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Reclamation of Gypsiferous and Nongypsiferous Sodic Soils by Leaching

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Abstract

Soil reclamation (both desalinization and desodification) is frequently required in arid and semiarid regions in order to keep the irrigated agriculture sustainable. Intermittent and continuous ponding are the most widely used leaching methods in this aspect. This study examined the efficiency of these two leaching methods in desalinization and desodification of two saline and sodic soils : a gypsyferous sandy loam and a nongypsiferous clay loam. Soil columns (100 and 200 mm high) were leached with irrigation water (EC = 1.8 dS/m, SAR = 3.2) under both methods. Effluent from the columns was collected continuously, and its cationic and anionic composition was analyzed. Intermittent ponding was more efficient than continuous ponding in desalinization and desodification of the clay loam. By contrast, in the sandy loam, efficiency was similar under the two leaching methods in desalinization, whereas desodification was more efficient under intermittent ponding. In the clay loam where soil aggregation is higher, unsaturated water flow that occurs in micropores under intermittent ponding resulted in higher leaching efficiency on desalinization compared with continuous ponding under which condition water flow is saturated and much of the water is conducted by the macropores. Conversely in the sandy loam, unsaturated water flow prevails under both intermittent ponding and continuous ponding explains the similar leaching efficiency on desalinization observed under the two leaching methods. Soil desodification was enhanced by intermittent ponding in both soils, because Na replacement is a slow process which is controlled by intra-aggregate diffusion of Na^+ and Ca^{2+} and the rate of gypsum dissolution. In the clay loam, the rate of intra-aggregate diffusion of Na^+ and Ca^{2+} determines the efficiency of desodification, and in the gypsiferous sandy loam, the rate of gypsum dissolution determines the efficiency of desodification.

Key words : Intermittent ponding, continuous ponding, leaching efficiency, soil desalinization, soil desodification

1. Introduction

In arid and semiarid regions, irrigation water usually contains some quantity of soluble salts. Irrigation water of poor quality, coupled with the limited scarce rainfall and high evapotranspiration, often results in increase of soil salinity and sodicity of the irrigated land. The presence of excessive salts in the soil profile deteriorates soil physical condition, impairs plant growth and causes reduction in crop yield (Ayers and Westcot, 1985). Therefore, desalinization and desodification related soil reclamation becomes a key role in keeping the irrigated agriculture sustainable. To reclaim saline soils, leaching is commonly commenced to remove accumulated salts from the soil profile. Leaching efficiency is defined as the depth of leaching water per unit depth of soil required to reclaim a saline soil (Hoffman, 1986 ; Oster *et al.,* 1996). Leaching efficiency varies with water application mode. Field reclamation studies show that under continuous ponding, leaching efficiency decreased with increase in clay content in the soil and was lowest in peat soils (Hoffman, 1986). Under continuous ponding, saturated water flow prevails and most of the water is conveyed from macropores in sandy loams where inter-aggregate pores are negligible, thus, higher leaching efficiency can be obtained within short time. Conversely, in fine textured soils where more aggregates and soil pores of various sizes exist, bypass flow through macropores and cracks reduces leaching efficiency. However, the effect of soil texture on leaching efficiency can be reduced by intermittent application of ponded water. It was found that the leaching efficiency is independent of soil texture and is similar for silty clay loam and sandy soils when ponding water intermittently (Hoffman, 1986). High leaching efficiency in heavy soils under intermittent ponding is attributed to the unsaturated flow that prevails during the leaching and the prevention of bypass flow in macropores and cracks.

In addition to soil texture, concentration and composition of salt present in the soil are other variables that affect reclamation process. In arid and semiarid region, soil salinity usually is accompanied with sodicity. Since excessive exchangeable Na impairs the physical condition of soils (Shainberg and Letey, 1984), replacing of exchangeable Na with divalent cations (usually Ca^{2+}) is also required in the reclamation of saline and sodic soils. Ca^{2+} can be supplied either from irrigation water, or by the presence of naturally occurring lime or gypsum in the soil, or by the addition of gypsum (Oster *et al.,* 1996 ; Nadler *et al.,* 1996). When gypsum or lime is present in the soil, soil solution reaches equilibrium with these sparingly soluble salts only when the contact time between an elemental volume of solution and gypsum or lime fragment is sufficiently long (Oster and Frenkel, 1980). Also in well controlled laboratory studies, the effectiveness of gypsum or lime in reclamation of sodic soils was found to be dependent on the flow rate of the percolating solution ; increasing the water flow rate decreased the gypsum or lime dissolution, and the slower the soil water flow, the higher the efficiency of replacing Na by Ca (Keren and O'Connor, 1982 ; Nadler, *et al.,* 1996). However, less study was conducted on such type of soils by leaching that simulate field conditions, e.g. intermittent ponding and continuous ponding.

In the previous study of reclamation of a highly saline soil, we examined the chemical changes of the soil during leaching by simulating field conditions in the laboratory. It proved that intermittent ponding was more efficient in both desalinization and desodification of the soil than continuous ponding (Wang *et al.,* 1998). Still, when dealing with the salt-affected soils that contain naturally occurring gypsum or lime as is often the case in arid and semi-arid regions, it is necessary to study the effect of leaching methods on these soils regarding to soil texture and chemical components for providing useful information to field reclamation works. Under intermittent ponding, soil water flow rate is much lower compared with continuous ponding, and the contact time between unit volume of soil solution and fragments of gypsum or lime is longer than in continuous ponding. We hypothesized that the efficiency of desodification of nongypsiferous soil is determined by Na^+ and Ca^{2+} intra-aggregate diffusion ; whereas, in the calcareous and gypsiferous soil, the kinetics of $CaCO_3$ and $CaSO_4$ dissolution supplementing the intra-aggregate diffusion are controlling the efficiency of desodification. The leaching efficiency of intermittent ponding was supposed to be more pronounced on desodification than that on desalinization. Therefore, the objective of this study was to compare the efficiency of intermittent ponding and continuous ponding in the desalinization and desodification (replacement of Na by Ca) of the saline gypsiferous sandy loam and the saline nongypsiferous clay loam.

2. Materials and Methods

2.1 Experimental materials

Two soils were used for this study : a gypsiferous (and also calcareous) sandy loam from the A horizon of an abandoned field (due to high salinization) located in Kzyl-Orda region in Kazakstan, and a nongypsiferous clay loam from the A horizon of a local paddy field from Tottori Prefecture Agricultural Station. The sandy loam was formed from the alluvial plain of Syr Darya river and contained 5.4% of gypsum and 14.5% of lime. The texture of this soil is 71.2% sand, 15.3% silt and 13.5% clay. The major clay minerals of the sandy loam are mica, chlorite, kaolinite and vermiculite. The paddy soil was originally free of any salts, and consists of 46.7% sand, 31.5% silt and 21.8% clay with major clay minerals as halloycite, kaolinite and illite. Some physical and chemical properties of the two soils are presented in Table 1. However, in order to simulate the saline conditions that prevails in Kazakstan, this soil was salinized by repeated leaching with a saline water that has an EC of 78 dS/m and sodium adsorption ratio (SAR) of 79. The major ionic concentrations of the saline water were 102.0 cmol$_c$/L Na^+, 31.2 cmol$_c$/L Mg^{2+}, 2.8 cmol$_c$/L Ca^{2+}, 58.9 cmol$_c$/L SO_4^{2-}, and 73.1 cmol$_c$/L Cl^-. The soil samples were air dried, crushed and passed through a 2 mm sieve and analyzed for soluble salts and exchangeable cations. Soluble ions in saturation extract were analyzed using the atomic absorption method for cations, and ion chromatograph for anions. Soil CEC and ex-

Table 1 Some physical and chemical properties of the soils

Soil properties	Paddy soil	Kazakstan soil
Clay mineralogy	halloycite, kaolinite, illite	mica, chlorite, kaolinite, vermiculite
Saturation percentage[1]	51.9	20.0
CEC (cmol$_c$ kg^{-1})	17.4	7.7
Exchangeable cation (cmol$_c$kg^{-1})		
Ca	6.2	2.6
Mg	6.2	1.8
Na	4.3	2.7
K	0.7	0.7
Exchangeable sodium percentage	24.5	34.8
Major ions in saturation extract (cmol$_c$ L^{-1})		
Ca^{2+}	2.0	2.8
Mg^{2+}	21.0	31.2
Na^+	80.1	102.0
K^+	0.4	0.7
Cl^-	78.0	73.1
SO_4^{2-}	51.56	14.7
EC (dS m^{-1})	69	143.7
SAR[2]	74.8	78.2

Note :

[1] Saturation percentage : The moisture percentage of a saturated soil paste, expressed on a dry basis.

[2] SAR (sodium adsorption ratio) is defined as SAR $= Na^+/[(Ca^{2+}+Mg^{2+})/2]^{1/2}$, ion concentration in mmol$_c$/L.

changeable cations of the nongypsiferous soil were analyzed by ammonium acetate extraction method. The CEC of Kazakstan soil was determined by the method proposed by Polemio and Rhoades (1977). Exchangeable Ca of the gypsiferous soil was estimated by subtracting exchangeable sodium, potassium and magnesium from CEC. Irrigation water was synthesized with chemicals to simulate Syr Darya river water, and the composition is presented in Table 2.

2.2 Experimental procedures

Soil samples were packed uniformly into acrylic cylinders that were 50 mm in inner diameter and 200–300 mm long. Preceding the soil packing, fine glass beads (20 mm deep in the column) were placed above a bronze screen at the bottom of each cylinder. The soil depth in the cylinders was 100 mm for the sandy loam (soil weight=274.0 g, bulk density=1.40 g/cm^3) and 200 mm for the clay loam (soil weight=486.7 g, bulk density=1.24 g/cm^3), respectively. Filter paper was placed on the soil surface to prevent surface disturbance caused by water application.

Irrigation water was applied to the column surface by either intermittent ponding or continuous ponding. Pore volume (PV) was used to quantify the leaching water amount applied to each soil. Pore volume of a bulk soil was the total volume of voids in it (Soil Sci. Soc. Am., 1996). 1 PV was 90.7 mL for the sandy loam (46.2 mm in depth), and 201.5 mL (102.7 mm in depth) for the clay loam. In intermittent ponding, 0.1 PV of water was delivered uniformly to the soil surface through a pipette once for every 24 hr. Wax paper was used to cover the surface of soil columns to reduce evaporation after each water application. Under continuous ponding, constant water depth was kept at 10 mm for the sandy loam and 50 mm for the clay loam through a Mariotte tank. A fraction collector was used to collect effluents in continuous ponding, while beakers were used in intermittent ponding. Effluent volume, EC and chemical composition were measured.

Experiments were terminated after leaching with 1.5 PV for the clay loam and 1.8 PV for the sandy loam. Then, the soil columns were sliced at 20 mm interval and the sections were oven dried at 105℃. Soil solutions were made at 1 : 1 (soil : water) ratio for the sandy loam and saturation extract for the clay loam. EC and soluble ions were measured in the soil solution. Exchangeable cations were calculated from selectivity coefficients for each soil following the procedure proposed by Robbins (1980). All treatments were replicated for 5–7 times and the average values were used for making all the graphs.

3. Results and Discussion

3.1 Water Infiltration and Drainage

Under intermittent ponding, each 0.1 PV of irrigation water was allowed to redistribute for 24 hours before next application, and drainage started after 8 applications of 0.1 PV in both of the soils. Under continuous ponding, collecting 1.5 PV of drainage needed 38 hr for the clay loam and 3 hr for the sandy loam. Whereas under intermittent ponding, because of the redistribution time between each 0.1 PV application, 1.5 PV of drainage took 360 hr for the clay loam and 1.8 PV needed 432 hr for the sandy loam. The effect of the water application method on the degree of saturation in the two soils is shown in Fig. 1, where the amount of

Table 2 Chemical composition of irrigation water

	Ions concentration (cmol$_c$ L^{-1})						EC (dS m^{-1})	SAR
	Ca^{2+}	Mg^{2+}	Na^+	K^+	Cl^-	SO_4^{2-}		
Irrigation water	0.5	0.6	0.8	0.01	0.7	1.2	1.8	3.2

drainage water as a function of cumulative irrigation water in the two soils is presented. In the clay loam, drainage started after 182.1 mL and 204.1 mL of irrigation water infiltrated into the soil under intermittent ponding (IP) and continuous ponding (CP), respectively (Fig. 1). The pore volume of the clay loam is 201.5 mL and water retention capacity of the glass beads is 5 mL. Thus for continuous ponding, the soil column was almost completely saturated and for intermittent ponding, the degree of saturation was only 0.88. In the sandy loam, drainage under the two leaching methods started at 78 mL, compared with the soil pore volume of 90.7 mL, the degree of saturation was 0.85. As indicated in Fig. 1, the saturation degree of each soil was constant during leaching processes under both leaching methods, because the amount of water infiltrated into the soil was equal to that drained out. The unsaturated condition in the soil profile of the sandy loam, even under ponding condition, is possibly caused by the formation of a layer with low hydraulic conductivity at the soil surface (Bodman and Coleman, 1944 ; Mullins *et al.*, 1990). The sandy loam is from the A horizon of Kazakstan field and is a hardsetting soil that soil structure breaks down when wetted. The mobilized silt and clay from the breakdown of aggregates form a layer with low hydraulic conductivity on the soil surfaces which causes the unsaturated condition in the soil under both water application methods (Mullins *et al.*, 1990).

3.2 Leaching Efficiency

Leaching efficiency is often defined as the quantity of soluble salts leached per unit volume of water applied, and quantitatively expressed as the relationship between the fraction of initial salt concentration remaining in the profile C/C_o, and the depth of water infiltrated D_w, through a given depth of soil, D_s : $(C/C_o)(D_w/D_s)=K$, where constant K differs with soil type (Hoffman, 1986 ; Keren and Miyamoto, 1990 ; Oster *et al.*, 1996). The relationship between the soluble salts removed and the amount of leaching water applied under continuous ponding (CP) and intermittent ponding (IP) is shown in Fig. 2. PV was used to quantify the leaching water instead of

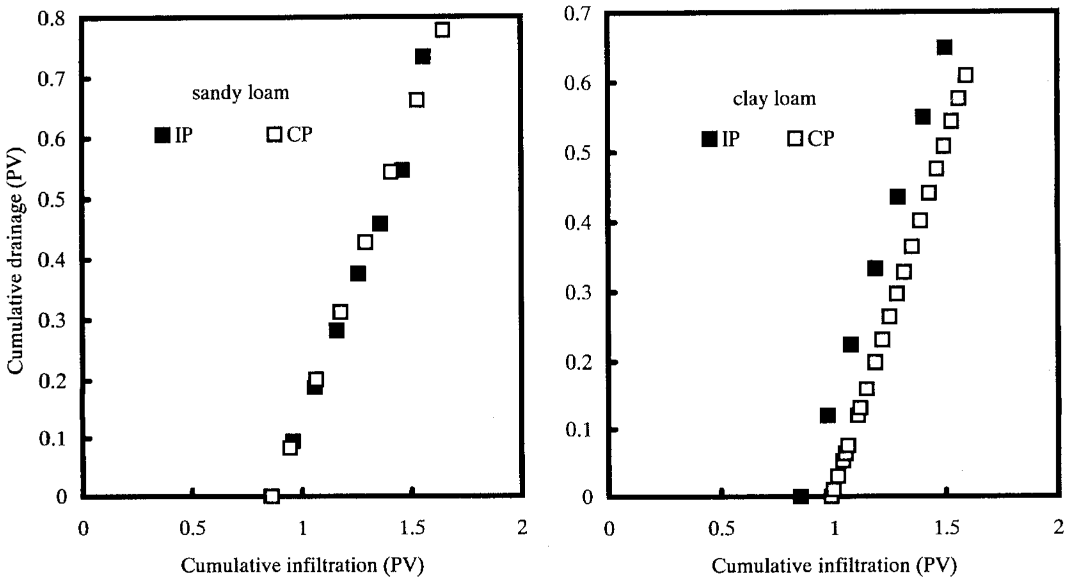

Fig. 1 Relation of cumulative infiltration and drainage in the clay loam and the sandy loam under the two leaching methods.

D_w/D_s. The fraction of initial salinity remaining in the soil profile after leaching was expressed as $(EC_f-EC_w)/(EC_i-EC_w)$, where EC_f and EC_i is the salinity of soil solution after and before leaching, and EC_w is the EC of leaching water. It follows that when EC_f approaches to EC_w for a longer time, the ratio of above expression eventually becomes zero which means the complete reclamation is approached. The fraction of initial salt concentration remaining in the column as a function of PV was estimated from the fraction of initial salt remaining in each section. For example, in saturation condition when 1.8 PV irrigation water passed through the column, the depth of water that leached the uppermost section of 20 mm was 1.8×5=9.0 PV. Similarly the depth of water that leached the uppermost 2 sections (40 mm soil) was 1.8×2.5=4.5 PV. In unsaturated condition, the actual water content in each soil section was used to estimate PV of irrigation water that passed through the section.

The efficiency of leaching in the clay loam depended on the leaching method, whereas no significant difference was observed in the sandy loam. In the clay loam, 1 PV of irrigation water removed nearly 95% of total soluble salt under intermittent ponding, compared with only 70% of the salt in continuous ponding. With increase in leaching volume, the effect of water application methods on the efficiency of salt removal was less pronounced (Fig. 2). Conversely in the sandy loam, leaching methods had no effect on desalinization, and 90% of the salt was removed after 1 PV. It should be noted that the EC of sandy loam remained constant at an EC value of about one tenth of the initial salinity with prolonged leaching. This is because the Kazakstan soil contains 5.4% gypsum and dissolution of gypsum accounts for the high EC (EC=3.0 dS/m) in the soil solution.

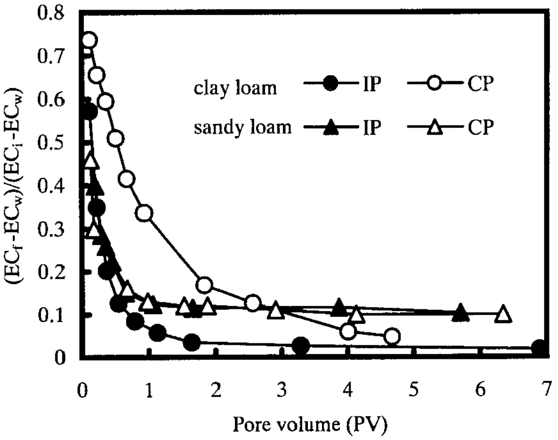

Fig. 2 Leaching curves of the clay loam and the sandy loam under continuous ponding and intermittent ponding.

Desalinization of soil and leaching efficiency depend on water flow and salt transport processes. Assuming water flow is a simple piston flow, the initial solute can be replaced completely after 1 PV of water application. However, in soil, water flow is not ideal, and 5%-30% of the initial soluble salts still remained in the soil profile following leaching with 1 PV (Fig. 2). This is due to the fact that in soils there are two populations of pores distinguished by their pore size : micropores within and between the aggregates, and macropores between aggregates. Under intermittent ponding, soil is unsaturated (Fig. 1), and water flow through micropores prevails. Whereas under continuous ponding (Fig. 1), soil is saturated and most of the water is transported by the macropores. Under saturated condition, water flow in the macropores between aggregates is fast, and salt from macropores is removed fast ; conversely, flow in the fine pores is slow and salt in the fine pores is not removed efficiently. Since aggregates stability increases with clay content (Kemper and Koch, 1966), the more inter-aggregate pores exist in the clay loam, the more water conducted by the macropores, the less efficient is the leaching, as in the case of continuous ponding (Fig. 2). Under intermittent ponding, unsaturated water flow prevails and preferential flow in macropores and cracks is prevented ; and with more ionic diffusion from micropores to water-conducting macropores, the more efficient is the leaching. By contrast, in the sandy loam, due to the structure breakdown under both continuous ponding and intermittent ponding, there is less difference in water flow in soil pores, and hence there is a small difference in leaching efficiency between continuous ponding and intermittent ponding (Fig. 2).

The unsaturated soil condition during both water application methods in the sandy loam, in addition to the absence of micropores inside aggregates, explain the high leaching efficiency in the soil. In the soil with stable aggregates (the clay loam), formation of a layer with low hydraulic conductivity is less likely and saturated condition prevails under ponding. In the clay loam, unsaturated conditions are created mainly by intermittently ponding water and this is the major factor accounting for the efficient salt leaching.

3.2 Removal of soluble ions

3.2.1 Removal of soluble anions

Figure 3 shows the changes of anion concentrations in the effluent as a function of drainage pore volume for clay loam and sandy loam soils under intermittent ponding (IP) and continuous ponding (CP) conditions. In the clay loam, no gypsum was present. In the early stages of leaching (up to 0.25 PV) of the clay loam, the concentrations of Cl^- and SO_4^{2-} were higher for continuous ponding compared with intermittent ponding. With further leaching, the trend was reversed and the concentrations of the two anions in the intermittent ponding were higher. This phenomenon can be explained as follows. The clay loam soil is well-aggregated and electrolyte content in all the columns before leaching was the same. Under intermittent ponding, water flow is unsaturated and soil remains stable. It is plausible therefore, that the fraction of the immobile water under such condition is greater than that exists under continuous ponding where saturated water flow prevails (Fig. 1). For the same effluent volume, less salt is removed from the soil under intermittent ponding because of the fraction of the soil which is associated with the water conductance is smaller than for continuous ponding. Therefore, in the initial stage of leaching, the anionic concentrations in the effluent for the intermittent ponding are lower than that observed for the continuous ponding. As the leaching continues under intermittent ponding, ionic diffusion from the immobile water to the water in the conducting pores becomes more pronounced, and this anionic concentration in the effluent of the intermittent ponding exceeds the concentration under continuous ponding. Whereas salt removal from micropores continues in soil under continuous ponding, the effluent is diluted by the irrigation water of low salinity that flows in the macropores. Therefore, the ionic concentrations in the effluent of continuous ponding became lower than that under intermittent ponding (Fig. 3).

The sandy loam has less clay content and less aggregation. Also, unsaturated flow prevails under both methods of water application (Fig. 2). Thus, the difference in chloride concentration between intermittent ponding and continuous ponding was not significant over the whole range of effluent volume (Fig. 3). However, SO_4^{2-} concentration behaved differently. In the first fraction of effluent (<0.2 PV), the concentration of SO_4^{2-} was similar in both continuous ponding and intermittent ponding. With further leaching, SO_4^{2-} concentration became significantly lower in continuous ponding compared with intermittent ponding. The high concentration of SO_4^{2-} in the effluent of intermittent ponding is due to gypsum dissolution. The sandy loam contains 5.4% gypsum. When intermittent ponding is applied where the average flow velocity is low and water kept in the soil is longer, there is more time for gypsum to dissolve and the concentration of SO_4^{2-} in the effluent is higher (Fig. 3). Gypsum dissolution does not contribute to the SO_4^{2-} concentration in the initial stages of leaching because of the high concentration of SO_4^{2-} in the soil solution before leaching commenced.

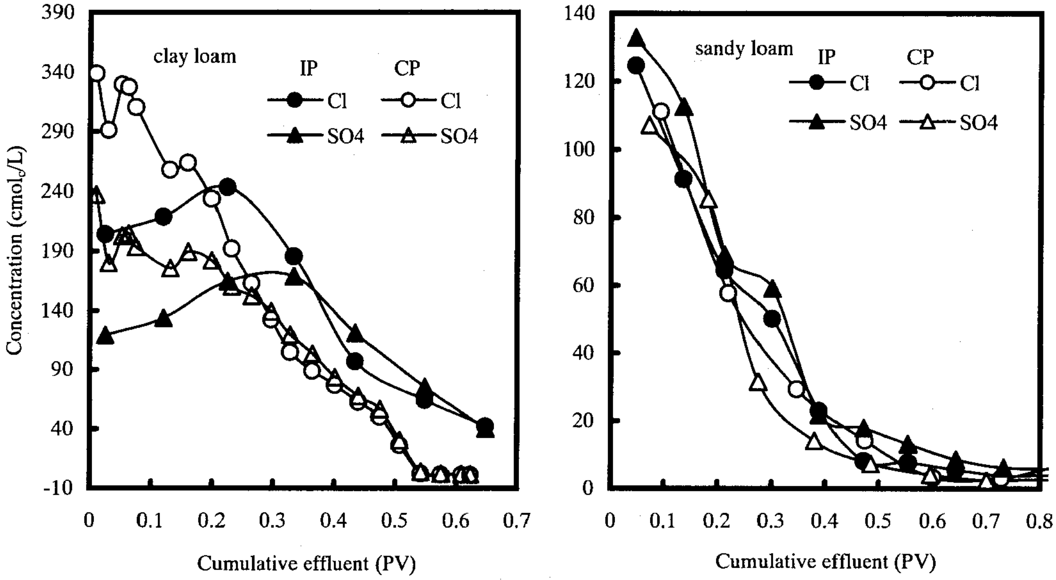

Fig. 3 Anion concentrations of the effluents from the clay loam and the sandy loam as affected by leaching methods.

3.2.2 Removal of cations

Figures 4 and 5 show the changes of cationic concentrations in the effluent as affected by leaching methods for clay loam and sandy loam soils, respectively. Changes in concentration of ($Na^+ + Mg^{2+} + K^+$) in the effluents for both soils were similar to those of the anions. Concentrations of ($Na^+ + Mg^{2+} + K^+$) in the effluent of the clay loam in the initial stage of leaching were higher in continuous ponding, compared with intermittent ponding (Fig. 4. a). With more leaching, the concentrations of these cations became lower in continuous ponding than that in intermittent ponding. The explanation that was proposed for changes in concentrations of Cl^- and SO_4^{2-} can be applied to ($Na^+ + Mg^{2+} + K^+$) cations.

In the nongypsiferous clay loam, Ca^{2+} concentration in the effluent of continuous ponding was consistently higher than under intermittent ponding (Fig. 4. b). Lower concentrations of Ca^{2+} in the effluent imply that more of the Ca^{2+} ions were adsorbed on the clay replacing exchangeable Na. The lower concentration of Ca^{2+} in the effluent of intermittent ponding compared with continuous ponding suggests that replacement of exchangeable Na is more efficient under intermittent ponding. This is because in intermittent ponding, flow velocity is low and there is more opportunity time for the exchange reaction to be completed. Intar -diffusion of ions within aggregates determine the kinetics of Na/Ca exchange and with low flow velocity more Ca^{2+} ions penetrate into the aggregate to exchange sites and replace exchangeable Na.

The situation is completely different in the sandy loam that contains gypsum (Fig. 5). The concentrations of Ca^{2+} of the effluent were higher in the effluent exposed to intermittent ponding than that exposed to continuous ponding at the effluent volume<0.6 PV. Whereas, the concentration of ($Na^+ + Mg^{2+} + K^+$) was similar in the first 0.2 PV of the drainage under both leaching methods, but was higher in intermittent ponding than that in continuous ponding after 0.2 PV until the effluent volume reached 0.6 PV. In the gypsiferous sandy loam, dissolution of gypsum determines Ca^{2+} and SO_4^{2-} concentrations in the soil solution. More gypsum dissolution under intermittent ponding because of the low velocity of water flow and longer contact time between unit volume of water and gypsum particles caused more Ca^{2+} ions in the effluent (Fig. 5. b). Consequently, there were more ($Na^{+}+Mg^{2+}+K^{+}$) ions in the effluent due to cation exchange under intermittent ponding (Fig. 5. a). By contrast, under continuous ponding there was less gypsum dissolution, and thus lower ionic concentrations were observed in the effluent (Figs. 3 and 5).

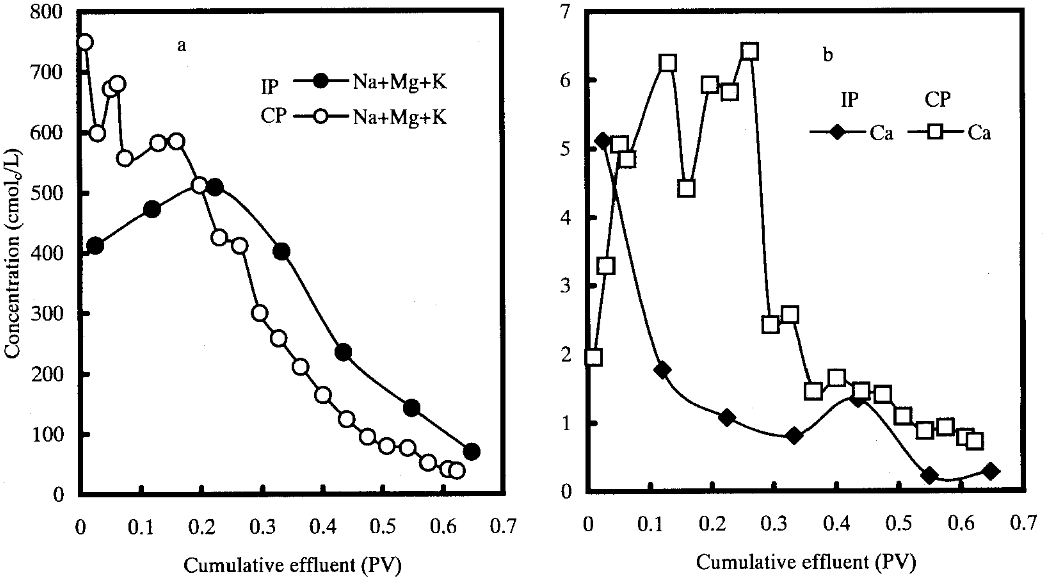

Fig. 4 Cation concentrations of the effluent from the clay loam as affected by leaching methods.

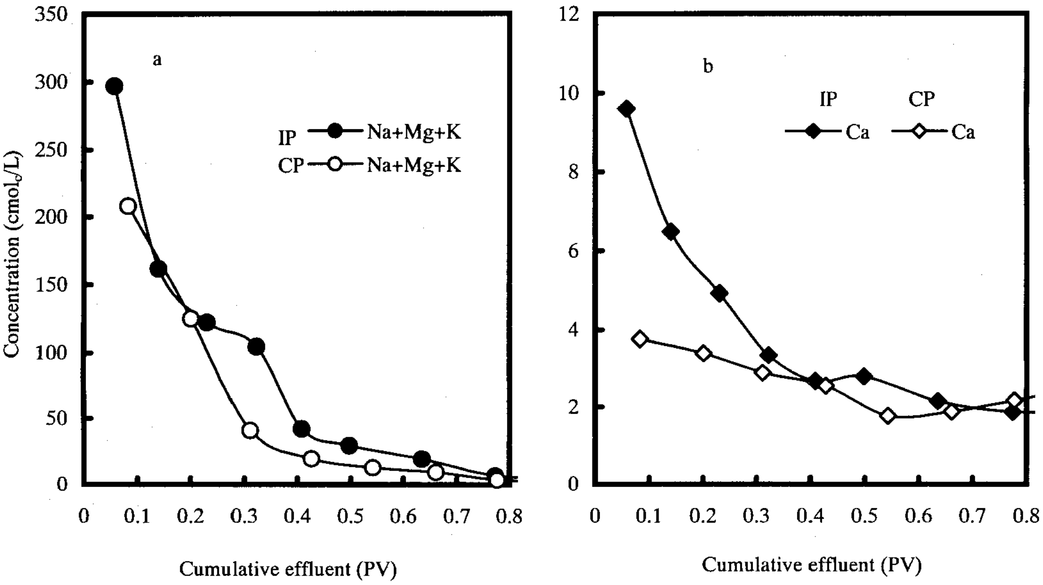

Fig. 5 Cation concentrations of the effluent from the sandy loam as affected by leaching methods.

3.3.3 Removal of exchangeable Na

The extent of reduction of exchangeable sodium percentage (ESP) in the soil depends upon the amount of Ca^{2+} and Mg^{2+} in the irrigation water, the amount and dissolution of $CaCO_3$ and $CaSO_4$, the CEC and ESP of the soil, and the time required to reach dissolution and exchange equilibria. With increase in Ca^{2+} and Mg^{2+} in the solution phase, more exchangeable Na is replaced by exchangeable divalent cations and the ESP of the soil is reduced.

Figure 6 shows the changes of ESP fraction in the two soils as a function of leaching water applied under the two application methods. ESP_i and ESP_f are the soil ESP corresponding to that before and after leaching, respectively. Under intermittent ponding, desodification of both soils was more efficient compared with continuous ponding (Fig. 6). However, the process responsible for the high efficiency of intermittent ponding was different in the two soils. In the sandy loam, soluble salt removal was not affected by leaching method (Fig. 2), whereas soil desodification was affected significantly by the leaching method. Intermittent ponding was much more effective in desodification of this soil, compared with continuous ponding. For example, following leaching with 1 PV, the ESP remaining in the soil were 0.15 and 0.3 of the initial ESP in the soil profile, for intermittent ponding and continuous ponding, respectively. Since the sandy loam contains 5.4% gypsum, gypsum dissolution during leaching played a major role in desodification. The extent of gypsum dissolution depends on the composition of irrigation water, the length of contact time between gypsum particles and soil water, water velocity and soil ESP. Longer contact time between gypsum particles and water, which is the result of lower water velocity, increases gypsum dissolution (Oster and Frenkel, 1980 ; Keren and O'Connor, 1982). Similarly, high soil ESP also increases the rate of gypsum dissolution because exchangeable Na acts as a sink to soluble Ca^{2+} (exchange reaction) and more gypsum (and $CaCO_3$) dissolves (Oster and Shainberg, 1979). Therefore, higher soil ESP accelerates gypsum dissolution. Under intermittent ponding, flow velocity is low, gypsum dissolution rate is high and desodification of the sandy loam is more efficient.

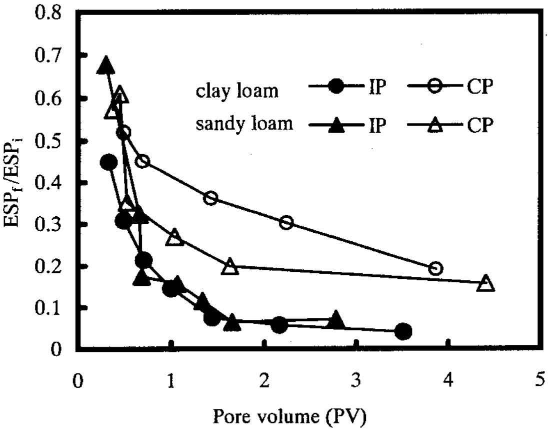

Fig. 6 Desodification curves of the clay loam and the sandy loam under continuous pounding and intermittent ponding.

The effect of leaching method on soil desodification was more pronounced in the clay loam. Following leaching with 1 PV, the ESP remaining in the soil were 0.14 and 0.42 for intermittent ponding and continuous ponding, respectively. Intermittent ponding was three times more efficient in desodification of the clay loam, compared with continuous ponding. Since the clay loam does not contain $CaCO_3$ or gypsum, dissolution of these compounds can not explain the difference. However, long residence time for water in soil not only favors gypsum dissolution, but also Ca/Na exchange reaction. In the course of Ca/Na exchange, adsorbed Na must migrate from inside of the aggregate into the solution. Simultaneously, a Ca^{2+} ion in the solution must go the other way and be adsorbed on the clay. Three processes determine the rate of exchange process : a) ion diffusion which is the intra-diffusion of the counter-ions within the aggregates, b) film diffusion which is ion diffusion of the interdiffusion of the counter-ions in the stationary water films around the aggregates, and c) the exchange reaction (Aharoni and Sparks, 1991). The exchange reaction is a fast process and the diffusion process controls the rate of the exchange reaction. In stable aggregates, inter-aggregate diffusion process controls the rate of exchange reaction. Thus, in the clay loam, the exchange reaction is a slow process and low flow velocity increases the efficiency of desodification. Under intermittent ponding, as Ca^{2+}-carrying solution flow is slow, there is more opportunity time for Ca^{2+} to penetrate into aggregates and replace exchangeable Na. Conversely, under continuous ponding, water velocity is fast and less exchange between Ca and Na is taking place.

4. Conclusions

In this column study, we compared the efficiency of intermittent ponding and continuous ponding in desalinization and desodification of two soils, the natural gypsiferous sandy loam and the nongypsiferous clay loam. Water application method greatly affected the efficiency of desodification of these two sodic soils compared with that of desalinization. In the clay loam, intermittent ponding was more efficient than continuous ponding in both of desalinization and desodification of the soil. Whereas in the sandy loam, efficiency of desalinization was similar under the two leaching methods, and intermittent ponding was more efficient only in desodification of the soil.

Salt leaching efficiency is determined by the uniformity of soil porosity, which is a function of soil clay content. In the clay loam, there are more aggregates and more macropores between aggregates, and more micropores within the aggregates. Water flow in the macropores reduces leaching efficiency. Under continuous ponding, soil is saturated and much of the water is conducted by the macropores, therefore, leaching efficiency is low. Whereas under intermittent ponding, soil is unsaturated, most of water flow occurs in micropores and leaching efficiency increases. In the sandy loam, unsaturated water flow prevails under both continuous ponding and intermittent ponding, and inter-aggregate porosity is negligible. Thus, the efficiency of desalinization in the sandy loam is similar under both leaching methods.

Removal of adsorbed Na from soil (desodification) is determined by the following four mechanisms : 1) the exchange rate between Ca^{2+} and Na^+ on the clay platelets ; 2) supply of soluble Ca and removal of soluble Na which are determined by salt leaching ; 3) intra-aggregate Na^+ and Ca^{2+} diffusion, and 4) the rate of dissolution of $CaCO_3$ or $CaSO_4$. In the clay loam, desodification rate was controlled by particle diffusion, and that of the sandy loam was controlled by the rate of dissolution of gypsum. Both of these processes are slow and determine the Ca/Na exchange rate. Under intermittent ponding, water flow velocity in soil is low which is favorable to both particle diffusion and gypsum dissolution, therefore, the efficiency in desodification of the two soils is higher compared with continuous ponding.

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