Column Experiments on the Salt Accumulation in Adjoining Different-Textured Soil Profiles with a Shallow Water Table

Kobayashi, Tetsuo
Laboratory of Applied Meteorology, Division of Regional Environment Science, Department of Biological Environmental Sciences, Faculty of Agriculture, Kyushu University

Yokoyama, Daisuke
School of Engineering, The University of Tokyo

Ebohara, Kenji
九州大学大学院生物資源環境科学府

Sonoda, Yasutaka
Ex-student

他

https://doi.org/10.5109/12869

出版情報：九州大学大学院農学研究院紀要. 53 (2), pp.529-534, 2008-10-28. 九州大学大学院農学研究院
バージョン：
権利関係：

J. Fac. Agr., Kyushu Univ., **53** (2), 529–534 (2008)

Column Experiments on the Salt Accumulation in Adjoining Different–Textured Soil Profiles with a Shallow Water Table

Tetsuo KOBAYASHI*, Daisuke YOKOYAMA[1], Kenji EBIHARA[2], Yasutaka SONODA[3], Yoshinobu SAKATA[3], Kazuki URAYAMA[2], Hiroyuki CHO[4], Hisashi YOSHIKOSHI and Masaharu KITANO

Laboratory of Applied Meteorology, Division of Regional Environment Science, Department of Biological Environmental Sciences, Faculty of Agriculture, Kyushu University, Fukuoka 812–8581, Japan
(*Received June 27, 2008 and accepted July 16, 2008*)

Two column experiments on the relation between soil texture and salinization in soil profiles with a shallow water table were conducted under rainless conditions using the concept of EC_{SAT}. The buildup of salts due to evaporation from bare soil was confined within the superficial layer and its amount during a period could be assumed to equal the product of the total of evaporation during the period and the salinity of water supplied into the soil profile, such as irrigation water and/or groundwater. This amount of salt accumulation became larger on the portions consisting of fine–textured soils than of coarse–textured soils in course of time from a heavy irrigation. The shape of the depth profile of EC_{SAT} obtained in these experiments was similar to the actual shape observed at cornfields in the Yellow River valley (Kobayashi *et al.*, 2006b). The least salt–affected layer appeared just beneath the surface layer, below which EC_{SAT} increased with increasing depth to the EC of groundwater (EC_{GW}). This suggests that the existence of the soil layer with EC_{SAT} larger than EC_{GW} is a sign of inadequate leaching of salts.

Keywords: capillary rise, EC_{SAT}, irrigation, leaching, salinity, salt accumulation

INTRODUCTION

The scenery of salt–affected regions is characterized by large and small, white saline spots found here and there. Salts accumulate spontaneously and/or by human activities on specific soil–surfaces. This phenomenon is ascribed to spatial variations in (a) the depth to a water table, (b) the amount of irrigated water, (c) soil texture, and others. The cause (a) is a natural and/or artificial one and the cause (b) is an artificial one; however, the cause (c) is pure, natural cause why saline plots form locally, although this is not sufficiently recognized so far (Kobayashi *et al.*, 2006b).

In an alluvial plain, soil texture varies from place to place and the spatial variation in the hydraulic conductivity, which controls surface infiltration and capillary rise, is very large. Therefore, it is essential to elucidate the mechanism that is in charge of the formation of saline spots, and to invent special techniques for removing drainage water from such spots, because the inadequate removal of drainage water is the main process that facilitates the buildup of salts in soil (Wang *et al.*, 2008).

Column experiments on the effects of the spatial variation in soil texture on the salt accumulation were conducted. In this experiment, the amounts of salt accumulated in adjoining different–textured soil profiles with a shallow water table were measured using the concept of EC_{SAT} (Kobayashi *et al.*, 2006a; Yoshikoshi *et al.*, 2008). This paper describes the results of two experiments, one is a simulation of the salt accumulation after a heavy irrigation, and the other is an experiment on the soil salinization under rainless conditions, such as in greenhouses.

EXPERIMENTS

Experiment I

The first experiment (Experiment I) was conducted during the period July to September 2005. Two plastic tanks 45 cm in height and 45 cm in internal diameter, having the bottom punctuated with many small holes (**Fig. 1**), were filled with the Tottori Dune sand (coarse–textured soil; hereafter, sand) except for the core col-

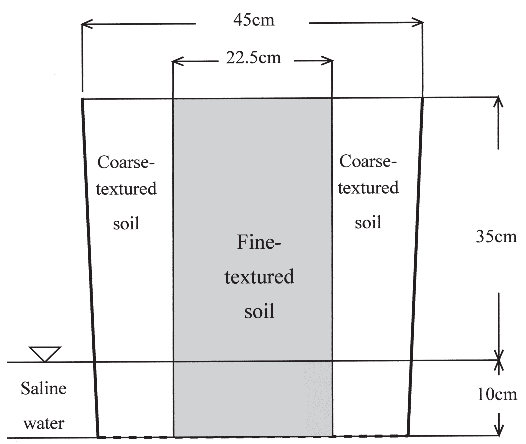

Fig. 1. Schematic diagram of this column experiment.

[1] School of Engineering, The University of Tokyo, Tokyo 113–8656, Japan
[2] Graduate School of Bioresource and Bioenvironmental Sciences, Kyushu University, Fukuoka 812–8581, Japan
[3] Ex–student
[4] Department of Agricultural Sciences, Saga University, Saga 840–8502, Japan
* Corresponding author (E–mail: kotetsu@bpes.kyushu–u.ac.jp)

umn of 22.5–cm diameter that was plugged with a fine–textured soil (hereafter, loam). The sand core and the loam outer shell were separated with a bleached cotton cloth of coarse fiber.

The physical properties of the two soils are shown in **Table 1**. **Fig. 2** shows the matric potential (suction) – volumetric water content relations for the two soils. The curves are van Genuchten equation fits to the measurements (Jury and Horton, 2004). **Fig. 3** shows the matric potential (suction) – unsaturated hydraulic conductivity relations for the two soils obtained by the van Genuchten parametric model (Jury and Horton, 2004).

Table 1. Physical properties of the soils used in Experiment I

Particle size (mm)	% by weight	
	Loam	Sand
< 0.002	19.4	0.0
0.002~0.075	33.5	1.6
0.075~0.25	22.4	33.5
0.25~0.85	20.8	64.7
0.85~2	3.9	0.2
Particle density (g cm^{-3})	2.64	2.65
Dry density (g cm^{-3})	1.61	1.54
Porosity (–)	0.390	0.419
Saturated hydraulic conductivity (cm s^{-1})	3.71×10^{-4}	2.11×10^{-2}

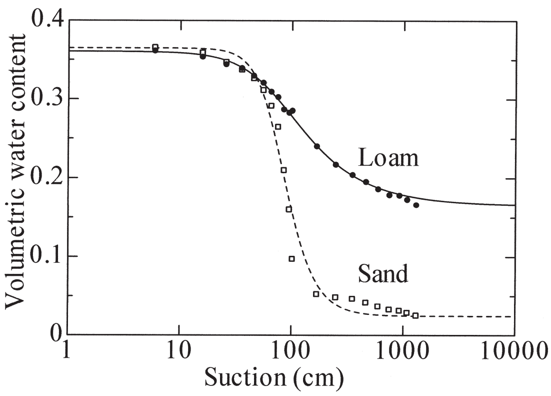

Fig. 2. Matric potential (suction) – volumetric water content relations for the two soils used in Experiment I.

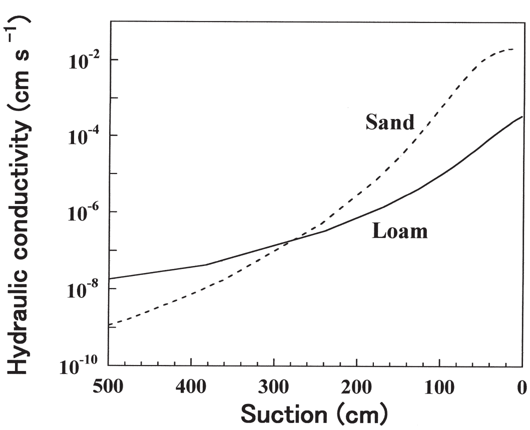

Fig. 3. Matric potential (suction) – unsaturated hydraulic conductivity relations for the two soils used in Experiment I.

Each tank was supplied with plenty of tap water (electrical conductivity EC=0.47 dS m^{-1}) to the surface and allowed to stand for one day in order to deplete the detention storages by gravitational force; subsequently, it was placed upright in a tub filled with saline water, 50.5 cm in diameter. The initial values for the depth from the surface to the water table and the thickness of saline water in the tub were 35 cm and 10 cm, respectively (**Fig. 1**). The saline water was made of tap water by dissolving NaCl into it so that its EC was 2 dS m^{-1}. Although the evaporation from the tub was prevented using plastic sheets, the depth and thickness were changing, as shown below, due to the soil–surface evaporation during the experiment.

Two tanks were set in a laboratory on July 9, 2005, and depth distributions of soil moisture and EC_{SAT} in one tank were measured after the 68–day evaporation on September 15, and those in the other tank after the 107–day evaporation on October 24, 2005. Although the thermal and ventilation conditions in the laboratory were not controlled, the daily evaporation averaged for each period shown below suggests that the two columns were exposed to almost the same environment.

Experiment II

The second experiment (Experiment II) was conducted in the period December 2007 to January 2008. Plastic columns 100 cm in height and 50 cm in internal diameter were used as soil containers. The details of the experimental device are shown elsewhere (Urayama *et al.*, 2008). One of the columns was filled with arkose sand except for the core column of 25–cm diameter, which was filled with another fine–textured soil (hereafter, loamy sand) (**Table 2**) in the same manner as was done in Experiment I, but no material was used to separate the arkose sand outer shell from the loamy sand core. The suction – volumetric water content relations and the suction –unsaturated hydraulic conductivity relations for the two soils are shown in **Figs. 4** and **5**, respectively.

The column was supplied with a solution from the bottom until the top surface was submerged and then the water table was lowered to a depth of 50 cm, and allowed to stand for a few days in order to promote internal drainage and redistribution. The solution was

Table 2. Same as Table 1, but for Experiment II

Particule size (mm)	% by weight	
	Loam sand	Arkose sand
< 0.002	8.7	6.2
0.002~0.075	15.8	5.2
0.075~0.25	10.2	17.0
0.25~0.85	47.9	36.2
0.85~2	17.4	35.4
Particule density (g cm^{-3})	2.63	2.73
Dry density (g cm^{-3})	1.57	1.53
Porosity (–)	0.40	0.44
Saturated hydraulic conductivity (cm s^{-1})	2.64×10^{-4}	1.55×10^{-3}

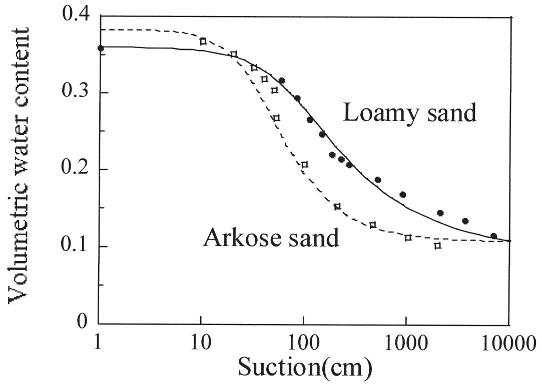

Fig. 4. Same as Fig. 2, but for the soils used in Experiment II.

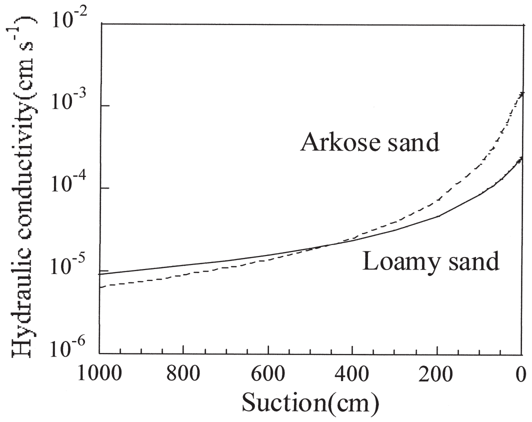

Fig. 5. Same as Fig. 3, but for the soils used in Experiment II.

made of tap water by dissolving NaCl, $MgSO_4$, $CaSO_4 \cdot 2H_2O$, and others so that its EC was 5 dS m^{-1}. The other columns connected to the same solution tank were used for another experiment of growing crops (Urayama *et al.*, 2008), and hence this solution was prepared for cultivation use.

The depth to the water table was set at 50 cm using a water level control device. The amount of solution supplied to each column was measured with a flow meter. However, the meter often broke down and the total amount of soil–surface evaporation could not been obtained. However, the depth to the water table was fixed at 50 cm within the permissible range during the experiment.

The column experiment system was set in a greenhouse, and the evaporation experiment started on December 10, 2007. The soil–surface evaporation was artificially enhanced by sending air to the soil surface with an electric fan. Depth distributions of soil moisture and EC_{SAT} were measured after the 52–day evaporation on January 31, 2008.

EVAPORATION EQUIVALENT TO SOIL SALINIZATION, E_{SAL}

The daily evaporation equivalent to soil salinization, E_{SAL} (mm d^{-1}), is defined as follows:

Under rainless conditions, an increase in the amount of dissolved salt in a soil profile above a water table in a day (mg cm^{-2}d^{-1}) is equal to the product of the salinity of ground water (mg cm^{-3}) and the daily evaporation (cm d^{-1}). Since the amount of total dissolved solids in a solution, TDS (mg L^{-1}), can be assumed to be in direct proportion to the EC of the solution (dS m^{-1}) (Tanji, 1990), if an increase in EC_{SAT} in a day is designated as ΔEC_{SAT} (dS m^{-1}d^{-1}), the integral of the increase multiplied by the soil porosity, ε, from the surface (z=0) to the depth at which vaporization of liquid water becomes negligible (z=D) with respect to depth, z (cm), is used to define the daily evaporation equivalent to soil salinization as follows:

$$E_{SAL} = \frac{10}{EC_{GW}} \int_0^D \varepsilon \cdot \Delta EC_{SAT} dz \qquad (\text{mm d}^{-1}) \qquad (1)$$

where EC_{GW} is the EC of groundwater, or of evaporating solution.

The separation of solvents and solutes in soil occurs by evaporation and root absorption of soil water. Thus, if the soil is free of vegetation, D seems to be less than a few centimeters in magnitude.

RESULTS AND DISCUSSION

Experiment I

Depth profiles

The two columns were destructed and depth profiles of EC_{SAT} and volumetric water content were measured after the 68–day evaporation on September 15, and after the 107–day evaporation on October 24, 2005 (**Figs. 6** and **7**), respectively.

The surface soil was sampled by scraping the top layer approximately 1 cm thick, and hence the measurement of EC_{SAT} was its average taken over the 1–cm top layer of soil. The depth, D, at which vaporization of liquid water becomes negligible was, to a first approxima-

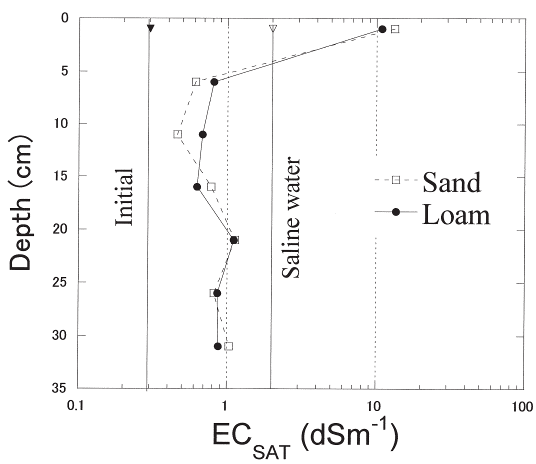

Fig. 6. Depth profiles of EC_{SAT} in the column measured after the 68–day evaporation on September 15, 2005. Two vertical lines depict the initial value for EC_{SAT} in the profile and the EC of the saline water in the tub.

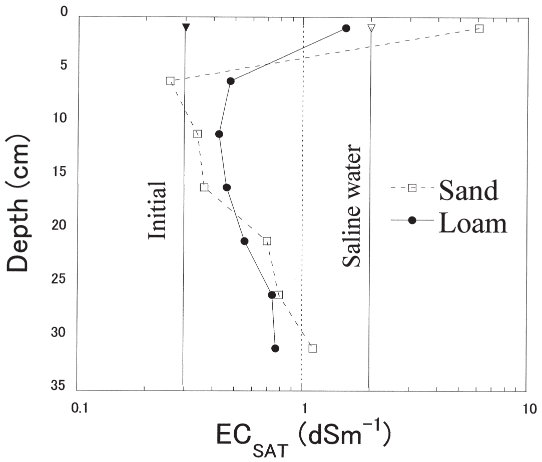

Fig. 7. Same as Fig. 6, but for after the 107–day evaporation on October 24, 2005.

tion, assumed to be 1 cm in this experiment.

Figure 8 shows the depth profiles of volumetric water content after the 107–day evaporation. Through the whole period of evaporation the soil wetness in the loam core did not change along the vertical and also had not changed with time, which suggests that main capillary tubes had continued from the water table to the soil surface. On the other hand, water content decreased with height in the sand outer shell.

In the early stage of evaporation, the soil water originated from the tap water (hereafter, irrigated water) evaporated from the soil surface and, to replenish the loss, the saline water in the tub was sucked up by capillary action. The EC_{SAT} increased both in the soil surface layer and in the layers near above the water table; the former mainly by surface evaporation and the latter exclusively by capillary rise. Therefore, the least salt–affected layer appeared just beneath the surface layer. This distribution shape of EC_{SAT} in the soil profile is similar to those observed at cornfields in the Yellow River valley (Kobayashi *et al.*, 2006b).

Initial conditions

It is reasonable to infer that, when this evaporation experiment started, the soil columns of 35 cm long, from the soil surface to the water table, retained approximately 105 mm of the irrigated water because the volumetric water content was estimated to be about 0.3. When soil–surface evaporation occurred, the saline water moved upward through the soil profile from the tub. If neither diffusion nor hydrodynamic dispersion were to take place at the interface between the displacing solution (saline water) and the displaced solution (irrigated water), or a piston flow were to occur, it would need over 300 days to deplete the whole irrigated water by soil–surface evaporation. In reality, however, a gradual mixing of the irrigated water with the saline water appears to have occurred as will be shown below (**Table 3**).

The initial value for EC_{SAT} is estimated to have been 0.35 dS m^{-1} because a large amount of tap water (EC=0.47 dS m^{-1}) was irrigated to the soil surface when this experiment started, and approximately one fourth of the pore water should have been depleted by gravitation before the column was placed in the tub (**Fig. 8**). Thus, the EC_{SAT} that is in direct proportion to TDS should have decreased to approximately three fourths of the EC of the irrigated water by the time when the evaporation experiment started.

Estimation of evaporation rate

The drop in water table level measured after the 68–day evaporation was 33 mm, and 50 mm after the107–day evaporation. Since the radii of the sections of circular loam core, column, and tub were 11 cm, 22.5 cm, and 25.5 cm, respectively, and the porosities of loam and sand were 0.42 and 0.39, respectively, the evaporation rate from the soil surface composed of loam and sand is 0.70 times as large as the rate of the drop in the water surface level in the tub. The rate during the 68–day period was 33 mm/68 days=0.48 mm d^{-1}; thus, the daily soil–surface evaporation rate averaged for the period E= 0.34 mm d^{-1}; for the 107–day period , 50 mm/107 days= 0.47 mm d^{-1}, and hence E=0.33 mm d^{-1}. These results suggest that the evaporation power of the atmosphere in the laboratory did not appreciably change through the whole period of experiment.

Mixing of irrigated water with saline water

The results obtained in Experiment I are summarized in **Table 3**, in which EC_{GW} designates the EC of evaporating solution that meets the relation

$$\Delta EC_{SAT} \times 1 \times \varepsilon = E_{SAL} \times EC_{GW} \quad (2)$$

and x is the mixing ratio of the saline water sucked up by capillary force to the irrigation water; that is, x=0 means that only the irrigated water was evaporating during the period. Further, the estimates of E obtained above were substituted for E_{SAL} in Eq.(2).

The mixing ratio, x, was larger for the sand outer shell than for the loam core in this experiment. The hydraulic conductivity of the sand at suction heads smaller than about 250 cm is larger than that of the loam (**Fig. 3**), which suggests that the larger the hydraulic

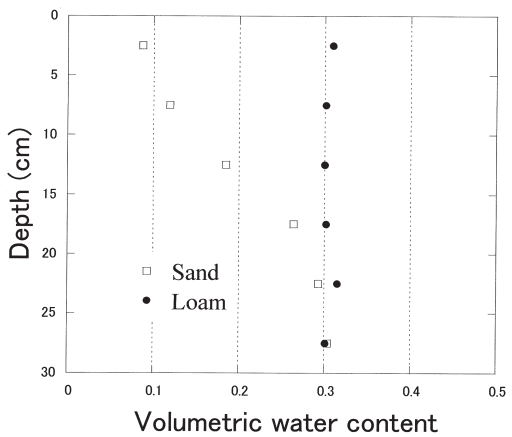

Fig. 8. Same as Fig. 7, but for the volumetric water content.

Table 3. Results obtained in Experiment I

Duration: Soil	ΔEC_{SAT}(dS $m^{-1}d^{-1}$)	ε	E (mm d^{-1})	EC_{GW} (dS m^{-1})	x
July9–Sep15: Sand	5.67/68	0.42	0.34	1.03	0.37
July9–Sep15: Loam	1.20/68	0.39	0.34	0.20	0
July9–Oct24: Sand	12.80/107	0.42	0.33	1.52	0.69
July9–Oct24: Loam	10.53/107	0.39	0.33	1.16	0.45

See the text for the details.

conductivity is, the more efficiently occurs a mixing of the irrigated water with the saline water. If the value of EC_{GW} is known, we can estimate the evaporation rate, E_{SAL}, from Eq.(2) using measurements of ΔEC_{SAT} and ε. This technique was tested in the second experiment. Further, in the first experiment, we could not evaluate the difference in the evaporation rate between the adjoining soil surfaces with different textures, because the salinity of evaporating solution was not controlled. Thus, in the second experiment, the pre–experiment irrigation was practiced using the same saline water as that stored in the tub.

Experiment II

Depth profiles

The column was destructed and depth profiles of EC_{SAT} and volumetric water content were measured after the 52–day evaporation on January 31, 2008 (**Figs. 9** and **10**). In this experiment, the surface soil was sampled by scraping the top approximately 0.5 cm of the profile, and hence the measurement of EC_{SAT} was the average for the upper 0.5 cm of soil. The D was assumed to be 0.5 cm. The average of EC_{SAT} was 103.3 dS m^{-1} for the loamy sand core, while that for the arkose sand outer shell was 46.9 dS m^{-1}. On the other hand, the depth profiles of volumetric water content for the two soils were unexpectedly almost the same except for the measurements made at a depth of 40 cm. However, the difference seems due to an error in measurement, because the soils were almost saturated at the depth and the specimen of the sand might let a small amount of water leak when it was taken.

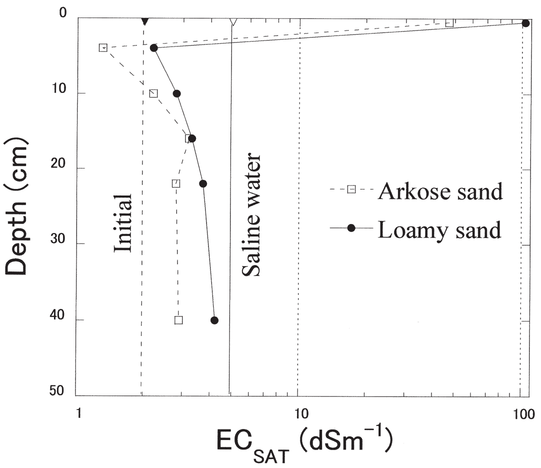

Fig. 9. Depth profiles of EC_{SAT} in the column measured after the 52–day evaporation on January 31, 2008. Two vertical lines depict the initial value for EC_{SAT} in the profile and the EC of the saline water in the tub.

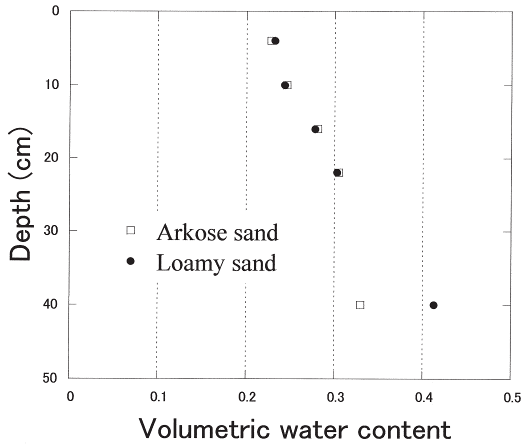

Fig. 10. Same as Fig. 9, but for the volumetric water content.

Initial conditions

The initial values for EC_{SAT} seems to depend on the soil texture and the height from the water table because the suction applied to the column that causes the depletion of the retention storage before the start of this experiment varied with depth from 50 cm at the surface to 0 cm at the water table. However, it seems that they were within a range of 1 dS m^{-1} to 3 dS m^{-1} for the arkose sand outer shell and of 2 dS m^{-1} to 4 dS m^{-1} for the loamy sand core. Thus, their initial values were assumed, to a first approximation, to be 2 dS m^{-1}.

Estimation of E_{SAL}

The measurements of ΔEC_{SAT} averaged over the period from November 10, 2007 to 31 January 31, 2008 was (103.3–2.0)/52=101.3/52 dS m^{-1} d^{-1} for the loamy sand core and (46.9–2.0)/52=44.9/52 dS m^{-1} d^{-1} for the arkose sand outer shell, respectively. Therefore, since the EC of evaporating solution, EC_{GW}, is 5.0 dS m^{-1}, the average E_{SAL} for the two soils over the 52–day evaporation are calculated from Eq.(1) as:

$(10\times0.44\times0.5\times44.9/52)/5$
$= 0.4$ mm d^{-1} for the arkose sand outer shell, and
$(10\times0.40\times0.5\times101.3/52)/5$
$= 0.8$ mm d^{-1} for the loamy sand core.

Although Experiment II was carried out in winter and the depth to the water table was set at 50 cm, these estimates were larger than those obtained in Experiment

I conducted in summer and the depth to the water table was set at 35 cm. This implies that soil–surface evaporation in Experiment II was considerably enhanced by applying air to the soil surface with an electric fan.

This experiment shows that, when there is a shallow water table, salt concentrations in the soil surface become higher on the portions consisting of fine–textured soils than of coarse–textured soils, if the salinity of evaporating solution is common to both areas.

Finally, it must be pointed out that, in these analyses, the precipitation or dissolution of salt that might occur with the decrease or increase in water content was ignored.

CONCLUDING REMARKS

Water is evaporated from the soil surface or adsorbed by plant roots and most of dissolved salts are left behind. This is the cause of salinization of the upper soil profile and of the soil surface. However, in a bare soil field, the buildup of salts due to evaporation was confined within the superficial layer and its amount during a period could be assumed to equal the product of the total of evaporation during the period and the salinity of water supplied into the soil profile, such as irrigation water and/or groundwater. Therefore, if the salinity of evaporating solution is known, the evaporation rate can be estimated by measuring the amount of salt accumulated in the surface, and the converse is also true.

Two column experiments on the relation between soil texture and salinization in soil profiles with a shallow water table were conducted under rainless conditions using the concept of EC_{SAT}. One of them was a simulation of the salt accumulation after a heavy irrigation, and the other was an experiment on the soil salinization in a greenhouse.

The amount of salts accumulated in the surface became larger on the portions consisting of fine–textured soils than of coarse–textured soils in course of time from a heavy irrigation. The shape of the depth profile of EC_{SAT} obtained in these experiments was similar to the actual shape observed at cornfields in the upper Yellow River valley (Kobayashi *et al.*, 2006b). The least salt–affected layer appeared just beneath the surface layer. Under this layer, EC_{SAT} increased with depth to the EC of groundwater (EC_{GW}). This suggests that the existence of the soil layer with EC_{SAT} larger than EC_{GW} is a sign of inadequate leaching of salts.

ACKNOWLEDGEMENTS

This research was supported by the Core Research for Evolutional and Technology (CREST) program of the Japan Science and Technology Corporation (JST), and also has been funded by a Grant–in–Aid for Scientific Research of the Japan Society for the Promotion of Science (JSPS) (No. 19405039). The authors wish to thank Mr. M. Hamakoga for his technical support for constructing the experimental device.

REFERENCES

Jury, W. A. and R. Horton 2004 *Soil Physics*. John Wiley & Sons, INC. Hoboken, New Jersey (USA)

Kobayashi, T., W. Wang, Y. Ikawa, H. Cho and W. He 2006a An easily measurable and practical index of soil salinity. *J. Japan Soc. Hydrol. & Water Resour.*, **19**: 183–188

Kobayashi, T., H. Cho, T. Kaneko, W. Wang and D. Yokoyama 2006b A survey of the relationship between soil salinization and soil texture in the upper Yellow River basin. *Kyushu J. Agric. Meteorol.*, **II**, **15**: 1–6

Tanji, K. K. (ed) 1990 *Agricultural Salinity Assessment and Management*. ASCE Manuals and Reports on Engineering Practice No. 71, ASCE

Urayama, K., Y. Sakata, Y. Sonoda, K. Ebihara, T. Araki, Y. Sago, H. Yoshikoshi, D. Yasutake, H. Cho, T. Kobayashi and M. Kitano 2008 Preliminary Column Experiment on Dynamics of Water and Ion Transport in Soil Affected by Root Absorption. *J. Fac. Agr. Kyushu Univ.*, **54** (this issue)

Wang, W., T. Kobayashi, D. Yasutake, M. Kitano, H. Cho, T. Araki and H. Yoshikoshi 2008 Experiments on the control of salinity and sodicity in surface–irrigated fields in the upper Yellow River valley (I) Objectives and Methodology. *J. Fac. Agr. Kyushu Univ.*, **53**: 251–256

Yoshikoshi, H., W. Wang, H. Cho, T. Araki, D. Yasutake, J. Zhou, K. Urayama, Y. Wu, T. Kobayashi and M. Kitano 2008 Experiments on the control of salinity and sodicity in surface–irrigated fields in the upper Yellow River valley (II) Observation system and calibration. *J. Fac. Agr. Kyushu Univ.*, **53**: 257–263