Infiltration into Cropped Soils: Effect of Rain and Sodium Adsorption Ratio–Impacted Irrigation Water

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The sodium adsorption ratio (SAR) and salinity criteria for water suitability for irrigation have been developed for conditions where irrigation water is the only water source. It is not clear that these criteria are applicable to environments where there is a combination of rain and irrigation during the growing season. The interaction of rainfall with irrigation water is expected to result in increased sodicity hazard because of the low electrical conductivity of rain. In this study we examined the effects of irrigation waters of SAR 2, 4, 6, 8, and 10 mmol$^{1/2}$ L$^{-1/2}$ and electrical conductivities of 1 and 2 dS m^{-1} on the infiltration rate of two soils with alternating cycles of rain (simulated with a rainfall sprinkler) and irrigation water, separated by drying cycles. The infiltration rate of surface samples from two soils, Kobase silty clay (fine, smectitic, frigid, Torrertic Haplustept) and Glendive very fine sandy loam (coarse-loamy, mixed superactive, calcareous, frigid Aridic Ustifluvent) were evaluated under alfalfa (*Medicago sativa*) cropped conditions for over 140 d and under full canopy cover. Reductions in infiltration were observed for both soils for SAR above 2, and the reductions became more severe with increasing SAR. Saturated hydraulic conductivity measurements taken from undisturbed cores at the end of the experiment were highly variable, suggesting that in situ infiltration measurements may be preferred when evaluating SAR effects.

Elevated levels of exchangeable sodium, especially under low salinity conditions, have adverse impacts on soil structure and cause reductions in water infiltration rates, decreased aggregate stability, clay dispersion, and swelling of expandable clays. The sodium adsorption ratio (SAR) (defined as Na/[Ca + Mg]$^{0.5}$ in solution, where concentrations are expressed in mmol L^{-1}) is a good estimator of the exchangeable sodium percentage (ESP) (U.S. Salinity Laboratory Staff, 1954) and has been used to develop numerous water quality criteria for irrigation (Ayers and Westcot, 1985). For a given SAR value, the adverse impacts on soil physical properties are reduced with increasing salinity (Ayers and Westcot, 1985), commonly reported as the EC in dS m^{-1} (electrical conductivity of the solution).

There are many studies documenting the adverse effects of sodicity on soil hydraulic properties, mostly saturated hydraulic conductivity (K_s) in packed columns run for short periods of time under continuous water flow. McNeal and others (McNeal and Coleman, 1966; McNeal et al., 1966, 1969; McNeal, 1968) characterized the effects of EC and SAR on soil K_s and soil swelling. They observed a range in soil stability for arid land soils of the southwestern USA. They concluded that soils high in kaolinite and sesquioxides seemed to be more stable and soils high in smectite the least stable (McNeal and Coleman, 1966). Frenkel et al. (1978) examined the saturated K_s of several soils of varying mineralogy as related to their response to different EC-SAR levels. The soil with kaolinitic clay was the most stable, followed by the soil with vermiculitic clay, and the smectitic clay soils were the most sensitive to SAR. However, these experiments lack data below SAR 10 and provide no information in the salinity range between EC = 1 dS m^{-1} and deionized water.

There are only a few studies where dilute waters were applied and infiltration or K_s measured. Shainberg et al. (1981a) examined a sand–soil mixture. The relative K_s decreased to 20% and 10% of the initial value when they leached the columns with deionized water after leaching with saline solutions of SAR 5 and 10 mmol$^{1/2}$ L$^{-1/2}$, respectively. The soil examined by Shainberg et al. (1981a) contained only traces of calcite and leached quickly to low EC. These results are considered descriptive because mixing of soil and clay resulted in high-flow velocities in the columns. In a subsequent paper,

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Abbreviations: EC, electrical conductivity; ESP, exchangeable sodium percentage; K_s, saturated hydraulic conductivity; SAR, sodium adsorption ratio.

Shainberg et al. (1981b) related the K_s of soils under deionized water to the drainage water EC, which was primarily related to the presence and reactivity of calcium carbonate in the soils.

Agassi et al. (1981) equilibrated soils to fixed SAR and compared changes in infiltration rates on application of irrigation water via rain simulator to changes in saturated K_s in columns irrigated with the same water compositions. He reported that the infiltration rates seemed to be more sensitive to sodicity than the column studies under saturation. Kazman et al. (1983) studied soils in trays at various ESP values and leached with a rainfall simulator. The infiltration rate for the three soils examined decreased in the range of ESP 2.2 to 6.4. These laboratory data, based on a single rain application to a disturbed soil sample, indicate that a reduction in infiltration occurs during rain events, even in the range of ESP 1.0 to 6.4. Kazman et al. (1983) noted that the sensitivity to Na was greater for infiltration rate of rain than for K_s of a saturated soil with the same solution composition. Rapid wetting into a dry soil can also cause a breakdown in aggregates and a reduction in the infiltration rate, especially for soils with good aggregation, such as high clay soils (Levy et al., 1997).

Although very useful, the direct application of most of the EC-SAR infiltration and K_s studies to field conditions is uncertain due to the omission of wetting and drying cycles among other factors. Drying allows for reformation of aggregates and the development of larger pores (cracks) for water movement. In non-desert regions, where rainfall is a factor, the use of studies that consider only irrigation water is questionable due to the lack of information on the interactive effects of rainfall and irrigation water. The impact of wetting and drying cycles has not been well studied. Oster and Schroer (1979) reported infiltration rates from an outdoor container experiment. They examined 18 waters of varying composition, one container for each treatment, and grouped the treatments into three salinities, approximately EC 0.5, 1.2, and 3.0 dS m^{-1} and three SAR values of 3, 10, and 22 $mmol^{1/2}$ $L^{-1/2}$. In two other treatments they used distilled water and alternate irrigation with distilled water and EC = 3 dS m^{-1} and SAR 20 $mmol^{1/2}$ $L^{-1/2}$. Even for waters in the range of SAR 2 to 4.6, $mmol^{1/2}$ $L^{-1/2}$ infiltration decreased as the irrigation water decreased from EC 2.8 to 0.5 dS m^{-1}. At SAR 20 $mmol^{1/2}$ $L^{-1/2}$, the container with alternate irrigation with EC = 3 dS m^{-1} and distilled water had a lower infiltration rate than the soil irrigated only with EC = 3 dS m^{-1}. Statistical significance cannot be evaluated, but the data suggest that decreases in infiltration may occur with SAR values as low as 2 to 4.6 when the irrigation water is at or below EC 0.5 dS/m.

In a recent study, Suarez et al. (2006) examined the changes in infiltration when soils were exposed to cycles of wetting and drying and sequential application of irrigation water via flood irrigation or rain (deionized water) via a rainfall simulator. They examined irrigation water with different SAR levels (2, 4, 6, 8, and 10 $mmol^{1/2}$ $L^{-1/2}$) and two EC (1.0 and 2.0 dS m^{-1}) levels on infiltration in soil sampled from surface horizons of two soils, a Kobase silty clay and Glendive very fine sandy loam. These soils are extensive in eastern Montana and Wyoming. Infiltration rates decreased with increasing SAR, with the loam soil reduction statistically significant above SAR 4 $mmol^{1/2}$ $L^{-1/2}$, indicating that the SAR 6 treatment had a significantly greater infiltration time than the SAR 2 treatment. For the clay soil, the infiltration rate at SAR 4 $mmol^{1/2}$ $L^{-1/2}$ was significantly lower than the rate for SAR 2. This study may be more representative of field conditions because it was conducted over a time period comparable to an entire growing season (140 d) with numerous cycles of wetting and drying. The impact of rainfall is particularly important in regions where rain is a substantial component of the total amount of water and is especially important if the rainfall is distributed over the year and during the growing season.

Almost all research on the response of a soil to solution salinity and composition has been conducted on arid land soils with the objective of determining the suitability of water for irrigation without consideration of rain (usually EC and SAR). These K_s studies were almost all based on disturbed soils packed into laboratory columns and run under continuously water saturated conditions over short time intervals. Based on studies done at the U.S. Salinity Laboratory and other locations, Rhoades (1977) and Ayers and Westcot (1985) developed water suitability relationships that were later adopted by Hanson et al. (1999), among others.

There is a very limited set of data on the effect of chemistry on infiltration under rain conditions, and these limited data were conducted without the critical wetting and drying cycles. The soils and conditions in the arid southwest USA and Mediterranean climates are also distinct from those in the Northern Great Plains of the USA. In the Mediterranean climate, almost all rain falls in the winter; thus, the hazard and dispersing effect of elevated soil SAR likely occurs primarily during that one season. Typically the recommendation is to surface apply gypsum in the winter to maintain the EC at the surface and to reduce the SAR at the surface during the rainy season (Kazman et al., 1983). Under a Mediterranean climate, cropland irrigation begins after the end of the winter rains. There is also some experience with this system in the Central Valley of CA, but with much lower relative inputs of rain, and almost all of the rain occurs in the winter.

The effect of clay mineralogy on soil sensitivity to SAR has been examined. What is less documented is the impact of other soil factors on soil stability under sodic conditions. The variation among soil types in laboratory studies is large, as indicated by Pratt and Suarez (1990). Most of this variability in soil stability is considered to be due to soil variations in organic matter and quantity of Fe and Al oxides and to clay type. In addition, elevated pH has an adverse impact on saturated K_s and clay dispersion, independent of EC and SAR (Suarez et al., 1984).

Water quality standards to protect agricultural production where rain and irrigation occurs regularly may be different from existing standards for arid areas (Suarez et al., 2006). There is the additional uncertainty as to how earlier published results relate to cropped conditions, where the plant canopy provides at least partial protection from the physical forces, and more specifically to Northern Great Plains conditions and soils. There are no quantitative data on the response of soils to various EC and SAR waters in a combined rain–irrigation system with surface wetting and drying and bare and cropped soils. The objective of this study was to evaluate the response of infiltration and saturated K_s of two Montana soils, Kobase silty clay from the Tongue River area and Glendive sandy loam from the Powder River area in the presence of a cover crop (alfalfa), to alternating cycles of irrigation water and rainfall, with various EC-SAR irrigation waters, and to compare the infiltration response to earlier studies conducted under non-cropped soil conditions.

Materials and Methods

Surface samples of Kobase silty clay (fine, smectitic, frigid, Torrertic Haplustept) were collected near the Tongue River north of Miles City (46.47607 N, 105.77404 W). Surface samples of Glendive very fine sandy loam (coarse-loamy, mixed superactive, calcareous, frigid Aridic Ustifluvent) were collected near the Powder River east of Miles City (46.49131 N, 105.32401 W). Both soils were collected from cultivated sites. Soils were crushed and passed through a 5-mm screen, air dried, and analyzed for texture and chemical characteristics.

Plastic containers (29.0 cm tall and 19.4 cm diameter at the base and 25.0 cm at the top) were fitted with ceramic extractors (5 by 6 cm) at the bottom of the containers in 7 cm of No. 90 fine quartz sand. After mixing each of the individual soils, 17 cm of soil was added above the sand, lightly packing during the filling process. Tap water (EC = 0.6 dS m^{-1} and SAR < 0.5 $mmol^{1/2}$ $L^{-1/2}$) was applied to enable soil settling before the initiation of the treatments. Alfalfa (*Medicago sativa*) seeds were planted in each of the containers. A vacuum of 50 kPa (0.5 bars) was applied to the extractors before, during, and after each water application. The vacuum was shut off when drainage ceased. The containers were irrigated with tap water until plants were established, and there was full canopy cover of the soil surface. After canopy cover, an initial rain event (deionized water) was applied to establish the starting infiltration rates before application of the treatment irrigation waters. After this rain event and subsequent drying, the first irrigation water treatments were initiated.

For each soil there were 10 treatments and three replications plus three controls, for a total of 33 containers. All containers were placed in an open outdoor area under a rainfall simulator in four rows, using a randomized design. Empty containers were placed into each of the four rows for monitoring of rain uniformity of application across rows. All plots were treated by alternating events of simulated rain and irrigation. The simulated rain water consisted of deionized water with an EC of 0.016 dS m^{-1}.

An overhead traveling rainfall simulator was used to sprinkle rain water uniformly over the buckets. The details of the rainfall simulator were reported earlier (Suarez et al., 2006). The variation in application rate of rain was less than 10% for each pass and almost always more than 5%, for each rain event. A complete rain event consisted of 20 passes of the rain machine in small groups to allow drainage and to deliver a total of 2.00 L (5.0 cm). Passes were made in sequence to form temporary ponded conditions. Infiltration times were recorded for the applied depth of water to infiltrate into the soil surface.

The 10 simulated irrigation waters consisted of two salinities (EC = 1.0 and 2.0 dS m^{-1}) at SAR 2, 4, 6, 8, and 10 $mmol^{1/2}$ $L^{-1/2}$. The control treatment consisted of tap water at EC = 0.6 dS m^{-1} and SAR < 0.5 $mmol^{1/2}$ $L^{-1/2}$ with the irrigation waters applied on the surface as flood irrigation events at applications of 2.00 L (5.0 cm height) per container. Irrigation waters were stored in 240-L containers. Infiltration in minutes and centimeters per day were calculated for each container. For rain events, infiltration was measured during several intervals during the rain for all applications. Local potential evapotranspiration was determined from an on-site weather station (ET_0), and total water applied was recorded.

On 14 Apr. 2004, the containers were irrigated with tap water. Nutrient additions were made to the irrigation water approximately monthly. Plots were seeded with alfalfa on 20 Apr. 2004 and irrigated weekly with tap water until 3 June 2004 to provide uniform canopy cover in all containers before initiating the treatments. The objective was to examine the impact on an established alfalfa crop under full cover. At this time the simulated rain and irrigation sequence was initiated. Plants were cut periodically for yield information. At the end of the season, undisturbed soil cores were collected from the containers for laboratory measurement of K_s.

Before collection of the undisturbed soil cores, the rain simulator was used to adjust the water content to slightly below field capacity for optimum sampling. For each sample, a 5.4-cm-diameter brass core sampler (sleeve) was pressed into the soil. The soil adjacent to the sampler was removed, and a flat plastic tool was inserted below the bottom of the core. We next carefully lifted out the core sampler with the soil, with the plastic tool holding the bottom of the core, to ensure that the sample did not slide out or separate. Before use, the bottoms of the cores were trimmed, and the cores in the brass sleeves were mounted in holders. The tested cores were 5.4 cm in diameter and 7 to 9 cm in length. Saturated K_s of the cores was measured in the laboratory using the same water compositions as used in the container experiment. Water was applied under constant pressure head until the K_s stabilized. Bulk density was determined by volume and dry weight determinations of the cores after the K_s measurements.

The infiltration data consisted of repeated measurements collected from a completely randomized, two-way factorial design. The factors in this study include EC (two levels: 1.0 and 2.0 dS m^{-1}) and SAR (five levels: 2, 4, 6, 8, and 10 $mmol^{1/2}$ $L^{-1/2}$). The response variable considered in this analysis is the natural log (ln) transformed infiltration time of the applied rain water. The ln transformation (on the infiltration time data) was used to help stabilize the variance and induce approximate symmetry in the response measurements collected during each sampling period.

For each sampling period, a balanced two-way factorial model (i.e., a traditional two-way ANOVA model with interaction) was used to assess the effects of EC and SAR on the ln infiltration time data. Additionally, the ln infiltration time data in both experiments was analyzed separately by soil type. A multivariate testing approach was adopted to formally test for changes in the estimated EC and/or SAR parameters across multiple sampling periods (Davis, 2002).

Table 1. Irrigation and rain application times.

Date	Application
14 Apr.	soil placed in containers, then tap water applied
20 Apr.	plant seeds, water and nutrient applications
3 June	last tap water application
7 June	rain, 5 cm
10 June	irrigation, 5 cm
15 June	rain, 5 cm
18 June	irrigation, 5 cm
25 June	rain, 5 cm
30 June	irrigation, 5 cm
4 July	rain, 5 cm
9 July	irrigation, 5 cm
14 July	rain, 5 cm
23 July	irrigation, 5 cm
27 July	rain, 5 cm
2 Aug.	irrigation, 5 cm
6 Aug.	rain, 5 cm
10 Aug.	irrigation, 5 cm
13 Aug.	rain, 5 cm
18 Aug.	irrigation, 5 cm
23 Aug.	rain, 5 cm
27 Aug.	irrigation, 5 cm
31 Aug.	rain, 5 cm
3 Sept.	irrigation, 5 cm
7 Sept.	rain, 5 cm
9 Sept.	irrigation, 5 cm
15 Sept.	rain, 5 cm
21 Sept.	irrigation, 5 cm
24 Sept.	rain, 5 cm
29 Sept.	irrigation, 5 cm
5 Oct.	rain, 5 cm
12 Oct.	irrigation, 5 cm; natural rain, 1.56 cm
3 Nov.	irrigation, 2.5 cm; natural rain, 1.56 cm
3 Nov.	irrigation, 2.5 cm
15 Nov.	rain, 5.5 cm
19 Nov.	irrigation, 5 cm; rains of 1 cm each
22 Dec.	irrigation, 2.5 cm
23 Dec.	rain, 1 cm
30 Dec. to 10 Jan.	natural rain, 2.44 cm
24 Jan. to 27 Jan.	rain, 5.2 cm; rains to wet soil, 2.6 cm
11 Feb. to 22 Feb.	natural rain, 1.93 cm

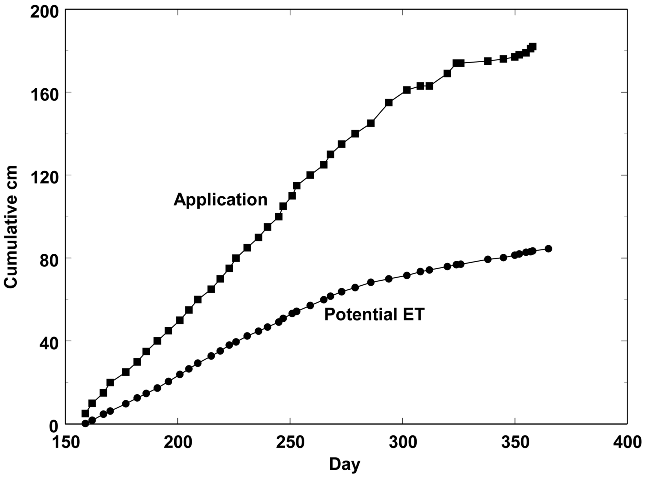

Fig. 1. Cumulative applied water (rain + irrigation) and potential evapotranspiration (ET_0).

Results and Discussion

Infiltration Response to EC-SAR

The compositions of the irrigation waters were designed to represent the major ion composition of the Tongue and Powder Rivers as sampled in May 2003, with a range in SAR. The major ion compositions used in this study are the same as that reported in Suarez et al. (2006); all waters were at the target EC and SAR values. The EC of the simulated rain water was in the range of 0.015 dS m^{-1}, likely toward the lower range in EC for western USA continental rain.

The soil texture of the soils is given in Suarez et al. (2006), and the calculated bulk density was similar to those reported earlier for these soils (Suarez et al., 2006). The Glendive soil contains high amounts of sand and more silt than clay. The Kobase soil is low in sand content (0.013 kg kg^{-1} soil or 1.3%) and is predominantly clay (0.54 kg kg^{-1} soil). The texture classification of our soil samples corresponded to the classification in the soil names. The sand layer was placed in the bottom of the containers to allow for a constant pressure head at the bottom of the soil when vacuum is applied, thus allowing for meaningful comparisons of infiltration rates.

The experiment was conducted from 14 Apr. 2004 until 18 Mar. 2005. The individual dates of the water applications and quantities are given in Table 1. The cumulative application of water and potential evapotranspiration (ET_0) with time is also given in Fig. 1. The total applied water was 185 cm, and the ET_0 was 84 cm. These water applications exceed typical applications for the Northern Great Plains. Higher water applications relative to ET_0 were necessitated by the high ET of the alfalfa in the containers (estimated crop coefficients of 1.2–1.4); thus, crop ET was in excess of $ET_{0.}$ Water applications were determined by visual evidence of water stress by the alfalfa crop and the relation of water applications and ET_0 since the last water application. Thus, the leaching fraction (fraction of water applied that leaches below the rootzone) was below 0.45 and within the range of field conditions for irrigated agriculture. Due to the hotter, drier climate in the test area as compared with eastern Montana, this experiment simulates about 1.5 yr of water applications in Montana.

The experiment was initiated by application of rain and measurement of the infiltration rates before application of the irrigation treatments with various water compositions. In addition to obtaining initial baseline data, this allowed us to establish the alfalfa crop uniformly in each treatment for full canopy cover. There was no trend in the infiltration within the containers designated for the SAR treatments, and there were no differences between the containers scheduled for EC 1.0 dS m^{-1} water and those scheduled for EC 2.0 dS m^{-1} water (Fig. 2). This was expected because the SAR-EC treatments had not been imposed. These data were collected near the end of the rain application. The loam soil, as expected, had a higher infiltration rate than the clay soil.

During this experiment, there was considerable variability in infiltration rates. This variability was likely due to the development of root channels and soil cracking. For the last irrigation event for the loam soil, the variability is sufficiently large for in-

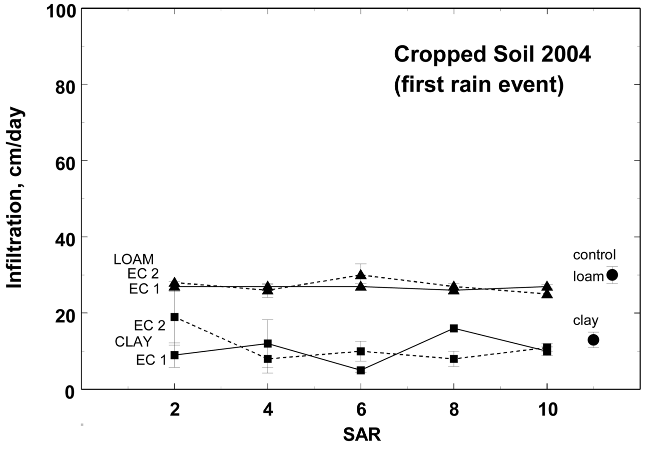

Fig. 2. Rain infiltration rates before application of treatments. Infiltration rates were measured after application of 2.25 cm of rain during the 5.0 cm rain event. Triangles represent loam soil, and squares represent clay soil. SAR, sodium adsorption ratio (mmol$^{1/2}$ L$^{-1/2}$); EC, electrical conductivity of the irrigation water (dS m^{-1}).

dividual events that we can only conclude that there are general trends (Fig. 3). In the case of the last event, we can only say that infiltration decreased with increasing SAR for EC 2.0 dS m^{-1} water and that there was no trend of infiltration with SAR for EC 1.0 dS m^{-1} water. In the following sections we present statistical analysis of the data within the experiment, providing analysis with time and for the different treatments.

Infiltration rates are affected by the initial water content. Analysis of the data is complicated by differences in initial water contents at different times and by the changes in water content during a specific event (time dependence within the infiltration event). During the initial rain application for each event, cracks in the clay soil resulted in very high infiltration rates, greatly in excess of the infiltration rates for the loam soil. Once the cracks sealed, the clay infiltration rate decreased dramatically.

Table 2 lists the measurement dates and sampling irrigation pass used in the analysis of rain infiltration. We attempted (when available) to only analyze data from the 12th pass, thus minimizing the effects of differential water content between events. Additionally, each analyzed period was the averaged infiltration data from two adjacent measurement dates. This averaging was done to reduce the variance in the infiltration data, thus mitigating the influence of marginal outliers present in this data. All statistical analyses were performed using SAS version 8 (GLM and MIXED procedures; SAS Institute Inc., 1999). The data were natural log (ln) transformed infiltration times (i.e., ln minutes), and no data points were removed from any of the sampling periods. A full listing of the experimental data analyzed here is available on request from the authors.

First we analyzed the covariance structures of the ANOVA model residual errors (across sampling periods). This analysis was made to determine if a mixed linear modeling approach could be adapted (Davis, 2002). Six mixed linear model covariance structures were evaluated: (i) unstructured multivariate; (ii) diagonal multivariate; (iii) toepliz; (iv) AR-1: auto-regressive order 1; (v) compound symmetry; and (vi) independent (e.g., no temporal correlation, common variance estimate across time). The covariance structure analysis was based on examining the difference between the -2LL scores (using the unstructured score as the alternative hypothesis in all cases) and computing the asymptotic Chi-square *p* value associated with this difference. These results suggested that the unstructured multivariate covariance hypothesis was the only covariance structure that adequately fit the data. Thus, a traditional repeated measurement modeling approach was adopted (i.e., a MANOVA analysis), instead of the mixed linear modeling approach (Davis, 2002).

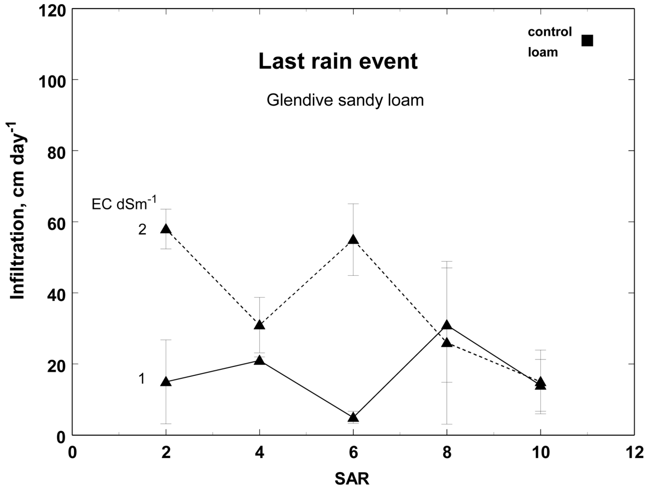

Fig. 3. Relationship among infiltration rates, sodium adsorption ratio (SAR; mmol$^{1/2}$ L$^{-1/2}$), and electrical conductivity (EC; dS m^{-1}) for loam soil during the last rain event of the experiment. Triangles represent loam soil. The solid lines represent EC = 1 dS m^{-1} treatments, and the dashed lines represent EC = 2 dS m^{-1} treatments.

Table 3 presents the primary statistical results associated with the repeated measurement analysis of the infiltration data. These results include the time-averaged model summary statistics (i.e., the summary statistics associated with the univariate ANOVA model fit to the time averaged ln infiltration data), the *F* test significance levels associated with the time-averaged main factor and interaction experimental effects, and the Wilks lambda significance levels associated with the time-dependent multivariate effects, respectively (Johnson and Wichern, 1988).

The univariate ANOVA models with the clay and loam soil data had statistically significant overall model *F* test values below the 0.05 level (p = 0.0154: clay; p = 0.0033: loam). In the time-averaged models for each of the soils, only the SAR effect exhibited statistical significance (p = 0.0013: clay; p = 0.0002: loam). Neither the clay nor loam models exhibited statistically significant univariate interaction effects.

The Wilks lambda significance level quantifies the degree of time-dependent multivariate effects as determined by the

Table 2. Measurement dates for rain infiltration events.

Date (2004)	Sampling period	Irrigation pass
15 June and 25 June	1	12/12
9 July and 27 July	2	12/12
6 Aug. and 13 Aug.	3	12/12
23 Aug. and 31 Aug.	4	12/15
7 Sept. and 15 Sept.	5	16/18
24 Sept. and 5 Oct.	6	12/12

Table 3. Primary statistical tests on ln infiltration data from repeated measures analysis.

Time averaged model summary statistics	Clay	Loam
R^2	0.5871	0.6572
RMSE	0.3116	0.1024
Overall model *F* test significance level	0.0154	0.0033
	F test significance levels	
Time-averaged experimental effects	Clay	Loam
EC†	0.5870	0.4980
SAR	0.0013	0.0002
EC × SAR	0.8925	0.8693
	Wilks Lambda significance levels	
Time-dependent multivariate effects	Clay	Loam
Time	0.0001	0.0001
Time × EC	0.5058	0.0191
Time × SAR	0.0087	0.5978
Time × EC × SAR	0.1256	0.8234

† EC, electrical conductivity; SAR, sodium adsorption ratio.

MANOVA analysis. In the MANOVA model for the clay soil data, the Time effect was highly significant ($p = 0.0001$), and the Time × SAR effect was significant at the 0.01 level ($p = 0.0087$). For the loam soil MANOVA model, the Time effect was also highly significant ($p = 0.0001$), and the Time × EC effect was significant at the 0.05 level ($p = 0.0191$). Neither MANOVA model exhibited statistically significant Time × EC × SAR effects.

These results are similar to the results obtained in a related experiment where the rain-irrigation effects on infiltration were evaluated for non-cropped soils (Suarez et al., 2006). An increase in SAR significantly increased the ln infiltration time average for the clay soil, and these SAR effects change over the course of the experiment (time). Likewise, the SAR levels significantly influence the ln infiltration time average associated with the loam soil. However, for the loam soil, the SAR effects do not significantly change over time. Additionally, the mean ln infiltration times significantly change across the different sampling periods for both soil types, but neither soil type exhibits time averaged (univariate) or multivariate EC × SAR interaction effects. Thus, we conclude that the EC and/or SAR effects, when present, seem to affect the ln infiltration times independently.

Table 4 presents the marginal EC and SAR mean estimates and 95% confidence limits for the clay and loam soil and the *t* test significance levels associated with the SAR contrasts (again using SAR = 2 $\text{mmol}^{1/2}\ \text{L}^{-1/2}$ as a control). The marginal EC ln infiltration time estimates for both soil types seem to be quite similar. Additionally, the ln infiltration time levels associated with both soil types tend to increase in a fairly linear manner. The *t* test significance levels associated with both soils indicate that although the ln infiltration times at SAR = 4 $\text{mmol}^{1/2}\ \text{L}^{-1/2}$ are greater than those at SAR = 2 $\text{mmol}^{1/2}\ \text{L}^{-1/2}$, they are not significantly different. The SAR = 6 versus 2 ln infiltration times are significant ($p = 0.0226$: clay; $p = 0.0156$: loam).

Table 4. Marginal mean estimates of ln infiltration, with 95% confidence intervals (CI) and sodium adsorption ratio (SAR) test results (2 vs. 4, 6, 8, 10); time averaged across sampling periods.

	Clay			Loam		
Effect	Estimate	95% CI	SAR contrasts	Estimate	95% CI	SAR contrasts
EC(1)†	3.29	3.12–3.45		2.64	2.59–2.70	
EC(2)	3.22	3.06–3.39		2.61	2.56–2.67	
SAR(2)	2.80	2.53–3.06		2.47	2.39–2.56	
SAR(4)	3.09	2.83–3.36	0.1123	2.56	2.47–2.65	0.1556
SAR(6)	3.24	2.98–3.51	0.0226	2.63	2.54–2.72	0.0156
SAR(8)	3.57	3.30–3.83	0.0004	2.68	2.59–2.77	0.0021
SAR(10)	3.59	3.31–3.84	0.0003	2.81	2.72–2.90	0.0001

† EC, electrical conductivity.

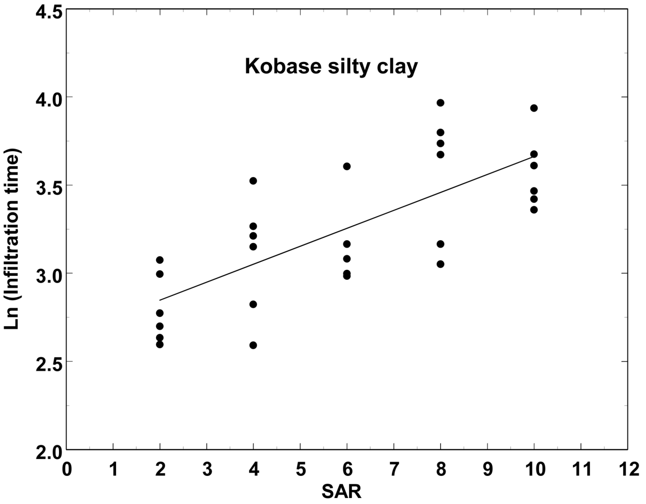

Fig. 4. Relationship between sodium adsorption ratio (SAR; $\text{mmol}^{1/2}\ \text{L}^{-1/2}$) and ln infiltration time for clay soil, with data averaged across sampling periods.

Orthogonal contrasts associated with the SAR effects on the marginal mean ln infiltration times were also computed in both time-averaged ANOVA models. These results confirmed that the SAR effects were entirely linear ($p < 0.0001$ for linear effects; $p > 0.4$ for higher order effects in both soil types). Based on these results, we conclude that simple linear regression models can be used to describe both the clay and loam soil ln infiltration time data. The corresponding fitted linear regression models were estimated to be for clay soil,

$$y = 2.644 + 0.102(\text{SAR}) \qquad [1]$$

and for loam soil,

$$y = 2.393 + 0.040(\text{SAR}) \qquad [2]$$

where y is ln infiltration time. Time is expressed in minutes and SAR in $\text{mmol}^{1/2}\ \text{L}^{-1/2}$.

The R^2 values for these models were 0.583 and 0.616 for the clay and loam soil, respectively, and the calculated SAR slope coefficients were statistically significant at the 0.0001 level. Predicted versus observed ln infiltration time plots for both models are shown in Fig. 4 and 5, respectively. The model for both soils predicts increasing ln infiltration time with SAR, starting at the SAR = 2 $\text{mmol}^{1/2}\ \text{L}^{-1/2}$ control.

The time-dependent (multivariate) test results presented in Table 3 suggest that the marginal SAR effects (for the clay soil) and marginal EC effects (for the same soil type) may have changed during the course of the experiment. Given this possibility, we examined the statistical results from the individual ANOVA models. The individual ANOVA model test results for both the clay and loam soils (Table 5) exhibited more between-period variability than the data from the earlier non-cropped soil experiment (Suarez et al., 2006). The primary difference is that in the present experiment, a number of the ANOVA models were not found to be statistically significant. Most likely this is due to the increased variability in infiltration time for the cropped as compared with non-cropped soil experimental data, caused in part by formation of root channels. It could also be expected that the effect of SAR on infiltration would be less in the cropped soil because the surface is partially protected from the physical impact of the rain. However, the general trends present in Table 5 are consistent with the previously discussed time-averaged models. For the clay and loam soil ANOVA models, the SAR main effect was always statistically significant, provided that the overall model *F* test was significant.

The time interaction plots (Fig. 6–9) show the changes in the estimated cropped soil ln infiltration time (over the six sampling periods) for the various SAR and EC levels. As seen in these figures (and shown by the statistical tests in Table 3), ln infiltration times increased significantly over the course of the experiment. These results were expected because the initial condition can be considered comparable to a field-tilled soil with subsequent increase in infiltration time over subsequent irrigations.

Figures 6 and 7 show how the average clay and loam ln infiltration times changed over time across the five SAR levels, and Fig. 8 and 9 show how these same infiltration times changed across the two EC levels. Based on the multivariate tests in Table 3, the patterns shown in Fig. 6 and 9 can be considered statistically distinct. The SAR-related interaction pattern shown in Fig. 6 for clay soil strongly suggests that the SAR effects (on the ln infiltration time) tended to become more pronounced over the course of the experiment. This is confirmed by the high Time × SAR significance level for clay soil in Table 3. In contrast as seen in Fig. 7 (and Time × SAR nonsignificance in Table 3), there was no statistically significant interaction between the SAR and ln infiltration time in the loam soil over the course of the study. Instead, the ln infiltration time tended to increase in a statistically consistent manner regardless of the SAR level.

The time dependence issue is critical to discussion as to whether or not SAR or EC effects become more pronounced over time. We saw a significant time interaction for the clay but not the loam soil. The EC-related time interaction pattern shown in Fig. 9 does not seem to lend itself to simple interpretation. In all instances, the differences from one time event to another are related to the specific moisture condition at the time of the rain event. In most respects, the time-averaged cropped soil ANOVA and regression models can be used to adequately describe, quantify, and summarize the experimental data. However, based on Table 3 and Fig. 6, there also seems to be evidence that the SAR-related effects on the clay soil increased over time; thus, inferences drawn from the corresponding time averaged model with respect to the SAR effect are likely conservative. This also suggests that short-term experiments to evaluate SAR effects on infiltration may not properly represent the long-term effects experienced over one or more growing seasons.

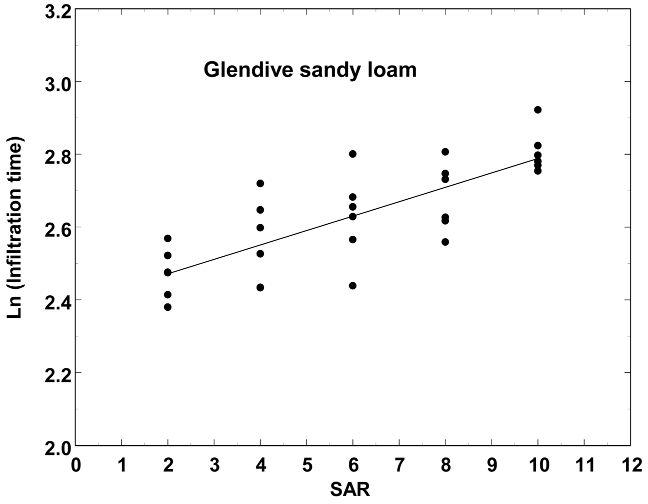

Fig. 5. Relationship between sodium adsorption ratio (SAR; mmol$^{1/2}$ L$^{-1/2}$) and ln infiltration time for loam soil, with data averaged across sampling periods (and electrical conductivity).

We define the SAR risk factor as the degree to which the ln infiltration time increases as the SAR level increases. These risk factors can be ascertained from the time-averaged statistical results in two ways: (i) determining the first SAR level >2 for which a statistically significant increase in the ln infiltration time is detected (using the ANOVA modeling results) or (ii) calculating the relative predicted percent increase in infiltration time per unit increase in SAR (using the estimates SAR coefficients derived from the fitted regression models).

Using the first (ANOVA analysis) approach from Table 4, increasing the SAR from 2 to 6 mmol$^{1/2}$ L$^{-1/2}$ significantly increases the ln infiltration time of clay and loam soil types. With the second approach (using the regression models), the relative percent increase in infiltration time per unit increase in SAR in the presence of a crop is approximately 10.7% for the clay soil and 4.1%

Table 5. Individual sampling period ANOVA model summary statistics and *F* test significance levels for ln infiltration.

Soil	Statistic	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6
Clay	R^2	0.3977	0.4600	0.6106	0.7274	0.2144	0.5860
	RMSE	0.2401	0.4523	0.5657	0.4075	0.9718	0.3594
Loam	R^2	0.4439	0.2491	0.2537	0.6673	0.6938	0.3787
	RMSE	0.3330	0.2120	0.1203	0.1451	0.1218	0.2184
	F test significance levels associated with specified tests						
Clay	Overall	0.2265	0.1126	0.0096	0.0005	0.7772	0.0157
	EC†	n/a‡	n/a	0.6606	0.5156	n/a	0.2839
	SAR	n/a	n/a	0.0015	0.0001	n/a	0.0022
	EC × SAR	n/a	n/a	0.3293	0.6727	n/a	0.6351
Loam	Overall	0.1369	0.6714	0.6567	0.0026	0.0013	0.2720
	EC	n/a	n/a	n/a	0.0129	0.1518	n/a
	SAR	n/a	n/a	n/a	0.0006	0.0007	n/a
	EC × SAR	n/a	n/a	n/a	0.7910	0.0322	n/a

† EC, electrical conductivity; SAR, sodium adsorption ratio.

‡ Not applicable.

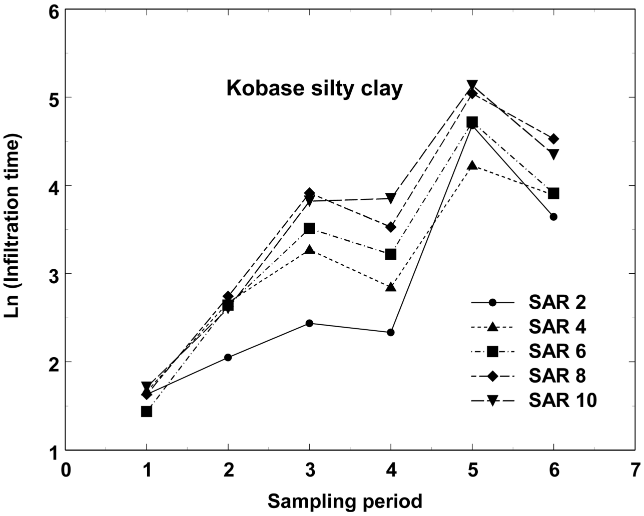

Fig. 6. Average ln infiltration time interaction plot for clay soil data (plotted by sampling period) as related to sodium adsorption ratio (SAR; mmol$^{1/2}$ L$^{-1/2}$).

for the loam soil. In summary, the regression model predictions are that an increase in SAR from 2 to 4 increases the ln infiltration time for clay and loam soil under cropped conditions.

Comparison of SAR Response: Cropped and Non-cropped Soil

An important consideration for the evaluation of the sodicity hazard on infiltration is the interaction of SAR effect and crop cover. An evaluation of the interaction of the SAR effect and cropping is possible by comparing the response in this present study with the results reported earlier (Suarez et al., 2006) for the same soils and experimental conditions under bare (non-cropped) soil conditions. Table 6 shows the linear SAR slope effects for the clay and loam soils types without cropping (data from Suarez et al., 2006) along with the cropped results from the present study. In the previous experiment for the loam soil, a cubic polynomial regression function was found to provide the best fit to the ln infiltration/SAR relationship (Suarez et al., 2006). Table 6 shows the corresponding estimate for a linear effect, determined by refitting the earlier data to a simple linear function.

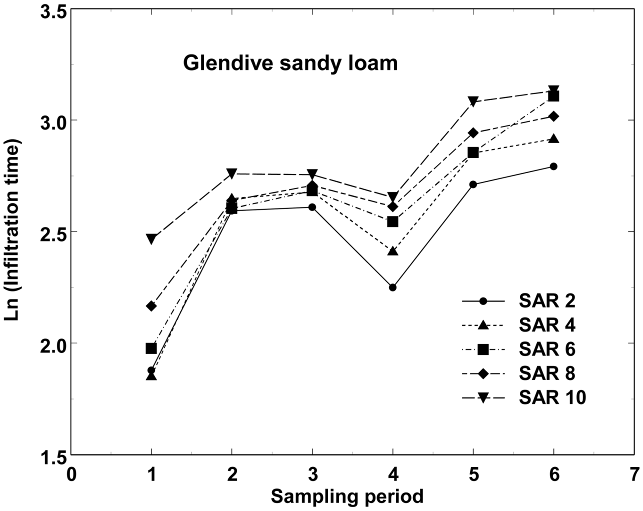

Fig. 7. Average ln infiltration time interaction plot for loam soil as related to sodium adsorption ratio (SAR; mmol$^{1/2}$ L$^{-1/2}$) of irrigation water (plotted by sampling period).

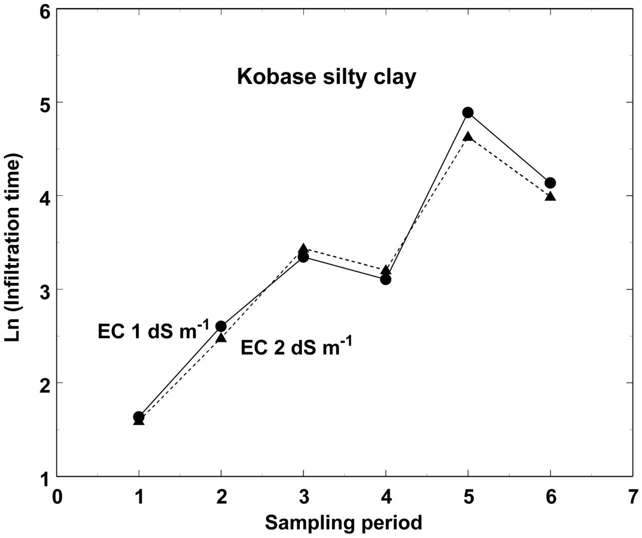

Fig. 8. Average ln infiltration time interaction plot for the clay soil data (plotted by sampling period) for electrical conductivity (EC) of 1.0 and 2.0 dS m^{-1}.

Examining the slope estimates in Table 6, it seems that there may be differences between the cropped and non-cropped results. To formally test this hypothesis, the following ANCOVA model was fit to the ln infiltration data for each soil type:

$$y = \beta_0 + \beta_1(\mathrm{EC}) + \beta_2(\mathrm{SAR}) + \theta_1(\mathrm{C}) + \theta_2(\mathrm{C} \times \mathrm{EC}) + \theta_3(\mathrm{C} \times \mathrm{SAR}) + \varepsilon \quad [3]$$

where y represents the time-averaged ln infiltration data; C represents a 0/1 indicator variable corresponding to the cropping effect (non-cropped versus cropped); the β_1 and θ_1 parameters

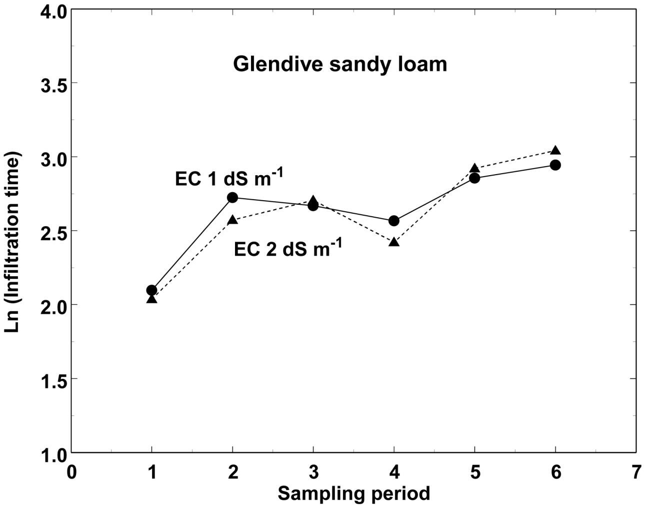

Fig. 9. Average ln infiltration time interaction plot for the loam soil data (plotted by sampling period) for electrical conductivity (EC) of 1.0 and 2.0 dS m^{-1}.

quantify the EC and cropping and SAR and cropping interaction effects, respectively; and ε represents a random error component assumed to follow the usual ANOVA model assumptions. The *F* score associated with the θ_3 parameter estimate was used to test the hypothesis that the estimated linear SAR effects (on the ln infiltration time) changed across cropping.

When Eq. [3] was estimated using the clay soil ln infiltration data, the corresponding *F* score was 3.46 ($p = 0.068$), which is significant at the 0.1 level. Upon estimating Eq. [3] using the loam soil ln infiltration data, the corresponding *F* score was 58.6 ($p < 0.0001$). This latter test indicates that the linear SAR effects can be judged to be clearly different in the loam soil for cropped versus non-cropped conditions. The results of the first test suggest that the linear SAR cropping effects may not be different in the clay soil, at least at the 0.05 level of confidence.

Barring other confounding effects, these results suggest that the effect of a crop on the ln infiltration time varies by soil type. For the loam soil, where the presence of a crop is clearly influential, the crop seems to mitigate the effect that increasing SAR levels have on the ln infiltration times. In other words, when there is no crop, an increase in the SAR level of the loam soil tends to produce a much more pronounced increase in the average ln infiltration time. However, in the presence of a crop, an increase in the SAR level tends to produce a proportionally less noticeable increase in the average ln infiltration time. In contrast, there were no significant differences between the response of the cropped and non-cropped clay soils to SAR.

Equation [3] can also be used to compare the infiltration response to SAR across soil types. Because there were no significant differences between the response of the cropped and non-cropped clay soils to SAR, we refit Eq. [3] without the interaction terms to estimate a common linear SAR effect for the clay soil. We then constructed approximate tests of the clay versus loam slope estimate differences using a standard Normal *z*-score test (where the pooled standard error was computed from the calculated standard error estimates reported in Table 6). Both tests yielded *z*-score values ($z = 3.03$, $p < 0.005$; $z = -4.00$, $p < 0.001$) that suggest that the two loam soil type slope estimates are each different from the pooled clay estimate at or below the 0.01 significance level. These test results suggest that the cropped loam soil was less adversely affected by SAR as compared with the clay soil (combined cropped and non-cropped) and that the non-cropped loam soil was more adversely affected by SAR as compared with the clay soil.

An important caveat to this interpretation is that later irrigation passes were analyzed for the cropped soils as compared with the earlier non-cropped soils. The effect of this difference is unknown, but after saturation of the soil and sealing of cracks we expect that results from subsequent passes would be comparable. Furthermore, we have no reason to expect that there would be an interaction between the pass selected and the response to SAR.

Hydraulic Conductivity

The K_s results from undisturbed cores taken from the loam soil after the termination of the cropped experiment are shown in Fig. 10. Each sample had water applied of the same composition as it experienced earlier in the outdoor infiltration experiment. There was a decrease in K_s with increasing SAR of the irrigation water. The samples from the EC = 2 dS m^{-1} treatments had higher K_s than did the samples from the EC = 1.0 dS m^{-1} treatments, and the K_s with the rain water was lower than with the irrigation waters. Data were variable due to channels and soil separation around the roots.

Table 6. Estimated linear sodium adsorption ratio (SAR) effects on ln (infiltration rates) by soil type and crop condition.

Treatment	Estimated linear SAR effect	Corresponding SE†
Clay soil		
No crop	0.0622‡	0.0151
Cropped	0.1018‡	0.0151
Common (pooled) estimate	0.0820	0.0108
Loam soil		
No crop	0.1363	0.0089
Cropped	0.0396	0.0089

† All SEs based on Eq. [1].

‡ Data from Suarez et al. (2006).

The data were statistically analyzed using the two-way factorial model without interaction, where the response data are the ln-transformed K_s values. These data have been analyzed separately by soil type and event. Table 7 lists the relevant statistical results. Only the EC = 1 dS m^{-1} cores were run for the clay soil type; thus, no *F* test *p* values are reported for this effect. Based on this analysis, we cannot detect a statistically significant effect of SAR on ln(K_s) measurements with either soil type. However, the ln(K_s) readings associated with the loam soil type were affected by the changing EC levels during both events. Specifically, the average ln(K_s) levels seem to significantly increase as the EC level increases.

The regression model summary statistics, parameter estimates, and *t*-test results for the loam soil type are shown in Table 8 (no results are shown for the clay soil type because these models were not found to be statistically significant). These results confirm that the increase in the EC resulted in a statistically significant increase in ln(K_s) in the loam soil type during the irrigation and

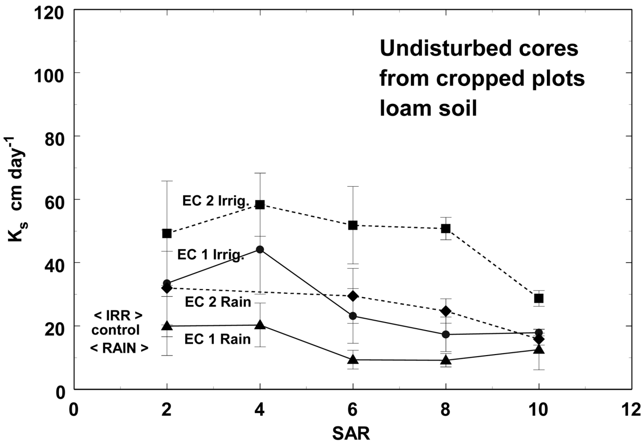

Fig. 10. Saturated hydraulic conductivity (K_s) as related to sodium adsorption ratio (SAR; mmol$^{1/2}$ L$^{-1/2}$) of applied water. Undisturbed cores taken from loam soil treatments at the end of the outdoor infiltration experiment. The same SAR and electrical conductivity (EC; dS m^{-1}) water compositions were used for the irrigation data; deionized water was used for the points designated "rain."

Table 7. ANOVA model summary statistics and *F* test significance levels for main effects and specific sodium adsorption ratio (SAR) contrasts; undisturbed soil cores, ln (K_s) response variable.

	Clay		Loam	
Statistic	**Irrigation**	**Rain**	**Irrigation**	**Rain**
R^2	0.1311	0.2043	0.4826	0.4767
RMSE	1.140	0.903	0.519	0.603
F test significance levels associated with specific tests				
Overall	0.8197	0.6448	0.0051	0.0057
EC			0.0009	0.0009
SAR	0.8197	0.6448	0.1195	0.1518
F test significance levels associated with SAR contrasts				
2 vs. 4	n/a†	n/a	0.1375	0.3484
2 vs. 6	n/a	n/a	0.9376	0.3972
2 vs. 8	n/a	n/a	0.6178	0.3238
2 vs. 10	n/a	n/a	0.2345	0.1538

† Not applicable.

rain laboratory tests. These results also indicate that the increasing SAR levels caused a significant (or near significant) decrease in the ln(K_s) levels during both events ($p = 0.060$ and $p = 0.036$, irrigation and rain water applications, respectively). This linear regression model predicts a decrease in the ln K_s with an increase from SAR 2 to SAR 4 mmol$^{1/2}$ L$^{-1/2}$.

The bulk density was determined on the undisturbed cores used in the laboratory K_s study. There were no clear trends related to the irrigation water treatments (data not shown). This result suggests that the reduction in infiltration with increasing SAR was due to clay dispersion or surface crusting rather than swelling, which would decrease the bulk density.

The cumulative alfalfa fresh weight yields for the irrigation water treatments were relatively uniform for all treatments, trending around 150 g per container for the clay soil and 115 g per container for the loam soil (data not shown). The lower yield of the loam soil is explained by the lower water-holding capacity of the soil and thus increased water stress caused by the irrigation regime. The soils are relatively shallow; therefore, we irrigated the cropped containers at the first signs of water stress, which occurred in the loam soil due to lower water-holding capacity.

Based on ANOVA evaluation of yield vs. SAR and EC levels (data not shown), neither the changing EC nor SAR levels affected the final, fresh-weight crop yields ($0.16 < p < 0.9$). The lack of a decrease in yield with increasing SAR indicates that the soil physical properties did not directly affect yield in this 1-yr experiment. We did not see clear trends in the bulk density as related to water treatments. In this experiment, every container received the same amount of water, and water was the yield-limiting factor. Under field conditions, a decreased infiltration rate is expected to result in increased surface runoff and decreased infiltration. Decreased water infiltration results in decreased yield if the crop is water limited.

Table 8. Regression model summary statistics: SAR and EC parameter estimates, standard errors, and *t* test significance levels for the ln(K_s) data associated with the loam soil (by event).

Soil type	Event	R^2	Variable	Estimate	SE	Pr† > |t|
Loam	Irrigation	0.3925	SAR	−0.0671	0.0342	0.0602
			EC	0.7136	0.1935	0.0010
	Rain	0.4203	SAR	−0.0855	0.0386	0.0356
			EC	0.8370	0.2185	0.0007

† Probability.

Conclusions

The increase in SAR of the irrigation water had an adverse impact on water infiltration (increased infiltration time) for cropped loam and clay soils. The differences in infiltration time were statistically significant at SAR 6 mmol$^{1/2}$ L$^{-1/2}$ based on paired *t* test analysis. However, the fitted regression model showed predicted increases in infiltration time for cropped clay soil and for cropped loam soil as the SAR increased from 2 to 4 mmol$^{1/2}$ L$^{-1/2}$. These results are similar to those obtained earlier for the same soils under non-cropped conditions and suggest that any increase in SAR adversely affects infiltration. The relative increase in infiltration time with increasing SAR was greater for non-cropped as compared with cropped conditions for the loam soil, consistent with the idea that cropped conditions provide surface protection from dispersion. The clay cropped and non-cropped responses to SAR were not statistically significantly different.

Measurements of saturated K_s on undisturbed cores at the end of the experiment were consistent with the increased infiltration times measured during the experiment for loam soil. The changes in K_s as related to SAR were significant for loam soil under irrigation and rain. The linear regression model predicted decreases in K_s as the SAR is increased from 2 to 4 mmol$^{1/2}$ L$^{-1/2}$. The SAR trends were not significant for clay soil, due in part to increased variance. These data suggest that field infiltration measurements may be preferred over determination of undisturbed laboratory hydraulic conductivity measurements when evaluating SAR effects.

Acknowledgments

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