

# Experiments on the Control of Salinity and Sodicity in Surface-Irrigated Fields in the Upper Yellow River Valley (IV) : Tools for Analysing Soil Salinity and Sodicity and Related Properties of the Field Soils

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<https://doi.org/10.5109/12870>

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出版情報 : 九州大学大学院農学研究院紀要. 53 (2), pp.535-541, 2008-10-28. Faculty of Agriculture, Kyushu University

バージョン :

権利関係 :



## Experiments on the Control of Salinity and Sodicity in Surface-Irrigated Fields in the Upper Yellow River Valley (IV)

### Tools for Analyzing Soil Salinity and Sodicity and Related Properties of the Field Soils

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(Received June 27, 2008 and accepted July 16, 2008)

The electrical conductivity of the solution in a saturated soil,  $EC_{SAT}$ , which is determined by the dilution extraction (DE) method, is used in these experiments. The DE method is based on a regression equation of the electrical conductivity of the extract of the soil sample at 1: $x$  soil–water ratio,  $EC_{1:x}$ , on  $x$ . The  $EC_{SAT}$  can also be measured automatically using time domain reflectometry (TDR) in the field, when the parameters of two models have to be identified for the soil concerned. The concentrations of exchangeable ions, such as  $Na^+$ , in the solution in a saturated soil, such as  $[Na^+]_{SAT}$ , are used as well. They are also determined by the DE method.

The physical properties of the field soils of the Pingbu experimental field and the parameters of the two models identified for the typical soil in the field were presented. Example measurements of time changes in the depth profiles of volumetric soil water content and  $EC_{SAT}$  obtained in the field were also illustrated. Further, a comparison of the regression equations of  $EC_{1:x}$  on  $x$  and  $[Na^+]_{1:x}$  on  $x$  for several soil samples with different salinities was made. The results suggest that the difference in the concentration of an ion between the bulk solution and the electric double layer, or the diffusive force acting on the ion influences the power exponent in the regression equation for the ion.

**Keywords:** dilution extraction method, electrical conductivity, irrigation, ion concentration, TDR

## INTRODUCTION

A situation in which excess salts are contained in surface soils is common in arid and semiarid regions where evapotranspiration exceeds precipitation. These salts are derived from a number of sources, including *in situ* weathering, saline water bodies (cyclic salts), atmospheric depositions, sedimentary rocks (fossil salts), and anthropogenic activities (secondary salinization sources) (Essington, 2004). Fossil salts, which enter the ground and surface waters through the dissolution of sedimentary rock, are a primary salt source; however, soil salinization with fossil salts is an anthropogenic process because they enter the soil with irrigation waters. Ineffective leaching of salts and/or the inadequate removal of drainage water are the processes that facilitate the buildup of salts in soil. Therefore, a sufficient knowledge about the soil properties related to water movement and

leaching of salts in the soil profile is indispensable to control soil salinization and alkalization.

This paper describes the physical properties of the soils sampled at the Pingbu experimental field (Wang *et al.*, 2008; Yoshikoshi *et al.*, 2008; Yasutake *et al.*, 2008), the parameters of the models that are used for estimating soil wetness and salinity, which were identified for the typical soil in the field, and an index showing the concentration of an ion in soil solution, which is determined by the dilution extraction method (Yasutake *et al.*, 2008). A lot of research workers and students have made experiments on the field soils for their own objectives, and their results are collected in this paper in order that the full information on the properties of the field soils and tools used in these experiments for analyzing soil salinity and sodicity can be obtained.

## SOIL SAMPLING

Sample soils were taken around two TDR measurement points (P1, P3) in the field (**Fig. 1**). P1 was located in the most salt-affected part and P3 in the least salinized part of the field. The geological stratum at a site where a pumping up well (#3) was drilled is shown in **Fig. 2**.

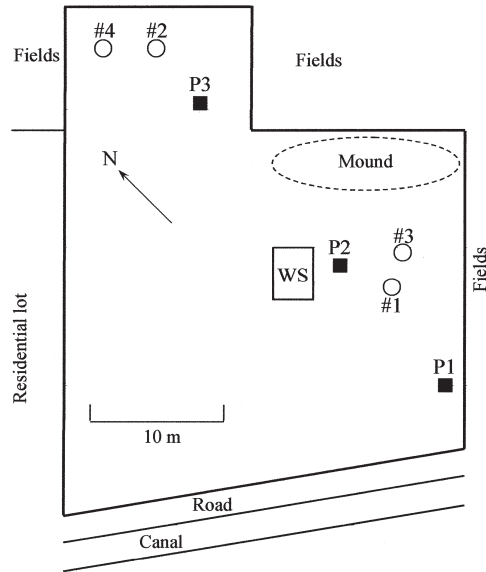
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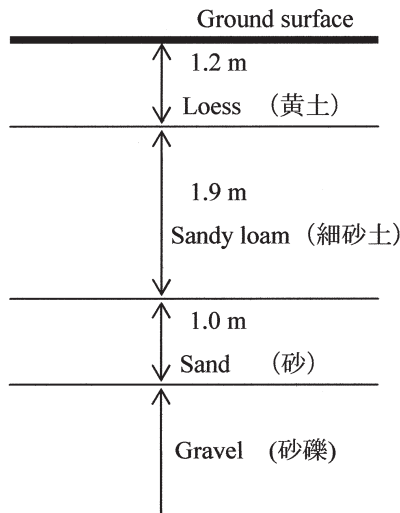
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**Fig. 1.** A ground plan of the Pingbu experimental field. WS: weather station, ○: well, ■: TDR. Two wells, #3 and #4, were drilled in March 2008.



**Fig. 2.** The geological stratum at the site where a well #3 was drilled.

### PHYSICAL PROPERTIES

**Table 1** shows the physical properties of the field soils collected around P1 and P3. The  $x_{SAT}$  designates the value for the mass ratio of water to soil,  $x$ , when the soil is saturated, or  $\theta = \varepsilon$ .

$$x = \frac{\theta \rho_w}{(1-\varepsilon) \rho_s} \quad (1)$$

where  $\theta$ : volumetric water content,  $\rho_s$ : porosity,  $\rho_w$ : density of liquid water,  $\rho_s$ : density of soil particles.

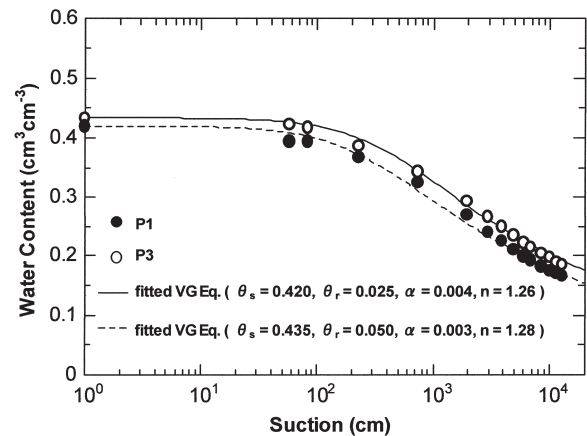
**Figure 3** shows the matric potential (suction) – water content relations for the two soils. The curve depicts a van Genuchten equation fit to the measurements (Jury and Horton, 2004; Yoshikoshi *et al.*, 2008). **Fig. 4** shows the matric potential (suction) – hydraulic

conductivity relations for the soils obtained by the van Genuchten parametric model (Jury and Horton, 2004; Yoshikoshi *et al.*, 2008).

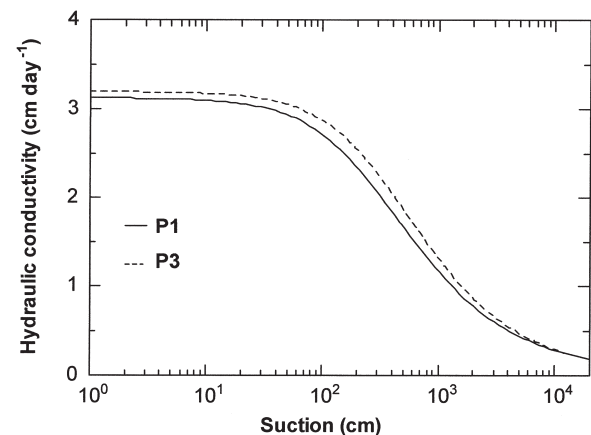
**Table 1.** Physical properties of the field soils

Particle size (mm)	P1	P3
	% by weight	
< 0.002	14.9	14.7
0.002~0.075	74.2	72.1
0.075~0.25	10.9	13.2
0.25~0.85	0	0
0.85~2	0	0
Particle density ( $\text{g cm}^{-3}$ )	2.71	2.68
Dry density ( $\text{g cm}^{-3}$ )	1.60	1.52
Porosity (-)	0.41	0.43
$x_{SAT}$	0.26	0.28
Saturated hydraulic conductivity ( $\text{cm s}^{-1}$ )	$3.62 \times 10^{-5}$	$3.70 \times 10^{-5}$
( $\text{cm day}^{-1}$ )	3.12	3.20

P1 and P3 are TDR measurement points (Fig. 1). The definition of  $x$  is given in the text by Eq.(1).



**Fig. 3.** Matric potential (suction) – volumetric water content relations for the field soils (P1 and P3). The curves are van Genuchten equation fits to the measurements.



**Fig. 4.** Matric potential (suction) – hydraulic conductivity relations for the field soils (P1 and P3) obtained by the van Genuchten parametric models. Numerical values for the parameters of each soil are shown in Fig. 3.

## SOIL WATER CONTENT

Sample soils used in the experiments on the identification of model parameters were taken around P3 on 19 Sept. 2007. The electrical conductivity of an aqueous extract of a soil sample at 1:5 soil–water ratio,  $EC_{1:5}$ , for the soil was  $0.7 \text{ dS m}^{-1}$  and  $EC_{SAT}$  was  $4.5 \text{ dS m}^{-1}$  (Eq.5) (Kobayashi *et al.*, 2006; Wang *et al.*, 2008), and the EC of the groundwater in #2 was  $2.2 \text{ dS m}^{-1}$ .

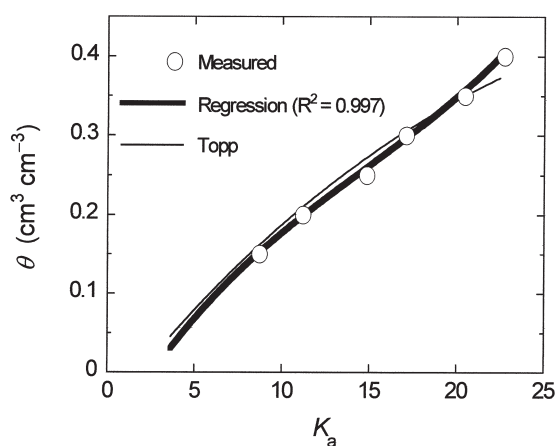
Time domain reflectometry (TDR) sensors were used for the simultaneous measurement of volumetric water content,  $\theta$ , and bulk soil electric conductivity,  $EC_a$ , in this field. The TDR system measures the dielectric constant,  $K_a$ , and connects it with  $\theta$  empirically.

**Figure 5** shows the relation between  $K_a$  and  $\theta$  for the sample soil. The thick line in the figure depicts the following regression equation:

$$\theta = 3.4 \times 10^{-5} K_a^3 - 1.5 \times 10^{-3} K_a^2 + 3.84 \times 10^{-2} K_a - 0.09 \quad (0.15 < \theta < 0.4) \quad (R^2 = 0.997) \quad (2)$$

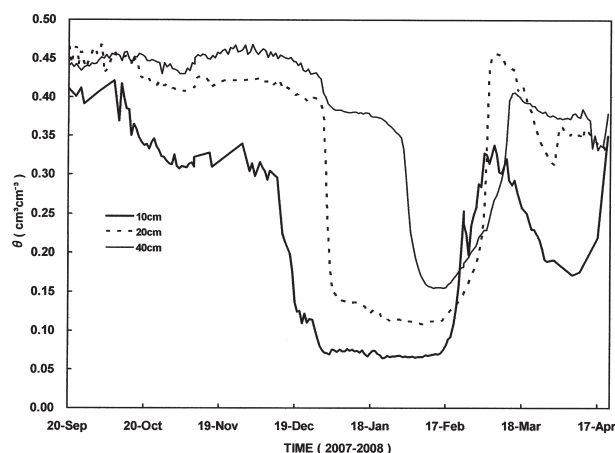
The Topp relation (Topp *et al.*, 1988) also is shown in the figure for reference by a thin line. Since both curves fit each other well and the range of applicability of Eq. (2) is limited, it is recommended to use the Topp relation (Eq.3) for estimating the volumetric water content regardless of soil wetness.

$$\theta = 4.3 \times 10^{-6} K_a^3 - 5.5 \times 10^{-4} K_a^2 + 2.92 \times 10^{-2} K_a - 5.3 \times 10^{-2} \quad (3)$$



**Fig. 5.** Relationship between the TDR permittivity (dielectric constant),  $K_a$ , and volumetric water content,  $\theta$ , for the field soil (P3). The regression equation can be written as Eq.(2). The Topp relation is also plotted for reference.

Example measurements of volumetric liquid water content made at depths of 10 cm, 20 cm and 40 cm at P3 for a period from September 2007 to April 2008 are shown in **Fig. 6**. A post-harvest irrigation was practiced at the end of September; in the top layer of soil, freezing started at the beginning of December and spring thawing started at the end of February (Kaneko *et al.*, 2006); it snowed in the middle of April. These events are appeared in the graphic representation of these measurements.



**Fig. 6.** Time changes in volumetric water content,  $\theta$ , at depths of 10 cm, 20 cm, and 40 cm at P3.

## SOIL SALINITY

Soil solution electrical conductivity ( $EC_w$ )

Dasberg and Dalton (1985) showed that the  $EC_a$  measured by the TDR technique and that calculated from the soil solution electrical conductivity,  $EC_w$ , using a model shown below, agreed within  $\pm 0.1 \text{ dS m}^{-1}$ :

$$EC_a = EC_w T(\theta) + EC_s \quad (4)$$

where  $T$  is a transmission coefficient ( $\leq 1$ ) that is envisaged as correcting for the tortuosity, and  $EC_s$  is the electrical conductivity of the solid phase of the soil due primarily to exchangeable cations adsorbed on clay minerals.

First, the relationship between the amount of dissolved salts and water content was experimentally determined as follows:

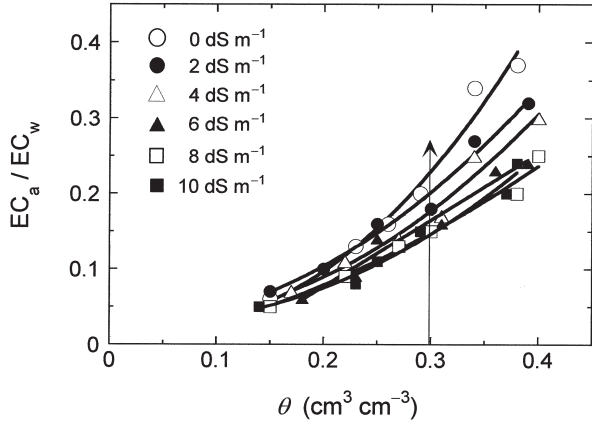
$$EC_{1:x} = 2.0x^{-0.64} \quad \text{dS m}^{-1} \quad (5)$$

where  $EC_{1:x}$  is the electrical conductivity of an aqueous extract of a soil sample at 1: $x$  soil–water ratio and  $x$  is the variable defined by Eq.(1). This regression equation with a power exponent larger than  $-1$  means, if interpreted literally, that the amount of dissolved salts decreases with decreasing water content. However, this seems to be involved in a problem peculiar to the dilution extraction method. This subject will be discussed below.

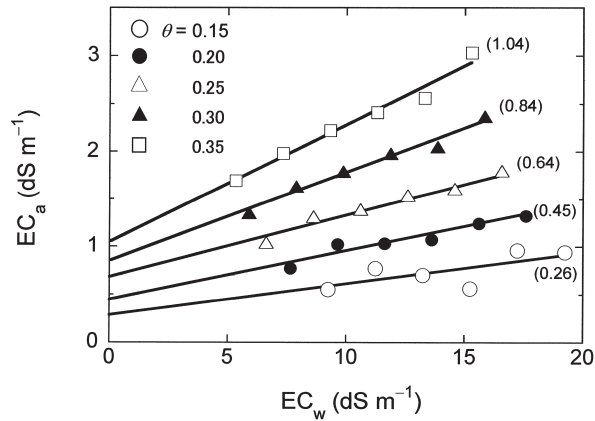
Soil samples were made as follows: A measured volume of one of NaCl solutions of salinity  $EC_{NC}=2, 4, 6, 8, 10 \text{ dS m}^{-1}$ , or of distilled water was sprayed over a weighed amount of oven-dried soil, and they were mixed up and kept air tight for a period longer than several hours. The amount of salts dissolved from soil particles was calculated from Eq.(5) (Kobayashi *et al.*, 2008), which was designated as  $EC'_w$ . Therefore,  $EC_w = EC_{NC} + EC'_w$ . The  $\theta$  and  $EC_a$  of these soil samples were determined using TDR (Yoshikoshi *et al.*, 2008).

**Figure 7** shows the relationship between  $\theta$  and  $EC_a$  /  $EC_w$ . Solid lines depict the regression quadratic curves for the measurements. The numerical values shown in

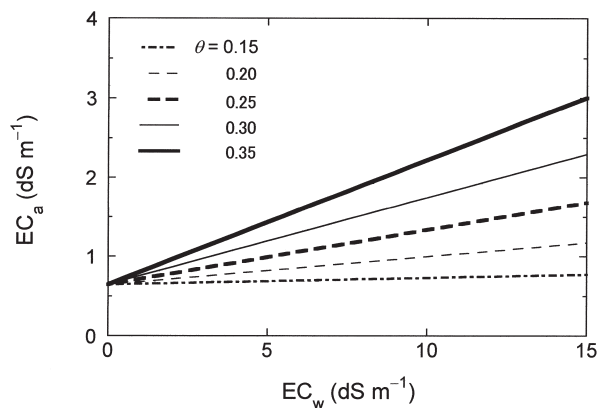
the legend indicate  $EC_{NC}$ . Since the  $EC'_w$  for specified  $\theta$  can be calculated from Eqs.(1) and (5), the relationship between  $EC_w$  and  $EC_a$  can be determined from the intersection of a vertical line drawn through a specified  $\theta$  and



**Fig. 7.** Relationship between  $EC_a / EC_w$  and  $\theta$  for the field soil (P3). Numbers in the legend indicate  $EC_{NC}$ .



**Fig. 8.** Relationship between  $EC_a$  and  $EC_w$  for given values of  $\theta$  for the field soil (P3). Numbers in parentheses indicate the y-intersections of the regression lines.



**Fig. 9.** Relationship between  $EC_a$  and  $EC_w$  when  $EC_s$  is assumed to be  $0.64 \text{ dS m}^{-1}$ .

the curve for a specified  $EC_{NC}$ , which are shown in **Fig. 8**. If this model describes the  $EC_a - EC_w$  relationship correctly, the y-interceptions of the regression equations should be converged into a point, or  $EC_s$  should be a constant. However, as Amente *et al.* (2000) showed,  $EC_s$  increased with decreasing soil water content ( $0.26 \sim 1.04 \text{ dS m}^{-1}$  with an average of  $0.64 \text{ dS m}^{-1}$ ).

In this study, we regard  $EC_s$  as a constant of  $0.64 \text{ dS m}^{-1}$ , and hence the accuracy of the estimates made using this model are not good for extremely dry or wet soil conditions, and also for extremely small and large soil salinities. **Fig. 9** shows the  $EC_a - EC_w$  relationship based on the assumption that  $EC_s$  is  $0.64 \text{ dS m}^{-1}$ .

According to Eq.(4),  $T$  is expressed as:

$$T = \frac{(EC_a - EC_s)}{\theta \cdot EC_w} \quad (6)$$

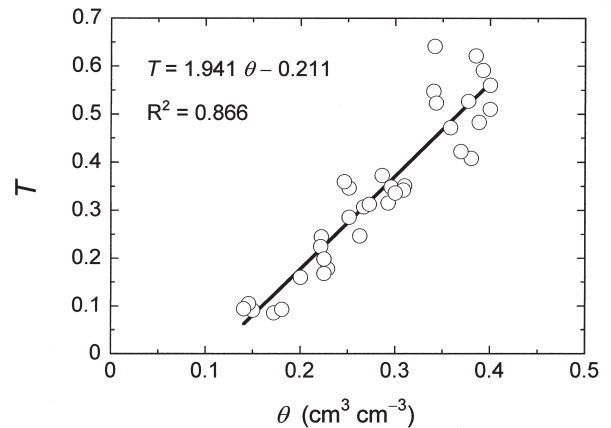
Substituting the numerical values for  $EC_a$ ,  $EC_w$ , and  $EC_s$  in Eq.(6) yields the relationship between  $\theta$  and  $T$  as shown in **Fig. 10**. The regression equation for the soil sampled around P3 is

$$T = 1.941\theta - 0.211 \quad (0.15 < \theta < 0.4) \quad (R^2 = 0.866) \quad (7)$$

Therefore, the mathematical model for the field soil sampled around P3 can be written as:

$$EC_a = EC_w \theta (1.941\theta - 0.211) + 0.64 \quad \text{dS m}^{-1} \quad (8)$$

( $0.15 < \theta < 0.4$ ;  $0.7 < EC_s < 3.0 \text{ dS m}^{-1}$ )



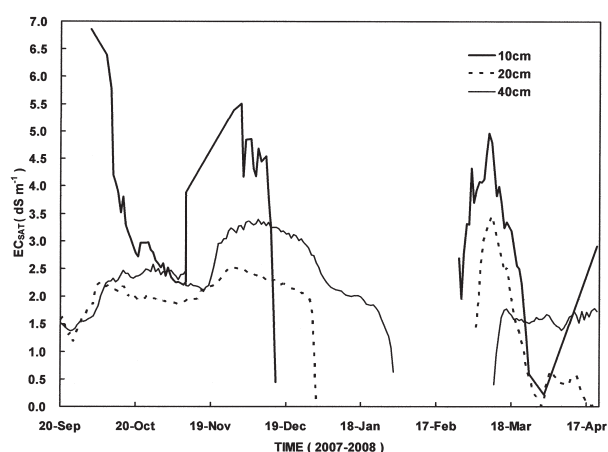
**Fig. 10.** Relationship between  $T$  and  $\theta$  for the field soil (P3).

#### **$EC_w$ in a saturated soil: $EC_{SAT}$**

The electrical conductivity of the solution in a saturated soil,  $EC_{SAT}$ , is calculated from a regression equation of  $EC_{1:x}$  on  $x$  by substituting  $x_{SAT}$  for  $x$  in the equation (**Table 1**) (Kobayashi *et al.*, 2006; Wang *et al.*, 2008). **Table 2** shows the regression equations,  $R^2$  and  $EC_{SAT}$  obtained using the measurements of  $EC_{1:x}$  ( $x=1, 3, 5$ ) made for each sample soil taken at five depths around P1 on 22 April 2008. In this experiment, sample solutions were sucked up with a syringe from the supernatant of the soil sample at 1:x soil–water ratio. As mentioned above, all the power exponents in the regression

**Table 2.** Regression equations of  $y \equiv EC_{1-x}$  on  $x$  ( $x = 1, 3, 5$ ) (Eq.1),  $R^2$  and  $EC_{SAT}$  for sample soils taken at five depths around P1

Point & Depth	Regression equation ( $dSm^{-1}$ )	$R^2$	$EC_{SAT}$ ( $dSm^{-1}$ )
P1: 0 cm	$y=3.209x^{-0.8593}$	0.9999	10.2
10 cm	$y=2.724x^{-0.8259}$	0.9995	8.3
20 cm	$y=0.645x^{-0.7072}$	0.9988	1.7
40 cm	$y=0.502x^{-0.5923}$	0.9927	1.1
60 cm	$y=0.465x^{-0.5378}$	0.9962	1.0

**Fig. 11.** Time changes in  $EC_{SAT}$  at depths of 10 cm, 20 cm, and 40 cm at P3.

equations were larger than  $-1$ , which seemingly means that the amount of dissolved salts in soil pores decreases with decreasing water content. However, Kobayashi *et al.* (2006) conjectured that this was involved in a problem peculiar to the DE method and interpreted this phenomenon based on the mobile-immobile water model (Jury and Horton, 2004) and two assumptions as follows:

- Diffusion processes of soluble salts between the fine and coarse pores become active as the salt concentration in the soil sample decreases.
- The difference in salt concentration between the mobile and immobile water decreases as the salt concentration in the soil sample increases.

The numerical value for the power exponent in the regression equation appears to convey some information on the salt distribution in the solution, which will be further discussed below.

Example measurements of  $EC_{SAT}$  made at depths of 10 cm, 20 cm and 40 cm at P3 for a period from September 2007 to April 2008 are shown in **Fig. 11**. The

$EC_{SAT}$  indicates the total amount of dissolved salts in soil pores and they move with soil water, and hence it seems natural that the peak values for  $EC_{SAT}$  appeared in order of depth after the events of post-harvest irrigation and the spring thaw of frozen soil layers. However, the present model cannot be applied to the frozen soil layers, and hence the data on soil salinity could not be taken during a period when soil water was frozen.

### Concentration of an ion in a saturated soil

Yasutake *et al.* (2008) applied the concept of  $EC_{SAT}$  to the concentration of a specified ion in soil solution. The concentration of exchangeable sodium ion,  $Na^+$ , for example, in the solution in a saturated soil,  $[Na^+]_{SAT}$ , can be calculated from a regression equation of  $[Na^+]_{1-x}$  on  $x$  by substituting  $x_{SAT}$  for  $x$  in the equation. **Table 3** shows the regression equations,  $R^2$  and  $[Na^+]_{SAT}$  obtained using the measurements of  $[Na^+]_{1-x}$  ( $x=1, 3, 5$ ) made for each sample soil taken at five depths of 0 cm, 10 cm, 20 cm, 40 cm, and 60 cm around P1 on 22 April 2008. The sample soils used in this experiment were the same as those used in the  $EC_{SAT}$  determination for the sampling depths of 10 cm, 40 cm and 60 cm. However, the 0-cm and 20-cm sample soils for the two experiments were taken from separate locations. This may be the reason why the  $[Na^+]_{SAT}$  at a depth of 10 cm was larger than that at the soil surface contrary to the case of  $EC_{SAT}$  in which  $EC_{SAT}$  decreased with increasing depth. As in the case of  $EC_{SAT}$ , all the power exponents were larger than  $-1$ , and the larger the  $[Na^+]_{SAT}$ , the larger the absolute value of the power component. Further, they were a little larger for  $[Na^+]_{1-x}$  than for  $EC_{1-x}$  even if the same extract was used.

### The power component in the regression equation

The phenomenon mentioned above may be related to the diffuse layer, or the electric double layer of an ion at the particle surface in the soil sample. The thickness of the layer at 298.15 K (Gouy–Chapman double layer) is

**Table 3.** Regression equations of  $y \equiv [Na^+]_{1-x}$  on  $x$  ( $x = 1, 3, 5$ ) (Eq.1),  $R^2$  and  $[Na^+]_{SAT}$  for sample soils taken at five depths around P1

Point & Depth	Regression equation ( $mg^{-1}$ )	$R^2$	$[Na^+]_{SAT}$ ( $mgL^{-1}$ )
P1 : 0 cm*	$y=259.07x^{-0.8501}$	0.9999	812.6
10 cm	$y=366.75x^{-0.8827}$	0.9999	1196.9
20 cm*	$y=127.11x^{-0.8287}$	1	389.4
40 cm	$y=65.72x^{-0.7034}$	0.9959	171.0
60 cm	$y=62.699x^{-0.6544}$	0.9967	152.2

\* Sampled at locations different than the others.



written as

$$\kappa^{-1} = \frac{3.042(10^{-10})}{ZI^{0.5}} \quad \text{m} \quad (9)$$

where  $Z$  is the ion valence,  $I$  is the ionic strength of the bulk solution expressed in moles per liter and ion valence (Essington, 2004). The above relation demonstrates that a decrease in the ion valence thickens the diffuse layer, while an increase in the ionic strength thins the layer.

The difference in the concentration of an ion, such as  $\text{Na}^+$ , between the bulk solution,  $c_B$ , and that at the distance of  $\kappa^{-1}$  from the particle surface,  $c_D$ , can be written as

$$\frac{c_D - c_B}{c_B} = \exp(-14.32\psi_0 Z) - 1 \quad (10)$$

where  $\psi_0$  is the surface potential at 298.15 K with units of volts (negative in this case).

If we can replace the mobile water and the immobile water in the elucidation made by Kobayashi *et al.* (2006) with the bulk solution and the diffuse layer, respectively, the following results will be obtained.

An increase in soil water content, or in  $x$ , is equivalent to the decrease in  $c_B$ , which results in the decrease in the difference,  $c_D - c_B$ , according to Eq.(10). This suggests that the diffusive force acting on the ion in the diffuse layer becomes relatively large as  $x$  increases, which is consistent with what the assumption (a) means and interprets why the absolute value of the power exponent in the regression equation,  $n$ , is less than one.

An increase in the soil salinity causes the increase in  $c_B$ . Thus, contrary to what the assumption (b) asserts, the  $c_D - c_B$  increases with increasing soil salinity according to Eq.(10). A possible explanation of the increase in  $n$  with increasing soil salinity is that the increase in the diffusive force caused by a fixed increment in  $x$  decreases as soil salinity increases.

The ion valence also influences the  $c_D - c_B$  according to Eq.(10). Since the valence of sodium is the smallest among the exchangeable ions in soil solution,  $(c_D - c_B)/c_B$  is also the smallest, which means that the diffusive force for  $\text{Na}^+$  is the strongest among the exchangeable ions. The results of this experiment show that the  $n$  for  $[\text{Na}^+]_{1:x}$  was a little larger than for  $\text{EC}_{1:x}$  under the same ionic strength. This suggests that the diffusive force or the mobility of  $\text{Na}^+$  in soil solution is larger than the other exchangeable ions, and hence the increase in the diffusive force due to an increment in  $x$  for  $\text{Na}^+$  is smaller than for the other exchangeable ions.

## CONCLUDING REMARKS

Extraction of a soil sample that is saturated with distilled water (saturation extract) is the standard method to obtain a soil solution sample, and the electrical conductivity ( $\text{EC}_e$ ) and ion concentrations in the solution have been used when analyzing soil salinity and sodicity. However, getting a saturation extract is tedious and more art than science (Essington, 2004). Thus, the elec-

trical conductivity of the solution in a saturated soil,  $\text{EC}_{\text{SAT}}$ , which is determined by the DE method are used in these experiments. The DE method is based on a regression equation of the electrical conductivity of an extract of the soil sample at 1: $x$  soil–water ratio,  $\text{EC}_{1:x}$ , on  $x$ . The  $\text{EC}_{\text{SAT}}$  can also be automatically measured using TDR in the field based on the two models, the parameters of which have to be identified for the soil concerned. Further, the concentrations of ions, such as  $\text{Na}^+$ , in the solution in a saturated soil, such as  $[\text{Na}^+]_{\text{SAT}}$ , are used as well. They are also determined by the DE method.

The physical properties of the field soils of the Pingbu experimental field and the parameters of the two models identified for the typical soil in the field were presented. Example measurements of time changes in the depth profiles of volumetric soil water content and  $\text{EC}_{\text{SAT}}$  obtained in the field were also illustrated. Further, a comparison of the regression equations of  $\text{EC}_{1:x}$  on  $x$  and  $[\text{Na}^+]_{1:x}$  on  $x$  for several soil samples with different salinities was made. The results suggest that the electric double layer at the particle surface in the soil sample has an influence on the power exponent in the regression equation. The difference in the concentration of an ion between the bulk solution and the diffuse layer was formulated, and the concept of the diffusive force acting on the ion was introduced to interpret the relative magnitude of the power exponent in the regression equation.

## ACKNOWLEDGEMENTS

The authors wish to thank Prof. X. Li of the Cold and Arid Regions Environmental and Engineering Research Institute, CAS, for his cooperation. They would also like to thank the local government of Pingbu village for giving support to their experiments and many ex-students of Kyushu University and Saga University for their help in conducting laboratory experiments. This research was funded by a Grant-in-Aid for Scientific Research of the Japan Society for the Promotion of Science (JSPS) (No.19405039).

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