

Characteristics of Salt Leaching in Saline Soil with a Subsurface Hardpan: - A Study Using Undisturbed Soil Core Samples -

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Summary

A comparative leaching experiment of saline soil using undisturbed core samples (20 cm in diameter and 74 cm in length) with and without a hardpan, was carried out following the conventional method of water supply. The samples were collected in salt-affected farmland in the Syrdarya Region of Uzbekistan, with a hardpan formed at a depth of 30 cm. Another sample, without a hardpan, was plowed manually to a depth of 40 cm. A 24-day leaching experiment with total water supply of 300 mm demonstrated clear differences between the two sample types. The amounts of leached water were 98.7 mm for with hardpan and 223.6 mm for without hardpan samples, and the amounts of salt leached from samples were estimated as 276 mg cm⁻² (discharge ratio: 16.4%) and 597 mg cm⁻² (35.8%), respectively.

Seventy-two days after the experiment, the saturated hydraulic conductivity of samples without a hardpan at depths of 30–60 cm was reduced to one-200th of that before the experiment. This suggested that hardpans could form not only by tractor compaction but also soil slaking and precipitation of gypsum by leaching operations. It is necessary to develop methods to maintain the effects of breaking the hardpan and confirm their validity through on-site testing.

Keywords

Hardpan, Leaching, Salt-affected soil, Undisturbed soil, Uzbekistan

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1. Introduction

In Uzbekistan, most of the land is arid and semi-arid, but the Amu Darya and Syr Darya Rivers flow on both sides of the country, and irrigated agriculture has long been widely practiced utilizing the water from both rivers, as well as from their branch rivers (Saito, 2015). Large-scale irrigation projects started in the beginning of the 1960s, and irrigated farmland surrounding the Amu Darya and Syr Darya Rivers increased substantially from 1970 over approximately 20 years by 150% and 130%. Drainage facilities were also developed along with these irrigation projects, however, the salinization of farm soil has progressed ever since and agricultural production has been increasingly damaged due to excessive irrigation and inadequate drainage management. According to the Food and Agriculture Organization of the United Nations (FAO), 51% (2.14 million ha) of total irrigated farmland in the country (4.2 million ha) was saline in 1994 (FAO, 2013). In order to maintain sustainable agricultural production in the country, measures and preventive measures against chlorinated soil, which accounts for half of irrigation agricultural land, are required.

In the Syrdarya Region of Uzbekistan, saline groundwater rises to near the surface by capillary action and evaporates, increasing the salinity of the soil. Soil salinization also increases due to the addition of saline irrigation water to agricultural soils (e.g., Shirokova et al., 2000). As a measure to remove salt accumulated in soil, the Hydro-Geological Melioration Expedition (HGME) of the local governmental agency instructs farmers to conduct leaching. In Syrdarya, measures have been taken to supply the amount of leaching water to 2,500-4,500 m³ ha⁻¹ (250-450 mm) depending on the degree of salt damage, and the appropriate starting period is November to December (HGME, 2007). In response to this, farmers cultivate agricultural land to a depth of 20 cm prior to leaching, and then install leaching plots divided into approximately 20 × 20 m, and distribute water for each leaching plot. However, in the field where the drainage function is degraded, in the central of the field away from the drainage channel, and in the vicinity of the service channel, the leaching water is not sufficiently discharged to the outside of the field due to the continuation of the high groundwater level state, and the salinity of the soil remains high (Okuda et al., 2017).

In addition to these factors, salt accumulation due to agricultural engineering is considered to have occurred in Syrdarya. Matsumoto (1988) pointed out that if a hardpan is formed in dry land, stagnant water is temporarily formed above the hardpan, and salt accumulation is likely to occur due to the intense evaporation of the stagnant water. It has been confirmed that a hardpan is formed in a salt-accumulating field in the Syrdarya State immediately below the soil layer about 20 cm from the surface layer, by the impact of compaction due to large-scale tractor driving (Omori and Okuda, 2015). According to Matsumoto (1988), this hardpan under the cultivated soil layer could be one factor facilitating soil salinization.

The purpose of this study was to experimentally verify the assumption that crushing the hardpan promotes the infiltration of leaching water to efficiently leach out the salt of the crop layer and prevent the formation of stagnant water. To achieve this, an indoor leaching experiment was conducted using a soil core in which a hardpan was not disturbed (hereinafter referred to as with hardpan) or was disturbed

(hereinafter referred to as without hardpan), and the amount of leaching water, the leaching state of salts, and the chemistry of leaching water were compared. Since it is known that the measured values of lysimeters concerning leaching amounts of nitrogen and salt differ from the actual dynamic observation results in soil with disturbed layer positions and structures (e.g., Ozaki et al., 2001), undisturbed soil was used as the soil core. This is the first leaching experiment using an undisturbed soil core sample of salt soil with a hardpan.

2. Experimental method

2.1 Sampling of undisturbed soil core samples and configuration of experimental equipment

The undisturbed soil was collected from salt-accumulation farmland of the Yangiobad Water Consumers' Association (40°29'N, 68°39'E) located in Syrdarya on September 21–22, 2015. Weeds were removed before soil sampling, and the soil was then cultivated with excavators to a depth of approximately 20 cm so that the condition before leaching could be maximally reproduced. For the soil-core samples of the hardpan fracture, the hardpan was further fractured by cultivation to a depth of approximately 40 cm. For the collection of undisturbed soils, a tool capable of fixing handles to the upper part of a stainless-steel cylinder and having an inner diameter of 20 cm, a thickness 1.0 mm, and a height 100 cm, the tip of which was machined into a saw blade, was used. After inserting the cylindrical body to a depth 80 cm while turning it over manually, or driving it with hammers, soils around the cylindrical body were excavated and the cylindrical body was removed.

Fig. 1 shows an outline of a leaching experiment apparatus using an undisturbed soil core sample. The bottom 6 cm of the collected undisturbed soil was scraped off, a 75- μ m nylon mesh was laid on the lower end of the soil, gravel having a particle size of 5 to 10 mm was 3 cm filled, and a support plate (thickness 3 cm) in which a stainless-steel punched plate was processed, was installed (hereinafter referred to as "test piece"). Therefore, the height of the soil column of the test piece was 74 cm. The test piece was installed in a funnel made of stainless steel, and was structured to receive leachate water from the bottom of the test piece into a water sampling container. It was assumed that the leached solution was collected or discharged into the underdrain drainage.

For the leaching experiment, three specimens were prepared for each of the with hardpan and the without hardpan. Dielectric soil moisture sensors (5TE, manufactured by METER) were buried at four depths of 15, 30, 45, and 60 cm from the ground surface, parallel to the ground surface, in each of the with hardpan and the without hardpan specimens. The 5TE sensors were connected to data loggers (Em50, manufactured by METER) and recorded soil moisture and soil EC by depth at 5-minute intervals for one week after leaching water input and at 1-hour intervals thereafter.

The experiment commenced on September 23, 2015, and was terminated when the weight of the leached water became unchanged. In the case of the without hardpan, the leaching was completed with no change in the amount of leached water after 19 days from the start of the test. The test piece of the with hardpan had a constant amount of leached water 72 days after the start of the experiment, and thus the experiment was completed. Daily evaporative emissions in December in winter, when leaching

begins in the field, are approximately 0.5 mm (ADB et al., 2008). Due to the room temperature during the experiment being 22 to 24 °C and the relative humidity being 37% on average, the surface of the test pieces was covered to prevent evaporation so that the experimental system was as close as possible to resembling the site.

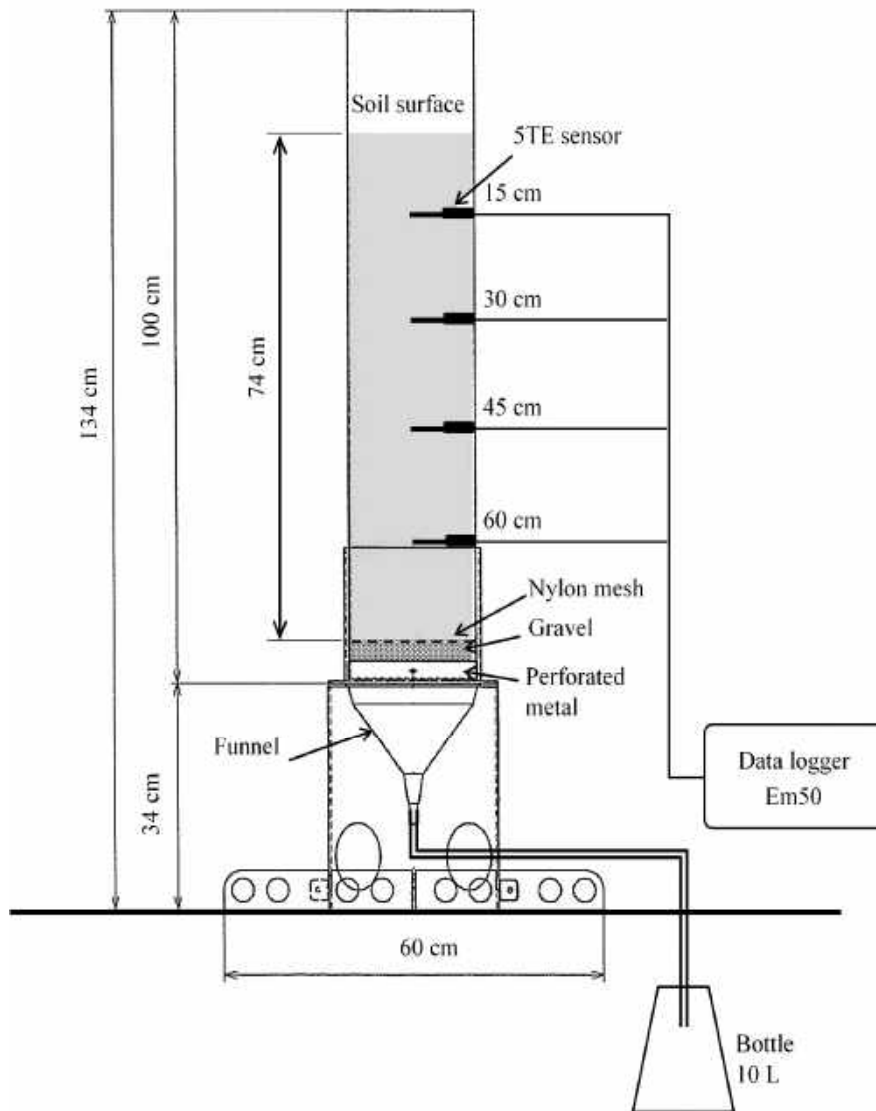


Fig. 1 Outline of a leaching experiment apparatus using an undisturbed soil core sample

2.2 Leaching water

Leaching water used for the experiment was collected from irrigation channels near the soil collection site. Based on the distribution of salt damage on agricultural land (HGME, 2013) in Mirzaabad, Syrdarya, the levels of salt damage on soil-collected agricultural land were classified as moderate (EC_e 4 to 8 dS m^{-1}). Therefore, regarding the amount of leaching water, the standard amount of 3,000 $m^3 ha^{-1}$ (300 mm) (HGME, 2007) at the time of moderate salt damage was used, and the amount of water was 9.2 L, which became the water depth of 300 mm was injected into the upper part of the test piece. At this time, water equivalent to 270 mm was gently supplied so as not to disturb the soil structure, and after the water level

at the top of the cylinder dropped to a level of 40 mm, water equivalent to the remaining 30 mm of was supplied. **Table 1** shows the chemical properties of the irrigation water used in the experiments and the amount of salt contained in the water supply of 9.2 L. Total dissolved solids were determined by weighing the evaporation residue in the 50 mL.

Table 1 Chemical properties of the irrigation water used in the experiments

	Concentration (mmolc L ⁻¹ , %)	Mass (g) (g L ⁻¹ × 9.2 L)
Ca ²⁺	8.98 (51.5)	1.66
Mg ²⁺	5.93 (34.0)	0.66
Na ⁺	2.26 (12.9)	0.48
K ⁺	0.28 (1.6)	0.1
Cl ⁻	3.95 (23.3)	1.29
SO ₄ ²⁻	12.34 (72.9)	5.45
NO ₃ ⁻	0.05 (0.3)	0.03
HCO ₃ ⁻	0.59 (3.5)	0.33
EC _w (dS m ⁻¹)	1.61	-
pH _w	8.21	-
TDS (g L ⁻¹)	1.13	10.33

TDS: Total dissolved salt

2.3 Measuring item

The soil compactness (Yamanaka method) was measured for the without and the with hardpan in the soil cross section at the sampling point of the undisturbed soil. For soil analyses prior to the initiation of experiments, disturbed soil and undisturbed soil samples were collected from 6 depths of 5, 15, 30, 45, 60 and 80 cm from the ground surface, using a 100 cm³ cylindrical sampler. The disturbed soil was analyzed for electric conductivity (EC_e) by saturation extraction solution, water-soluble cations (Ca²⁺, Mg²⁺, Na⁺, K⁺), water-soluble anions (SO₄²⁻, Cl⁻, HCO₃⁻) and total dissolved solids (TDS) by extracting supernatant solution of soil : water ratio = 1:5, for air-dried fine soil after passing through a 2 mm sieve. The undisturbed soil was subjected to measurement of the volumetric water content, dry bulk density, and saturated hydraulic conductivity (falling head permeability test). The TDS amount of the soil was obtained by multiplying the column volume (cm³) of each layer collected by the TDS amount (%: g g⁻¹) and dry bulk density (g cm⁻³) of the dry soil 1 g, and adding the TDS amount obtained for each layer. At this time, the soil column height of 74 cm was evenly divided into 15 parts, and the TDS quantity and dry density between the measured points were obtained by interpolating the TDS quantity and dry bulk density by the spline method.

Twenty-four days after initiation of the study, and approximately the same period as the leaching flood period in the field, the volume of leached water was measured, and the chemical properties of the

permeated water were analyzed using the internal 60 mL of the leached water. In order to measure the chemical and physical properties of the soil after completion of the experiments, undisturbed soil samples and disturbed soil samples were collected from a single sample of the with hardpan samples and the without hardpan at a depth of 5, 15, 30, 45, 60, and 71 cm using a 100 cm³ cylindrical sampler with a height of 5 cm.

For the values of soil moisture and soil EC obtained from the 5TE sensor, the calibration results of Omori (2018) was applied, and the volume moisture content (θ , m³ m⁻³) and soil EC_e (hereinafter referred to as EC_(e), dS m⁻¹) were estimated. This method combines the method of soil moisture analysis by Inoue et al. (2016) and the method of soil salinity analysis by Rhoades et al. (1976) to obtain the numerical solution of the volume moisture content by the two-fraction method.

The estimation equation of θ is expressed by the logarithmic equation of the equation (1) when the EC (EC_p) of the soil solution is used as a coefficient after plotting the experimentally obtained θ and the square root ($\varepsilon_a^{0.5}$) of the dielectric constant which is the sensor output value at that time.

$$\theta = (a_1 EC_p^2 + b_1 EC_p + c_1) \times \ln(\varepsilon_a^{0.5}) + (a_2 EC_p^2 + b_2 EC_p + c_2) \quad (1)$$

where, a_1 , b_1 , c_1 , a_2 , b_2 , and c_2 are experimental constants.

The Rhoades model is a model for estimating EC_p from measurements of apparent soil EC (EC_a) at any θ , and is represented by equation (2).

$$EC_p = \frac{EC_a - EC_s}{\theta (a\theta + b)} \quad (2)$$

where, EC_s is the electric conductivity of the solid phase (dS m⁻¹), and 0.19 dS m⁻¹ was obtained from the calibration test. a and b are experimental constants.

Table 2 shows the experimental constants of Eq. (1) and (2). By substituting Eq. (2) into Eq. (1), sensor output values EC_a and ε_a and the experimental constant values shown in **Table 2** are used, and only θ becomes an unknown formula. Since it is difficult to solve this equation algebraically with respect to θ , a numerical solution was obtained using the bisection method. The obtained value of θ was substituted into Eq. (2) to obtain EC_p .

Table 2 Experimental constants of Eq. (1) and (2)

Eq. (1)			Eq. (2)				
a_1	b_1	c_1	a_2	b_2	c_2	a	b
2.05×10^{-4}	-0.0133	0.4354	-1.70×10^{-4}	0.00893	-0.2132	1.1897	0.0079

$EC_{(e)}$ was obtained by the following equation (3).

$$EC_{(c)} = \frac{EC_p \theta}{\left(1 - \frac{\rho_d}{\rho_s}\right)} \quad (3)$$

where, ρ_d is the dry bulk density (g cm^{-3}) and ρ_s is the soil particle density (g cm^{-3}).

3. Results and discussion

3.1 Soil physics and chemical properties before experiment

Fig. 2 shows the vertical distributions of the without hardpan and the with hardpan soil compactness, volumetric water content, dry bulk density, and saturated hydraulic conductivity in the initial soil at the undisturbed soil sampling point, respectively.

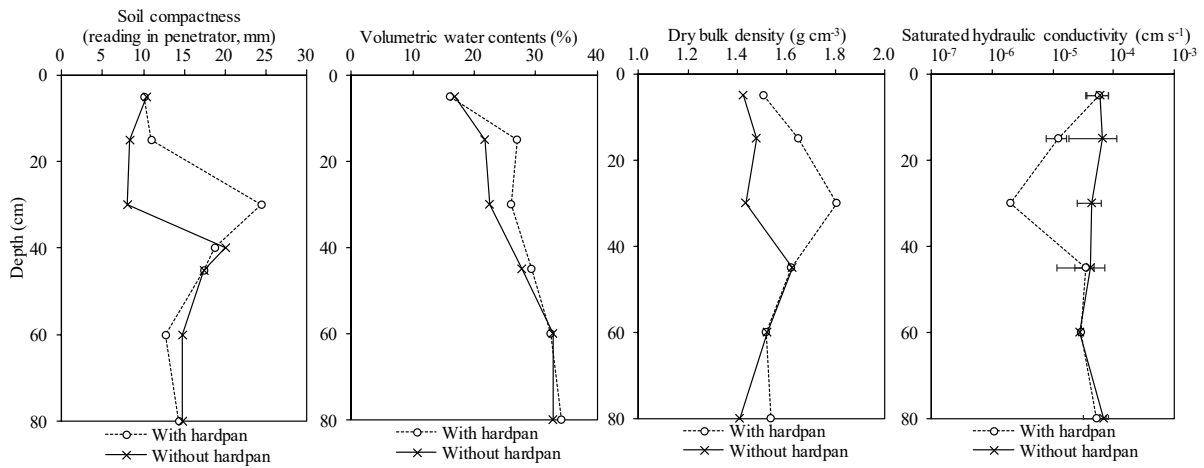


Fig. 2 Soil physics in the initial soil

(Soil compactness, Volumetric water content, Dry bulk density, and Saturated hydraulic conductivity)

From the soil profile survey, the hardpan was formed under the crop layer, and a white mottle was confirmed at the depths of 30 to 50 cm. Such a mottle was also observed in the surrounding area, and it was inferred that calcium carbonate and calcium sulfate were precipitated.

From the results of soil compactness, dry bulk density, and saturated hydraulic conductivity, it was confirmed that the hardpans were formed at the depth of 30 cm. The saturated hydraulic conductivities of the with hardpan at depths of 30 cm and 45 cm were $1.98 \times 10^{-6} \text{ cm s}^{-1}$ and $3.53 \times 10^{-5} \text{ cm s}^{-1}$, respectively. The saturated hydraulic conductivities of the without hardpan at the same depth were $4.40 \times 10^{-5} \text{ cm s}^{-1}$ and $4.24 \times 10^{-5} \text{ cm s}^{-1}$, respectively. Since the crushing of the hardpan was up to approximately 40 cm in depth, the soil physics at a depth of below 45 cm differed less, depending on whether or not the hardpan was crushed, and the soil physics were almost the same condition.

Table 3 shows the particle size composition and the soil particle density in the soil cross-section of the without hardpan and the with hardpan. They were divided into a layer position (5, 10, and 30 cm) shallower than the hardpan and a depth (50 and 80 cm) deeper than the hardpan. According to the International Society of Soil Sciences method, the soil property was clay loam soil (CL), regardless of

the depth of the without hardpan and the with hardpan. For sand, the percentage of fine sand (0.2–0.02 mm) was very high at all depths, and the percentage of coarse sand (0.2–2.0 mm) was as low as 0.1–0.3%. The dry bulk density, soil compactness, and saturated hydraulic conductivity tended to be characteristic at the depth of 30 cm, but it was confirmed that there was no change in the layer position in the soil property.

Table 3 Particle size composition and the soil particle density in the soil

Depth (cm)	Texture	Clay	Silt	Sand		Particle density (g cm ⁻³)
				Fine	Coarse	
[With hardpan]						
5, 10, 30	Clay loam	21.7	25.6	52.5	0.2	2.74
50, 80	Clay loam	19.2	28.1	52.6	0.1	2.81
[Without hardpan]						
5, 10, 30	Clay loam	22.1	26.2	51.4	0.3	2.74
50, 80	Clay loam	19.5	27.3	53.0	0.2	2.78

Fig. 3 shows the vertical distribution of the water-soluble ions by extracting supernatant solution of soil, water ratio = 1:5, in the initial soil with hardpan and without hardpan. Both conditions showed high salt concentrations at 5 cm depth, indicating that salts accumulated near the ground surface due to soil-surface evaporation. The composition of water-soluble cations was 48.3% and 42.5% for Ca²⁺ and 72.6% and 71.2% for SO₄²⁻, respectively, for the with hardpan and the without hardpans, respectively. The total amount of water-soluble cations per dry soil amount of the without hardpan was approximately 1.18 times higher on the whole layer average than that of the with hardpan, and in particular, Na⁺ was 1.50 times higher than that of the with hardpan. This difference is due to the heterogeneity of soil salinity in the field.

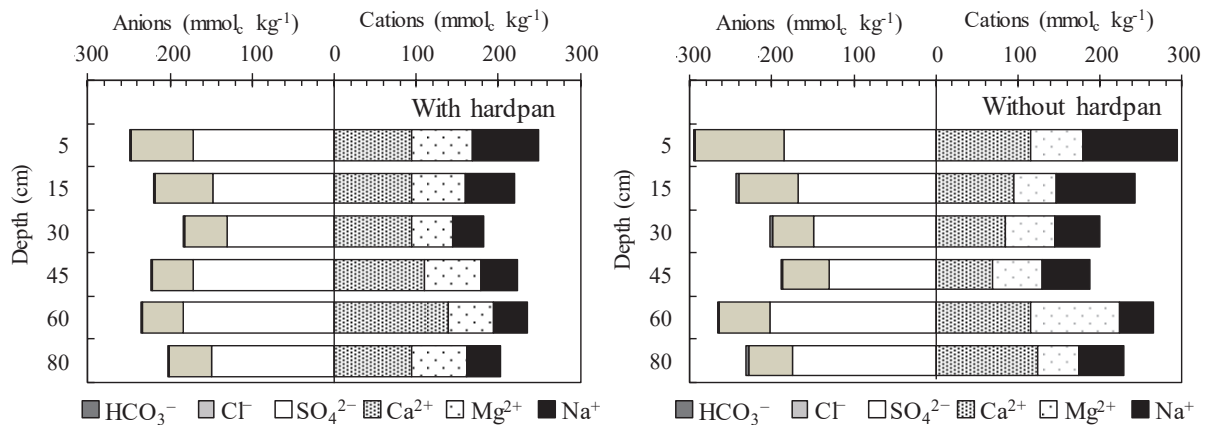


Fig. 3 Vertical distribution of the water-soluble ions in the initial soil

3.2 Amount of leachate and chemistry of leachate after 24 days

Fig. 4 shows the amount of the with hardpan and the without hardpan discharged water volume 24 days after the start of the experiment, and Fig. 5 indicates the amount of ions (g) obtained by multiplying the measured value of the water-soluble ion concentration of the discharged water volume by the amount of leachate. In the test pieces of with hardpan, the supplied water still remained about approximately 110 mm from the top of the soil surface.

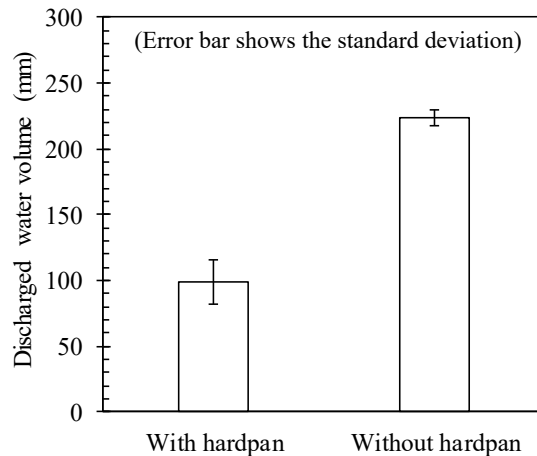


Fig. 4 Comparison of discharged volume after 24 days

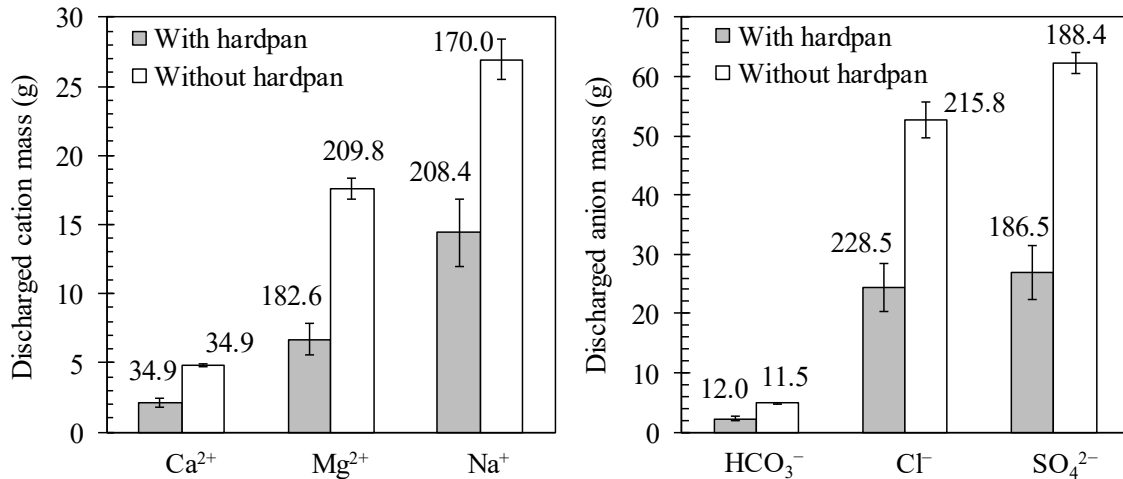


Fig. 5 Ionic content and concentration of discharge after 24 days

(The figure shows the ion concentration $\text{mmol}_c \text{L}^{-1}$ and the error bar shows the standard deviation.)

As a result of the leaching experiment at 24 days from the beginning of the experiment, the discharged water amount was 98.7 mm (32.9%) for the with hardpan and 223.6 mm (74.5%) for the without hardpan with respect to the supply water amount of 300 mm. Daily units of the saturated hydraulic conductivity correspond to mean 4.1 mm d^{-1} ($4.75 \times 10^{-6} \text{ cm s}^{-1}$) for the with hardpan, 9.3 mm d^{-1} ($1.08 \times 10^{-5} \text{ cm s}^{-1}$) for the without hardpan. In addition, the EC_w of the discharged water was approximately the same as 32.2 and 31.6 dS m^{-1} in the with hardpan and without hardpan, respectively.

The chemical equilibrium model Visual MINTEQ ver. 3.0 (Gustafsson, 2012) was used to estimate the salts dissolved or precipitated during the leaching experiments. Both the without hardpan and the with hardpan were presumed to be predominantly free ions of Na^+ and Cl^- in the discharged water, followed by sulfate species of MgSO_4 (aq) and NaSO_4^- . The salt mineral species that precipitated was estimated as dolomite ($\text{CaMg}(\text{CO}_3)_2$).

According to **Fig. 5**, discharged salts were eluted with water-soluble cations in the order of $\text{Ca}^{2+} < \text{Mg}^{2+} < \text{Na}^+$, and with water-soluble anions in the order of $\text{HCO}_3^- < \text{Cl}^- < \text{SO}_4^{2-}$ in both the without hardpan and the with hardpan. The TDS amount of the discharged water was estimated to be 276 mg cm^{-2} for with hardpan and 597 mg cm^{-2} for without hardpan per unit area of the test piece, and the TDS amount of the discharged water was estimated to be 84.3 g for the with hardpan and 182.1 g for the without hardpan. It was confirmed that 2.2-times salt was eluted by crushing the hardpan.

Assuming that the water-soluble cation compositions in the test specimens were equivalent to those in the initial soils prior to the beginning of the experiment, the average Ca^{2+} concentrations in the whole layer were 105, 101 $\text{mmol}_e \text{ kg-soil}^{-1}$, 63, 65 $\text{mmol}_e \text{ kg-soil}^{-1}$, and 51, 71 $\text{mmol}_e \text{ kg-soil}^{-1}$ in the with hardpan and without hardpan, respectively, in order of Mg^{2+} , and $\text{Na}^+ < \text{Ca}^{2+}$. However, the amount of Ca^{2+} in the discharged water was small, resulting in preferential discharging of Mg^{2+} and Na^+ .

3.3 Physics and chemistry of the test pieces after completion of the experiment

The test piece of the without hardpan had no change in the amount of discharged water 72 days after the start of the experiment, and thus the experiment was completed. The discharged water amount of the with hardpan became 222.0 mm and was 1.6 mm, 46 mL smaller than the discharged water amount of the without hardpan in which leaching was previously completed.

3.3.1 Soil physical property

Fig. 6 shows the vertical distributions of the volumetric water content, dry bulk density, and saturated hydraulic conductivity taken for each layer position from one test piece of the with hardpan and one test piece of the without hardpan after completion of the experiment. The water content by volume of both test pieces ranged from 34.1 to 37.3% in depth from 5 to 45 cm, and from 40.5 to 41.3% in depth from 60 to 74 cm. The volumetric water content of both test pieces was the same as the saturated volumetric water content of about 41% in depth from 60 to 74 cm. The dry bulk density and saturated hydraulic conductivity profiles tended to be almost the same for both test pieces. The saturated hydraulic conductivity of the without hardpan declined to approximately one-200 times compared to the initial state at 30 cm and 45 cm depths of $2.11 \times 10^{-7} \text{ cm s}^{-1}$, $1.77 \times 10^{-6} \text{ cm s}^{-1}$, respectively, and returned to the same state as with hardpan. The cause of this is considered to be as follows: After the water supply, the subsidence of the ground surface at the time when the flooded condition disappeared was 3 cm in the without hardpan, and 1 cm in the with hardpan. The amount of sedimentation remained unchanged after the end of the experiment. Therefore, it was presumed that when leaching water was supplied, the air in the interstices of the soil was compressed by the infiltration of water, the bonds between the clay mineral particles were weakened by the pressure, and the water permeability was lowered by increasing the

density of the soil (slaking phenomenon). A simple test was carried out to confirm the slaking property of salt soil in the field, and when a naturally dried soil mass was immersed in water, slaking started instantaneously, and the soil was rapidly shredded and muddy (Fig. 7). Local geology consists of tertiary mudstones (Morozov, 2014), which are generally highly slaking and swelling. After completion of the experiments, soils of 30 to 60 cm in depth had less voids and became denser (Fig. 8), and white patches of calcium carbonate and calcium sulfate were observed (Fig. 9).

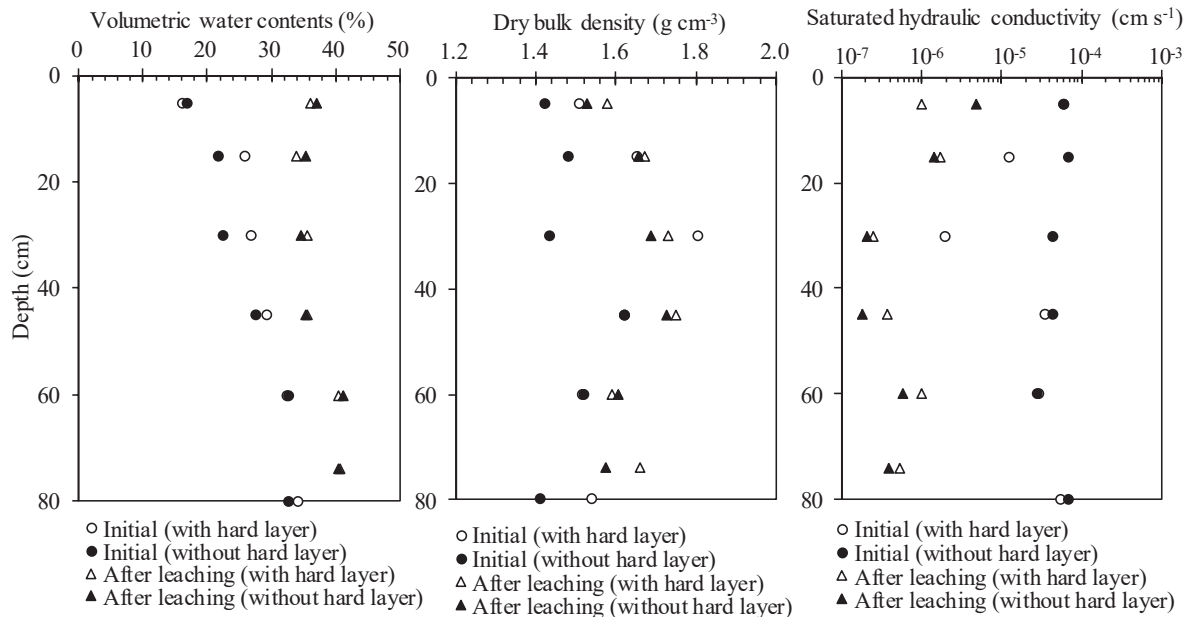


Fig. 6 Soil physics after completion of the experiment

Volumetric water content, Dry bulk density, and Saturated hydraulic conductivity

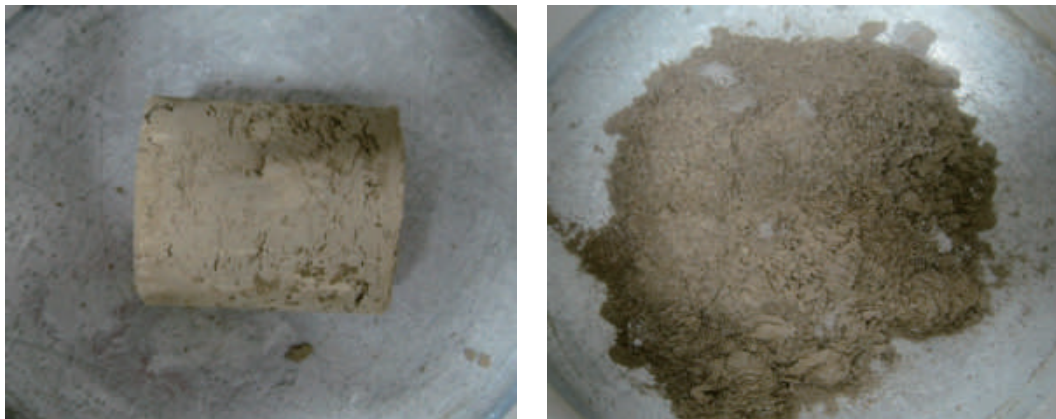


Fig. 7 Slaking test. Left, before flooding and right, after 5 minutes



15 cm in depth Left: 30 cm in depth, right 60 cm in depth
Fig. 8 Soil samples after leaching experiment (disturbed hardpan, after drying)



15 cm in depth Top: 60 cm in depth, bottom 30 cm in depth
Fig. 9 Soil samples after leaching experiment (broken soil cores of Fig. 8)

3.3.2 Soil chemistry

Fig. 10 shows vertical distributions of water-soluble ions of the with hardpan and the without hardpan at the end of the experiment. When the relationship between EC_e and the sum of cation concentration at each layer measured before and after the experiment was obtained, a clear linear relationship was obtained as follows:

$$\text{Total cations (mmol}_c \text{ kg}^{-1}) = 10.663 \times EC_e \quad (r^2=0.93) \quad (4)$$

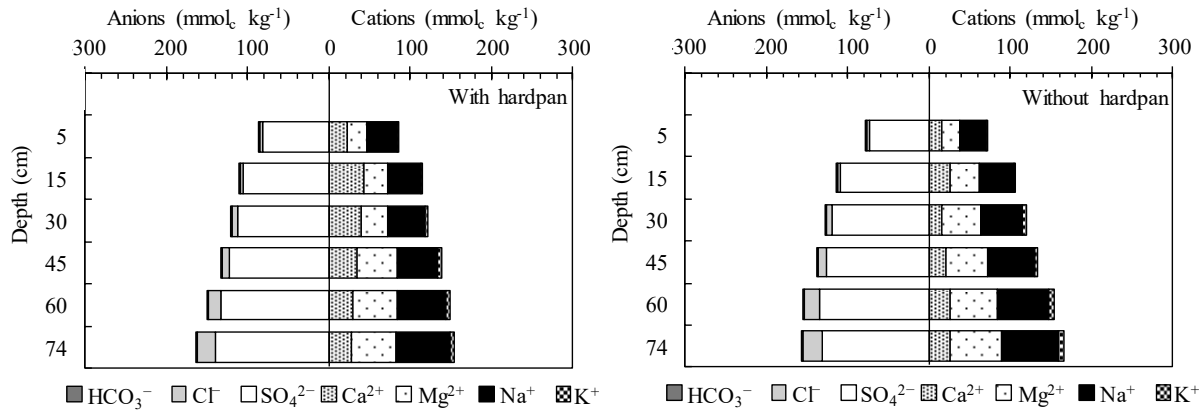


Fig. 10 Vertical distribution of the water-soluble ions after completion of the experiment

Table 4 shows the salt balance at the start of the experiment, 24 days after the start of the experiment, and 72 days after the end of the experiment in terms of the TDS amount and each ion amount. The amount of each ion in the soil at the beginning of the experiment was calculated by multiplying the column volume (cm³) of each layer collected by the amount of each ion in the dry soil 1 g (%: g g⁻¹) and the dry bulk density (g cm⁻³), and then summing the ion amounts of each layer for each ion, similar to the method of calculating the amount of TDS in the specimen. The ratio of the total of major ions such as Ca²⁺ to the TDS content of leachate at 24 and 72 days after the start of the experiment was an average of 0.908 (calculated from the values marked with * in **Table 4**). This difference was estimated to be the sum of undissociated components (e.g., H₄SiO₄) and trace components not detected by water-soluble ion analysis, and the major ions in the soil were also considered to have approximately the same ratio to TDS content. This ratio was multiplied by each ion amount to calculate the ion amount of the soil. The TDS and ion content of the soil after 24 and 72 days were determined by subtracting the measured values in the leachate after 72 days from the start of the experiment. The amounts of TDS in the test pieces prior to the start of leaching were estimated to be 505.2 g in the with hardpan and 497.9 g in the without hardpan. It was inferred that the TDS amount was calculated to be small in the test pieces of the hardpan crushing due to the impact that the dry bulk density became low at the time of the hardpan disturbance.

Table 4 Mass balance of TDS amount and each ion amount in leaching experiment

	Initial			Period (days)						
	Existing salts in soil	Salts in water supplied	Total (a)	24			72			Total
				Drained salts (b)	Remained salts in soil (a)-(b)	(%) (b)/(a)	Drained salts (c)	Remained salts in soil (a)-(c)	(%) (c)/(a)	
[With hardpan]										
Ca ²⁺	71.7	1.7	73.4	2.1	71.3	(2.9)	5.7	67.7	(7.8)	73.4
Mg ²⁺	24.4	0.7	25.1	6.7	18.4	(26.7)	16.9	8.2	(67.3)	25.1
Na ⁺	42.9	0.5	43.4	14.4	29.0	(33.2)	24.5	18.9	(56.5)	43.4
HCO ₃ ⁻	3.5	0.3	3.8	2.2	1.6	(57.9)	2.8	1.0	(73.7)	3.8
Cl ⁻	67.4	1.3	68.7	24.4	44.3	(35.5)	48.8	19.9	(71.0)	68.7
SO ₄ ²⁻	254.1	5.5	259.6	26.9	232.7	(10.4)	62.3	197.3	(24.0)	259.6
Total	464.0	10.0	474.0	*76.7	397.3	(16.2)	*161.0	313.0	(34.0)	474.0
TDS	505.2	10.3	515.5	*84.3	431.2	(16.4)	*179.9	335.6	(34.9)	515.5
[Without hardpan]										
Ca ²⁺	59.2	1.7	60.9	4.8	56.1	(7.9)	4.8	56.1	(7.9)	60.9
Mg ²⁺	26.1	0.7	26.8	17.4	9.4	(64.9)	17.4	9.4	(64.9)	26.8
Na ⁺	47.9	0.5	48.4	26.6	21.8	(55.0)	26.6	21.8	(55.0)	48.4
HCO ₃ ⁻	5.3	0.3	5.6	4.8	0.8	(85.7)	4.8	0.8	(85.7)	5.6
Cl ⁻	71.7	1.3	73.0	52.1	20.9	(71.4)	52.1	20.9	(71.4)	73.0
SO ₄ ²⁻	245.7	5.5	251.2	61.7	189.5	(24.6)	61.7	189.5	(24.6)	251.2
Total	455.9	10	465.9	*167.4	298.5	(35.9)	167.4	298.5	(35.9)	465.9
TDS	497.9	10.3	508.2	*182.1	326.1	(35.8)	182.1	326.1	(35.8)	508.2

Fig. 11 shows the leaching ratios of Mg²⁺ and Na⁺ at each soil layer. The negative range represents an increase in concentration over that found before the experiment. From the calculation of the balance, the Na⁺ leaching rate of the with hardpan after 72 days was calculated to be 56.5%. However, Na⁺ was hardly leached below 30 cm depth. In the water supply 300 mm, Na⁺ elutes directly above the hardpan, and moves and accumulates in the lower layer as the leaching water permeates. It was confirmed that even if the hardpan was disturbed, it could not leach deeper than 60 cm, and it accumulated in the lower layer.

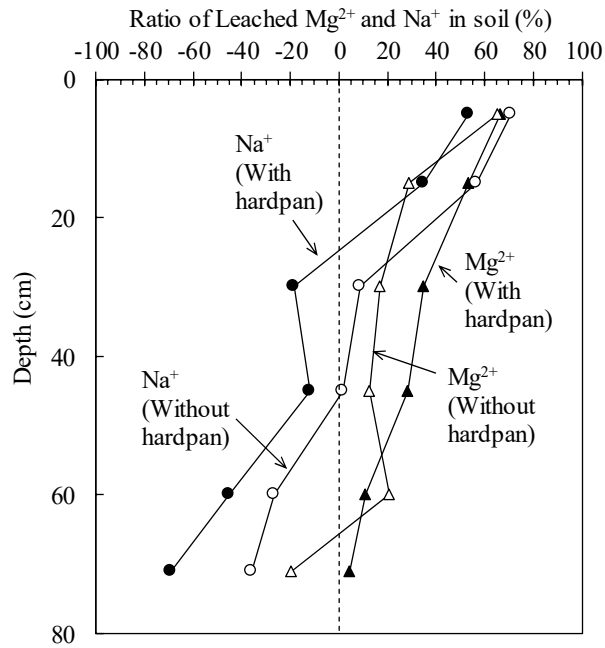


Fig. 11 Leaching ratio of Mg^{2+} and Na^+ at each soil layer

Focusing on the calcium content of the soil at the start of the experiment and after 72 days, it was suggested that the estimated calcium content in the test pieces of the with hardpan were 71.7 g (at the start of the experiment) and 67.7 g (after 72 days), and in the test pieces of without hardpan were 59.2 g (at the start of the experiment) and 56.1 g (after 72 days) and that Ca^{2+} remained in the soil even after the experiment (**Table 4**). However, the water-soluble Ca^{2+} concentration after 72 days was reduced by approximately 70% compared with before the experiment (Fig. 10). With regards to this discrepancy, dissolved species and salt mineral species in soils before and after experiments were confirmed by Visual MINTEQ. The results of **Fig. 3** and **Fig. 10** were used for the ion concentration for comparison by layer position. The salt minerals in the soils prior to the experiments were estimated to be dolomite, gypsum ($CaSO_4 \cdot 2H_2O$), calcite ($CaCO_3$), and gypsum after 72 days. **Fig. 12** shows the ratio of free ions Ca^{2+} and SO_4^{2-} to total dissolved species concentrations. The percentage of free Ca^{2+} was at maximum approximately 6%. The larger percentage of free Ca^{2+} in the pre-experiment of the without hardpan at the depth of the 45 cm compared with the with hardpan was considered to be the impact of the without hardpan. In addition to Ca^{2+} , water-soluble calcium was present in forms such as $CaSO_4$ (aq), $CaCl^+$, $CaHCO_3^+$, and $CaCO_3$ (aq). For free SO_4^{2-} , both the with hardpan and the without hardpan increased after the experiments. Apart from the addition of the SO_4^{2-} of the supplied water, it was inferred that the gypsum present in the soils was dissolved and increased.

VAN Hoorn et al. (1997) showed that, in leaching experiments using lysimeters, the calcium content in soil was almost the same for two years due to the aging dissolution of gypsum in clay soil (CL), and the carbonates of calcium and magnesium were discharged, which was similar to the experimental results. In the leaching process of calcium in this study, highly soluble $CaCl_2$ and similar are discharged, and the water-soluble calcium concentrations in soils are lowered. Conversely, although the gypsum in the soil was dissolved by the water supply, it was inferred that the gypsum was produced and precipitated

when the water supply required for the dissolution disappeared, and the poorly soluble calcium salt remained.

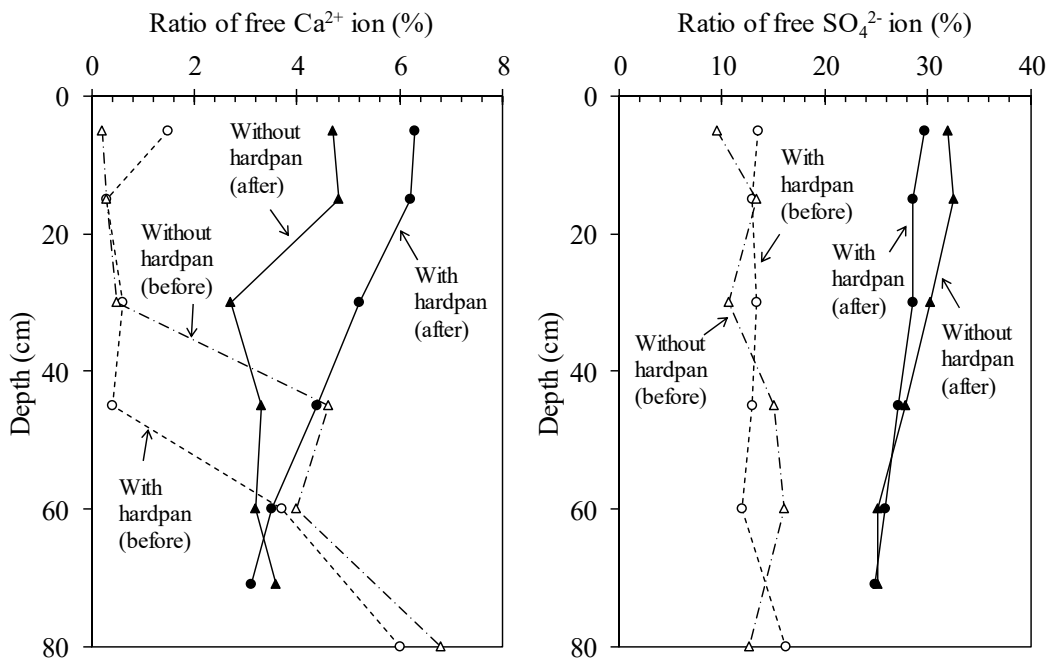


Fig. 12 Changes in free Ca²⁺ and SO₄²⁻ ratios at various depths before and after the leaching experiment

3.3.3 Changes in soil salinity by layer level

Fig. 13 and **Fig. 14** show the changes in EC_(c) during leaching process with 5TE sensor installed in each of the with hardpan and the without hardpan. **Fig. 13** shows from the start of the experiment to the end of leaching, and **Fig. 14** represents the start of the experiment to 3 hours. As shown in **Fig. 14**, prior to the beginning of the experiment, the soil EC_e (EC_(c)) obtained by the 5TE sensors at the 15 cm depth showed 10 dS m⁻¹ for both specimens. The EC_(c) at 15 cm depth measured prior to the initiation of the experiments were 19.6 and 21.6 dS m⁻¹ for the with hardpan and without hardpan, respectively. The differences between the sensor values and the measured values are due to the presence of air gaps between the sensor and the soil because the soil was cultivated to a depth of approximately 20 cm. After the leaching water reached the depth of 15 cm 10 minutes after the start of the experiment, the sensor values rose to 50 dS m⁻¹. Considering that the soil EC_e at the 5 cm depth was 24.5 and 28.1 dS m⁻¹ in the with hardpan and without hardpan, respectively, it was considered that the salt contained from the surface layer to the 15 cm depth was dissolved by the leaching water. With regards to the depth beyond the soil crop layer, when the hardpan was not disturbed, the lower EC_(c) decreased slowly at the 30 cm depth of the hardpan (**Fig. 13**). If the time at which EC_(c) started to decrease was defined as the leaching initiation time, as shown in **Fig. 13**, leaching started after one day in the without hardpan at 30 cm depth, after three days in the without hardpan at 30 cm depth, after five days in the without hardpan at 60 cm depth, and after 26 days in the without hardpan at 60 cm depth. The test piece of the with hardpan took 72 days to lower to the EC value discharged in 19 days in the without hardpan. In the case of without hardpan, salts in the test pieces were quickly removed with the infiltration of leaching water.

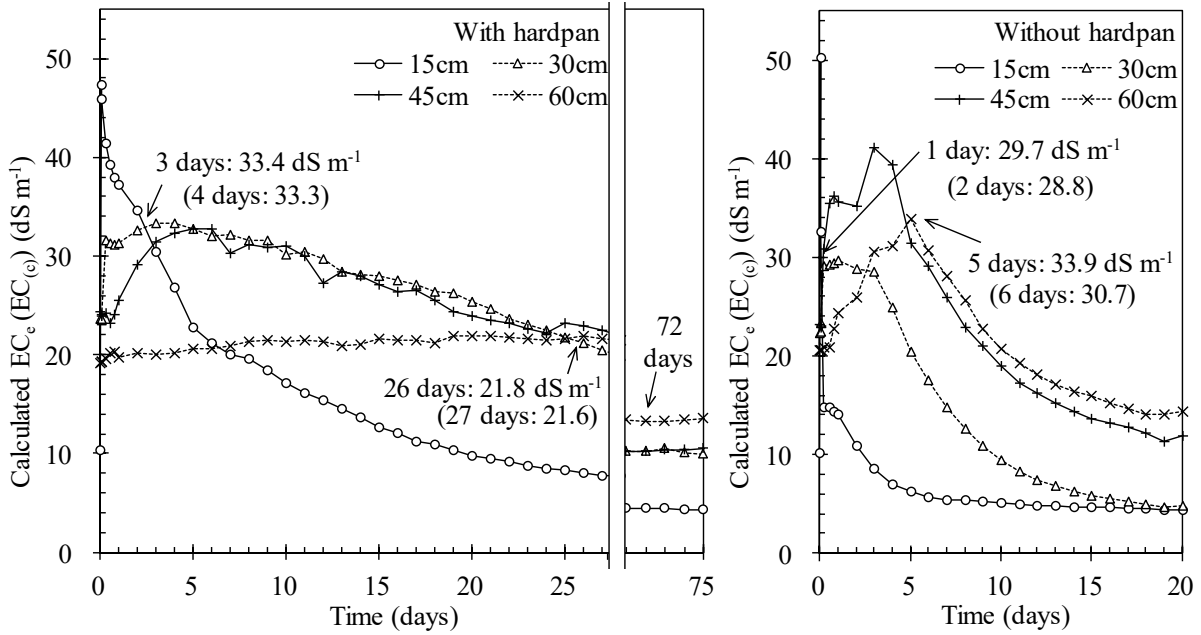


Fig. 13 Changes in EC_e during leaching process with 5TE sensor.
(Left, with hardpan, and right, without hardpan.)

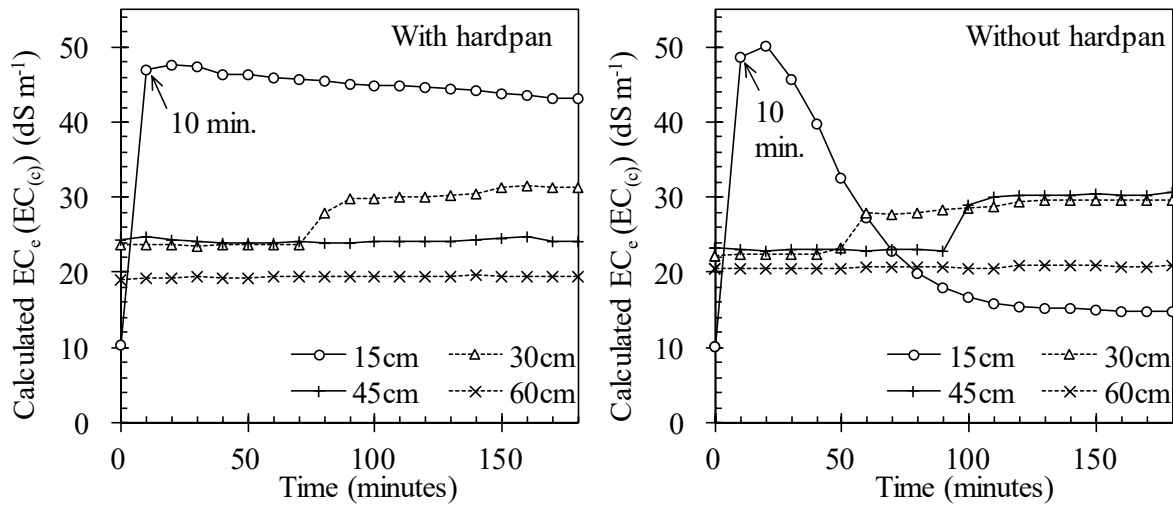


Fig. 14 Changes in EC_e up to 3 hours after leaching experiment.
(Left, with hardpan, and right, without hardpan.)

3.4 Comparison between leaching experiments and on-site conditions

From the results of this experiment, it was confirmed that the supplied water quickly permeated downward by the without hardpan, and the salt content in the soil was leached out. Conversely, even if the hardpan was formed, all of the supplied water was leached after 72 days, and the desalting effect was the same as that of the without hardpan. However, in the actual field, the leaching operation is approximately 14 to 24 days, and does not require a long period as shown in the present experimental result. From this, it was considered that the supplied water was desalted to a level shallower than the hardpan and flowed out in a horizontal direction, or permeated downward by selecting a place with good

partial water permeability.

4. Conclusion and Recommendations

Based on the results of this experiment, it was indicated that the formation of the hardpan lowered the soil physics not only by the tractor compaction but also by combined factors such as the slaking phenomenon and gypsum formation in the leaching process, accompanied by winter leaching operation. In addition, it was confirmed that the effect of the without hardpan was lost by a one-time leaching operation.

In these experiments, the soils were relatively finely loosened up to the depth 40 cm by using excavators for hardpan disturbing. It was also concluded that this caused a water permeability reduction of 30 to 60 cm in depth. Some farmers own a subsoil breaker (subsoiler, three to four crushing claws, depth 60 cm), but in the actual field, it seems to be a practical method to roughly crush the hardpan by the subsoil breaker. Subsoil breaking is often combined with underdrain drainage (Uchiyama, 1983).

As a counter measure based on the experimental results, we concluded that, in the case of the quantity of 300 mm for leaching operation, the method of hardpan crushing to approximately 40 cm depth in advance and preparing shallow underdrain water to approximately 60 to 70 cm depth was effective for quickly infiltrating the leaching water downward, and the method of discharging the salt washed out by the leaching to the open-channel drainage which was prepared around the agricultural land. In the future, it will be necessary to examine the method of sustaining the effect of the without hardpan, and to verify it through field tests and other research.

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*The above article was translated and reprinted from “Sand Dune Research, Vol. 66, No. 1, pp. 9-20 (2019)”, published by the Japanese Society of Sand Dune Research.