complex dielectric constant:

$$M^* = \frac{1}{\varepsilon^*} = \frac{\varepsilon'}{\varepsilon'^2 + \varepsilon''^2} + j\frac{\varepsilon''}{\varepsilon'^2 + \varepsilon''^2}$$

where M^* is the complex dielectric modulus, j is the imaginary unit, and the real and imaginary parts of the modulus (M' and M'') are:

$$M' = \frac{\varepsilon'}{\varepsilon'^2 + \varepsilon''^2}$$

$$M'' = \frac{\varepsilon''}{\varepsilon'^2 + \varepsilon''^2}$$

2.4 Model Methods

Random Forest (RF) is an ensemble learning method that integrates multiple decision trees for classification and prediction. The processing steps are: (1) Assuming the original dataset contains N samples with T features, bootstrap resampling with replacement is performed M times to generate M new datasets (out-of-bag data are those not selected); (2) M decision trees are trained using these datasets, with each tree randomly selecting t candidate features ($t \leq T$) and choosing optimal split nodes based on minimum Gini coefficient, resulting in M trees; (3) For unknown samples, the prediction is the average of all regression tree predictions:

$$\hat{y} = \frac{1}{M}\sum_{i=1}^{M} h(X, \theta_i)$$

where $\hat{y}$ is the predicted value, M is the number of regression trees, θ_i is an independent random vector, X is the input matrix, and $h(X, \theta_i)$ is each tree's prediction.

Variable importance can be assessed by calculating out-of-bag error. For each decision tree, out-of-bag error E_b is computed. Then, values of feature X_t in out-of-bag data are randomly permuted and new error E_b' is calculated. The importance of feature X_t is:

$$Importance(X_t) = \frac{1}{M}\sum_{i=1}^{M}(E_b' - E_b)$$

The modeling was implemented in R-3.5.3, using dielectric constants ε' and ε'' across 0.3–20.0 GHz as independent variables (1000 features) with soil salinity as the dependent variable.

2.5 Model Evaluation Metrics

Three datasets (one per soil texture) each contained 80 samples and were randomly split 7:3 into calibration ($n = 56$) and validation ($n = 24$) sets. Model performance was evaluated using: coefficient of determination (R^2), root mean square error ($RMSE$), and ratio of performance to interquartile distance ($RPIQ$). Since soil physicochemical data are typically non-normally distributed, $RPIQ$ provides more objective evaluation than residual prediction deviation (RPD). Good models generally have high R^2 and $RPIQ$, and low $RMSE$.

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(A_i - P_i)^2}{\sum_{i=1}^{n}(A_i - \bar{A})^2}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(A_i - P_i)^2}$$

$$RPIQ = \frac{Q_3 - Q_1}{RMSE}$$

where n is sample number, A_i is measured value, $\bar{A}$ is mean of measured values, P_i is predicted value, $\bar{P}$ is mean of predicted values, Q_3 is third quartile, and Q_1 is first quartile.

3. Results

3.1 Water Content Effects on Dielectric Constant

Figure 2 shows dielectric constants of samples with different water contents at the same salinity level (NaCl-Na SO , 20 g • kg ^{1}). All three dielectric constants (ε', ε'', M'') are affected by water content. Dry soil samples have very small dielectric constants, which increase with water content. At low water content, water exists primarily as bound water with weak ion mobility, so dielectric constant is mainly influenced by soil particles. As water content increases, free water increases, enhancing ion mobility and water molecule polarization, thus increasing dielectric constant.

Across all frequencies, ε' decreases with increasing frequency. At fixed frequency, higher water content yields larger ε' values, indicating water content affects ε' more than ε''. Overall, M'' increases with frequency, while at fixed frequency, M'' decreases with increasing water content. Similar trends are observed at other salinity levels.

3.2 Soil Salinity Effects on Dielectric Properties

Under constant water content and texture, soil dielectric constant is influenced by both salinity level and salt type.

3.2.1 Salinity Level Effects At 25% water content, salinity effects differ among textures. Salinity most significantly affects Soil No. 1 (silty loam) (Fig. 3), with ε' and ε'' of four salinity levels showing clear differences. Soils No. 2 (loamy sand) and No. 3 (sandy loam) show smaller salinity effects (Fig. 4). Taking NaCl-Na SO as an example (Fig. 3), ε' decreases with frequency, while at fixed frequency, ε' decreases with salinity. ε'' decreases with frequency and salinity up to ~10 GHz, then increases with frequency before decreasing again. Since M'' is the reciprocal of complex dielectric constant, at fixed frequency, M'' increases with salinity.

Without distinguishing texture, salinity affects ε' and ε'' of Soil No. 1 most significantly ($R^2 = 0.53$, $RMSE = 0.37$). Similar patterns appear at other water contents. For Soil No. 1, ε' decreases with frequency, while at fixed frequency, ε' decreases with salinity. M'' increases with salinity, particularly in the 0.3–5.0 GHz range.

3.2.2 Salt Type Effects To compare salt type effects, dielectric constants of NaCl-Na SO and Na SO -NaCl at the same salinity are shown in Figure 6. The three dielectric constants of both saline soil types show similar trends with frequency. Differences in ε'' are most pronounced at 0.3 GHz, a pattern also observed at other water contents.

Figure 7 clearly illustrates salt type effects on ε'' at 0.3 GHz for the same salinization grade. At 5% and 25% water content, ε'' of Na SO -NaCl $>$ ε'' of NaCl-Na SO , indicating salt type significantly affects ε''. For the same salinity level, Na SO -NaCl saline soil has greater impact on ε'' than NaCl-Na SO . M'' shows negative correlation with salinity at low frequencies (<1.76 GHz), transitioning to positive correlation as frequency increases.

3.3 Texture Effects on Dielectric Properties

Based on previous analysis, at the same salinity level, dielectric constants of different textures show no obvious differences at low water content. However, at constant water content, texture significantly affects dielectric constants at different salinities. For dry soils, ε' of different textures shows clear differences, with Soil No. 1 (silty loam) showing more pronounced variation with salinity. For wet saline soils, ε' differences among textures are more evident, generally following: $\varepsilon''_{\text{silty loam}} > \varepsilon''_{\text{sandy loam}} > \varepsilon''_{\text{loamy sand}}$.

3.4 Soil Salinity Estimation Model

Section 3.2 analysis shows salinity significantly affects dielectric properties. At constant water content, salinity influences ε' and ε''. To quantitatively evaluate dielectric constant effectiveness for estimating soil salinity, RF algorithms were applied using ε', ε'', and M'' to estimate salinity (Table 3). Models based on M'' performed best (average $R^2 = 0.92$, $RMSE_{\text{cal}} = 0.18$, $RPIQ = 2.43$), followed by ε'', then ε'. This indicates M'' can effectively predict soil salinity and better reflects dielectric characteristics of soils with different salinities, showing that salinity simultaneously affects ε' and ε''.

Figure 8 shows the relative importance of frequency bands in modeling. Important frequencies are concentrated in the low-frequency range ($f < 5.0$ GHz), where M'' responds strongly to salinity variations. As shown in Figure 9 for Soil No. 1, M'' is negatively correlated with salinity at low frequencies (~<5.0 GHz), transitioning to positive correlation with increasing frequency.

4. Discussion

4.1 Effects of Saline Soil Types on Microwave Dielectric Properties

Under natural conditions, saline soils contain mixed salts. Previous studies using single salts (NaCl, Na SO) found ε'' increases with salinity at low frequencies (<2.0 GHz), consistent with our results. This study investigated two saline soil types and found type differences are most pronounced in ε'' at low frequencies. At the same salinity level and water content, Na SO -NaCl saline soil has greater impact on ε'' than NaCl-Na SO , similar to findings that $\varepsilon''_{\mathrm{NaCl}} > \varepsilon''_{\mathrm{NaHCO_3}} > \varepsilon''_{\mathrm{Na_2SO_4}}$ at constant salinity.

Soil conductivity is affected not only by salinity but also by salt ion characteristics. Na and Cl in soil solution have the greatest influence on conductivity, causing $\varepsilon''_{\mathrm{Na_2SO_4\text{-}NaCl}} > \varepsilon''_{\mathrm{NaCl\text{-}Na_2SO_4}}$. The patterns of ε'' for both saline soil types indicate that while salinity affects both ε' and ε'', they are not independent. Developing dielectric models for saline soils must consider salinity effects on both components; ignoring salt types may introduce errors in salinity estimation.

4.2 Effects of Texture on Soil Microwave Dielectric Properties

Texture effects on dielectric properties can be significant, especially for fine-textured soils. Differences among dry soils of different textures mainly appear at low frequencies (0.3–5.0 GHz), where salinity and texture notably affect ε'. Salinity significantly affects Soil No. 1 dielectric properties, consistent with previous research showing salt and texture effects on ε' are more evident below 5.0 GHz.

At 0% water content, dielectric loss comes from soil matrix properties. However, salinity shows no obvious effect on Soil No. 2 and No. 3 dielectric constants, likely due to texture. In fine-grained dry soils, salt adheres to particle surfaces, indirectly changing air proportion and causing dielectric constant to be affected by both mechanical composition and salinity. Soil No. 1 has high sand content (51.09%–73.31%) and large air proportion, so salt content doesn't significantly affect air proportion. This suggests microwave remote sensing can potentially monitor salinization in fine-grained soils (with lower sand content) under dry surface conditions in arid and semi-arid regions.

At low frequencies, wet saline soils of different textures show clear differences, with $\varepsilon''_{\text{silty loam}}$ being smallest and $\varepsilon''_{\text{loamy sand}} > \varepsilon''_{\text{sandy loam}} > \varepsilon''_{\text{silty loam}}$. This occurs because Soil No. 1 is finer-textured. Additionally, texture differences may cause actual water content variations when configuring samples with the same gravimetric water content, as clay content affects soil dielectric polarization.

In salinity estimation models, M'' outperforms ε' and ε'', with R^2 of 0.48–0.56 for ε' models, indicating M'' better reflects dielectric characteristics of different salinities and that salinity simultaneously affects both components. Important frequencies are concentrated in low frequencies ($f < 5.0$ GHz), where M'' shows strong response to salinity. Combining experimental analysis with machine learning to identify important dielectric constants and frequency ranges provides a foundation for developing saline soil dielectric models and monitoring salinization using spaceborne radar sensors.

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5. Conclusion

This study measured dielectric constants of soils with different water contents, salinity levels, and salt types using a microwave network analyzer, and investigated effects of water content, salinity, salt type, and texture on soil dielectric properties. RF algorithms were used to develop soil salinity estimation models and identify dielectric constants and frequency ranges closely related to soil salinity. Main conclusions are:

1. The complex dielectric constant ε^* is affected by salinity. At 0% water content, ε' of silty loam decreases with salinity at fixed frequency. At certain water contents, ε' of all three textures decreases with salinity, while ε'' increases with salinity, particularly in the 0.3–5.0 GHz range.
2. For wet saline soils of the same class, Na SO -NaCl type has greater impact on ε'' than NaCl-Na SO type at 0.3 GHz frequency, with $\varepsilon''_{\text{Na}_2\text{SO}_4\text{-NaCl}} > \varepsilon''_{\text{NaCl-Na}_2\text{SO}_4}$. M'' is more sensitive to salinity than ε' and ε''.
3. Texture affects soil dielectric properties. For dry silty loam, ε' differences are evident at low frequencies; for wet saline soils, texture effects on ε' are most significant, generally following $\varepsilon''_{\text{loamy sand}} > \varepsilon''_{\text{sandy loam}} > \varepsilon''_{\text{silty loam}}$.
4. The M''-based RF model effectively estimates soil salinity, with important frequencies concentrated in the 0.3–5.0 GHz range. This experimental study combined with machine learning analysis provides recommendations for developing saline soil dielectric models and is significant for monitoring soil salinization using radar sensors.

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