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Salt Accumulation Process Near the Soil Surface Induced by Soil Water Evaporation: Measurements and Analyses

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ABSTRACT

Experiments were conducted to measure the amount of salt and water during evaporation from soil in a lysimeter. A new analytical solution to express the accumulation patterns of the salt was derived. Using the new solution, the experimental results were analyzed successfully.

The measured evaporation rate was highly correlated with the solar radiation intensity. Even after sunset, however, evaporation continued for several hours.

The distribution patterns of soil water and salt were characteristic. In the early stage of evaporation, soil water decreased almost homogeneously. After that, the drying up advanced near the soil surface. The salt naturally accumulated near the soil surface. There was a distinctive depth where the amount of salt was the same as the initial one. The solute concentration in deeper soil remained constant during the whole evaporation period. This evidence proved that the salt moved as a liquid solution of the same mixing ratio as the initial one.

Based on the evidence obtained, an analytical solution was newly developed to express the accumulation patterns of the salt in the soil during the water evaporation. The observed patterns of salt accumulation were very well fitted with the analytical solution. The best fitting values of the average velocity of soil water were consistent with the values obtained experimentally using mass balance of salt, whereas the apparent diffusion coefficient of salt in soil ranged from 1/27 to 1/10 of the diffusion coefficient of NaCl in free water, 1.30 cm^2 day^{-1}. The newly developed analytical solution thus proved to be useful in expressing the distribution patterns of salt accumulation. Although the smallness of the apparent diffusion coefficient of salt in unsaturated soil is not surprising, the functional relationship between water content and values of the diffusion coefficient should be investigated further.

INTRODUCTION

Of 1.5×10^9 ha of cultivated land in the world, about 0.34×10^9 ha (23%) are saline and another 0.56×10^9 ha (37%) are sodic (Tanji, 1990b). Soil and water salinity decreases the availability of soil water and retards germination, growth, yields of crops (Tanji, 1990b) and thus agricultural production. In 24% of the irrigated land in five major countries, agricultural production was damaged by the salt accumulation (Postel, 1990).

To avoid further accumulation of salt and to ameliorate the saline soil, the process of both salt accumulation and salt leaching in soil should be well understood and controlled. For this purpose, several publications (e.g. Richards, 1954; Nielsen et al., 1972; Bresler et al., 1982; Tanji, 1990a) are available. Methods to analyze the solutes concerned are introduced in a monograph by Klute (1986, pp. 985–1087). In studying these, the salt accumulation during evaporation has been less studied compared with the solute dispersion during leaching. Both experimental and theoretical investigations should be pursued further in order to understand and control the salt accumulation occurring in agricultural land.

The important characteristics of salt-affected soil in Thailand and trials to improve it were investigated by a research project that included the authors (Takai et al., 1987). Salt accumulation near the soil surface is one of the most apparent symptoms of saline soil. The question of to what depth and how much salt will accumulate are the most common concerns of the process. In the present paper, the experiments and theoretical analyses are pursued in order to obtain a clear understanding of the accumulation process.

In the experiments, the measurement of salt and water in soil was carried out during the soil–water evaporation. In order to analyze the measured values of salt accumulation, an analytical solution was newly developed for the process of salt accumulation during soil–water evaporation The comparison of measured values with those theoretically obtained from the newly developed analytical solution showed excellent agreement within experimental errors. Therefore the new solution was proved to be suitable in expressing the distribution patterns of salt accumulation in the top soil.

MATERIALS AND METHODS

Experimental apparatus

A lysimeter was used to hold the soil during the experiments. The size of the lysimeter was 905 mm (W) × 1885 mm (L) × 400 mm (D) and the horizontal area was 1.71 m^2 (A_{so}). In order to make the walls and bottom of the lysimeter impermeable to heat and moisture penetration, they were made of a combination of outer wooden boards, perforated polystyrene blocks, inner wooden boards and PVC (poly vinyl chloride) films, respectively, starting from outside. An electric heating wire, 40 m in length and 20 Ω in resistance, was attached on the inner board of the bottom and operated with the power of 33 W m^{-2} during the period from the 39th to the 53rd day since the soil water evaporated, because the ambient air temperature was so low as to freeze the soil.

To avoid rainfall while receiving solar radiation, the top of the lysimeter was covered with transparent plastic housing 2.0 m^3 in volume and referred to hereafter as 'the covering'. The ventilation system at the constant rate ($Q = 0.375\ m^3\ min^{-1}$) and circulating fans were installed inside the covering.

Soil and procedures

The top soil of the upland field at the Iwate University Experimental Farm was used for the experiments. Taxonomically, the soil was classified as Kurobokudo or Ando soil in Japan and more recently as Andisols (Wada, 1986). The parent material of the soil was volcanic ash and the texture was loam. Several interesting characteristics of the soil were reported by Hara (1990) regarding the heat and moisture transfer.

After removing impurities with a 5 mm mesh sieve, a measured amount of salt (NaCl) solution was added to the soil to obtain appropriate initial water content (130 cm H_2O in soil water tension) and salinity (1.7% in solute concentration) as observed in Northeast Thailand (Takai et al., 1987, pp. 23–29).

The lysimeter was filled to a depth of 38 cm with the prepared experimental soil as homogeneously as possible and the total weight, water content and salt content were measured. From the measurement, the bulk density, ϱ_b[kg m^{-3}], was calculated. Immediately after filling, the soil surface was covered with a thick mat, which inhibited the heat exchange and the vapor exchange on the soil surface. After the establishment of equilibrium, the mat was removed and the evaporation started on December 18th, 1989 — 33 days since the soil was filled. The date will be referred as date 0, $t = 0$ or $T = 0$, hereafter. Fifty-six days after the evaporation, the tap water measured was irrigated on the soil surface for three successive days, $t = 57$–59 day, to observe the dilution of soil solution due to leaching. Although discussion including the leaching would be very interesting, it will not be presented in this paper.

Measurement

Dew-point hygrometers were set inside and outside the covering to measure the exchanging rate of the water vapor. Tensiometers were installed to measure the matric component of pressure potential of soil water at points at a depth of 10, 20 and 30 cm, respectively. Pyranometers were used to measure the flux of total solar radiation outside and inside the covering and that of the reflection from the soil. Thermocouple thermometers were set to measure the ambient air temperature as well as the soil temperature at the surface and at each point at a depth of 4, 8, 12, 16, 20, 24, 32 and 38 cm. In addition, thermocouples were set in the soil to check the horizontal evenness of the temperature field.

The data logging system was set up using a computer. Signals were measured every 1 min. The averaged values for 30 min were recorded on magnetic discs.

The soil sampled from points at depths of 0–2, 2–10, 10–20, 20–40, 40–60, and so on in increments of 20 mm to 360–380 mm was measured for the values of water content, salt content and pH. The soil sampler was an aluminum circular pipe, with the wall 0.5 mm thick, an inner diameter of 8 mm and a length of 45 cm. The water content was measured with the 105°C, 24-h oven dry method. The oven dried soil was moistened with 29 times mass of pure water, stirred for 5 min, settled for 24 h and then the EC (electrical conductivity) and the pH of the supernatant fluid were measured.

Each amount of water W_s[g], salt N_s[g] and solid S_s[g] in the sampled soil was then calculated separately from the measured values of the dry weight W_d[g], water content W[(g of water) (g of dry matter)$^{-1}$], added amount of pure water W_p[g] and the EC value, σ[dS m^{-1}], via the calibrated concentration of the solution c_n[(g of salt)(g of solution)$^{-1}$] with:

$$c_n = f(\sigma) = 5.16 \times 10^{-4} \times (\sigma/[\mathrm{dS\ m^{-1}}])^{1.030} \quad (1a)$$

$$N_s = W_p \cdot c_n/(1 - c_n) \quad (1b)$$

$$S_s = W_d - N_s \quad (1c)$$

$$W_s = W_d \cdot w \quad (1d)$$

(The notation $\sigma/[\mathrm{dS\ m^{-1}}]$ is used to obtain the abstract number of EC in the unit of [$\mathrm{dS\ m^{-1}}$] as a quotient. For example, if the EC value is 2.16 $\mathrm{dS\ m^{-1}}$ then $\sigma/[\mathrm{dS\ m^{-1}}]$ is 2.16 because $(2.16\ \mathrm{dS\ m^{-1}})/(\mathrm{dS\ m^{-1}}) = 2.16$.)

The volume basis contents of water W[$\mathrm{kg\ m^{-3}}$] and salt N[$\mathrm{kg\ m^{-3}}$] were then calculated with:

$$W = \rho_b \cdot (W_s/S_s) \quad (2)$$

$$N = \rho_b \cdot (N_s/S_s) \quad (3)$$

The measured values of pH were converted to the values for the conventional 1:2.5 solution with:

$$y = f(x, n) = -\log_{10}[\{n \times 10^{-x} - (n - 2.5) \times 10^{-7}\}/2.5] \quad (4)$$

where $n = 29$; x, y = the pH values for 1:n and 1:2.5, respectively. (It should be noted that there is some possibility that values of pH for 1:2.5 solution calculated with Equation (4) using measured values of pH for 1:29 solution may be different from those measured directly for 1:2.5 solution, although it may not be serious. The large mixing ratio, $n = 29$, was adopted to obtain the necessary amount of fluid to measure the EC and the pH using electrodes against the small amount of soil sample.)

Evaporation rate E[$\mathrm{kg\ m^{-2}\ min^{-1}}$] was calculated from the dew points, $t_{dp,in}$ and $t_{dp,out}$ [°C] and ventilation rate Q[$\mathrm{m^3\ min^{-1}}$] with the formulas by Hara and Nishiyara (1983) and

$$G = Q/v_{out} \quad (5a)$$

$$E = G \cdot (x_{in} - x_{out})/A_{so} \quad (5b)$$

where G = ventilation rate of dry air [$\mathrm{kg'\ min^{-1}}$]; v_{out} = specific volume [$\mathrm{m^3\ kg'^{-1}}$]; x_{in}, x_{out} = absolute humidity [$\mathrm{kg\ kg'^{-1}}$].

RESULTS

Experiments

Water content, salt content and pH

The mean bulk density was 659.4 kg $\mathrm{m^{-3}}$ not including salt into solid phase. Figure 1 shows the volume basis water content in soil for the days, t = 0, 10, 22 and 53. Figures 2(a–c) show the ratio (r_N) of salt content (N) to its mean value ($\overline{N}$). Table 1 shows the mean values of the water and salt contents together with their several derivatives.

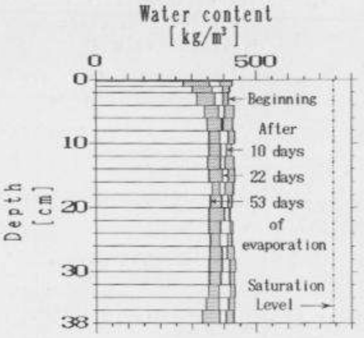

Fig. 1. Soil water content observed in the evaporation experiment. Values for the dates T = 0, 10, 22 and 53 days are indicated.

The mean evaporation rates $\overline{E}$[mm day^{-1}] shown in Table 1 were calculated from the decreases of the mean water content from the beginning to the specified dates.

Changes in the mean salt contents were considered as experimental fluctuations because the salt should neither have left nor entered the soil. Thus the ratio r_N, rather than the salt content (N) itself, is more suitable to express the distribution patterns of salt accumulation.

Figure 3 shows the ratio of the salt to water content, c[$\mathrm{kg\ kg^{-1}}$], for T = 0 and 53 day. The mean value ($\overline{c}$) of the ratios of the salt to water content for the soil between the points at the depth of 4 and 38 cm (bottom) are shown in Table 1.

The values of pH (1:2.5) ranged between 4.55 and 4.86 at the beginning, and between 4.55 and 5.16 at T = 53 day. The lowest values were observed in the topmost soil.

Tensiometer readings

The tensiometer readings for the points in the depths of 10, 20 and 30 cm changed from 507, 400 and 362 cm H_2O for t = 0 to 675, 633 and 603 cm H_2O for 22 day. After that, the tensiometer readings became unreliable because of air entry.

Temperature

The surface temperature of the soil changed within the range between −5 and 25°C. The daily mean values of the surface temperature ranged between 0 and 9°C. The minimal surface temperatures lower than 0°C were observed every day during the period, t = 26 to 47 day. The daily maximal values of

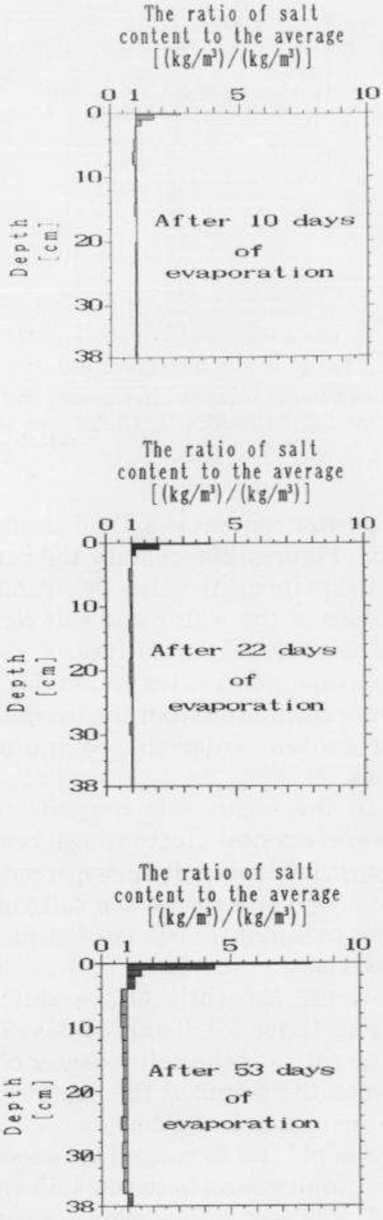

Fig. 2. Ratio of salt content to its averaged value in the profile observed in the evaporation experiment. Values for the dates T = 10 (a), 22 (b) and 53 (c) days are indicated.

the surface temperature did not fall lower than 2°C during the whole evaporation period.

The horizontal gradient of the soil temperature was so small that only the vertical temperature gradient predominated in the soil–temperature field.

Hourly evaporation rate

Figure 4 shows the evaporation rate (E) for every 30 min on a typical sunny day, February 7th ,1991, together with the flux of total solar radiation (R) outside the covering and the absolute humidities (x_{in} and x_{out}) inside and outside the covering.

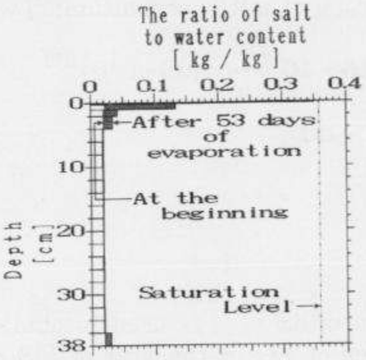

Fig. 3. Salt to water ratio in the soil observed in the evaporation experiment. Values for the dates T = 0 and 53 days are indicated.

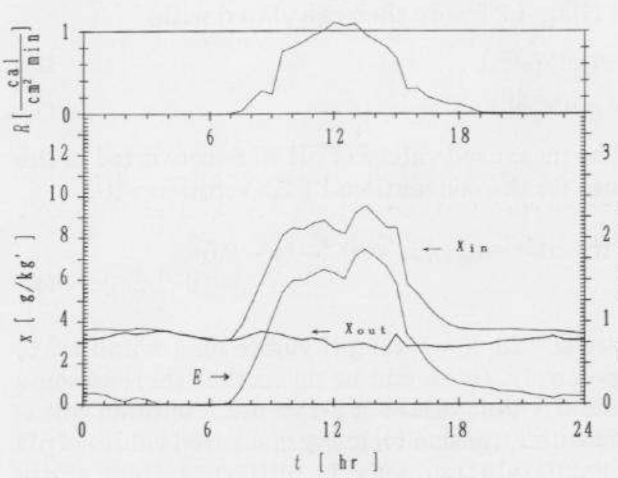

Fig. 4. Evaporation rate, the flux of total solar radiation outside the covering and the absolute humidity inside and outside the covering. The averaged values for every 30 min on a typical sunny day are indicated.

Cumulative evaporation and solar radiation intensity

Between the cumulative solar-radiation flux outside the covering and the evaporation from the soil, a linear relationship was found. The regression line passed at the points (40 Mcal m^{-2}, 12.5 kg m^{-2}) and (130 Mcal m^{-2}, 25.0 kg m^{-2}). The gradient of the line is 7.20 Mcal kg^{-1}, which is 12.2 times greater than that of the latent heat of water for vaporization at 10°C, 0.592 Mcal kg^{-1}.

Analyses

Solute flux equations and initial and boundary conditions

One-dimensional movement of salt in the soil may be expressed by the equation

$$J_s = -\theta D \frac{\partial C}{\partial z} + qC \qquad (6)$$

where J_s = solute flux [kg m^{-2} s^{-1}]; θ = volumetric water content [m^3 m^{-3}]; D = apparent diffusion coefficient [m^2 s^{-1}]; C = volume-averaged solute concentration [kg m^{-3}]; z = vertical coordinate (positive downward) [m]; q = volumetric fluid flux density [m^3 m^{-2} s^{-1}].

The equation of continuity unless adsorption and sources is

$$\frac{\partial(\theta C)}{\partial t} = -\frac{\partial J_s}{\partial z} \qquad (7)$$

Substituting Equation (6) into (7) yields the transport equation

$$\frac{\partial(\theta C)}{\partial t} = \frac{\partial}{\partial z}\left(\theta D \frac{\partial C}{\partial z} - qC\right) \qquad (8)$$

If steady water flow in a homogeneous soil profile is further assumed (θ and q are constant in time and space), Equation (8) reduces to

$$\frac{\partial N}{\partial t} = D\frac{\partial^2 N}{\partial z^2} - v\frac{\partial N}{\partial z} \qquad (9)$$

where $v = q/\theta$ (average interstitial flow velocity) [m s^{-1}]; $N = \theta C$ (salt content) [(kg salt)(m^3 soil)$^{-1}$].

The initial condition:

$$N = N_0(\text{constant}) \text{ at } z > 0,\ t = 0 \qquad (10)$$

The boundary condition for the evaporation is $J_s = 0$, or

$$D\frac{\partial N}{\partial z} = vN \qquad \text{at } z = 0,\ t > 0 \qquad (11)$$

for the evaporating surface and $\partial N/\partial z = 0$ at $z = L = 38$ cm, $t > 0$ for the bottom. Instead of the finite boundary condition for the lower end, a semi-infinite one may be applicable.

$$\partial N/\partial z = 0 \ \text{ at } z = \infty,\ t > 0 \qquad (12)$$

Analytical solution for evaporative salt accumulation

The analytical solution of Equation (9) with the conditions, Equations (10), (11) and (12), was derived using the technique of Laplace transforms as

$$\frac{N}{N_0} = 1 + \frac{1}{2}\left[1 + \frac{v}{D}(z + vt)\right]\exp\left(\frac{vz}{D}\right)\operatorname{erfc}\left[\frac{z + vt}{2(Dt)^{1/2}}\right]$$
$$-\frac{1}{2}\operatorname{erfc}\left[\frac{z - vt}{2(Dt)^{1/2}}\right] - v\left(\frac{t}{\pi D}\right)^{1/2}\exp\left[-\frac{(z - vt)^2}{4Dt}\right] \qquad (13)$$

Application of the new solution to the experimental data

In order to apply the analytical solution (Equation (13)) to the experimental results, the values of D and v are necessary. The value of v can be estimated with several ways.

Method 1: The value of v may be obtained according to the definition, $v = q/\theta$. Since $q + q_v = -E$, q is expressed as $q = -E - q_v$ where q_v is the flux of vapor flow noting that q and q_v are positive downward. While the value of E were shown as $\overline{E}$ in Table 1, q_v is unknown. We may assume that $q_v = 0$. The value of θ for the soil at the points at depths of between 1 and 2 cm may be appropriate. Table 3 shows the measured values of θ for that depth. Values of v obtained with $v = -\overline{E}l\ \theta$ are shown under Method 1 in Table 2.

Method 2: According to Equation (6) v is expressed as $v = J_s/N$ if $\partial C/\partial z = 0$ where $N = \theta C$. As shown in

TABLE 1

Soil water content, average evaporation rate, salt content and the ratio of salt to water content during evaporation and after irrigation

T (day)	W (kg/m³)	W(T)–W₀ (kg/m³)	$\overline{E}$[**] (mm/day)	N (kg/m³)	N(T)–N₀ (kg/m³)	$\overline{c}$(z_c<z<38 cm)[****] (kg/kg)
0	429.6	0.0	na[***]	8.475	0.000	0.0196[#]
10	410.7	–18.9	0.72	7.755	–0.721	0.0182[#]
22	388.7	–40.9	0.71	7.885	–0.591	0.0192[#]
53	347.2	–82.4	0.59	8.331	–0.145	0.0199[#]
63[*]	508.2	78.6	na	6.812	–1.664	0.0177[##]

[*] The 40 l/day of water was irrigated for 3 days, 57 ≤ T ≤ 59.

[**] Average values for the period, 0<t<T.

[***] Not applicable.

[****] z_c = 4 and 14 cm for [#] and [##], respectively.

TABLE 2

Estimated values of average water velocity

	Method*		
	1	2	3
T (day)	v** (cm/day)		
10	–0.176	–0.122	–0.126
22	–0.179	–0.083	–0.082
53	–0.158	–0.112	–0.117

*See text.

**Average values for the period, $0<t<T$.

TABLE 3

Apparent diffusion coefficient of salt in soil solution and soil water content

T (day)	D* (cm²/day)	D/D₀** (1)	θ(1<z<2 cm)* (cm³/cm³)
10	0.127	0.098	0.408
22	0.048	0.037	0.394
53	0.082	0.063	0.374

*Average values for the period, $0<t<T$.

**D_0 denotes the diffusion coefficient of NaCl in the free water, 1.30 cm²/day.

Fig. 3 and Table 1, the value of C had practically no gradient and remained constant for 53 days in the soil below 4 cm. The salt accumulation occurred only in the top soil at depths of less than 4 cm. Obtained values of v are shown under Method 2 in Table 2.

Method 3: The so-called curve fitting method was used to estimate both values of v and D in the Equation (13). The value of N/N_0 of Equation (13) was divided by its average for $0 < z < 38$ cm, compared with the values shown in Fig. 2 and evaluated for the top 10 cm using the least square criterion. The best fitted values of v and D are shown under Method 3 in Tables 2 and 3. Figures 5(a–c) show the best fitted distribution patterns of the salt accumulation in the form of curves as well as expressing the measured values by a rectangular form.

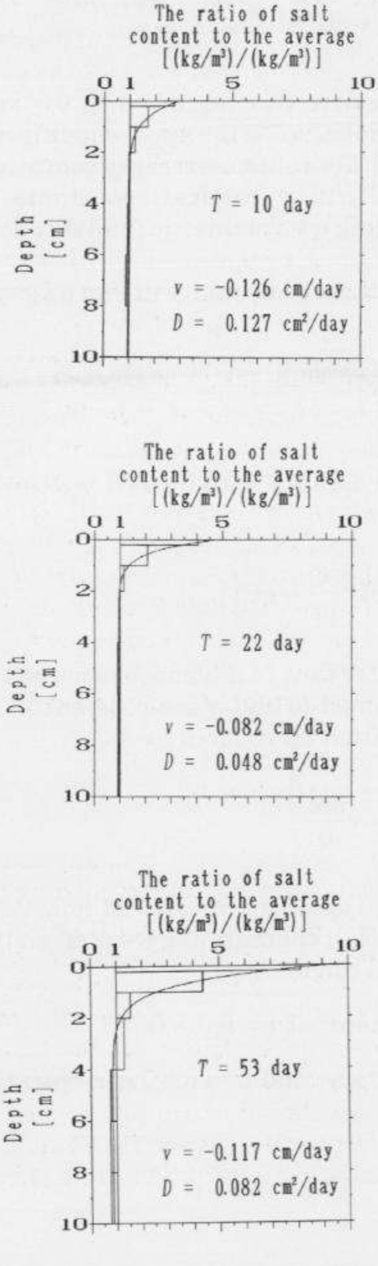

Fig. 5. Analytical solution for the distribution of salt accumulated near the soil surface with evaporation of water at the soil surface. The curves were obtained with Equation (13) using the best fitting parameter values of D and v. Measured values are also indicated by a rectangular form for comparison. Values for the dates T = 10 (a), 22 (b) and 53 (c) days are indicated.

CONCLUSIONS

The hourly evaporation rate was strongly affected by the flux of the solar radiation. Even after sunset, however, the evaporation continued for several hours. The energy required for evaporating at night may have come from the heat stored in the soil in the daytime. The finding of a linear relationship between the cumulative evaporation and solar radiation intensity indicates that the energy for the evaporation has consequently been supplied from solar energy. However, only 9.0% of total solar energy was used for soil–water evaporation in the experimental set-up.

The soil–water evaporation brought about the desiccation of soil and derived the upward solute desiccation of soil and derived the upward solute movement in the soil, which resulted in salt accumulation near the soil surface. The salt concentration of the solution in the soil below the accumulation zone remained constant during the whole evaporation period. This evidence indicates that the salt moved as a liquid solution of the same mixing ratio as the initial one and that the increase in the amount of salt in the accumulation zone is obtained as the product of the solute concentration and the amount of solution entered across the bottom of the zone.

The newly obtained analytical solution, Equation (13), for the process of salt accumulation during soil–water evaporation proved useful in expressing the distribution patterns of salt in the soil including the accumulation zone. The value of parameter v in the solution was estimated well with Method 2 in the preceding section using the total amount of accumulated salt, the duration of accumulation, the salt concentration of soil solution beneath the accumulation zone and the volumetric water content there. Obtaining the value of v, the value of D could be estimated using the thickness of the accumulation zone.

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REFERENCES

Bresler, E., McNeal, B.L. and Carter, D.L., 1982. Saline and Sodic Soils, Principles — Dynamics — Modeling. Springer-Verlag, Berlin, Heidelberg, New York, 236 pp.

Hara, M., 1990. Heat and moisture transfer characteristics of Ando soil. In: Trans. 14 Int. Congr. Soil Sci., Kyoto, 1990. Vol. I, Commission 1: 256–257.

Hara, M. and Nishiyama, Y., 1983. Mathematical expressions of moist air condition. J. Fac. Agric. Iwate Univ., 16: 107–121.

Klute, A., 1986. Methods of Soil Analysis. Part 1.Physical and Mineralogical Methods, 2nd ed., No. 9 (Part 1) in the series Agronomy, Am. Soc. Agron. and Soil Sci. Soc. Am., Madison, Wisconsin, 1188 pp.

Nielsen, D.R., Jackson, R.D., Cary, J.W. and Evans, D.D., 1972. Soil Water. Am. Soc. Agron. and Soil Sci. Soc. Am., Madison, Wisconsin, 175 pp.

Postel, S., 1990. Saving Water for Agriculture. In: K. Matsushita and A. Kitano, 1990. Chikyu Hakusyo 1990–91. Diamond, Tokyo, pp. 63–125. Japanese translation of L.R. Brown (Editor), 1990. State of the World 1990. W.W. Norton & Company, Inc., New York.

Richards, L.A., 1954. Diagonis and Improvement of Saline and Alkali Soils. USDA Handbook No. 60, Washington D.C., 160 pp.

Takai, Y., Nagano, T., Kimura, M., Sugi, J. and Vacharotayan, S., 1987. Coastal and Inland Salt-Affected Soils in Thailand, Their Characteristics and Improvement. Nodai Res. Inst., Tokyo Univ. of Agric., Tokyo, 280 pp.

Tanji, K.K., 1990a. Agricultural Salinity Assessment and Management. ASCE Manuals and Reports on Engineering Practice No. 71, New York, 619 pp.

Tanji, K.K., 1990b. Nature and Extent of Agricultural Salinity. In: K.K. Tanji (Editor), Agricultural Salinity Assessment and Management. ASCE Manuals and Reports on Engineering Practice No. 71, New York, pp. 1–17.

Wada, K., 1986. Ando Soils in Japan. Kyushu Univ. Press, Fukuoka, Japan, 275 pp.