Experiments on the Control of Salinity and Sodicity in Surface : Irrigated Fields in the Upper Yellow River Valley (III)

Yasutake, Daisuke
Faculty of Agriculture, Kochi University

Araki, Takuya
Department of Plant Resources, Faculty of Agriculture, Kyushu University

Kitano, Masaharu
Department of Bioproduction Environmental Sciences, Faculty of Agriculture, Kyushu University

Wang, Weizhen
Cold and Arid Regions Environmental and Engineering Research Institute

他

https://doi.org/10.5109/10102

出版情報：九州大学大学院農学研究院紀要. 53 (1), pp.265-270, 2008-02-28. Faculty of Agriculture, Kyushu University

J. Fac. Agr., Kyushu Univ., **53** (1), 265–270 (2008)

Experiments on the Control of Salinity and Sodicity in Surface–Irrigated Fields in the Upper Yellow River Valley (Ⅲ)

The State of Salinization and Alkalization in and around the Pingbu Experimental Field

Daisuke YASUTAKE[1], Takuya ARAKI[2], Masaharu KITANO, Weizhen WANG[3], Kazuki URAYAMA[4], Hiroyuki CHO[5] and Tetsuo KOBAYASHI*

Laboratory of Applied Meteorology, Division of Regional Environment Science, Department of Bioproduction Environmental Sciences, Faculty of Agriculture, Kyushu University, Fukuoka 812–8581, Japan

(*Received November 9, 2007 and accepted November 30, 2007*)

In order to analyze the state of salinization and alkalization in and around an experimental irrigated field newly established in an alluvial valley of the Yellow Ricer, concentrations of ions contained in waters, soils and crops relevant to these phenomena were measured there. During the intensive surveys conducted in June, August and September 2007, the Yellow River water, irrigation canal water, groundwater, field soils and crops, etc. were sampled and their chemical characteristics such as electrical conductivity, pH, concentrations of ions Na^+, Ca^{2+}, Mg^{2+}, K^+, Cl^-, SO_4^{2-} and NO_3^- were measured. The results obtained are summarized as follows:

Irrigation seems to cause increases in the concentrations of ions Na^+, Cl^- and SO_4^{2-} in the groundwater. Although those are also major ions contained in the field soil, the soil is classed as saline but not sodic according to the standard classification. On the other hand, Na^+ is not concentrated in the crops because of their poor ability to absorb it. This seems to be one of the factors that cause salinization and alkalization of soil and water in irrigated fields. Therefore, cultivation techniques that use the ability of specific crops to absorb much Na^+ and store it in shoots should be developed for effective and sustainable use of the irrigated field.

KEY WORDS: ion concentration, irrigated field, root uptake, salinity, sodicity

INTRODUCTION

Soil salinization and alkalization are caused by the accumulation of soluble salts (ions) in the soil solum to a level that depresses plant production, and are serious problems in irrigated agriculture in semiarid and arid regions (Rengasamy, 2006). The ions accumulation in irrigated fields is affected by dynamics of water and ion transport through physical and physiological processes in the plant–environment system (Kitano *et al*., 2006). Therefore, these transport processes have to be controlled optimally for effective and sustainable use of the irrigated field.

In order to develop soil physical and biological methods for controlling salinity and sodicity in surface–irrigated fields within a normal range, an experimental field was newly established at Pingbu village in Jingyuan prefecture in the upper Yellow River valley. Wang *et al*. (this issue) described the background and objectives of the experiments, and Yoshikoshi *et al*. (this issue) summarized the observation system installed in the field for measuring meteorological and hydrological elements. In this paper, spatial distribution of ions relevant to the present subject observed in and around the experimental field is shown, and the state of salinization and alkalization in the field is analyzed.

MATERIALS AND METHODS

Experimental field and cultivation conditions

Figure 1 shows a ground plan of the experimental field newly established and its surroundings at Pingbu village in Jingyuan prefecture in the upper Yellow River valley (N 36° 25.5’, E 104° 25.4’, 1461 m ASL). The climatic characteristics of Jingyuan and the observation systems installed in the field for measuring meteorological and hydrological elements are described in detail by Wang *et al*. (this issue) and Yoshikoshi *et al*. (this issue), respectively. In the experimental field with an area of about one mu (Chinese unit of area, 667 m^2), corn was cultivated in 2007 and irrigation is applied from a canal with the water diverted from the Yellow River. A salinized field, where growth of corn was depressed greatly by the excessive salt accumulation in the surface soil in 2007, is adjacent to the experimental field, and extensive

[1] JSPS Research Fellow, Faculty of Agriculture, Kochi University, Kochi 783–8502, Japan
[2] Laboratory of Plant Production Physiology, Division of Soil Science and Plant Production, Department of Plant Resources, Faculty of Agriculture, Kyushu University, Fukuoka 812–8581, Japan
[3] Laboratory of Remote Sensing and GIS, Cold and Arid Regions Environmental and Engineering Research Institute, CAS, Lanzhou 730000, China
[4] Graduate School of Bioresource and Bioenvironmental Sciences, Kyushu University, Fukuoka 812–8581, Japan
[5] Department of Agricultural Sciences, Saga University, Saga 840–8502, Japan
* Corresponding author (E–mail: kotetsu@bpes.kyushu–u.ac.jp)

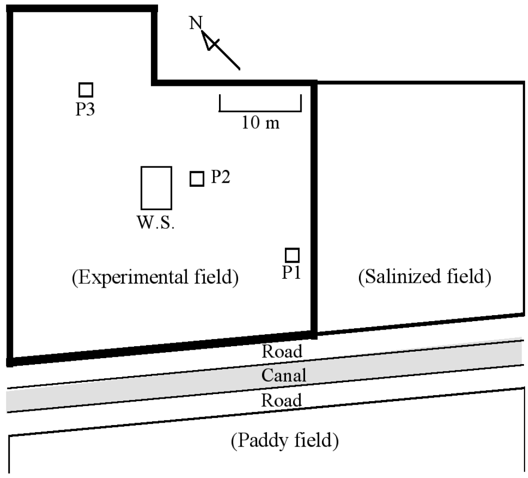

Fig. 1. A ground plan of the experimental irrigated field at Pingbu village in the upper Yellow River valley: Solid squares (P1, P2 and P3) indicate measurement points of soil moisture and electrical conductivity; W. S. weather station.

Fig. 2. Photograph of a mixed cultivation (corn and wheat) field in Pingbu village early in June.

paddy fields spread out from the other side of the canal. A cliff of the yellow loess about 150 m high rises at about 500 m far from the field in a southeasterly direction, and corn is grown on this river terrace extending from the top of the cliff to the back mountainous area by applying the water pumped up from the Yellow River. Therefore, saline seeps occur at the foot and wall face of the cliff, and the saline seep water flows to a drain ditch next to the cliff that leads to the Yellow River. On the other hand, groundwater level in and around the experimental field is relatively shallow (about 50 cm in depth) during the growing period because the canal is filled with water in the period.

The crops grown in and around the experimental field are mainly corn and rice, and also wheat, sesame and legume are grown by the mixed cultivation with corn, as shown in **Fig. 2**.

Sampling water, soils and crops

Intensive surveys were practiced three times during the periods 2–9 June, 10–20 August and 17–23 September 2007, for analyzing the spatial distribution of ion concentrations in waters, soils and crops in and around the experimental field. On 7 June in the first survey, the Yellow River water, irrigation canal water and flooded surface water in the paddy field were sampled, and then the surface soils (0–5 cm in depth) and root zone soils (20–25 cm in depth) were also sampled in the experimental field and the salinized field (**Fig. 1**). Furthermore, crops grown in and around the experimental field (corn, wheat, sesame, legume and rice) were sampled and their dry weight and height were measured. On 12 August and 19 September in the second and third surveys, the saline seep water and the groundwater in the field as well as the Yellow River water were sampled.

Chemical analyses, and salinity and sodicity

The electrical conductivity (EC) at 25 °C, concentrations of different ions (Na^+, Ca^{2+}, Mg^{2+}, K^+, Cl^-, SO_4^{2-} and NO_3^-) and pH for the Yellow River water, irrigation water, paddy field water, saline seep water and groundwater were measured with an EC meter (B–173, HORIBA), an ion chromatograph system (ICS–90, DIONEX) and a pH meter (B–212, HORIBA). Furthermore, the sodium adsorption ratio (SAR) and the exchangeable sodium percentage (ESP), which are good indicators of sodicity, were calculated for the respective water sample from the measurements of ion concentrations (Wang *et al*., this issue):

$$\mathrm{SAR} = C_{\mathrm{Na}} / (C_{\mathrm{Ca}}+C_{\mathrm{Mg}})^{1/2} \quad (1)$$

$$\mathrm{ESP} \approx 1.5\mathrm{SAR} / (1+0.015\mathrm{SAR}) \quad (2)$$

where C is the ion concentration in mol m^{-3}, and subscripts of Na, Ca and Mg refer to sodium, calcium and magnesium, respectively.

The state of salinization and alkalization of soils can be diagnosed on the basis of EC, and SAR or ESP of the saturation extract of soil, which is obtained from a saturated soil–paste made by adding distilled water to a sample of soil while stirring with a spatula. As an easily measurable and practical index of soil salinity, the EC of the extract of a saturated soil ($\mathrm{EC_{SAT}}$) was defined by using EC of the extract of a 1:x soil–water ratio ($\mathrm{EC}_{1:x}$) as follows (Kobayashi *et al*., 2006):

$$\mathrm{EC_{SAT}}=\mathrm{EC}_{1:x} \quad (3)$$

with

$$x=\varepsilon \rho_{\mathrm{w}} / (1-\varepsilon) \rho_{\mathrm{S}} \quad (4)$$

where ε is the porosity of the soil under actual field conditions, ρ_{S} is the density of soil particles and ρ_{w} is the density of water. $\mathrm{EC_{SAT}}$ is estimated by extrapolation using a regression equation as $\mathrm{EC}_{1:x}=x^{-n}\,\mathrm{EC}_{1:1}$ obtained from more than three EC values of dilution extract ($\mathrm{EC}_{1:x}$) for x=1~5. The parameter n is determined by experiment.

On the other hand, EC of a solution is an indicator of the sum of concentrations of each ion present in the solution. Therefore, the concentration of an ion M in the extract of a saturated soil ($[M]_{SAT}$) can also be expressed by using the concentration of M of the dilution extract of a soil sample at 1:x soil–water ratio ($[M]_{1:x}$) as

$$[M]_{SAT}= [M]_{1:x}=x^{-n} [M]_{1:1} \quad (5)$$

In this study, dilution extracts of a soil sample at soil–water ratios of 1:1, 1:3 and 1:5 were obtained and their electrical conductivities and ion concentrations were measured with the EC meter and the ion chromatograph system. As an example, relationships of EC and Na^+ concentration with soil–water ratio x for the surface soils sampled at the experimental field and the salinized field are shown in **Fig. 3**.

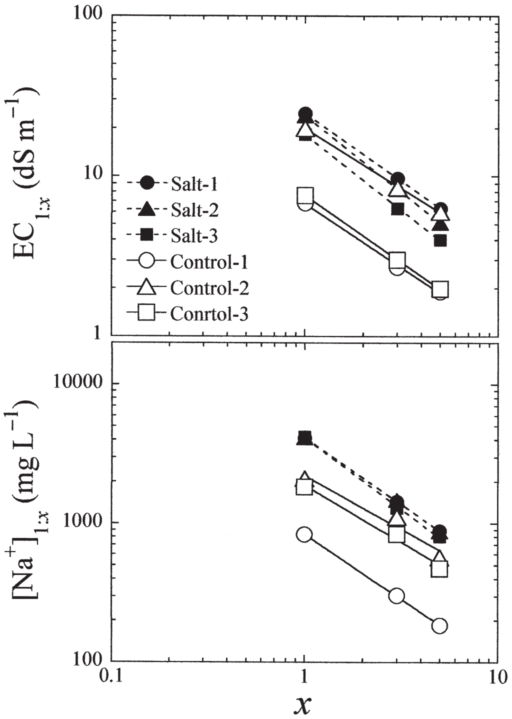

Fig. 3. Relationships of the electrical conductivity ($EC_{1:x}$) and Na^+ concentration ($[Na^+]_{1:x}$) of the dilution extract of a soil sample at 1:x (soil–water ratio) with x for the surface soils sampled in the experimental field and the salinized field on 7 June 2007. Open symbols (Control–1, 2 and 3) indicate values of soils sampled in the experimental field, and closed symbols (Salt–1, 2 and 3) indicate values of soils sampled in the salinized field.

By using the relationships as Eqs.(3) and (5), EC and concentrations of ions Na^+, Ca^{2+}, Mg^{2+}, K^+, Cl^-, SO_4^{2-} and NO_3^- for the extract of saturated soil were estimated and designated as EC_{SAT}, $[Na^+]_{SAT}$, $[Ca^{2+}]_{SAT}$, $[Mg^{2+}]_{SAT}$, $[K^+]_{SAT}$, $[Cl^-]_{SAT}$, $[SO_4^{2-}]_{SAT}$ and $[NO_3^-]_{SAT}$, respectively. Physical properties of the soil in the experimental field are shown elsewhere (Yoshikoshi *et al.*, this issue). Furthermore, SAR and ESP of the soil samples were evaluated using $[Na^+]_{SAT}$, $[Ca_2^+]_{SAT}$ and $[Mg_2^+]_{SAT}$ from Eqs.(1) and (2).

The contents of ions Na^+, Ca^{2+}, Mg^{2+}, K^+, Cl^- and SO_4^{2-} in the sampled crops of corn, wheat, sesame, legume and rice were measured following the standard procedures (Kitano *et al.*, 2006). The ash of shoot and root, or the whole of each crop was dissolved in dilute nitric acid (HNO_3) to achieve complete decomposition of organic matter, and then the ions content and accumulation in crops were evaluated from the ion analysis of the dissolved ash solution with the ion chromatograph system. In this procedure, the content of NO_3^- was not measured.

RESULTS AND DISCUSSION

Table 1 shows the EC, concentrations of ions (Na^+, Ca^{2+}, Mg^{2+}, K^+, Cl^-, SO_4^{2-} and NO_3^-), pH, SAR and ESP for the Yellow River water, irrigation canal water, paddy field water, saline seep water and groundwater. Concentrations of ions Na^+, Mg^{2+} and Cl^- increased as water flowed down from the Yellow River to the canal and therefore EC was a little higher in the irrigation canal water than that in the Yellow River water. For the paddy field water, ions such as Na^+, Cl^- and SO_4^{2-} took a large part of the total ions present in it and EC was 1.0 dS m^{-1}. This EC value is much higher than the average value of 0.2 dS m^{-1} for a paddy field water in Fukuoka prefecture, Japan (Mizuta *et al.*, 2001). The saline seep water had a very large amount of ions and EC was 52.2 dS m^{-1}, which is nearly equal to that of the seawater. The paddy field water and the saline seep water as well as the irrigation canal water may percolate into the water table in the study area. The groundwater in the field contained a large amount of ions Na^+, Cl^- and SO_4^{2-} and EC was 3.5 dS m^{-1}. The EC value and the concentration of ions, except for K^+, of the groundwater were somewhat higher than those at an irrigated cornfield in

Table 1. Electrical conductivity (EC), ion concentrations, pH, sodium adsorption ratio (SAR) and exchangeable sodium percentage (ESP). Means of three to nine samples are shown with the standard error in parenthesis

Water	EC (dS m^{-1})	Na^+	Ca^{2+}	Mg^{2+}	K^+	Cl^-	SO_4^{2-}	NO_3^-	pH	SAR	ESP
		(mg L^{-1})									
Yellow River	0.5	28.0	55.5	20.0	2.2	23.3	58.6	4.0	8.2	0.8	1.2
	(0.01)	(1.14)	(1.17)	(1.26)	(0.09)	(2.24)	(5.44)	(0.16)	(0.08)	(0.04)	(0.05)
Irrigation canal	0.6	50.5	50.8	31.0	2.1	36.6	59.6	5.3	8.4	0.9	1.4
	(0.01)	(1.72)	(0.07)	(0.73)	(0.03)	(1.71)	(1.39)	(0.15)	(0.10)	(0.23)	(0.33)
Paddy field	1.0	113.8	45.7	38.8	3.7	100.7	174.2	6.2	7.8	1.7	2.5
	(0.03)	(3.80)	(1.56)	(0.32)	(0.04)	(3.86)	(4.18)	(1.42)	(0.07)	(0.40)	(0.58)
Saline seep	52.2	11002.3	680.2	1592.6	27.2	18242.3	10958.7	1547.4	7.9	45.0	37.8
	(0.78)	(126.56)	(4.28)	(36.17)	(1.06)	(706.66)	(262.34)	(64.51)	(0.08)	(6.55)	(5.47)
Groundwater	3.5	393.9	222.6	143.8	6.8	856.0	737.8	26.6	8.2	5.2	6.8
	(0.23)	(30.53)	(11.44)	(14.89)	(0.93)	(76.94)	(81.30)	(11.69)	(0.03)	(0.26)	(0.29)

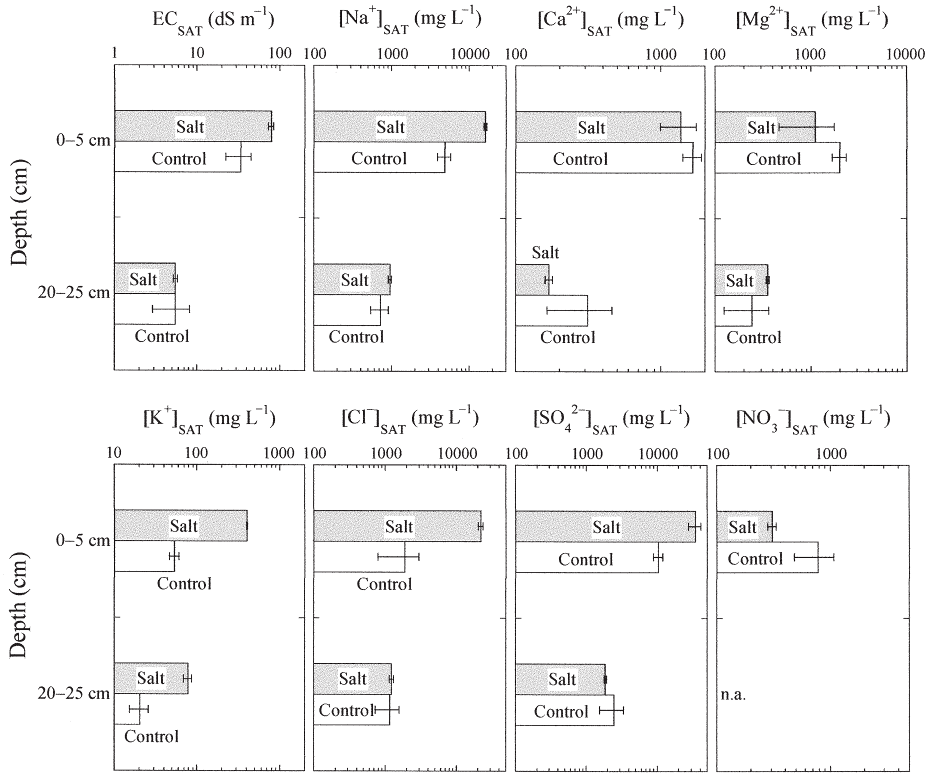

Fig. 4. Electrical conductivity (EC_{SAT}) and ion concentrations ($[Na^+]_{SAT}$, $[Ca^{2+}]_{SAT}$, $[Mg^{2+}]_{SAT}$, $[K^+]_{SAT}$, $[Cl^-]_{SAT}$, $[SO_4^{2-}]_{SAT}$ and $[NO_3^-]_{SAT}$) of the extract of saturated soils for the 0–5 cm and 20–25 cm depth layers in the experimental field (Control) and the salinized field (Salt) on 7 June 2007. Means of three samples are shown with the standard error.

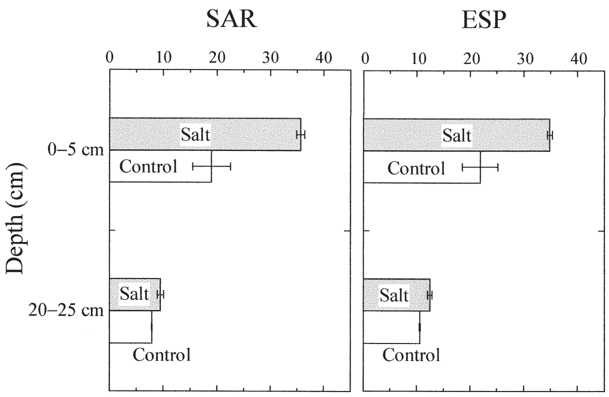

Fig. 5. Sodium adsorption ratio (SAR) and exchangeable sodium percentage (ESP) of the extract of saturated soils for the 0–5 cm and 20–25 cm depth layers in the experimental field (Control) and the salinized field (Salt) on 7 June 2007. Means of three samples are shown with the standard error.

Inner Mongolia, China, reported by Kitano *et al.* (2006). Furthermore, all the water samples were weakly alkaline because the values of pH were about eight, but judged normal with respect to sodicity, except for the saline seep water, because their SAR values were within the low level range shown by Akae *et al.* (2004) and ESP values were smaller than 15 (Wang *et al.*, this issue).

Figure 4 shows the EC_{SAT}, $[Na^+]_{SAT}$, $[Ca^{2+}]_{SAT}$, $[Mg^{2+}]_{SAT}$, $[K^+]_{SAT}$, $[Cl^-]_{SAT}$, $[SO_4^{2-}]_{SAT}$ and $[NO_3^-]_{SAT}$ of the soils sampled in 0–5 cm and 20–25 cm depth layers in the experimental field (Control) and the salinized field (Salt) on 7 June 2007. Concentrations of all ions were higher in the 0–5 cm depth layer than those in the 20–25 cm depth layer, and hence EC_{SAT} was also larger for the soil taken in the 0–5 cm depth layer. This suggests that evapotranspiration brought the upward movement of water and ions in the soil profile and thereafter only ions were remained in the surface soil. On the other hand, it is obvious that Na^+, Cl^- and SO_4^{2-} were major ions contained in the experimental and the salinized field soils, because $[Na^+]_{SAT}$, $[Cl^-]_{SAT}$ and $[SO_4^{2-}]_{SAT}$ were extremely higher than the others. Between the experimental and salinized fields, large differences in these major elements $[Na^+]_{SAT}$, $[Cl^-]_{SAT}$ and $[SO_4^{2-}]_{SAT}$ were found for the 0–5 cm depth soil, but there was no significant differences for the 20–25 cm depth soil. Therefore, a similar distribution as for the major elements concentrations in soils was appeared for EC_{SAT}; EC_{SAT} for the 0–5 cm depth soil in the experimental and salinized fields were 33.8 dS m^{-1} and 78.9 dS m^{-1}, respectively, while EC_{SAT} for the 20–25 cm depth soil in both fields took the same value as 5.5 dS m^{-1}. Furthermore, the SAR and ESP evaluated using $[Na^+]_{SAT}$, $[Ca^{2+}]_{SAT}$, $[Mg^{2+}]_{SAT}$ in **Fig. 4** were shown in **Fig. 5**. SAR and ESP were also higher for the surface soil, and the ESP of the 0–5 cm depth soil in the experimental and salinized fields were 21.9 and 34.9, respectively, while the ESP of the 20–25 cm depth soil in both fields were 10.6 and 12.5, respectively.

According to the diagnosis of soil by US Salinity Laboratory Staff (1954), a soil is considered to be saline if EC_{SAT} is above 4.0 dS m^{-1} and is considered to be sodic if ESP is above 15.0. The soils in the root zone

Table 2. Ion concentrations in crops grown in and around the experimental field on 7 June 2007. Means of three samples are shown with the standard error in parenthesis

Plants	Part	Na^+	Ca^{2+}	Mg^{2+}	K^+	Cl^-	SO_4^{2-}
		($mg\ L^{-1}$ D. W.)					
Corn (Control)	Shoot	1.2 (0.19)	4.1 (0.07)	8.0 (0.27)	20.9 (1.97)	9.6 (0.44)	2.4 (0.18)
	Root	6.2 (0.36)	4.3 (0.10)	5.5 (0.25)	12.4 (0.84)	6.8 (0.22)	6.4 (0.48)
Corn (Salt)	Shoot	3.2 (0.33)	2.7 (0.19)	7.0 (0.30)	29.8 (1.00)	12.3 (1.04)	4.9 (0.51)
	Root	9.4 (0.48)	4.0 (0.68)	5.8 (0.21)	15.6 (0.85)	9.6 (1.31)	9.4 (0.34)
Wheat	Shoot	1.8 (0.26)	2.2 (0.12)	2.0 (0.18)	10.6 (0.99)	4.2 (0.33)	3.2 (0.21)
	Root	3.2 (0.28)	7.7 (3.28)	2.5 (0.47)	6.7 (0.28)	1.8 (0.16)	6.5 (0.19)
Sesame	Shoot	3.8 (0.67)	5.6 (1.35)	3.8 (0.80)	12.9 (1.41)	3.1 (0.68)	4.2 (0.87)
	Root	2.2 (0.22)	1.4 (0.15)	1.3 (0.06)	5.9 (0.55)	1.1 (0.04)	0.8 (0.09)
Legume	Whole	2.6 (0.50)	7.6 (0.41)	7.3 (0.71)	16.5 (0.55)	7.1 (0.59)	10.3 (0.72)
Rice	Whole	3.0 (0.42)	9.8 (4.09)	2.3 (0.11)	6.0 (0.69)	2.1 (0.56)	4.8 (0.11)

Table 3. Ion accumulations in shoots and roots of corn plants grown in the experimental field (Control) and the salinized field (Salt) on 7 June 2007. Means of three samples are shown with the standard error in parenthesis

Corn	Part	Na^+	Ca^{2+}	Mg^{2+}	K^+	Cl^-	SO_4^{2-}
		($mg\ part^{-1}$)					
Control	Shoot	6.3 (0.76)	22.8 (2.08)	44.3 (2.36)	117.8 (18.43)	54.1 (6.71)	13.6 (2.24)
	Root	8.9 (0.31)	6.2 (0.54)	7.9 (0.95)	18.2 (2.97)	9.9 (1.10)	9.3 (1.61)
Salt	Shoot	9.4 (3.00)	7.5 (1.28)	19.8 (3.89)	86.8 (22.39)	36.0 (10.56)	13.3 (1.67)
	Root	6.3 (1.60)	2.4 (0.23)	3.8 (0.70)	10.4 (2.72)	6.6 (2.24)	6.1 (1.18)

(20–25 cm depth soil) in the both fields were classed as saline but non–sodic, while the surface soils (0–5 cm depth soil) were highly saline and sodic. These results suggest that corn can grow almost normally in the experimental field but not in the salinized field.

Table 2 shows the concentrations of ions Na^+, Ca^{2+}, Mg^{2+}, K^+, Cl^- and SO_4^{2-} in crops (corn, wheat, sesame, legume and rice) grown in and around the experimental field on 7 June 2007. The ion concentrations in plant body (shoot and root, or whole) are considered to reflect the active and selective ion uptake by roots (Kramer and Boyer, 1995). K^+ is the major essential nutrient for plant growth (Taiz and Zeiger, 2002), and therefore its concentration was found to be relatively high in all the crops. On the other hand, Na^+, which is not the essential element for crop growth, was not highly concentrated in plant body, although a large amount of Na^+ existed in the soil in and around the experimental field (**Fig. 4**). **Table 3** shows ion accumulations in shoots and roots of corn, which has the largest dry biomass of a single plant among the cultivated crops, in the experimental field (Control) and the salinized field (Salt) on 7 June 2007. High Na^+ concentration in the soil induced an increase of Na^+ concentration in corn (**Table 2**), but caused the growth depression. Plant heights in the experimental field and the salinized field averaged for several specimens were 0.78 m and 0.38 m, respectively. Consequently, the difference of Na^+ accumulation in the whole plant body (shoot + root) of corn was not so significant between the experimental and salinized fields. These results indicate that all crops grown in and around the experimental field have a poor ability to absorb Na^+ from soils, and this poor ability seems to be one of the factors causing the soil salinization and alkalization.

Therefore, techniques such as mixed cultivation or crop rotation using the plant with high ability of roots to absorb Na^+ should be developed for controlling salinity and sodicity in surface–irrigated fields within a normal range. Quintero *et al*. (2007) examined the root Na^+ uptake and Na^+ accumulation in the shoot of sunflower plants, and Irshad *et al*. (2005) dealt with the reclamation of saline wastelands by using halophytes.

CONCLUDING REMARKS

During the crop growing period, leaf transpiration accompanied by root water uptake induces the most significant driving force for mass flow transporting the groundwater toward the root zone (Yasutake *et al*., 2007), in which zone dynamics of ion balance largely depends on the root function of active and selective nutrient uptake (Kitano *et al*., 2006). Therefore, not only physical but also physiological transport processes in the soil–plant–atmosphere continuum should be taken into consideration for analysis of soil salinization and alkalization in irrigated fields.

In this study, waters (Yellow River water, irrigation canal water, paddy field water, saline seep water, groundwater), soils (experimental field and salinized field) and crops (corn, wheat, sesame, legume and rice) were sampled and their chemical characteristics such as EC, ion concentration, pH, SAR and ESP were measured, and the state of salinization and alkalization in and around the experimental field was analyzed using mainly the data obtained on June 2007. To get more detailed information about the dynamics of water and ion transport, which causes salinization and alkalization of soil and water, seasonal change in the spatial distribution of ion concentrations in and around the field should be analyzed by conducting intensive surveys frequently.

ACKNOWLEDGEMENTS

This research was supported by Grant–in–Aid for Scientific Research (No. 19405039 and No. 17380151) and a Grant–in–Aid for JSPS Fellows from the Japan Society for the Promotion of Science. The authors would like to thank Prof. X. Li (the Cold and Arid Regions Environmental and Engineering Research Institute, CAS) for his cooperation, and Prof. K. Iwasaki, Mr. Y. Sago and Mr. K. Yokoyama (Faculty of Agriculture, Kochi University) for helping the chemical analysis.

REFERENCES

Akae, T., T. Uno, H. Shi and Y. Li 2004 Changed cation composition of water in the Hetao irrigation district, Inner Mongolia: from irrigation to drainage. *Trans. JSIDRE*, **250**: 661–669 (in Japanese with English abstract)

Irshad, M., T. Endo, T. Honna, S. Yamamoto and A. E. Eneji 2005 The reclamation of saline wastelands by halophytes. *J. Arid Land Stud*., **14**: 199–207

Kitano, M., D. Yasutake, T. Kobayashi, K. Hidaka, T. Wajima, W. Wang and W. He 2006 Dynamics of water and ion transport driven by corn canopy in the Yellow River basin. *Biologia*, **61(Suppl.19)**: S275–S279

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

Kramer, P. J. and J. S., Boyer 1995 *Water Relations of Plants and Soils*. Academic Press, San Diego, p. 495

Mizuta, K., K. Kadoshige and T. Hirano 2001 The change in the quality of irrigation water in ten years in Fukuoka prefecture. *Jpn. J. Crop Sci*., **70**: 255–260 (in Japanese with English abstract)

Quintero, J. M., J. M. Fournier and M. Benlloch 2007 Na^+ accumulation in shoot is related to water transport in K^+–starved sunflower plants but not in plants with a normal K^+ status. *J. Plant Physiol*., **164**: 60–67

Rengasamy, P. 2006 World salinization with emphasis on Australia. *J. Exp. Bot*., **57**: 1017–1023

Taiz, L. and E. Zeiger 2002 *Plant Physiology. 3rd edition*. Sinauer Associates, Sunderland, p. 691

United States Salinity Laboratory Staff 1954 *Saline and Alkali Soils*. Agriculture Handbook No. 60, US Department of Agriculture, Washington D. C., p. 160

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. Agri. Kyushu Univ*., **52**: 251–256

Yasutake, D., T. Kobayashi, D. Ikegami, R. Iwanaga, W. Wang, W. He and M. Kitano 2007 Analyses of crop coefficients and water balance in an irrigated cornfield in the Upper Yellow River basin. *J. Agric. Meteorol*., **63**: 115–124

Yoshikoshi, H., W. Wang, H. Cho, T. Araki, D. Yasutake, J. Zhou, K. Urayama, Y. Wu, T. Kobayashi 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. Agri. Kyushu Univ*., **52**: 257–263