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Quantitative evaluation of soil ion content using an imaginary part model of soil dielectric constant

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ABSTRACT: An imaginary part model of soil dielectric constant for predicting the soil salinity status was developed based on a series of relations between dielectric imaginary part and soil bulk conductivity, soil bulk conductivity and soil solution electrical conductivity, and soil solution electrical conductivity and ion contents in soil using pot trials with different soil salinity levels in the 2008 growing season. This model was calibrated and tested with data from the 2009 growing season. The results showed that the inverted values of the total concentration of salt (Sc), Cl^-, and Ca^{2+} at low frequencies (P-band of microwave observations) from the imaginary part model fitted well with the observed values, since root mean square errors (RMSEs) were 0.34 g kg^{-1}, 0.09 g kg^{-1} and 0.13 g kg^{-1}, respectively, but the inversion effect of Na^+ was relatively poor. Moreover, the Sc, Cl^-, and Na^+ could be well inverted at high frequencies (C-band of microwave observations), since RMSEs were minor, with values of 0.25 g kg^{-1}, 0.02 g kg^{-1}, and 0.15 g kg^{-1}, respectively. The close fit between the observed and inverted values indicated that the present models could be used to estimate soil ion content quickly and reliably under different saline conditions, which, when suitable measures are taken, can be used to reduce the effects of soil salinity on crop growth.
Keywords: microwave sensing, prediction, soil salinity

Introduction

At the turn of the century salt-affected land worldwide was more than 77 million hectares and approximately 43 million hectares of land was suffering from secondary salinization (FAO, 2000). Salinity stress has become one of the major soil problems in agricultural production, and many agriculture experts have turned their attention to the improving saline soil (Richards, 1954). Usually, soil salinization has been detected using traditional chemical methods which have proved to be exceptionally labor intensive and time wasting (Shrestha and Farshad, 2008). This has been expected to lead to the rapid development of inexpensive tools for assessing soil salinity (Metternicht and Zinck, 2003). Several researchers have attempted to identify soil salinity status using visible and near-infrared waves (Peñuelas et al., 1997; Wiegand et al., 1994). However, given that the amount of soil salt detected using remote sensing is higher than the actual value (Sreenivas et al., 1995), there is a need to evaluate sensors that use electrical properties such as microwave radars.

Compared with optical sensing, microwave sensing offers expressive advantages for detecting soil conditions. Several studies have utilized C-band, P-band and L-band to detect the characterization of soil (Sreenivas et al., 1995; Taylor and Mah, 1996; Xiong and Shao, 2006). Several mixing models of dielectric constant have been conducted on the soil-water systems, such as the four-component mixing model and the Dobson semi-empirical model (Wang and Schmugge, 1980; Dobson et al., 1985; Jackson and O'Neill, 1987; Peplinski et al., 1995). However, the models are not applicable to all particular kinds of soil. When soils have a high salt content, the conductance of soil will be high, and the imaginary part of dielectric constant in this case will also be higher, indicating that the imaginary part of dielectric constant is more dependent on the salt ion in soil media (Sreenivas et al., 1995; Bell et al., 2001). Xiong and Shao (2006) also reported that the influences of salinity on dielectric constant should be specifically considered. In recent years, the rapid development of microwave remote sensing enables us to measure the imaginary part of dielectric constant speedily and easily. If we could establish the relation between the imaginary part of dielectric constant and soil ion contents, measuring the soil ion concentrations would be a very easy task, which will reduce labor intensity and save time. Consequently, this study tried to construct an imaginary part model of a dielectric constant to monitor the soil ion contents.

Materials and Methods

Experimental design

A pots experiment was conducted in a half open greenhouse construction to control precipitation in 2008 and 2009 in Nanjing, China (32°02′ N, 118°50′ E, 26 m). Cotton cultivars CCRI-44 and Sumian 12 were used. Seeds were planted in a nursery bed on 25 Apr in 2008 and 2009. At the three true leaves stage, seedlings were transplanted into plastic pots. Pot size was 50 cm high and 33 cm wide and the pots were filled with air dried soil (30 kg per pot) after passing through a 2 mm sieve. The soil was collected from the topsoil layer (0-30 cm) in the experimental field and the physical and chemical properties of the soil are presented in Table 1.

Table 1 – Nutrients contents, physical and chemical properties of the basic soil in 2008 and 2009.

Year	Nutrient content (mg kg^{-1})			Physical and chemical properties										
	TNC[a]	APC[b]	AKC[c]	pH	BD[d]	FWC[e]	EC[f]	HCO_3^-	SO_4^{2-}	Cl^-	Ca^{2+}	Mg^{2+}	Na^+	K^+
					g cm^{-3}	%	ds m^{-1}	cmol kg^{-1}						
2008	1.11×10^3	27.83	132.73	6.62	1.23	28.55	1.22	0.21	4.72	0.53	1.96	0.37	5.33	0.29
2009	0.92×10^3	31.94	120.55	7.80	1.27	28.02	1.25	0.19	4.52	0.53	2.06	0.40	5.66	0.33

[a]Total N content; [b]Available P content; [c]Available K content; [d]Bulk density; [e]Field water capacity; [f]Electrical conductivity.

Seven types of salt ($NaHCO_3$: Na_2CO_3 : NaCl : $MgSO_4$: $CaCl_2$: $MgCl_2$: Na_2SO_4 = 1:1:1:1:1:1:1) were mixed into the sieved soils before starting the experiment (Zhang et al., 2012). Five levels of salinity were designated as 0 mg kg^{-1} (CK, control), 35 mg kg^{-1} (S1), 60 mg kg^{-1} (S2), 85 mg kg^{-1} (S3) and 100 mg kg^{-1} (S4), which corresponded to the soil solution conductivity (soil:water = 1:5) of 1.25, 5.80, 9.61, 13.23, and 14.65 dS m^{-1}, respectively, and were similar to the local coastal saline soil (Zhang et al., 2012). The layout of the pots was random. Each treatment had 20 pots considered as 20 replications. The dielectric constant and soil ion content were recorded on 1 June (seedling stage), 3 July (budding stage), 15 Aug (boll-setting stage) and 10 Sept (boll-opening stage) in both years.

Laboratory analysis

For each treatment, four replicate soil cores (diameter = 3 cm, depth = 20 cm) were selected and mixed. The instantaneous soil water content was measured using the gravimetric method after the soil samples were dried at 105 °C (Zhang et al., 2012). The soil was filled in an aluminum cup to a known volume. All soil samples required distilled water to be added to treat the soil water content as the original measurement. After 24 h an open-ended coaxial probe and a network analyzer were used to measure the imaginary part of dielectric properties at 0.5 GHz (P-band) and 5.25 GHz (C-band). To perform these measurements, the probe tip was inserted in the material and was kept in close contact with the material, and the ancillary software of the network analyzer extracted the imaginary part from the reflected signal. Additionally, EC, pH, and salt compositions in the soil-water (1:5) extract were assayed by the standard methods (Liu et al., 2008; Zhang et al., 2017).

Statistical analysis

The data collected in 2008 were used to develop the imaginary part model of the dielectric constant. The model was tested using independent data from 2009. Root mean square error (RMSE) values were used to evaluate the goodness of fit between predicted values and observed values in the 1:1 plotting of the two sets of values. The RMSE is calculated using the following equation:

$$RMSE = \sqrt{\frac{1}{n}\sum_{j=1}^{n}\left(Y_j - X_j\right)^2} \quad 1$$

where Y_j are the predicted values, X_j the observed values, and n the sample number.

All statistical calculations were performed using the SPSS program (version 16.0).

Results and Discussion

Effects of soil salinity on the ion content in soil

The results in Table 2 showed that as the growth stage progressed, the concentration of Na^+, K^+, Ca^{2+}, Mg^{2+}, HCO_3^-, Cl^-, SO_4^{2-} decreased, although the decreasing amplitude became larger as the soil salinity increased, differing from the former study in the field (Van Hoorn et al., 1997). The concentration of Na^+, K^+, Ca^{2+}, Mg^{2+}, HCO_3^-, Cl^-, and SO_4^{2-} increased with elevated soil salinity at every growth stage of cotton, suggesting that soil salinity had significant effects on ion content in soil.

Model development

Xiong and Shao (2006) built an imaginary part model for a mixture of water and soil to which with sodium chloride based on a series of relations was added. According to the guiding ideology of establishing the model in an experiment, the imaginary part model in our study can utilize the method of relationship derivation to connect the imaginary part of dielectric constant to the soil ion content. Previous studies have reported the relation between dielectric imaginary part and soil bulk conductivity (Xiong and Shao, 2006), and that between soil bulk conductivity and soil solution electrical conductivity (Shainberg et al., 1980). In the current experiment, we needed to establish the relation between soil solution electrical conductivity and soil ion contents. Then, based on the series of relationships, we could use the easily measured imaginary part of dielectric constant to predict the soil salinity status. The detailed derivation process was described in the following subsections.

The relation between the imaginary part of the soil dielectric constant and soil bulk electrical conductivity

Soil is a complex of air, water, and soil particles. The imaginary part of the soil dielectric permittivity is usually expressed in terms of dielectric losses, which are influenced by soil electrical conductivity and the soil itself (Corwin and Lesch, 2003). Previous research has shown that electrical conductivity loss plays a very important role in determining the imaginary part of dielectric constant (ε'') at both low and high frequency, the relaxation

Table 2 – Changes of ion contents in cotton pots under different soil salinity rates in 2008.

Growth stage	Salinity rate (dS m^{-1})	Ion content (g kg^{-1})						
		HCO_3^-	Cl^-	SO_4^{2-}	Ca^{2+}	Mg^{2+}	K^+	Na^+
Seedling stage	1.25	0.0091 e	0.0111 e	0.0193 e	0.1700 e	0.1098 e	0.0069 e	0.1250 e
	5.80	0.0104 d	0.0554 d	0.0362 d	0.4000 d	0.1891 d	0.0137 d	0.3625 d
	9.61	0.0131 c	0.1365 c	0.0610 c	0.4720 c	0.2097 c	0.0200 c	0.7125 c
	13.23	0.0143 b	0.1418 b	0.0696 b	0.5500 b	0.2745 b	0.0227 b	0.8515 b
	14.65	0.0151 a	0.1737 a	0.0720 a	0.5950 a	0.3172 a	0.0288 a	1.0875 a
Budding stage	1.25	0.0086 e	0.0113 e	0.0176 e	0.1410 e	0.0732 d	0.0068 e	0.0800 e
	5.80	0.0095 d	0.0456 d	0.0286 d	0.3815 d	0.1542 c	0.0113 d	0.2722 d
	9.61	0.0116 c	0.0886 c	0.0534 c	0.4800 c	0.1543 c	0.0187 c	0.6375 c
	13.23	0.0125 b	0.1108 b	0.0581 b	0.5161 b	0.2562 b	0.0207 b	0.8125 b
	14.65	0.0137 a	0.1586 a	0.0672 a	0.5616 a	0.2928 a	0.0275 a	1.0250 a
Flowering and boll-forming stage	1.25	0.0056 e	0.0119 d	0.0168 c	0.1200 e	0.0632 e	0.0068 e	0.0625 e
	5.80	0.0076 d	0.0326 c	0.0345 b	0.3466 d	0.1325 d	0.0103 d	0.2253 d
	9.61	0.0104 c	0.0905 b	0.0432 b	0.4200 c	0.1769 c	0.0150 c	0.5875 c
	13.23	0.0110 b	0.0959 b	0.0480 ab	0.4594 b	0.2075 b	0.0188 b	0.6875 b
	14.65	0.0119 a	0.1489 a	0.0600 a	0.4900 a	0.2135 a	0.0237 a	0.8875 a
Boll-opening stage	1.25	0.0043 e	0.0115 e	0.0144 e	0.1406 d	0.0405 d	0.0065 d	0.0250 e
	5.80	0.0070 d	0.0316 d	0.0240 d	0.3066 c	0.0793 c	0.0068 d	0.2125 d
	9.61	0.0092 c	0.0642 c	0.0331 c	0.3900 b	0.1281 b	0.0113 c	0.4375 c
	13.23	0.0103 b	0.0717 b	0.0336 b	0.3905 b	0.1342 b	0.0137 b	0.6750 b
	14.65	0.0110 a	0.1294 a	0.0480 a	0.4200 a	0.1575 a	0.0225 a	0.7750 a

For each growth stage, different letters in the same column indicate a significant difference at 0.05 level.

loss becomes a more important factor (Zhang et al., 2012). Xiong and Shao (2006) have proved that dielectric losses of deionized water could be ignored at low frequency, but should be considered at high frequency. Moreover, a linear regression relationship was detected between ε″ and soil bulk conductivity (σ_a) at both low and high frequency in their experiment. Combining this knowledge with the relationship between ε″ and σ_a, the equation of ε″ was generated with a relatively simple form and a high degree of accuracy for both low and high frequencies.

At low frequency (P- band), a linear regression analysis was conducted between ε″ and σ_a.

$$\varepsilon'' = 2.1577\sigma_a - 2.7142 \quad (n=40,\ R^2=0.86) \quad f < 3\ Ghz \qquad 2$$

where f is the frequency. At high frequency (C-band), the dielectric loss caused by water cannot be ignored (Zhang et al., 2012). Thus, considering the water dielectric loss, ε″ calculated as:

$$\varepsilon'' = 0.446M_v\varepsilon''_w + 0.527\sigma_a - 4.995 \quad (n=40,\ R^2=0.84) \quad f \geq 3\ Ghz \qquad 3$$

where ε_w'' is the imaginary part of dielectric constant of deionized water, σ_a a constant at constant temperature, and M_v the soil volume water content.

The relation between soil bulk electrical conductivity and electrical conductivity of soil solution

The σ_a can serve as an indicator of soil salinity. Accordingly, σ_a is represented by the summation of two terms (Shainberg et al., 1980):

$$\sigma_a = c\sigma_w + \sigma \qquad 4$$

where c is a geometry factor, σ_w the electrical conductivities of the 1:5 soil-water extract and σ_s the matrix surface. At a high solution concentration, σ_s approaches an ultimate value, and equation (4) becomes a linear function of σ_w (Mualem and Friedman, 1991). However, as the soil water content increases, σ_a is further affected by the soil volumetric water content. Accounting for this effect, a new relationship for σ_a and σ_w was developed as follows:

$$\sigma_a = 3.341\sigma_w M_v + 0.810 \quad (n = 40,\ R^2 = 0.88) \qquad 5$$

The relation between electrical conductivity of soil solution and soil ion content

Soil salinity is quantified based on the total concentrations of salts, which could be indicated by the electrical conductivity of soil-water solution (dS m^{-1}) (Corwin and Lesch, 2005). However, the chemical composition also affects soil electrical conductivity. McNeal et al. (1970) established a relationship between electrical conductivity of soil-water solution and molar concentrations of salts. Griffin and Jurinak (1973) also detected a linear regression relationship between soil electrical conductivity and the ion contents of soils to which only NaCl was added. However, when soil salinity is indicated by σ_w, many factors, such as total salinity and soil salt composition will affect the measurement of σ_w of saline soil. For example, Zhang et al., (2017) found that the σ_w was higher in the water-soil system with high salt content relative to the water-soil system with low salt content. Correlation analyses were conducted between the dependent variable σ_w and independent variables including total salt content of soils, ion concentration, sodium adsorption ratio, and sodium dianion ratio (SDR) (Table 3).

Related factors such as total concentration of salt (Sc), Cl^-, Ca^{2+} and Na^+ had significant correlations ($R^2 > 0.90$) with σ_w of saline soil, indicating Sc, Cl^-, Ca^{2+}, and Na^+ were important factors when determining σ_w. Regression functions between σ_w and Sc, Cl^-, Ca^{2+} as well as Na^+ contents were established as follows:

$$\sigma_w = 4.222S_c + 0.474 \quad (n=40,\ R^2=0.92) \quad 6$$

$$\sigma_w = 6.028Ca^{2+} + 2.806S_c + 0.040 \quad (n=40,\ R^2=0.94) \quad 7$$

$$\sigma_w = 8.613Cl^- + 5.796Ca^{2+} + 2.150S_c + 0.223 \quad (n=40,\ R^2=0.94) \quad 8$$

$$\sigma_w = 2.028Cl^- + 0.122Ca^{2+} - 6.392Na^+ + 7.488S_c - 0.201 \quad (n=40,\ R^2=0.95) \quad 9$$

where S_c is the total concentration of salt, Cl^- the concentration of anion Cl^- in g kg^{-1}, Ca^{2+} the concentration of cation Ca^{2+} in g kg^{-1}, and Na^+ the concentration of cation Na^+ in g kg^{-1}.

Inversion of soil ion content based on the imaginary part model of dielectric constant

The data in 2009 were used for verifying the developed model. In Figure 1, a comparison of the inversed and observed values of Sc, Cl^-, Ca^{2+} and Na^+, was presented at different salinity levels at low frequency (P-band). A very strong agreement between the inversed and observed data was noted for Sc, Cl^- and Ca^{2+} (R^2 were 0.94, 0.69, 0.80, and RMSE were 0.34 g kg^{-1}, 0.09 g kg^{-1}, 0.13 g kg^{-1} for Sc, Cl^-, Ca^{2+}, respectively) (Table 4). As regards the Na^+, a large error occurring at low frequency (P-band) (R^2 and RMSE were 0.0015 and 0.21 g kg^{-1}, respectively), indicated that the Na^+ content in soil cannot be predicted well at low frequency using the model. The results in Figure 2 show a comparison of the inversed values and the observed values of Sc, Cl^-, Ca^{2+}, and Na^+ at high frequency (C-band). The good results were observed for Sc, Cl^- and Na^+ (R^2 were 0.87, 0.84, 0.82 and RMSE were 0.25 g kg^{-1}, 0.02 g kg^{-1}, 0.15 g kg^{-1} for Sc, Cl^-, Na^+, respectively), although the inversed Ca^{2+} values were lower than the observed values where Ca^{2+} content was high at high frequency (C-band) (R^2 and RMSE were 0.81 and 0.21 g kg^{-1}, respectively). These results showed the potential of this inversion model to accurately invert Sc, Cl^-, Ca^{2+}, and Na^+ in saline soil at both low and high frequencies. Compared to previous models constructed under signal NaCl salinity to estimate the soil electrical conductivity (Leao et al., 2010), our simulation could be used to further invert the ion content based on the imaginary part of soil dielectric constant. Xiong and Shao (2006) have also constructed an imaginary part model of soil dielectric constant to invert the total salt contents. However, their experiment was conducted in NaCl salinity only, but our experiment involved the inversion of a variety of salt ions. Wei et al. (2017) tried to obtain a new imaginary part model of dielectric constant for the salt soil by improving the Dobson semi-empirical model used in a water-soil system, but the modified imaginary part model was easily affected by the water content in soil, resulting in low accuracy in the model. However, the model developed in our experiment is highly reliable for predicting total salt and multiple ion concentrations, which was conducive to providing information for proper soil management.

Our experiment was carried out using pots. The practicability of the model for the saline field under wider moisture conditions can be further tested. Furthermore, other factors, such as soil texture, can influence the soil dielectric constant (Hallikainen et al., 1985; Sreenivas et al., 1995). Thus, further adjustment of the model should include further consideration of the soil texture under more variable environmental conditions.

Table 3 – Correlation coefficients between chemical properties of soil extract and EC, and between any two chemical properties of soil extract.

Item	$EC_{1:5}$	HCO_3^-	Cl^-	SO_4^{2-}	Ca^{2+}	Mg^{2+}	K^+	Na^+	Sc[a]	SSP[b]	SDR[c]	SAR[d]
$EC_{1:5}$	1.00											
HCO_3	0.78	1.00										
Cl^-	0.94	0.73	1.00									
SO_4^{2-}	0.88	0.64	0.92	1.00								
Ca^{2+}	0.94	0.74	0.91	0.86	1.00							
Mg^{2+}	0.81	0.65	0.75	0.72	0.70	1.00						
K^+	0.83	0.60	0.87	0.82	0.81	0.61	1.00					
Na^+	0.90	0.70	0.93	0.91	0.85	0.70	0.86	1.00				
Sc	0.96	0.75	0.97	0.93	0.93	0.79	0.87	0.98	1.00			
SSP	0.43	0.29	0.47	0.50	0.32	0.22	0.46	0.66	0.54	1.00		
SDR	0.26	0.19	0.32	0.36	0.14	0.08	0.32	0.53	0.38	0.97	1.00	
SAR	0.78	0.59	0.82	0.83	0.71	0.55	0.78	0.96	0.88	0.84	0.74	1.00

[a]The total concentration of salt; [b]The soluble sodium percentage (%), SSP = $100Na^+/[2(Ca^{2+} + Mg^{2+}) + Na^+]$; [c]The sodium dianion ratio, SDR = $Na^+/[2(Ca^{2+} + Mg^{2+})]$; [d]The sodium adsorption ratio; SAR = $Na^+/(Ca^{2+}+Mg^{2+})1/2$, n = 40, $r_{0.05} = 0.3$, $r_{0.01} = 0.4$.

Table 4 – Testing results of the imaginary part of dielectric constant model at low frequency (P-band) and at high frequency (C-band).

Frequency	Ion content	Regression equations	R^2	RMSE
P-band	Sc[a]	y = 0.8821x + 0.1669	0.69	0.34
	Cl^-	y = 1.1014x - 0.0099	0.80	0.09
	Na^+	y = -0.07x + 0.5589	0.0015	0.21
	Ca^{2+}	y = 1.8238x - 0.1966	0.82	0.13
C-band	Sc	y = 0.9383x - 0.0298	0.87	0.25
	Cl^-	y = 0.9274x - 0.0043	0.81	0.02
	Na^+	y = 0.9095x - 0.0106	0.84	0.15
	Ca^{2+}	y = 0.8475x - 0.0051	0.94	0.21

[a]The total concentration of salt.

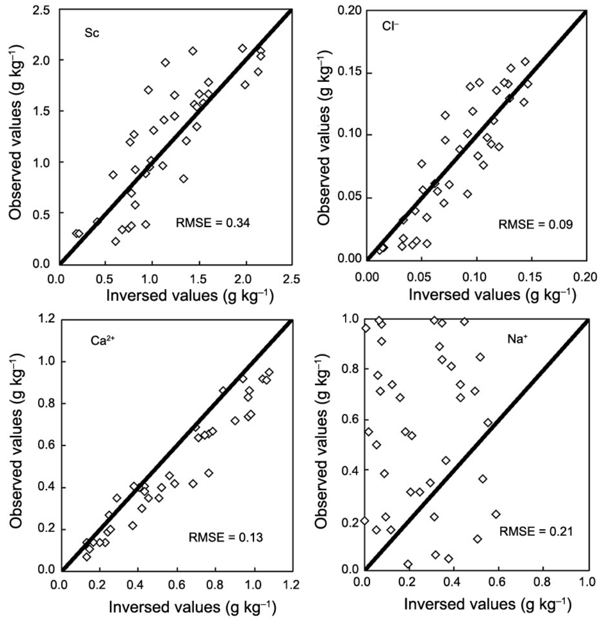

Figure 1 – Comparison between the inversed and the observed values of total salt (Sc), Cl^-, Ca^{2+} and Na^+ contents based on the imaginary part of dielectric constant model at low frequency (n = 40).

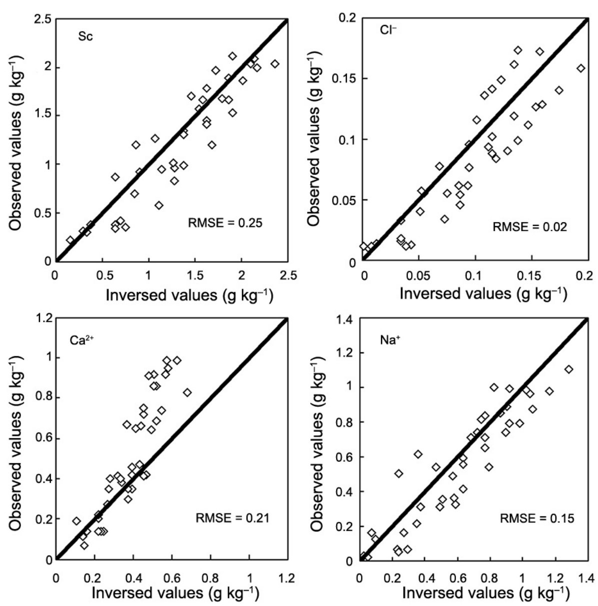

Figure 2 – Comparison between the inversed and the observed values of total salt (Sc), Cl^-, Ca^{2+} and Na^+ contents based on the imaginary part of dielectric constant model at high frequency (n = 40).

This study is the first attempt to characterize a group of soils with a wide range of soil ion content, and develop a new dielectric constant model relating to ε'' and soil ion content. This model inverts the soil ion content easily, which could provide references for producers to take appropriate measures to reduce the effects of soil salinity on crop growth.

Conclusions

In the present study, an imaginary part model of soil dielectric constant was constructed by studying the relations between the imaginary part of the dielectric constant and soil bulk conductivity, soil bulk conductivity and soil solution conductivity, and, finally, soil solution conductivity and the soil ion contents. The comparison between inverted values and observed values indicated that the soil ion contents (Sc, Cl^-, Ca^{2+} and Na^+) at different soil salinity levels could be well inverted using the imaginary part model of the dielectric constant. The present experiment confirmed the potential of microwave sensing in monitoring ion contents in soil. In the future, we shall also need to conduct more trials in the field with a wider range of soil textures and salt components.

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Authors' Contributions

Conceptualization: Zhou, Z.G. Data acquisition: Hu, W.; Zhang, L.; Chen, B.L. Data analysis: Hu, W.; Zhang, L. Design of Methodology: Hu, W.; Zhang, L.; Chen, B.L.; Zhou, Z.G. Writing and editing: Hu, W.; Zhang, L.; Zhou, Z.G.

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