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Evaluation of Water Quality Criteria for Rain-Irrigation Cropping Systems

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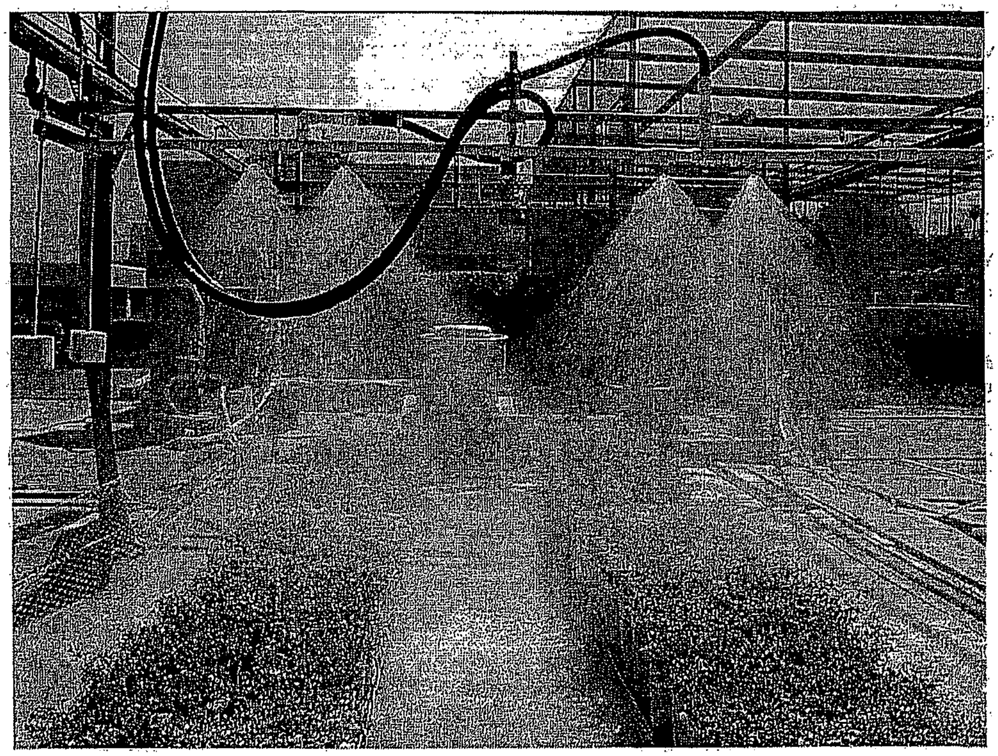

Final Report to EPA June 30, 2006

Introduction

This report documents research conducted by the Salinity Laboratory USDA-ARS under an interagency agreement (DW-12-95386801) with EPA Region 8. Water quality standards to be developed for Montana and other western states are to protect existing agricultural production from the adverse effects of salinity and sodicity. Salinity, generally represented by the solution electrical conductivity (EC), has an adverse effect on plant growth, while sodium adversely impacts soil physical properties such as infiltration. This report is focused on the effects of sodium (and interactive effects with salinity) on water infiltration.

Water quality criteria for irrigation must consider both the direct impact on crop yield and the indirect impact related to affects on soil chemical and physical properties. It is well recognized that the salinity of a irrigation water and the sodium adsorption ratio (SAR, defined as $Na/(Ca + Mg)^{0.5}$ in solution, where concentrations are expressed in millimoles/L), have an interactive effect on soil physical properties. For a given SAR value, the adverse impacts on soil physical properties are reduced with increasing salinity. Salinity is commonly reported as the EC in dS/m (electrical conductivity of the solution). The SAR is a useful parameter that it is closely related to the exchangeable sodium percentage in the soil.

There are an extensive series of scientific reports on the adverse effects of waters of varying quality on soil hydraulic properties. Almost all the research has consisted of laboratory studies with packed (disturbed) soil in columns under continuous water flow and saturated conditions. In a series of studies (McNeal and Coleman, 1966, McNeal et al., 1966, McNeal,, 1968, and McNeal et al., 1969) McNeal characterized the effects of EC and SAR on soil hydraulic conductivity and soil swelling. For arid land soils of the southwestern U.S. they observed a range in stability, concluding that soils high in kaolinite and sesquioxides appeared to be more stable and soils high in montmorillonite appeared to be the least stable (McNeal and Coleman, 1966). For the Gila soil (the most sensitive) there was a 25% reduction in hydraulic conductivity at EC=2 and SAR= 5 (no data below EC=2 and SAR=5).

Frenkel et al. (1978) examined 3 southern CA soils in laboratory columns, with predominant clay mineralogy of kaolinite, vermiculite and montmorillonite. They leached soils with waters of either SAR 10, 20 or 30 with successively more dilute waters of EC 10, 5, 1 dS/m and distilled water. At SAR 10, decreases in hydraulic conductivity for montmorillonitic soil occurred at EC=1 (as compared to EC=5). The kaolinitic soil decreased in hydraulic conductivity only for distilled water (as compared to EC=1 dS/m). The vermiculitic soil had a slight loss at EC= 1 (8 %) as compared to EC =5 dS/m and a sharp decrease with distilled water. While useful, these experiments lack information below SAR 10 and provide no information between EC =1 dS/m and distilled water.

There are a limited number of studies where dilute waters were applied and infiltration or hydraulic conductivity measured. Shainberg et al., (1981a) reported a decrease in relative hydraulic conductivity to 20 % and 10 % of the initial value when soil-sand mixtures of a soil, previously leached with saline solutions of SAR 5 and 10 respectively, were subsequently leached with deionized water. The adverse response was likely accentuated by the mixing of soil and clay and subsequent high flow rates of the solutions through the columns. However, the extent to which a sodic soil adversely responds to deionized water is related to the extent to which the soil can maintain an elevated EC (as a result of mineral dissolution), primarily presence and reactivity of calcium carbonate (Shainberg et al. 1981b), as well as the exchangeable sodium and salinity of the soil. The soil examined by Shainberg et al. (1981a) contained only traces of calcite and leached quickly to low EC.

Kazman et al. (1983), used disturbed soil prepared at various ESP values, packed in soil trays and leached with a rainfall simulator. The infiltration rate decreased as the ESP increased from 1.0 to 2.2 to 4.6 for Hamra-Netanya soil, from ESP 1.8 to ESP 6.4 for Nahal-Oz soil, and from ESP 2.5 to ESP 5.5 for Kedma soil. These laboratory data were based on a single rain application to a disturbed soil sample but indicate that even in the range of ESP 1.0 to 6.4, there may be a reduction in infiltration during rain events. Kazman et al. (1983) also noted that the sensitivity to sodium was greater for infiltration rate of rain than for hydraulic conductivity of a saturated soil with the same solution composition.

In one of the few studies of longer duration with wetting and drying, Oster and Schroer (1979) reported on infiltration studies on outdoor containers. Eighteen waters of varying composition were applied, one container for each treatment. They were grouped around 3 salinities, corresponding to approximately EC 0.5, 1.2 and 3.0 dS/m and 3 SAR values of 3, 10, and 22. Two other treatments consisted of distilled water and alternate irrigation with distilled water and EC=3 dS/m and SAR 20. They concluded that even for waters around SAR 2-4.6 there was increased infiltration as the irrigation water increased from EC 0.5 to 2.8. The container with alternate irrigation with EC= 3 dS/m at SAR 20 and distilled water had a lower infiltration rate than the bucket irrigated only with EC= 3 dS/m at SAR 20 irrigation water. Although statistical significance cannot be evaluated, the data suggest that decreases in infiltration may occur as low as SAR 2-4.6 when the irrigation water is at or below EC 0.5 dS/m.

While very useful, the direct application of these studies to field conditions is questionable, limited (except for Oster and Schroer, 1979) by omission of wetting and drying cycles among several factors. In non-desert regions, where rainfall is a factor, the application of these studies is questionable due to the lack of information on the interactive effects of rainfall and irrigation water. 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). Also these hydraulic conductivity studies were almost all based on disturbed soils packed into laboratory columns and run under continuously water saturated conditions. Based on these studies done at the Salinity Laboratory and other locations, Rhoades 1977 and subsequently Ayers and Westcot, (1985) developed water suitability relationships, later adopted by Hanson et al. 1999 among others.

Other water quality classifications include Gupta (1994), who classified all waters with EC <2 dS/m and SAR <10 as good, based on studies with soils in India. Quirk and Schofield (1955), based on laboratory studies, developed a permeability relationship related to exchangeable Na and electrolyte concentration. They considered waters at 2 $mmol_c/L$ to have decreasing permeability at all ESP levels, at 10 $mmol_c/L$, decreasing permeability for ESP above 25 (corresponding to about SAR 23) and at 20 $mmol_c/L$, at ESP below 37 (corresponding to about SAR 35). For the present discussion we can convert his concentration data to EC with the approximate relationship 10 $mmol_c/L$= an EC of 1 dS/m.

The Quirk and Schofield (1955) criteria were also utilized by Frenkel (1984). Pratt and Suarez (1990) considered that based on existing data, a "general relationship cannot be predicted because soils greatly differ, but a good SAR versus concentration relationship for a set of soils from a region or locality is possible". They further state that differences among soils are at least partly due to different experimental procedures.

The guidelines adopted by Ayers and Westcot (1985) and currently used throughout the world are based on earlier studies and guidelines, mostly those developed at the Salinity Laboratory (including Rhoades, 1977, Oster and Schroer, 1979). For example, as can be seen in Figure 1 from Ayes and Westcot (1985) , at an EC of 1 dS/m it is considered that there is no impact below SAR 3 and a severe reduction only above SAR 13, while at EC =2 dS/m, the corresponding SAR values are SAR 10 and SAR 21.

In Table 1 of Ayers and Westcot (1985) they cited the UC Committee of Consultants report (1974) and classified all water at SAR 1-3 as having no restriction on use if the EC was greater than 0.7 dS/m, and slight to moderate restriction if EC was 0.7 to 0.2 dS/m. For waters of SAR 6-12 they rated waters of EC >1.9 dS/m as having no restriction on use and waters of 1.9-0.5 dS/m as having slight to moderate restriction on use due to effects on infiltration. In discussion of assumptions in the guidelines they state "In a monsoon climate or areas where precipitation is high for part or all of the year, the guideline restrictions are too severe". However this statement is contrary to the criteria of all guidelines, where more dilute waters (such as rain) are more limiting in terms of infiltration. We thus assume that the statement refers primarily to the criteria related to salt tolerance and not to sodicity.

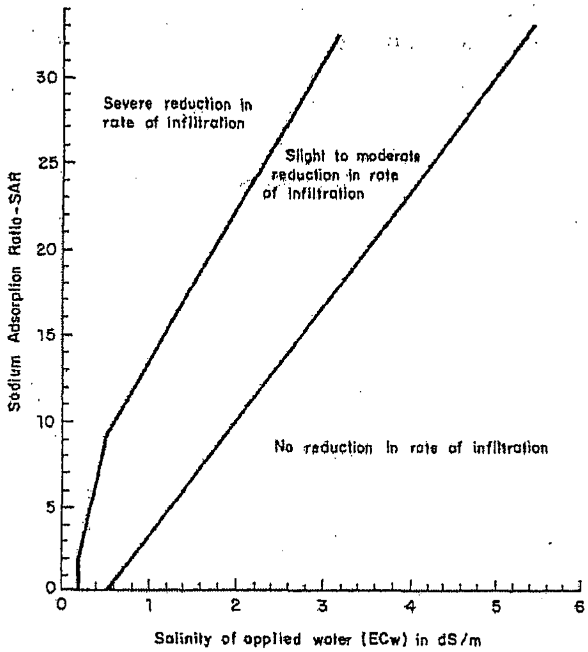

Figure 1. Effects of SAR and salinity on water infiltration (Ayers and Westcot, 1985; adopted from Rhoades, 1977 and Oster and Schroer, 1979).

There is a very limited set of data on the effect of chemistry on infiltration under rain and these limited data were conducted without the critical wetting and drying cycles. The soils and conditions in the desert south west and Mediterranean climates (Israel) are also distinct from that in Montana. In the Mediterranean almost all rain falls in the winter, thus the hazard and dispersing effect likely occurs only once a year during the transition from irrigated to rain. Typically they apply a surface dressing of gypsum in the winter to maintain the EC at the surface as well as reduce the SAR at the surface during the rainy season (Kazman et al., 1983). At the end of the winter rains they initiate irrigation. There is also some experience with this system in the Central Valley of CA, but with much lower relative inputs of rain, and again all in the winter.

Other very important factors affecting water quality standards are the differences among soil types- some are much more stable and others are less stable than indicated by a single stability line. The variation among soil types in laboratory studies is large, as indicated by Pratt and Suarez, (1990). In addition elevated pH has an adverse impact on soil stability as determined by Suarez et al., (1984).

There is still uncertainty as to how these published results from other studies and recommendations may relate to Montana soils, a combined rain and irrigation water sequence, and cropping conditions. Water quality standards to protect agricultural production where rain and irrigation occurs regularly may be different from existing standards for arid areas. There is 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 soil. Farmers in Montana have considered that problems with soil infiltration may start to occur with use of irrigation waters in the range of SAR 4-5. Although useful, such observations do not met scientific criteria of controlled studies. Thus there is a need to test the water quality impacts on Montana soils under cycles of wetting and drying comparable to field conditions.

The objective of the present study is to establish irrigation water suitability under conditions of combined rain and irrigation- a distinctly different condition from that of most earlier studies and standards. Under a combined rain irrigation system the soil may go from a relatively saline condition (for example EC 3.0 dS/m and SAR 10) to a nonsaline condition (EC 2.0 dS/m) in the upper part of the profile after a significant rain. The decrease in SAR will be slower than the decrease in EC (depending on the cation exchange composition and extent to which Darcy flow is approximated). This condition causes a potential sodium hazard (dispersion, loss of aggregate stability, and decrease in infiltration rate) during the rain event under conditions when the soil may have been stable under irrigation. In such systems the hazard is considered greatest during a rain event, thus the irrigation water criteria must consider not only the direct effect of the irrigation water but more importantly, the resultant effect of a subsequent rain event.

This experiment was designed to test infiltration and hydraulic conductivity of two Montana soils, Kobase Silty Clay from the Tongue River area and Glendive Sandy Loam from the Powder River area, both irrigated with 10 simulated river waters with two EC and five SAR levels and subjected to alternating rainfall. Soils were tested bare (uncropped) and cropped in outdoor containers. Soil cores were taken from the containers for saturated hydraulic conductivity tests after each season. Information obtained will contribute to newer water quality standards.

Materials and Methods

Soils

Cultivated surface soils were collected in Montana in May of 2003. Kobase Silty Clay, fine-montmorillonitic borollic camborthid, was collected near the Tongue River north of Miles City (46.47607 N, 105.77404 W). Glendive Very Fine Sandy Loam, coarse-loamy, mixed (calcareous), frigid ustic torrifluvent, was collected near the Powder River east of Miles City (46.49131 N, 105.32401 W). Soils were transported to Riverside, California, crushed and passed through a 5 mm screen, air dried, and analyzed for texture and chemical characteristics. River water samples were also collected to enable comparable water compositions to be used in the Riverside experiments.

Experimental design

Plastic containers 29 cm tall with a diameter of 19.4 at the base and 25 cm at the top were fitted with 5 by 6 cm ceramic extractors buried in the bottom of the containers into 7 cm of No. 90 fine quartz sand. A vacuum of 50 kPa (0.5 bars) was applied to the extractors before, during and after each water application but was shut off when flow ceased. After mixing each of the individual soils, 17 cm of soil was uniformly placed above the sand with light packing.

For the second experiment (cropped soil) the soil was reutilized. After removal of the soil from the containers, the soil was remixed, leached and added to a new set of plastic containers with new extractors and sand. The installation was similar except that tap water was added to allow for settling before the initiation of the treatments and alfalfa was planted into each of the containers. Treatments were initiated after the alfalfa plants were established and there was canopy cover.

For each soil we prepared 33 labeled containers. Four empty containers were also positioned in 4 rows all in an open outdoor area under the rainfall simulator. The plots were subjected to alternating simulated rain and irrigation events. The simulated rain water consisted of partially deionized Riverside tap water with an EC of 0.016 dS/m

An overhead traveling rainfall simulator was designed to sprinkle rain water uniformly over the buckets. The operating system is shown in Figure 2. The sprinkler heads, H ½ U SS 8070 (Spraying Systems Co. Wheaton IL[1]) were designed to simulate rain drop sizes of 1.6 mm in diameter with terminal velocity representative of rain. They were inserted into a chain driven overhead boom that traveled approximately 100 cm beyond each end of the rows of containers. The distance between the sprinkler heads were adjusted to optimize uniformity. Each container had a sprinkler overlap from 2 sprinkler heads. The system, 140 cm above the soil surface, delivered 100 mL per container or 0.25 cm of rain per pass at an intensity of 0.21 cm/s. Accuracy of the rain applicator (uniformity of the application as measured in random open buckets inserted into each of the container rows, was better than 10% for each pass and almost always better than 5%. A complete rain event consisted of 20 passes in small groups to allow drainage and to deliver a total of 2.00 L (5 cm) as measured in the empty containers. Passes were made in sequence to form temporary ponded conditions in order to measure infiltration times for the applied depth of water to disappear into the soil surface.

The simulated irrigation waters consisted of two different salinities (EC= 1.0 and 2 .0 dS/m) at SAR 2, 4, 6, 8, and 10, and one control (Riverside tap water at EC= 0.5 dS/m, SAR <1) The irrigation waters were applied on the surface (flood) at applications of 2 liters or 5 cm. Irrigation waters were stored in 11 barrels of 240 L each.

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[1] Trade names are provided for the benefit of the reader and do not imply endorsement by the USDA.

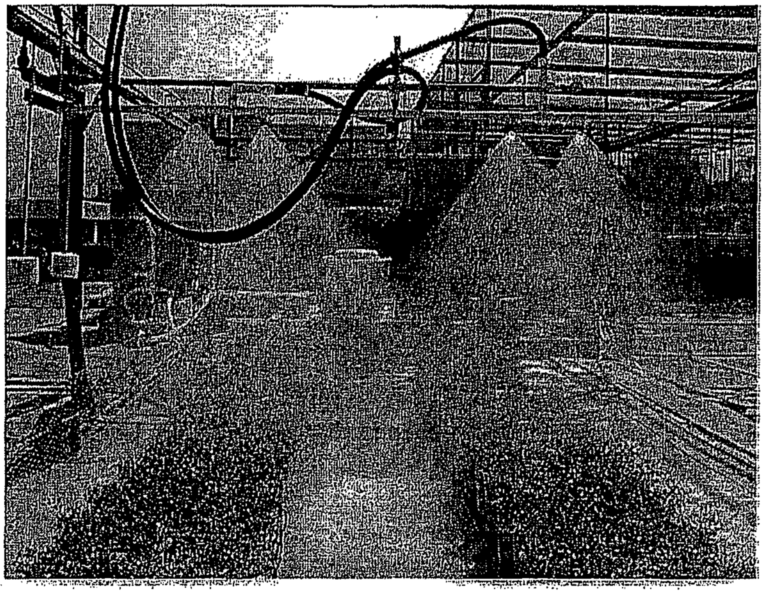

Figure 2. Operating rain simulator. Photo taken in August 2004 while conducting cropped soil experiment.

The EC-SAR combinations and control were replicated three times for each soil. During water applications, infiltration in minutes and cm per day were calculated for each plot. For rain applications infiltration was measured during several intervals for all applications. During the first year the soils were tested under bare (uncropped) conditions. During the second year the soils were cropped to alfalfa. Local potential evapo-transpiration determined from an on-site weather station (ET_0) and total water applied was recorded. At the end of each year's experiment, undisturbed soil cores and bulk soil samples were taken from each container for analysis.

At the end of the first year of the experiment, the soils were leached, recovered, air dried, screened, mixed and repacked into new containers with new extractors and sand for the 2004 season. In April 2004, the plots were irrigated with tap water and seeded with Alfalfa. Riverside tap water and nutrient solution was added through June 2004 to provide canopy cover 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 bulk samples were collected and tested in the lab as above.

Hydraulic conductivity of undisturbed cores

Before collection of the undisturbed soil cores we used the rain simulator 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 insure that the sample did not slide out or separate. Before use, the bottom of the cores were trimmed and the cores in the brass sleeves were mounted in holders. The tested cores were all of a diameter of 5.4 cm with lengths of 7 to 9 cm. Saturated hydraulic conductivity of the cores was measured in the laboratory using the same water compositions as used in the field. Bulk density was determined by volume and dry weight determinations of the cores folowing the hydraulic conductivity measurements. Water was applied until the hydraulic conductivity stabilized.

Infiltration rate of disturbed soil (laboratory)

Air dry soil was sieved to <2mm (40 g) and uniformly placed into 31mm diameter columns fitted with fritted glass base to permit free drainage. Filter paper was placed on the soil to minimize disruption before solutions at EC=1 or EC=2 dS/m and SAR 2, 4, 6, 8, or 10 were applied slowly to the soils with ponding and infiltration measured. Uniform applications were repeated several times with measurement of infiltration rates. Rain water was then applied with additional infiltration measurements.

Statistical analysis of infiltration data

Within each year, the infiltration data consisted of repeated measurements collected from a completely randomized, two-way factorial design. The factors in this study include EC (2 levels: 1.0 and 2.0 dS/m) and SAR (5 levels: 2, 4, 6, 8 and 10). The response variable considered in this analysis is the natural log (ln) transformed infiltration time of the applied rain water. Note that 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 assess the effects of EC and SAR on the ln infiltration time data. Data from each year (uncropped and cropped) represent distinct experiments, and thus were analyzed separately. 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).

UNSATCHEM simulations

We utilized the UNSATCHEM model (Suarez and Simunek, 1997) to simulate the effect of rain on soil salinity and SAR after the soil had been irrigated with SAR=10 and EC=1 dS/m water. The simulations utilized the specific cation exchange capacity and irrigation waters used in the field experiments.

Results

Water chemistry

Major ion analyses of the Tongue and Powder Rivers, sampled in May 2003 are presented in Table 1. On the sampling dates the EC values were 0.77 dS/m for the Tongue River north of Miles City and 2.07 dS/m for the Powder River east of Miles City, and the SAR values were 1.39 and 4.97 respectively. The analysis of the experimental irrigation waters used in 2003 and 2004, given in Table 1 indicate that all waters are close to the target EC and SAR values. The EC of the simulated rain water was in the range of 0.015 dS/m. Rain water is variable in composition with time and space, this simulated water is likely towards the lower range for western US continental rain.

Soil properties

The soil texture of the soils and calculated bulk density of the packed containers is given in Table 2. As expected the two soils provide a contrast in soil texture. The Glendive soil contains high amounts of sand and more silt than clay. The Kobase soil is low in sand content, containing only 1.3% sand and predominantly clay (54%). The texture classification of our soil samples corresponded to the classification in the soil names. The bulk density values in Table 2 were based on settling of the overall column and may be slightly overestimated due to the assumption that the sand layer did not settle. 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.

Infiltration studies

The first year experiment was conducted from Aug 19, 2003 until Jan 27, 2004, and the second year experiment was conducted from April 14, 2004 until March 18, 2005. The individual dates of the water applications and quantities for both years are given in Table 3. The cumulative application of water and potential evapotranspiration (ET_0) with time is given in Figure 3 for year one and in Figure 4 for year two. For the bare soil (year one) experiment the water applied was 71 cm and the ET_0 was 44 cm. Actual ET was not determined but is significantly less than ET_0 as the soil was bare.

Table 1. Montana river water and Riverside experiment irrigation water composition.

		EC	Na	K	Ca	Mg	sum +	SAR	SO_4	Cl
		dS m^{-1}			mmol$_c$ L^{-1}					
Montana Rivers:										
Tongue		0.77	2.52	0.14	3.05	3.49	9.2	1.39	4.22	0.11
Powder		2.07	12.53	0.23	7.28	5.41	25.45	4.97	17.37	2.13
2003 Season water										
Control		0.88	1.73	0.06	5.15	2.79	9.73	0.87	5.37	0.71
EC	SAR									
1.00	2.00	1.03	3.81	0.00	3.76	3.60	11.17	1.98	7.56	1.73
1.00	4.00	1.08	6.02	0.00	2.88	2.12	11.02	3.80	7.65	1.96
1.00	6.00	1.06	7.26	0.00	1.66	1.54	10.46	5.74	7.14	1.61
1.00	8.00	1.08	8.04	0.00	1.05	1.12	10.22	7.72	7.10	1.76
1.00	10.00	1.09	9.01	0.00	0.90	0.73	10.63	9.98	6.39	2.58
2.00	2.00	1.99	6.22	0.05	5.45	12.96	24.69	2.05	16.91	3.53
2.00	4.00	2.06	10.69	0.04	5.52	8.80	25.05	4.00	17.43	3.40
2.00	6.00	2.06	13.32	0.04	4.71	4.80	22.87	6.11	16.71	2.45
2.00	8.00	2.09	15.57	0.04	3.31	3.93	22.85	8.18	17.05	2.34
2.00	10.00	2.16	16.42	0.03	3.18	2.42	22.04	9.82	12.64	6.59
2004 Season water										
Control		0.54	1.80	0.10	3.06	0.77	5.73	1.30	1.31	0.88
EC	SAR									
1.00	2.00	0.98	3.73	0.01	3.27	3.60	10.61	2.01	7.37	2.24
1.00	4.00	1.07	6.19	0.04	2.80	2.09	11.11	3.96	7.51	2.21
1.00	6.00	1.04	7.33	0.03	1.51	1.52	10.39	5.96	7.09	2.23
1.00	8.00	1.04	7.99	0.04	0.93	1.08	10.04	7.97	6.83	2.29
1.00	10.00	1.06	8.70	0.05	0.80	0.73	10.27	9.96	7.13	2.14
2.00	2.00	2.00	6.03	0.04	5.13	12.95	24.14	2.00	16.30	6.36
2.00	4.00	2.12	10.74	0.05	5.36	8.57	24.72	4.07	16.11	5.19
2.00	6.00	2.05	13.04	0.06	4.23	5.04	22.37	6.06	16.11	5.61
2.00	8.00	2.14	15.21	0.06	3.14	3.97	22.38	8.07	16.71	5.65
2.00	10.00	2.27	17.19	0.06	3.29	2.45	22.99	10.15	16.82	6.27

Table 2. Physical properties of packed soils.

	Glendive "Loam"	Kobase "Clay"
(initial dry packing)		
Bulk Density, g cm^3	1.35	1.19
Depth, cm	17	17
Weight, Kg	8.72	7.69
(wetted and settled)		
Depth, cm	16	14
Bulk Density, g cm^3	1.46	1.50
(texture, percent)		
2 mm to 5 mm	0.88	0.00
50 um to 2 mm sand	46.37	1.34
2 um to 50 um silt	28.54	44.73
< 2 um clay	24.21	53.92
Cation exchange capacity meq 100gm	5.8	20.8

Containers were pre-filled with 7 cm of fine sand.

During the second experiment the containers were cropped to alfalfa and the total applied water was on the order of 185 cm and the ET_0 was 84 cm. Higher water applications relative to ET_0 were necessitated by the high ET of the alfalfa in the containers (estimated crop coefficients significantly greater than 1.0 thus crop ET was in excess of ET_0. Water applications during the second year 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 during the second year was below 0.5 and within the range of field conditions for irrigated agriculture. Due to the hotter, drier climate in Riverside CA as compared to eastern Montana this experiment simulates more than one year of water applications in Montana.

Table 3. Water application events.

2003 Season - Bare Soil
Date
8/19 - Soil placed in containers with 5 cm tap water then 2 cm of rain applied
8/22 - Irrigation 5 cm
8/27 - Rain 5.1 cm
9/4 - Irrigation 5 cm
9/12 - Rain 4.6 cm
9/17 - Irrigation 5 cm
9/23 - Rain 5.2 cm
9/30 - Irrigation 5 cm
10/8 - Rain 4.8 cm
10/30 - Irrigation 5 cm
11/13 - Rain 5.9 cm
12/9 - Irrigation 6.3 cm
12/22 - Rain 3.6 cm
12/26 - natural rain 1.4 cm
1/2 - Irrigation 5 cm
1/13 - Rain 3.5 cm

Soil recycled for 2004 work

2004 Season - Cropped Soil
Date
4/14 - Soil placed in containers then tap water applied
4/20 - Plant 88 seeds per container, continue tap and nutrient applications
6/7 - Rain 5 cm
6/10 - Irrigation 5 cm
6/15 - Rain 5 cm
6/18 - Irrigation 5 cm
6/25 - Rain 5 cm
6/30 - Irrigation 5 cm
7/4 - Irrigation 5 cm
7/9 - Rain 5 cm
7/14 - Irrigation 5 cm
7/19 - Rain 5 cm
7/23 - Irrigation 5 cm
7/27 - Rain 5 cm
8/2 - Irrigation 5 cm
8/6 - Rain 5 cm
8/10 - Irrigation 5 cm
8/13 - Rain 5 cm
8/18 - Irrigation 5 cm
8/23 - Rain 5 cm
8/27 - Irrigation 5 cm
8/31 - Rain 5 cm
9/3 - Irrigation 5 cm
9/7 - Rain 5 cm
9/9 - Irrigation 5 cm
9/15 - Rain 5 cm
9/21 - Irrigation 5 cm
9/24 - Rain 5 cm
9/29 - Irrigation 5 cm
10/5 - Rain 5 cm
10/12 - Irrigation 5 cm
natural rain 15.6 cm
11/3 - Irrigation 2.5 cm
11/15 - Rain 5.5 cm
11/19 - Irrigation 5 cm
Rains of 1 cm each
12/22 - Irrigation 2.5 cm
12/23 - Rain 1 cm
natural rain 12/30 to 1/10 24.4 cm
1/24 - 1/27 Rain 5.2 cm
rains to wet soil 2.6 cm
natural rain 2/11 to 2/22 19.3 cm

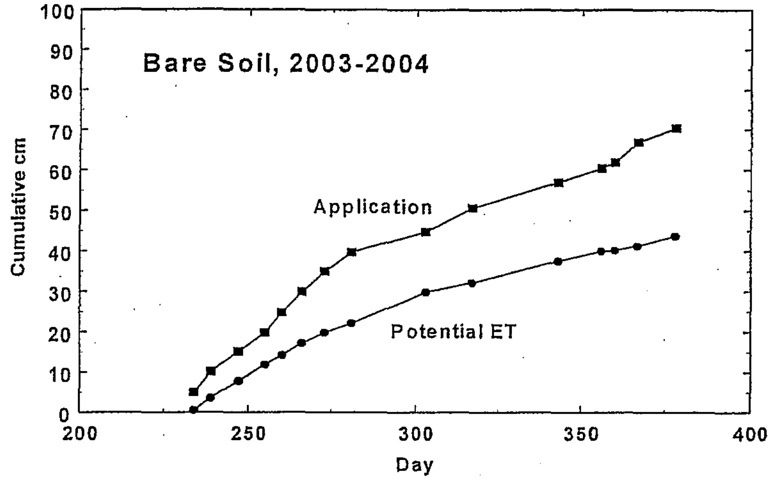

Figure 3. Bare soil experiment cumulative applied water (rain+ irrigation) and potential evapotranspiration (ET_0) at the Riverside Salinity Laboratory during 2003-2004.

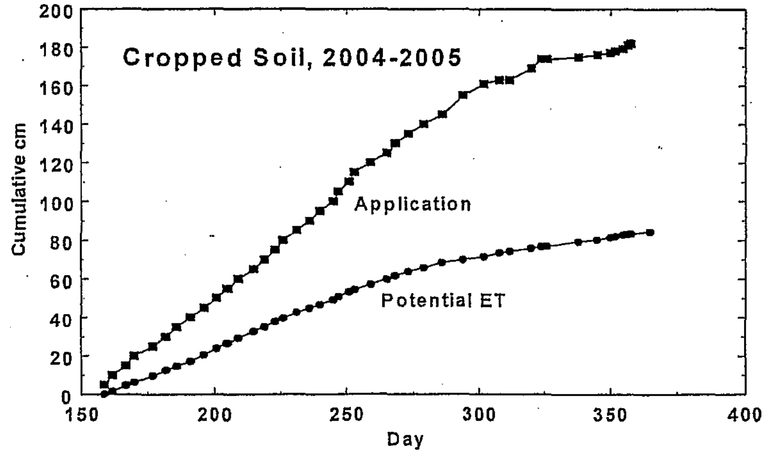

Figure 4. Cropped soil experiment, cumulative applied water (rain+ irrigation) and potential evapotranspiration (ET_0) at the Riverside Salinity Laboratory during 2004-2005.

During the bare soil experiment, infiltration was not measured during the first irrigation as the soil was dry and settling. As shown in Figure 5, the subsequent rain infiltration rates already showed trends with SAR after that one irrigation event. These data were collected after application of only 0.5 cm of rain, thus the soil was relatively dry and the clay soil infiltration rate exceeded that of the loam soil. This single event data is likely comparable to conditions in reported results in the literature for effects with rain infiltration.

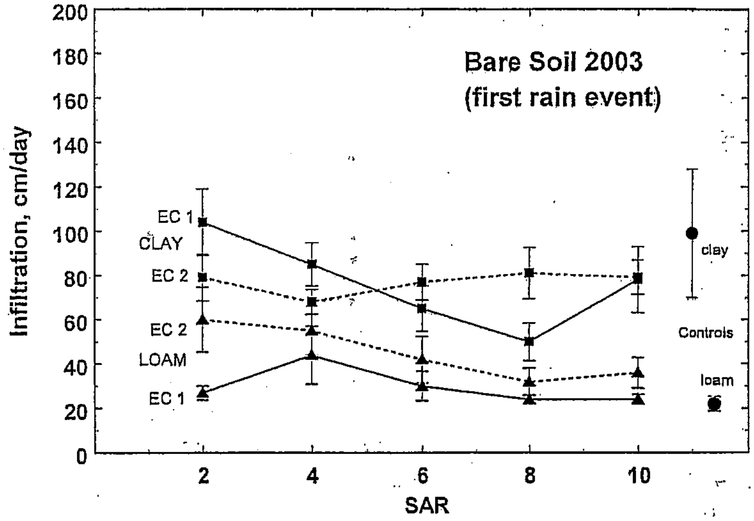

Figure 5. Infiltration rate after application of 1.0 cm of water during the first rain event. Each solid symbol represents the mean of three replicates, triangles represent loam soil and squares represent clay soil.

During the second year we applied rain and measured the infiltration rate before application of treatments. In addition to obtaining initial baseline data this also allowed us to establish the alfalfa crop uniformly in each treatment for full canopy cover. As shown in Figure 6 there was no trend with SAR nor salinity. Since 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.

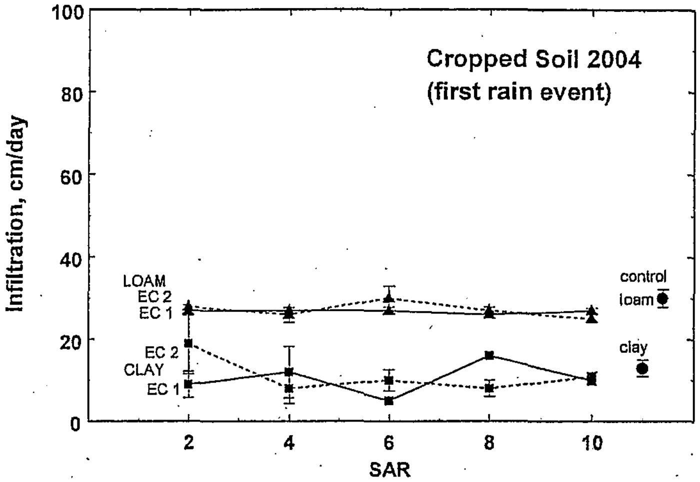

Figure 6. Rain infiltration rate before application of treatments for cropped soil experiment (2004-2005). Infiltration rate was measured after application of 2.25 cm of rain during the 5.0 cm rain event. Triangles represent loam soil and squares represent clay soil.

The data shown in Figure 7 represent the loam soil infiltration at the end of the bare soil experiment (last applied rain) As can be seen, there was a decrease in infiltration as the SAR increased from 2 to 4, for both EC= 1 dS/m and EC= 2 dS/m treatments, and further decrease with higher SAR treatments. There appeared to be little difference in response to SAR for the two different salinity waters, suggesting that in this salinity range, EC is not important. The clay soil had a much slower infiltration rate as shown in Figure 8 with an expanded scale. From Figure 8 we conclude that at SAR =2 there was no decrease in infiltration relative to the control but that at SAR 4 there was a large significant decrease in infiltration rate (about 30% decrease). The infiltration rate continued to decrease with increasing SAR. There were some differences between EC=1 and EC=2 however they appear minor and may be within statistical uncertainty in most instances.

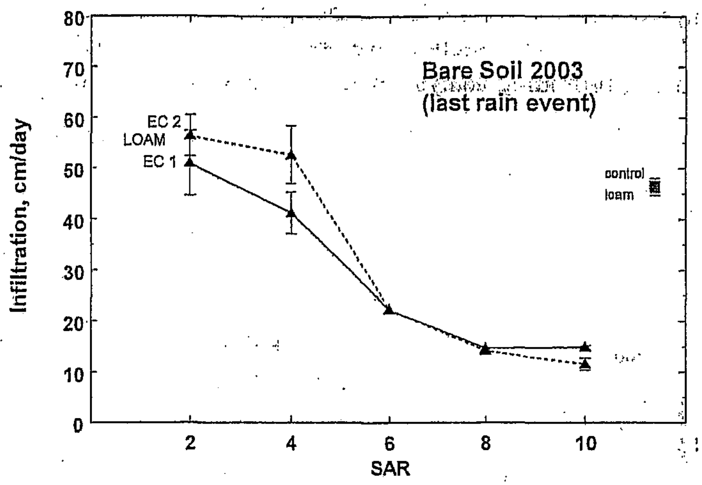

Figure 7. Relationship among infiltration rate, SAR and EC for bare loam soil experiment during the last rain event.

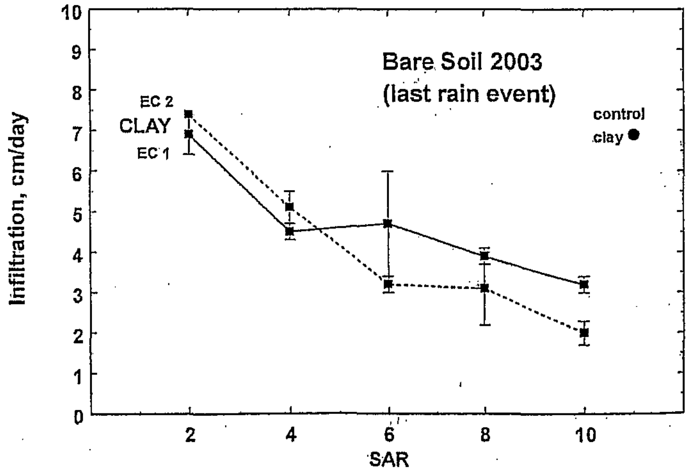

Figure 8. Relationship among infiltration rate, SAR and EC for bare soil experiment, clay soil, during the last rain event.

During the cropped soil experiment, the variability was greater than during the bare soil experiment. This was likely due to development of root channels and more severe cracking. As shown in Figure 9, the variability is sufficiently large for a single event that for this one event, we can only conclude that the rain infiltration trends down with increasing SAR. In the following sections we present statistical analysis of the data within the experiment, providing analysis with time as well as for the different treatments.

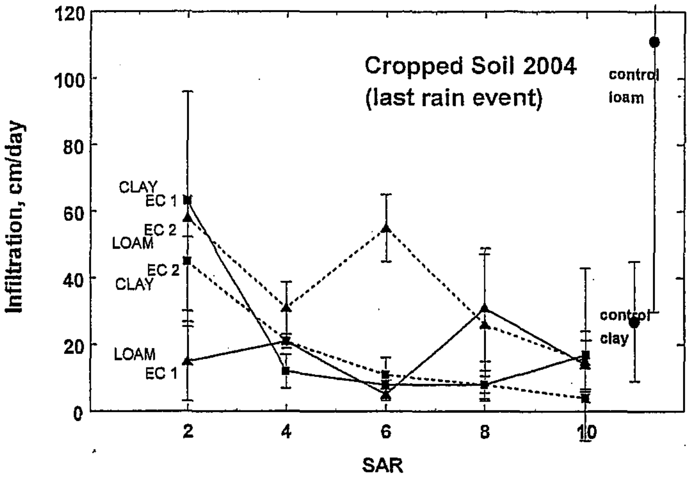

Figure 9. Relationship among infiltration rate, SAR and EC for cropped soil experiment, loam and clay soil, during the last rain event of the experiment. Triangles represent loam soil and squares represent clay soil. The solid lines represent EC=1 treatments and the dashed lines EC=2 treatments.

Statistical analysis of infiltration data

Determination of infiltration rates were complicated by the differences in initial water contents at different times and by the time dependence of the infiltration events. During initial events, cracks in the clay soil resulted in very high infiltration rates for the first cm of water, greatly in excess of the infiltration rates for the loam soil. In some instances the cracks extended to the bottom of the container and the initial water could flow directly into the extraction system at the bottom of the containers. Once the cracks sealed, the clay infiltration rate decreased dramatically.

As shown in Table 4, rain infiltration data from 6 sampling periods were analyzed in each of the experiments. Complete infiltration measurements in 2003, for the bare soil experiment, were generally collected between the 4th and 10th pass of the rain simulator, corresponding to infiltration after application of 1 to 2.5 cm of water. In this analysis we have attempted to use readings from different dates collected as close to the 6th pass as possible in order to minimize the effects of differential water application amounts on the infiltration time readings. In all instances comparison between treatments was made for the same irrigation or rain event and for the same interval or pass.

In the 2004 cropped soil experiment, infiltration measurements were typically collected during the 12th, 16th, and 20th pass. (Data from later passes were collected in 2004 due to the rapid infiltration of water during early passes, caused by the significant cracking of the soil surface due to soil drying and the presence of a crop.) In this second experiment we have attempted (whenever possible) to only analyze data from the 12th pass (again to minimize the effects of differential water application amounts). Additionally, each sampling period in the cropped soil 2004 experiment represents averaged infiltration data from two adjacent sampling dates. This averaging was done in order to reduce the noise in the infiltration data, thus mitigating the influence of marginal outliers present in this data. No outliers were removed.

Table 4. Monitoring times for rain event infiltration measurements

Season / Experiment	Date	Sampling Period	Irrigation Pass
2003 Experiment 1 (no crop)	08/27/03	1	7
	09/23/03	2	5
	10/08/03	3	4
	11/13/03	4	8
	12/22/03	5	4
	01/14/04	6	7
2004 Experiment 2 (cropped)	06/15/04 & 06/25/04	1	12 / 12
	07/09/04 & 07/27/04	2	12 / 12
	08/06/04 & 08/13/04	3	12 / 12
	08/23/04 & 08/31/04	4	12 / 15
	09/07/04 & 09/15/04	5	16 / 18
	09/24/04 & 10/05/04	6	12 / 12

In the following statistical analyses, results for each experiment are presented separately. The results for the 2003 bare soil experiment are presented first, followed by the 2004 cropped soil experimental results. All statistical analyses presented here were performed using SAS version 8 (proc GLM and MIXED), all results are presented in natural log (ln) transformed infiltration time units (i.e., ln minutes), and no data points were removed from any of the sampling periods. Note that a full listing of the experimental data analyzed here is given in Appendix A.

Bare soil (2003) statistical analysis

Before adopting the multivariate repeated measurement analysis approach, the covariance structures of the ANOVA model residual errors (across sampling periods) were analyzed. This analysis was performed in order to determine if a mixed linear modeling approach could be adapted to analyze the bare soil experimental data (Davis, 2002). Table 5 presents the covariance structure test results, determined using maximum likelihood estimation techniques. Six mixed linear model covariance structures were estimated in all: (1) *Uns(MV)*: unstructured multivariate, (2) *diagonal*, (3) *toepliz*, (4) *AR-1*: auto-regressive order 1, (5) *ComSym*: compound symmetry, and (6) *Indp*: independent (e.g., no temporal correlation, common variance estimate across time).

Table 5 presents the relevant results for determining which covariance structure best fit the residual errors; these results include the minus 2 ln likelihood scores (-2LL), the difference between the -2LL scores (using the unstructured score as the alternative hypothesis in all cases), the number of estimated covariance parameters in each assumed structure (df), and the asymptotic Chi-square p-value for testing if a simpler covariance structure might be used in place of the unstructured multivariate assumption. These results indicate that only the unstructured multivariate covariance structure adequately describes the temporal residual error correlation patterns associated with the clay soil, and that either the unstructured multivariate or diagonal covariance structure can be used to describe the temporal residual error patterns associated with the loam soil. Based on these results, we adopted a multivariate modeling approach on this repeated measurement data, as opposed to a mixed linear modeling approach.

Table 5. Covariance structure tests: bare soil 2003 data

Soil	Stat	Uns(MV)	Diagonal	Toepliz	AR-1	ComSym	Indp
	-2LL	-33.98	11.02	40.57	61.26	60.65	63.34
Clay	D		45.00	74.55	95.24	94.63	97.32
	df	21	6	6	2	2	1
	$P(D < \chi^2)$		0.0001	0.0001	0.0001	0.0001	0.0001
	-2LL	-40.18	-18.98	25.46	28.75	29.52	29.67
Loam	D		21.20	65.64	68.93	69.70	69.85
	df	21	6	6	2	2	1
	$P(D < \chi^2)$		0.1306	0.0001	0.0001	0.0001	0.0001

Table 6 presents the primary statistical results associated with the repeated measurement analysis of the bare soil experimental 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 & Wichern, 1988).

Table 6 presents the primary statistical results associated with the repeated measurement analysis of the bare soil experimental 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 & Wichern, 1988).

Table 6. Repeated measures analysis: primary statistical tests (bare soil data)

Time averaged model summary statistics	**Clay**	**Loam**
R-square	0.6481	0.9439
Root MSE	0.1722	0.1254
Overall model F-test significance level (ndf=9, ddf=20)	0.0042	0.0001
	F-test significance levels	
Time averaged experimental effects	**Clay**	**Loam**
EC (ndf=1, ddf=20)	0.7927	0.0001
SAR (ndf=4, ddf=20)	0.0002	0.0001
EC x SAR (ndf=4, ddf=20)	0.9828	0.2361
	Wilks Lambda significance levels	
Time dependent multivariate effects	**Clay**	**Loam**
Time (ndf=5, ddf=16, exact)	0.0001	0.0001
Time x EC (ndf=5, ddf=16, exact)	0.1856	0.0150
Time x SAR (ndf=20, ddf=54, apprx)	0.0085	0.0165
Time x EC x SAR (ndf=20, ddf=54, apprx)	0.1172	0.1428

The univariate ANOVA models associated with both the clay and loam soil data exhibited statistically significant overall model F-tests below the 0.01 level (p=0.00442: clay; p=0.0001: loam). For the clay soil ANOVA model, only the SAR effect exhibited statistical significance (p=0.0002). For the loam soil ANOVA model, both the EC and SAR main effects were statistically significant (p=0.0001: clay; p=0.0001: loam). Neither model exhibited any statistically significant univariate interaction effects.

The Wilks lambda significance levels quantify the degree of time dependent multivariate effects as determined by the MANOVA analyses, respectively. In the MANOVA model associated with the clay soil data, the Time effect was highly significant (p=0.0001) and the Time x EC effect was significant at the 0.01 level (p=0.0085). For the loam soil MANOVA model, the Time effect was again highly significant (p=0.0001) and both the Time x EC and Time x SAR effects were significant at the 0.05 level (p=0.0150 and p=0.0165, respectively). Neither MANOVA model exhibited any statistically significant Time x EC x SAR effects.

These results are interpreted as follows. The SAR levels significantly influence the time average ln infiltration data associated with the clay soil and these SAR effects appear to change over time. Likewise, both the EC and SAR levels significantly influence the time average ln infiltration data associated with the loam soil and these EC and SAR effects appear to also change over time. Additionally, the mean ln infiltration rates significantly change across the different sampling periods for both soil types, but neither soil type exhibits any time averaged (univariate) or multivariate EC x SAR interaction effects. In other words, the EC and/or SAR effects (when present) appear to affect the ln infiltration rates in an independent manner.

Table 7 presents some additional results associated with the time averaged ANOVA models. These results include the marginal EC and SAR mean estimates and 95% confidence limits for the clay and loam soil types, as well as the t-test significance levels associated with the SAR contrasts (using SAR=2 and a control). The marginal EC ln infiltration time estimates for the clay soil measurements are virtually identical for each EC level. (3.93 versus 3.91). However, the marginal EC=2 ln infiltration time estimate of 3.04 associated with the loam soil data is significantly lower than the EC= 1 ln estimate of 3.26. For both soil-types the marginal SAR time estimates tend to increase with increasing SAR levels. The ln infiltration time levels associated with the clay soil tend to increase in a fairly linear manner, while the levels associated with the loam soil appear to increase in a non-linear manner. Finally, the t-test significance levels associated with clay soil indicate that the ln infiltration time estimate at the SAR=4 level is significantly different from the SAR=2 level (p=0.0061). In contrast, the SAR=4 versus 2 contrast is not statistically significant (p=0.6917), but the SAR= 6 versus SAR=2 contrast is highly significant (p=0.0001).

Table 7. Marginal mean estimates, with 95% Confidence Intervals (CI's) and SAR test results (2 vs. 4, 6, 8, 10); bare soil data, averaged across sampling periods

	Clay			**Loam**		
Effect	**Estimate**	**95% CI**	**SAR Contrasts**	**Estimate**	**95% CI**	**SAR Contrasts**
EC (1)	3.93	(3.83, 4.02)		3.26	(3.19, 3.32)	
EC (2)	3.91	(3.82, 4.00)		3.04	(2.97, 3.11)	
SAR(2)	3.61	(3.47, 3.76)		2.68	(2.57, 2.78)	
SAR(4)	3.92	(3.77, 4.07)	0.0061	2.70	(2.60, 2.81)	0.6917
SAR(6)	3.84	(3.69, 3.99)	0.0338	3.20	(3.09, 3.30)	0.0001
SAR(8)	4.05	(3.90, 4.20)	0.0003	3.57	(3.46, 3.67)	0.0001
SAR(10)	4.17	(4.02, 4.32)	0.0001	3.61	(3.50, 3.71)	0.0001

Table 8 presents the corresponding significance levels associated with the SAR orthogonal contrasts of the marginal mean ln infiltration times in both time averaged

ANOVA models. These orthogonal contrast significance levels can be used to determine the appropriate polynomial regression model structure for the SAR effect (given that the SAR levels are viewed as continuous, rather than discrete). The results shown in Table 8 suggest that the trend in the marginal mean ln infiltration times associated with the clay soil is indeed linear, while the marginal mean times associated with the loam soil can be best described using a cubic polynomial regression model, respectively.

Table 8. SAR orthogonal contrasts; bare soil data, averaged across sampling periods

	F-test significance levels	
Orthogonal contrast	**Clay**	**Loam**
Linear	0.0001	0.0001
Quadratic	0.7615	0.6178
Cubic	0.2008	0.0001
4th Order	0.0895	0.3966

Based on these results (presented in Tables 5 through 8), the regression models shown in Table 9 below were fit to the time averaged clay and loam ln infiltration measurements, respectively. A simple linear regression model was used to describe the clay soil ln infiltration data (i.e., ln infiltration is modeled as a linear function of SAR), while a cubic polynomial regression model with an added linear ECe effect was used to describe the ln infiltration data associated with the loam soil. The R-square values for these models were 0.552 and 0.925, and both models were statistically significant at the 0.0001 level. Predicted versus observed ln infiltration time plots for both models are shown in Figures 7, 8, and 9, respectively. Note that the plots for the loam soil are shown for specific EC levels.

Table 9. Final time averaged ln infiltration time regression models for bare soil data. Note: y = ln(infiltration time) and E{y} = expected value of y

Soil-type	**Fitted regression model (with standard errors)**	**R-square / Root MSE**
Clay	$E\{y\} = \underset{(0.07)}{3.545} + \underset{(0.011)}{0.062}[SAR]$	0.5516 / 0.1642
Loam	$E\{y\} = \underset{(0.27)}{3.716} - \underset{(0.047)}{0.216}[EC] - \underset{(0.17)}{0.622}[SAR] + \underset{(0.032)}{0.147}[SAR^2] - \underset{(0.002)}{0.008}[SAR^3]$	0.9248 / 0.1299

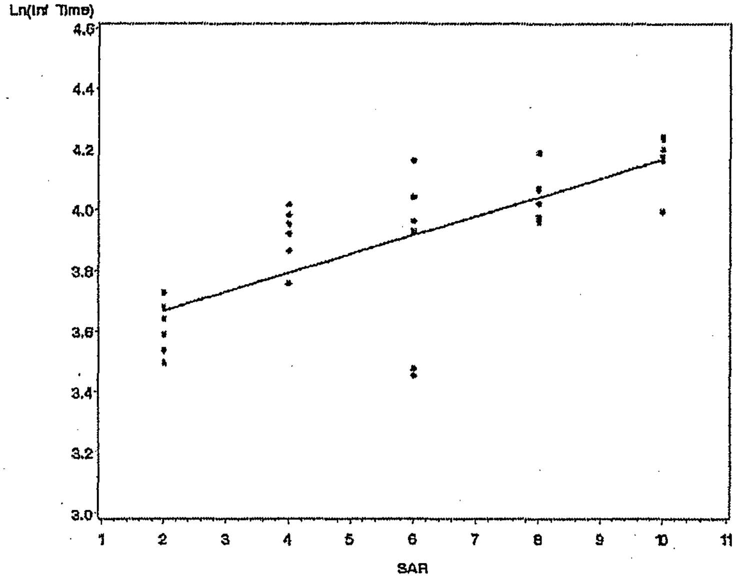

Figure 10. Relationship between SAR and ln infiltration time for bare clay soil (2003); data averaged across sampling periods.

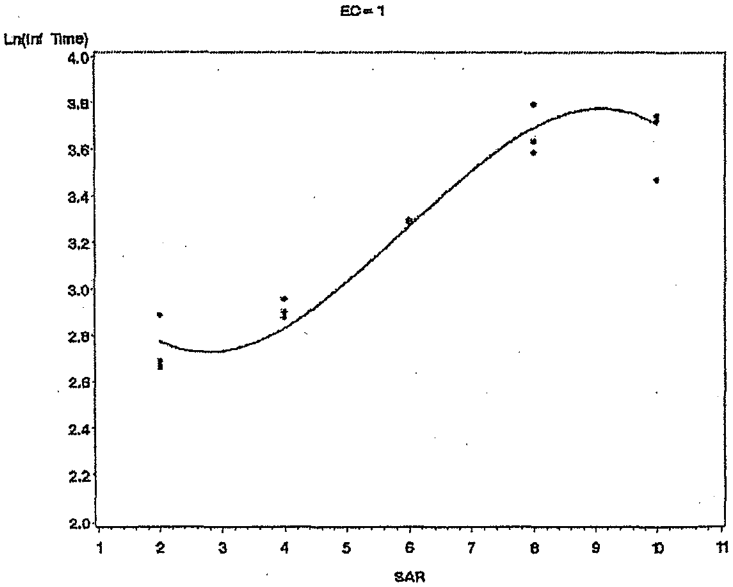

Figure 11. Relationship between SAR and ln infiltration time for bare loam soil, EC=1; 2003 data time averaged across sampling periods.

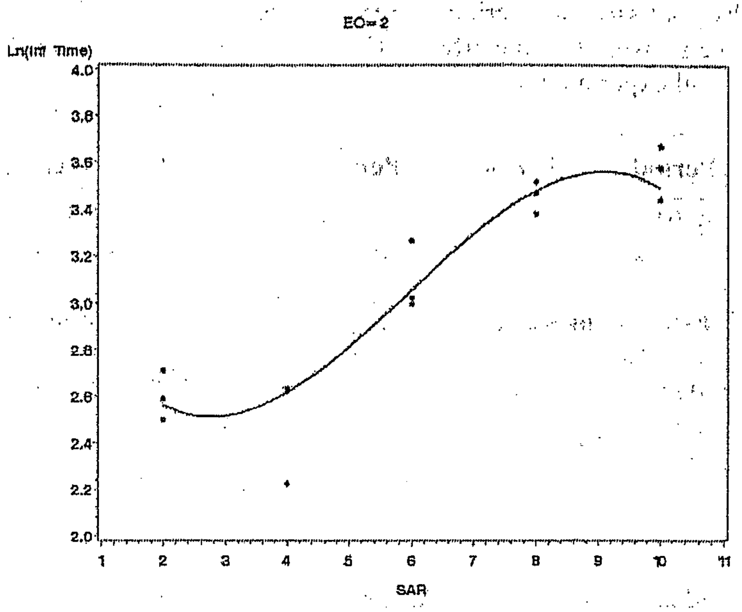

Figure 12. Relationship between SAR and ln infiltration time for bare loam soil, EC=2; data time averaged across sampling periods.

The time dependent (multivariate) test results presented previously in Table 6 suggest that the marginal EC and/or SAR effects may have changed somewhat during the course of this experiment. In order to examine these effects more closely, the statistical results from the individual ANOVA models are presented in Tables 10 and 11. Additionally, time interaction plots for both the marginal SAR and EC levels by soil-type are presented in Figures 13 through 16, respectively.

The individual ANOVA model test results for the clay soil (Table 9) and loam soil (Table 10) exhibit some between- period variability in results. However, the general trends present in both tables are consistent with the previously discussed time averaged models. For example, in both 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 (Figures 13, 14, 15, and 16) show the changes in the estimated ln infiltration time (over the 6 sampling periods) for the various SAR and EC levels. Figures 13 and 14 show how the average clay and loam ln infiltration times changed across the five SAR levels, while Figures 15 and 16 show how these same infiltration times changed across the two EC (EC=1 dS/m and EC=2 dS/m) levels, respectively. Time dependent interaction in either main effect is indicated by overlapping (non-parallel) lines, provided the various lines are separated far enough apart to be considered statistically distinct. The SAR related patterns shown in Figures 13 and 14 indicate some moderate amount of interaction, but do not suggest any clear, simple time dependent pattern with respect to either the clay or loam soil.

Table 10. Individual sampling period ANOVA model summary statistics and F-test significance levels (overall model effect, EC, SAR, and EC x SAR interaction); clay soil data from bare soil experiment

Statistic	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6
R-square	0.6147	0.5760	0.2855	0.5353	0.1805	0.7984
Root MSE	0.2089	0.1813	0.4920	0.4692	0.3928	0.2371
	F-test significance levels associated with specified tests:					
Overall	0.0088	0.0190	0.5523	0.0384	0.8646	0.0001
EC	0.0077	0.7159	n/a	0.5738	n/a	0.0465
SAR	0.0058	0.0041	n/a	0.0193	n/a	0.0001
EC x SAR	0.5582	0.2778	n/a	0.1478	n/a	0.1448

Table 11. Individual sampling period ANOVA model summary statistics and F-test significance levels (overall model effect, EC, SAR, and EC x SAR interaction); loam soil data from bare soil experiment

Statistic	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6
R-square	0.4736	0.8858	0.7221	0.7818	0.6459	0.9702
Root MSE	0.4851	0.2537	0.3476	0.2852	0.3222	0.1256
	F-test significance levels associated with specified tests:					
Overall	0.0946	0.0001	0.0005	0.0001	0.0044	0.0001
EC	n/a	0.0001	0.1975	0.2477	0.0491	0.8377
SAR	n/a	0.0001	0.0001	0.0001	0.0010	0.0001
EC x SAR	n/a	0.0204	0.2451	0.3022	0.5036	0.0308

The two EC lines shown in Figure 15 are not statistically different from one another. The two EC lines shown in Figure 16 suggest that the EC induced reduction in the average ln infiltration time associated with the loam soil might have dissipated over the course of the experiment.

Although Table 6 indicates that there were statistically significant time dependent multivariate effects, only the loam soil Time x EC effect (shown in Figure 16) exhibits a simple interpretation. Additionally, none of these interaction effects appear to be particularly pronounced in an absolute sense. Thus, we believe that the time averaged ANOVA and regression models can be used to adequately describe, quantify, and summarize the bare soil (2003) experimental data.

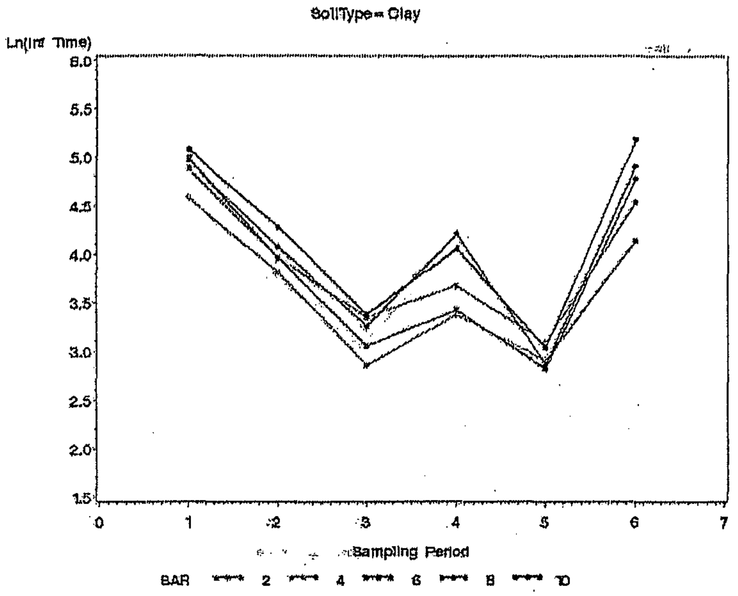

Figure 13. Average ln infiltration time interaction plot for clay soil data (plotted by sampling period); colored lines represent specific SAR levels.

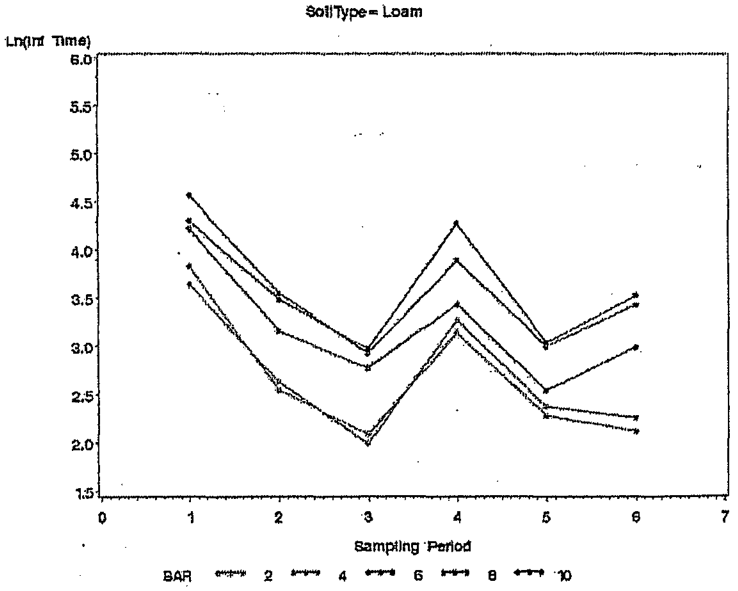

Figure 14. Average ln infiltration time interaction plot for loam soil data (plotted by sampling period); colored lines represent specific SAR levels. Data is from the bare soil experiment.

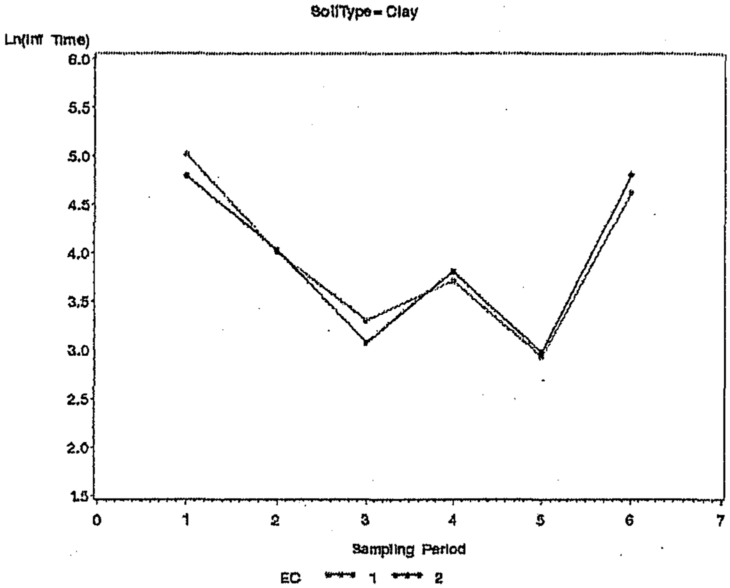

Figure 15. Average ln infiltration time interaction plot for clay soil data (plotted by sampling period); colored lines represent specific EC levels. Data is from the bare soil experiment.

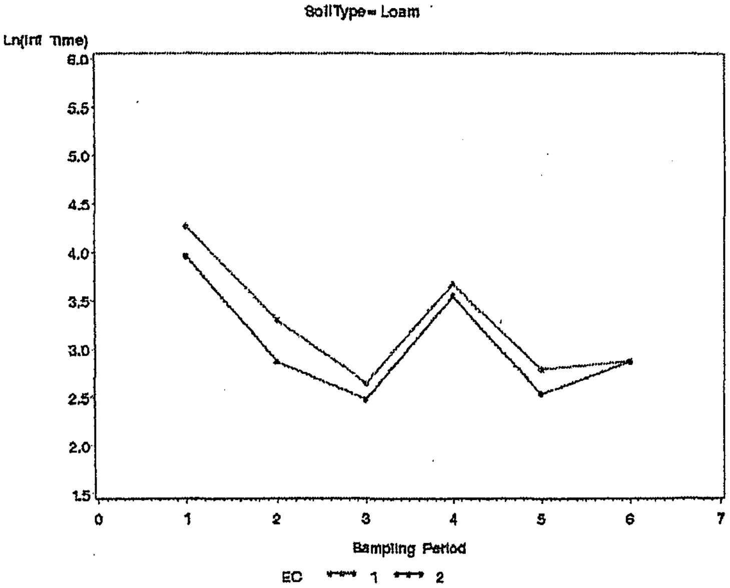

Figure 16. Average ln infiltration time interaction plot for loam soil data (plotted by sampling period); colored lines represent specific EC levels. Data is from the bare soil experiment.

Cropped soil (2004) statistical analysis

As with the bare soil experimental data, the covariance structures of the cropped soil ANOVA model residual errors (across sampling periods) were first analyzed to determine an appropriate modeling approach. Table 12 presents the results from the covariance structure test, again determined using maximum likelihood estimation techniques. The same six mixed linear model covariance structures were estimated; note that essentially the same results were obtained. In other words, the cropped soil results indicate that only the unstructured multivariate covariance structure adequately describes the temporal residual error correlation patterns associated with the clay soil and that either the unstructured multivariate or diagonal covariance structure can be used to describe the temporal residual error patterns associated with the loam soil. Based on these results, we once again chose to adopt a multivariate modeling approach on this repeated measurement data.

Table 12. Covariance structure tests: Cropped soil experimental data

Soil	Stat	Uns(MV)	Diagonal	Toepliz	AR-1	ComSym	Indp
Clay	-2LL	97.35	153.47	192.33	205.29	212.38	223.29
	D		56.12	94.98	107.94	115.03	125.94
	df	21	6	6	2	2	1
	$P(D < \chi^2)$		0.0001	0.0001	0.0001	0.0001	0.0001
Loam	-2LL	-197.51	-181.70	-137.31	-133.36	-134.89	-131.42
	D		15.81	60.20	64.15	62.62	66.09
	df	21	6	6	2	2	1
	$P(D < \chi^2)$		0.3948	0.0001	0.0001	0.0001	0.0001

Table 13 presents the primary statistical results associated with the repeated measurement analysis of the cropped soil data. These results again include the time averaged model summary statistics, 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.

The univariate ANOVA models associated with both the clay and loam soil data exhibited statistically significant overall model F-tests below the 0.05 level (p=0.0154: clay; p=0.0033: loam). In both time averaged models, only the SAR effect exhibited statistical significance (p=0.0013: clay; p=0.0002: loam. Neither model exhibited any statistically significant univariate interaction effects.

The Wilks lambda significance levels once again quantify the degree of time dependent multivariate effects as determined by the MANOVA analyses, respectively. In the MANOVA model associated with the clay soil data, the Time effect was highly significant (p=0.0001) and the Time x SAR effect was significant at the 0.01 level (p=0.0087). For the loam soil MANOVA model, the Time effect was again highly significant (p=0.0001) and the Time x EC effect was significant at the 0.05 level (p=0.0191). Neither MANOVA model exhibited any statistically significant Time x EC x SAR effects.

These results are similar to the results obtained in the bare soil experiment. The SAR levels significantly influence the time average ln infiltration data associated with the clay soil and these SAR effects appear to change over time. Likewise, the SAR levels significantly influence the time average ln infiltration data associated with the loam soil. However, for the loam soil, these SAR effects do not appear to change over time (although there is some evidence that the EC effects may be time dependent). Additionally, the mean ln infiltration rates significantly change across the different sampling periods for both soil types, but neither soil type exhibits any time averaged (univariate) or multivariate EC x SAR interaction effects. In other words, the EC and/or SAR effects (when present) again appear to affect the ln infiltration rates in an independent manner.

Table 13. Repeated measures analysis: primary statistical tests (cropped soil data)

Time averaged model summary statistics	**Clay**	**Loam**
R-square	0.5871	0.6572
Root MSE	0.3116	0.1024
Overall model F-test significance level (ndf=9, ddf=20)	0.0154	0.0033
	F-test significance levels	
Time averaged experimental effects	**Clay**	**Loam**
EC (ndf=1, ddf=20)	0.5870	0.4980
SAR (ndf=4, ddf=20)	0.0013	0.0002
EC x SAR (ndf=4, ddf=20)	0.8925	0.8693
	Wilks Lambda significance levels	
Time dependent multivariate effects	**Clay**	**Loam**
Time (ndf=5, ddf=16, exact)	0.0001	0.0001
Time x EC (ndf=5, ddf=16, exact)	0.5058	0.0191
Time x SAR (ndf=20, ddf=54, apprx)	0.0087	0.5978
Time x EC x SAR (ndf=20, ddf=54, apprx)	0.1256	0.8234

Table 14 presents the marginal EC and SAR mean estimates and 95% confidence limits for both the clay and loam soil, as well as the t-test significance levels associated with the SAR contrasts (again using SAR = 2 as a control). The marginal EC ln infiltration time estimates for both soil types appear to be quite similar. Additionally, the ln infiltration time levels associated with both soil types tend to increase in a fairly linear manner. Finally, the t-test significance levels associated with both soils indicate that ln infiltration time estimates at the SAR= 4 level are not significantly different from the SAR= 2 level, but that the SAR= 6 versus 2 contrast are significant (p=0.0226: clay; p=0.0156: loam).

Table 14. Marginal mean estimates, with 95% CI's and SAR test results (2 vs 4, 6, 8, 10); cropped soil data, 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

Table 15 presents the corresponding significance levels associated with the SAR orthogonal contrasts of the marginal mean ln infiltration times in both time averaged ANOVA models. These orthogonal contrast significance levels confirm that the trends in the marginal mean ln infiltration times associated with both soil types are indeed linear.

Table 15. SAR orthogonal contrasts; cropped soil data, time-averaged across sampling periods

	F-test significance levels	
Orthogonal contrast	**Clay**	**Loam**
Linear	0.0001	0.0001
Quadratic	0.4203	0.6944
Cubic	0.6986	0.4935
4th Order	0.4490	0.8032

Based on the results presented in Tables 13, 14, and 15, simple linear regression models were used to describe both the clay and loam soil ln infiltration data. The pertinent statistics associated with these models are given in Table 16. The R-square values for these cropped soil models were 0.583 and 0.616, and both models were again statistically significant at the 0.0001 level. Predicted versus observed ln infiltration time plots for both models are shown in Figures 17 and 18, respectively. For the cropped soil loam data there is only one plot shown, since the EC effect was not found to be statistically significant in this experiment.

Table 16. Final time averaged ln infiltration time regression models for 2004 experimental data. Note: y = ln(infiltration time) and E{y} = expected value of y

Soil-type	**Fitted regression model (with standard errors)**	**R-square / Root MSE**
Clay	$E\{y\} = 2.644 + 0.102[SAR]$ (0.12) (0.018)	0.5829 / 0.2813
Loam	$E\{y\} = 2.393 + 0.040[SAR]$ (0.04) (0.006)	0.6158 / 0.0916

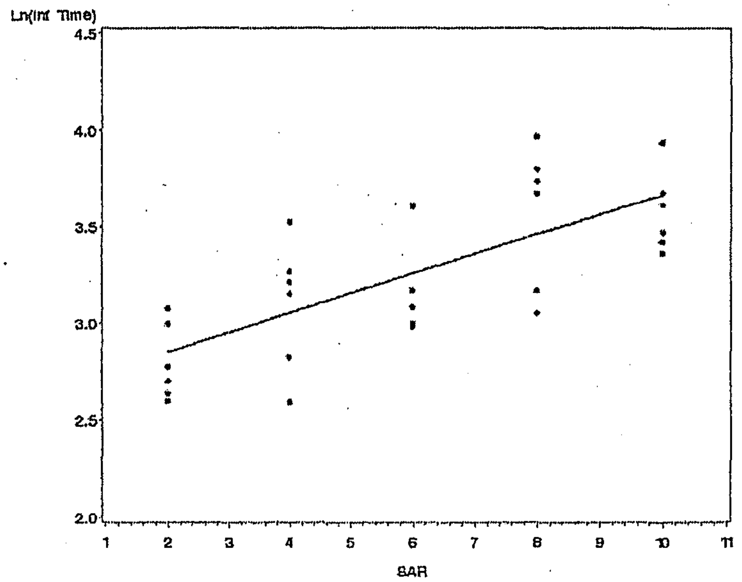

Figure 17. Relationship between SAR and ln infiltration time for clay soil; data is averaged across sampling periods, cropped soil experiment.

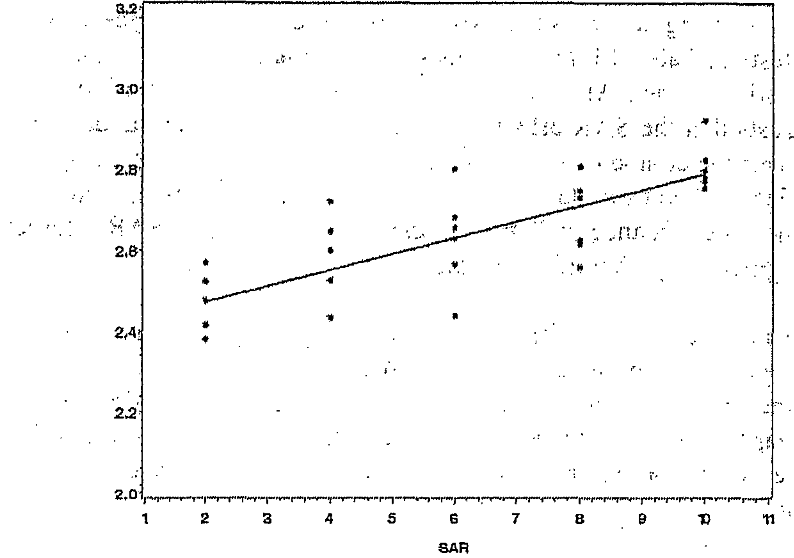

Figure 18. Relationship between SAR and ln infiltration time for loam soil; data is averaged across sampling periods (and EC), cropped soil experiment.

The time dependent (multivariate) test results presented in Table 13 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 this cropped soil experiment. Given this possibility, the statistical results from the individual ANOVA models are presented in Tables 17 and 18. Additionally, time interaction plots for both the marginal SAR and EC levels by soil type are presented in Figures 19 through 22, respectively.

The individual ANOVA model test results for the clay soil (Table 17) and loam soil (Table 18) exhibited more between -period variability in the cropped experiment (as compared to the bare soil experiment). The primary difference in the cropped soil experiment as compared to the bare soil was that a number of the ANOVA models were not found to be statistically significant. Most likely this difference is due to the increased noise in the cropped soil experimental data (caused in part by formation of root channels), as well by the more protected surface in the cropped experiment. However, the general trends present in both tables are again consistent with the previously discussed time averaged models. As in the bare soil experiment, for both 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 (Figures 19, 20, 21, and 22) show the changes in the estimated cropped soil ln infiltration time (over the 6 sampling periods) for the various SAR and EC levels. As seen in these Figures (and shown by the statistical tests in Table 13), ln infiltration times increased significantly over the course of the experiment. These results are expected as the initial condition can be considered comparable to a field-tilled soil with subsequent increase in infiltration time over subsequent irrigations.

Figures 19 and 20 show how the average clay and loam ln infiltration times changed over time across the five SAR levels, while Figures 21 and 22 show how these same infiltration times changed across the two EC levels, respectively. Based on the multivariate tests in Table 13, the patterns shown in Figures 19 and 22 can be considered statistically distinct. The SAR related interaction pattern shown in Figure 19 for clay soil strongly suggests that the SAR effects (on the ln infiltration time) tended to become more pronounced over the course of the 2004 experiment. This is confirmed by the high Time x SAR significance level for clay soil in Table 13. In contrast as seen in Figure 20 (and Timex SAR non-significance in Table 13) the ln infiltration and SAR interaction for loam soil did not significantly change over time.

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 Figure 22 does not appear to lend itself to any 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 again be used adequately describe, quantify, and summarize the experimental data. However, based on Table 13 and Figure 19, there also appears to be evidence that the SAR related effects on the clay soil increased over time, and thus any inferences drawn from the corresponding time averaged model with respect to SAR effects might also be argued to be conservative.

Table 17. Individual sampling period ANOVA model summary statistics and F-test significance levels (overall model effect, EC, SAR, and EC x SAR interaction); cropped experiment, clay soil data

Statistic	**Period 1**	**Period 2**	**Period 3**	**Period 4**	**Period 5**	**Period 6**
R-square	0.3977	0.4600	0.6106	0.7274	0.2144	0.5860
Root MSE	0.2401	0.4523	0.5657	0.4075	0.9718	0.3594
	F-test significance levels associated with specified tests:					
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 x SAR	n/a	n/a	0.3293	0.6727	n/a	0.6351

Table 18. Individual sampling period ANOVA model summary statistics and F-test significance levels (overall model effect, EC, SAR, and EC x SAR interaction); cropped experiment, loam soil data

Statistic	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6
R-square	0.4439	0.2491	0.2537	0.6673	0.6938	0.3787
Root MSE	0.3330	0.2120	0.1203	0.1451	0.1218	0.2184
	F-test significance levels associated with specified tests:					
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 x SAR	n/a	n/a	n/a	0.7910	0.0322	n/a

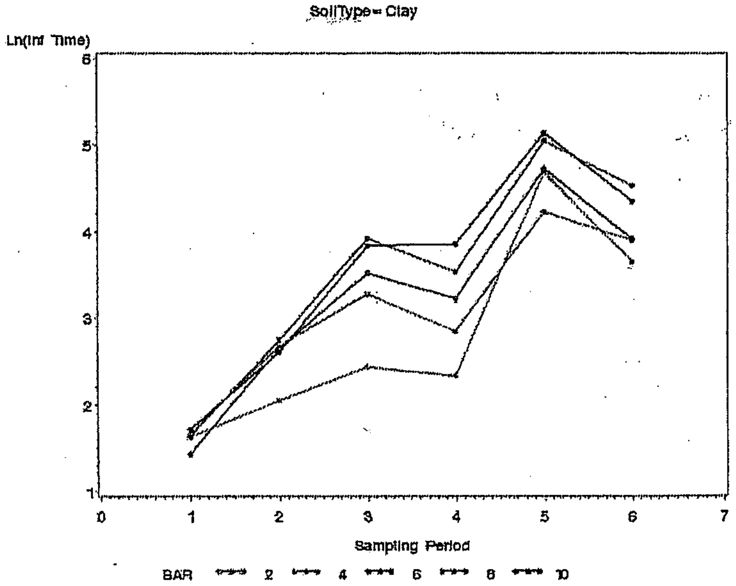

Figure 19. Average ln infiltration time interaction plot for cropped experiment, clay soil data (plotted by sampling period); colored lines represent specific SAR levels.

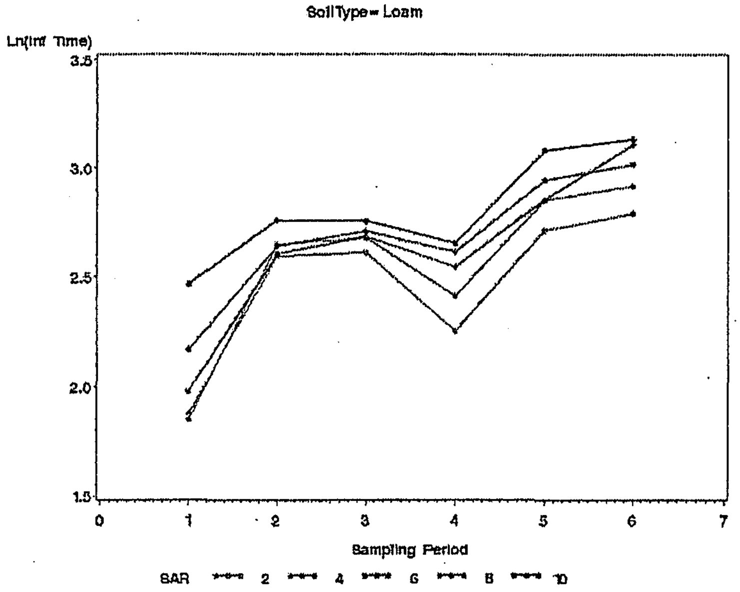

Figure 20. Average ln infiltration time interaction plot for cropped experiment, loam soil data (plotted by sampling period); colored lines represent specific SAR levels.

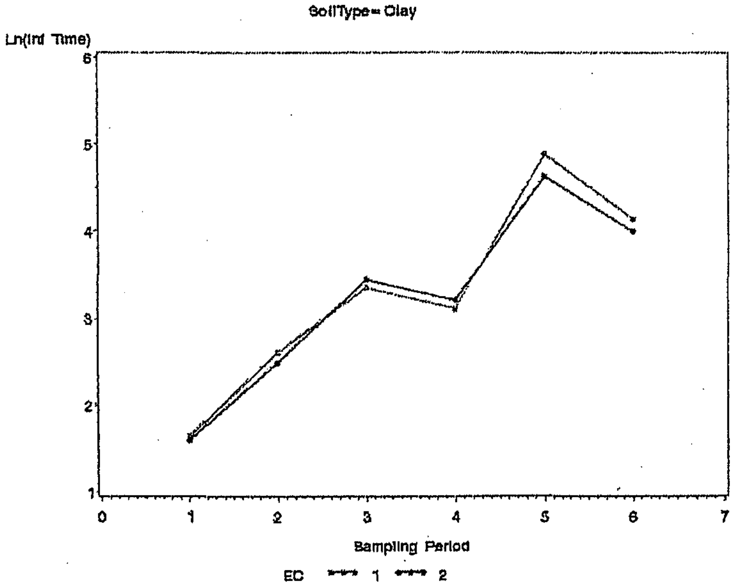

Figure 21. Average ln infiltration time interaction plot for the cropped experiment, clay soil data (plotted by sampling period); colored lines represent specific EC levels.

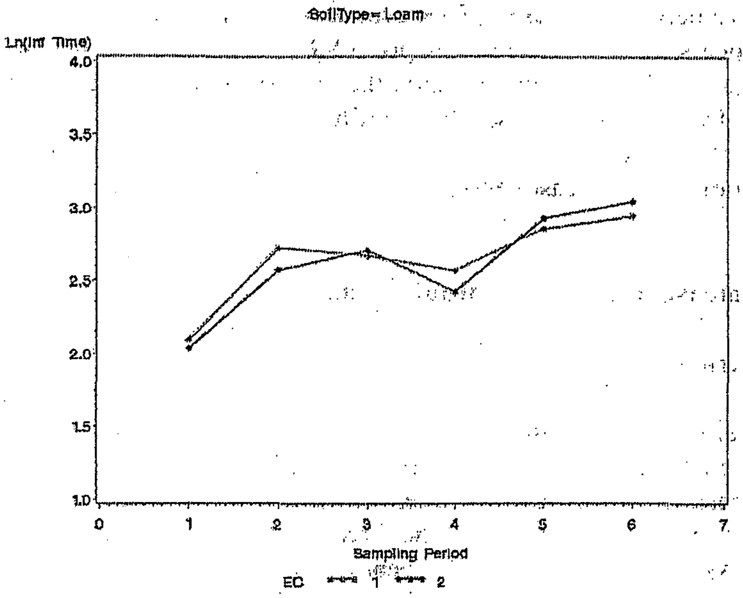

Figure 22. Average ln infiltration time interaction plot for the cropped experiment, loam soil data (plotted by sampling period); colored lines represent specific EC levels.

Assessment of the SAR risk factors for rain infiltration

In these two experiments, we define the SAR risk factor as the degree in which the ln infiltration time increases as the SAR level increases. These risk factors can be ascertained from the time averaged statistical results in one of two ways:

(1) by 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

(2) by calculating the relative predicted percent increase in infiltration time per unit increase in SAR (using the estimates SAR parameters derived from the fitted regression models).

Using the first approach, Table 7 (bare soil experimental data) suggests that if no crop is present then increasing the SAR from 2 to 4 significantly increases the ln infiltration time on the clay soil. Likewise, increasing the SAR from 2 to 6 significantly increases the ln infiltration time on the loam soil. In the presence of a crop, (Table 14) increasing the SAR from 2 to 6 significantly increases the ln infiltration time on both soil-types.

Using the second approach, Table 9 indicates that the relative percent increase in infiltration time per unit increase in SAR on a clay soil (without any crop cover) is approximately 100[exp(0.062)-1] = 6.4 %. In the presence of a crop, Table 16 suggests that the relative percent increase in infiltration time per unit increase in SAR is approximately 10.7 % for the clay soil and 4.1 % for the loam soil, respectively. Note that the relative percent increase is SAR dependent for a loam soil-type without any crop cover, but appears to vary between 0 % (for SAR < 4) to a maximum of about 24 % (in the SAR range of 5.5 to 6.5). In summary, the regression model predictions are that the SAR increase from 2 to 4 increases the ln infiltration time for clay soil under bare and cropped conditions and for loam soil under cropped conditions, while for bare loam soil the ln infiltration time increases above SAR 4.

Laboratory measurements of hydraulic conductivity on undisturbed soil cores

Bare soil experiment

At the conclusion of each of the two rain-irrigation infiltration experiments, saturated hydraulic conductivity experiments were performed in the laboratory. The hydraulic conductivity results for the loam soil after the bare soil experiment are shown in Figure 23. Each point represents the mean of the three replicates. The data are presented in Appendix C. As noted in the Appendix clear outliers were removed from the plots, but not removed for the statistical analysis. Each sample had water applied of the same composition as it experienced in the field experiment. As can be seen there was a consistent decrease in hydraulic conductivity with increasing SAR of the irrigation water. The decreases in hydraulic conductivity were approximately 50% as the SAR increased from 2 to 10. The samples from the EC=2 dS/m treatments had higher hydraulic conductivity than did the samples from the EC=1.0 dS/m treatments.

As expected the hydraulic conductivity decreased with application of simulated rainwater (of the same EC and composition as used in the outdoor container experiments). The decrease in hydraulic conductivity with SAR relationship also is observed when all cores were exposed to rain water (Figure 23).

The saturated hydraulic conductivity of undisturbed soil cores taken at the end of the bare soil experiment are presented in Figure 24. As with the loam soil there is increased hydraulic conductivity at the higher EC level. There is a general trend of decreasing hydraulic conductivity with increasing SAR. Large error bars are at least in part caused by observed cracks in the clay soil.

The data were statistically analyzed using a 2-way factorial model without interaction, where the response data are the natural log transformed saturated hydraulic conductivity. As shown earlier for the infiltration data and confirmed in this data set, there was no interaction between salinity level and SAR for a specific soil type and irrigation or rain event. Table 19 shown below shows the relevant statistical results.

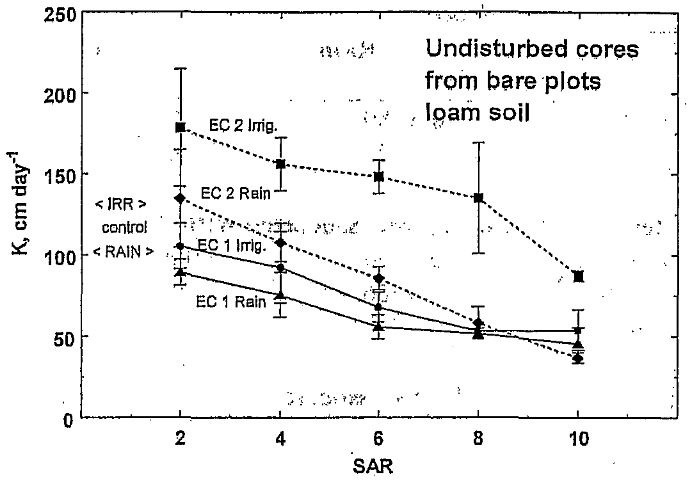

Figure 23. Saturated hydraulic conductivity as related to SAR of applied water. Undisturbed cores taken from loam soil treatments in rain- irrigation bare soil field experiment.

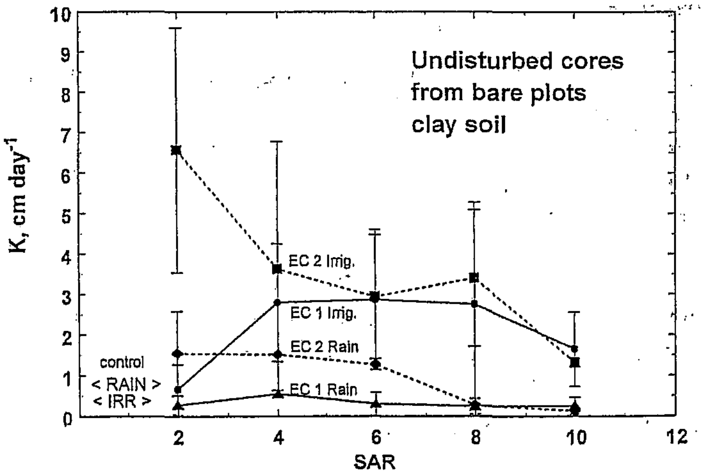

Figure 24. Saturated hydraulic conductivity as related to SAR of applied water. Undisturbed cores taken from clay soil treatments in rain- irrigation bare soil field experiment.

Table 19. ANOVA model summary statistics and F-test significance levels for both main effects and specific SAR contrasts; undisturbed cores for 2003 bare soil experiment, ln(Ks) response variable

	Clay		**Loam**	
Statistic	**Irrigation**	**Rain**	**Irrigation**	**Rain**
R-square	0.0520	0.3189	0.7162	0.6941
Root MSE	2.168	1.760	0.285	0.278
	F-test significance levels associated with specific tests:			
Overall	0.9286	0.1094	0.0001	0.0001
EC	0.3931	0.0366	0.0001	0.0891
SAR	0.9656	0.2877	0.0014	0.0001
	F-test significance levels associated with SAR contrasts:			
2 vs 4	n/a	n/a	0.7597	0.5925
2 vs 6	n/a	n/a	0.0923	0.0115
2 vs 8	n/a	n/a	0.0075	0.0003
2 vs 10	n/a	n/a	0.0003	0.0001

These results indicate that the ln(Ks) measurements associated with the loam soil were clearly affected by the changing SAR levels for both irrigation water and rain water applications and by the change in EC during the irrigation event. Increasing SAR and decreasing EC had an adverse effect on ln(k). The individual SAR contrasts indicate that significant differences (decreases in ln(k)), are detected beginning at the SAR 6 level (using 2 as a baseline).

For the clay soil we did not detect statistically significant differences in ln (K) with changing EC or SAR levels, despite the observed trends seen in Figure 24. The clay soil had much greater variance as can be seen by comparing Figure 23 with Figure 24 and confirmed by the almost 10 tenfold increase in RMSE for clay as compared to loam shown in Table 19.

It should be noted that the power of these tests (for detecting significant SAR effects) is weaker than the power achieved from a regression modeling approach. Hence, the following multivariate linear regression model was used to analyze these data:

$$\mathrm{Ln}(K) = \beta 0 + \beta 1[SAR] + \beta 2[EC] + \varepsilon$$

where this model was applied separately by soil type to each event. Additionally, this model was also used to analyze the differences in ln(infiltration) rates (i.e., the differences between the natural log transformed irrigation and rain event infiltration data). Note that the ANOVA model permits the testing of individual contrasts, while the regression model assumes strictly linear effects (if any) and allows for an estimate of relative risk to be calculated.

The regression model summary statistics, parameter estimates and t-test results for the loam soil-type are shown in Table 20 (no results are shown for the clay soil-type since these models were not found to be statistically significant). These results confirm that the increasing SAR levels resulted in a statistically significant linear decrease in ln(Ks) in the loam soil-type during both the irrigation and rain event. The linear model suggests that the increase in SAR from 2 to 4 would cause an increase in infiltration time (decrease in infiltration rate) for the loam soil for both irrigation events and rain events and that we cannot detect a change in infiltration associated with SAR for the clay soil.

Table 20. Regression model summary statistics: SAR and EC parameter estimates, standard errors, and t-test significance levels for the bare soil (2003), ln(Ks) data associated with the loam soil (by event)

Soil-type	**Event**	**R-square**	**Variable**	**Estimate**	**Std.Error**	**Pr > | t |**
Loam	**Irrigation**	0.7081	SAR	-0.0902	0.0176	0.0001
			EC	0.6219	0.0994	0.0001
	Rain	0.6787	SAR	-0.1273	0.0174	0.0001
			EC	0.1802	0.0982	0.0777

Cropped soil experiment

The hydraulic conductivity results for the loam soil after the cropped soil experiment are shown in Figure 25. Again, each sample had water applied of the same composition as it experienced in the field experiment. As can be seen there was a decrease in hydraulic conductivity with increasing SAR of the irrigation water. The samples from the EC=2 dS/m treatments had higher hydraulic conductivity than did the samples from the EC=1.0 dS/m treatments, and the hydraulic conductivity with the rain water was lower than with the irrigation waters. These results are similar to those obtained under the bare soil experiment (Figure 23) only with greater variability, attributed to the presence of root material and root channel in the samples from the cropped soil experiment.

Data for the undisturbed cores from the cropped plots were extremely variable due to channels and soil separation around the roots.

The data were statistically analyzed, again using the 2-way factorial model without interaction, where the response data are the natural log transformed saturated hydraulic conductivity. As before, these data have been analyzed separately by soil type and event. Table 21 shown below shows the relevant statistical results. Note that only the EC=1 cores were run for the clay soil type.

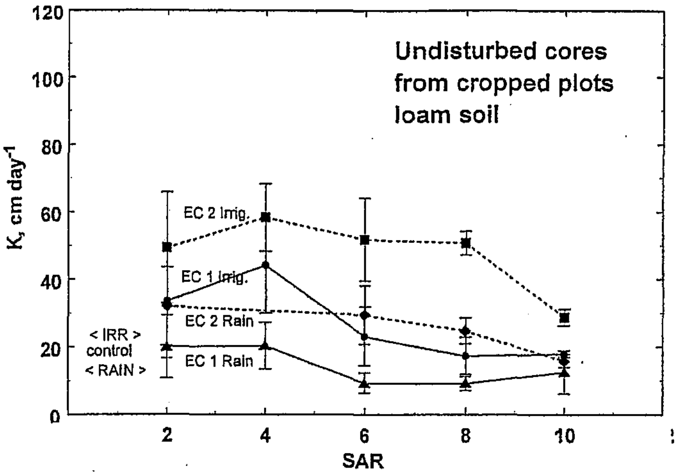

Figure 25. Saturated hydraulic conductivity as related to SAR of applied water. Undisturbed cores taken from loam soil treatments in rain- irrigation cropped soil field experiment.

Table 21. ANOVA model summary statistics and F-test significance levels for both main effects and specific SAR contrasts; cropped experiment (2004) undisturbed soil cores, ln(Ks) response variable

	Clay		**Loam**	
Statistic	**Irrigation**	**Rain**	**Irrigation**	**Rain**
R-square	0.1311	0.2043	0.4826	0.4767
Root MSE	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

Based on this analysis we cannot detect a statistically significant effect of SAR on ln(Ks) measurements with either soil type (at the 10 % confidence level). Note that the RMSE for the loam soil (Table 21) in the cropped experiment is about twice as great as that of the uncropped experiment (Table 19). However, the ln(Ks) readings associated with the loam soil-type were affected by the changing EC levels during both events. More specifically, the average ln(Ks) levels appear 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 22 (again, no results are shown for the clay soil-type since 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(Ks) in the loam soil-type during both the irrigation and rain event. These results also indicate that the increasing SAR levels caused a significant decrease in the ln(Ks) levels during both events ($p = 0.060$ and $p=0.036$, irrigation and rain events, respectively). This linear regression model predicts a decrease in the ln hydraulic conductivity with an increase from SAR 2 to SAR 4.

Table 22. Regression model summary statistics: SAR and EC parameter estimates, standard errors, and t-test significance levels for the cropped soil experiment (2004) ln(Ks) data associated with the loam soil (by event)

Soil-type	Event	R-square	Variable	Estimate	Std.Error	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

Laboratory measurements of infiltration on disturbed soil cores

The infiltration rates of the disturbed soil cores as related to EC and SAR is presented in Figure 26 for the loam soil. In these experiments soil at the native EC and SAR was packed into columns and each of the 12 columns was equilibrated with a fixed EC and SAR water composition. After stabilization of the hydraulic conductivity, the influent solutions in all columns were switched to rain water. As seen in Figure 26 there was a decrease in hydraulic conductivity with increasing SAR starting at SAR 2 versus SAR 4 at both EC levels. Similar results were obtained with the clay soil, as can be seen in Figure 27. In both instances the hydraulic conductivity with rain water was much lower than with irrigation water.

The results of these short- term laboratory hydraulic conductivity experiments are generally consistent with the results from the long-term field infiltration studies and the hydraulic conductivity measurements taken from the field experiments and run in the laboratory. The procedure used in this disturbed soil experiment is comparable to the procedure used in the earlier laboratory experiments (McNeal and Coleman, 1966, Frenkel et. al., 1978, Suarez et al., 1984). These column infiltration measurements represent a type of repeated measurement data, where each column is measured twice (first under the irrigation event, then under the rain event). The column measurements are not replicated. The ANOVA and regression modeling results for this data are presented in Tables 23 and 24.

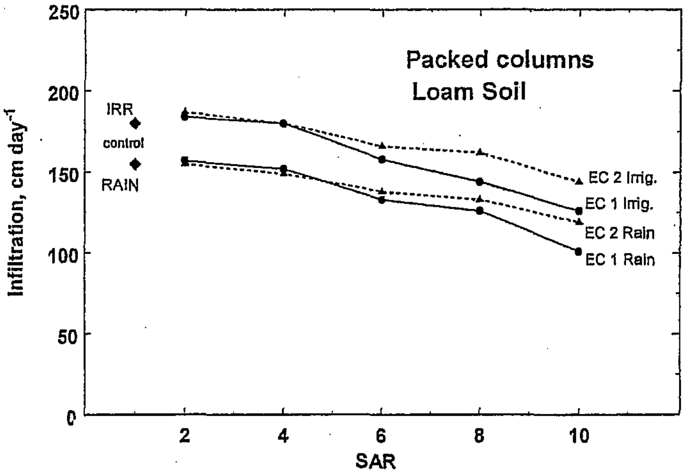

Figure 26. Infiltration rate as related to SAR of applied water. Disturbed (laboratory packed) cores of untreated loam soil.

The ANOVA model F-test values and significance levels (shown in Table 23) confirm a significant SAR effect in three out of 4 events, respectively. The individual SAR contrasts suggest that significant differences begin to show up at the SAR= 4 level (using SAR=2 as a baseline and 90 % confidence limits). However, the power of these tests is very weak (due to the small sample sizes in this experiment) and thus these contrast tests do not represent an optimal approach for determining when significant differences occur.

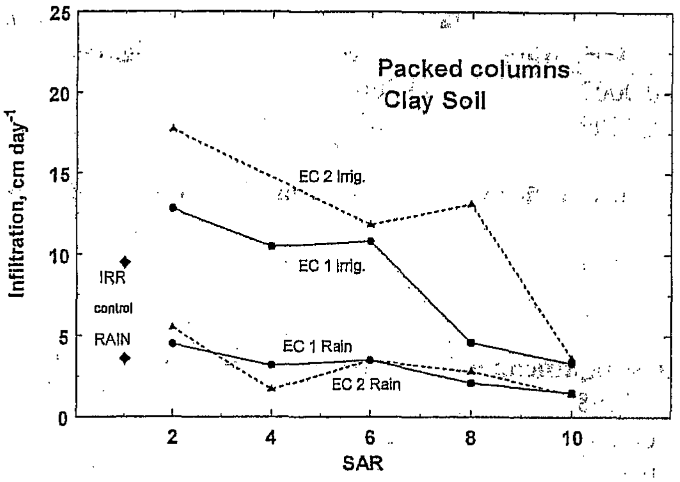

Figure 27. Infiltration rate as related to SAR of applied water. Disturbed (laboratory packed) cores of untreated clay soil.

The regression model summary statistics, parameter estimates and t-test results shown in Table 24 give a much more clear indication of the degree of SAR induced effects. These results indicate that the SAR parameter estimates were always statistically significant (below the 0.01 level) during both the irrigation water and rain water applications. In all four cases these estimates are negative, indicating that the ln(infiltration) rates decrease as the SAR levels increase. Note that the rate of reduction (per unit increase in SAR) can be calculated from these parameter estimates. Note also that the EC parameter estimates were generally not significant, suggesting that changing the EC from 1 to 2 dS/m did not significantly alter the ln(infiltration) rates. The linear regression model would predict a decrease in the infiltration rate at SAR 4 as compared to SAR 2.

Bulk density of undisturbed soil cores

The bulk density was determined on the undisturbed cores used in the laboratory hydraulic conductivity study. As shown in Appendix B there were no clear trends related to the irrigation water treatments. The loam soil had a decreased bulk density in the cropped soil experiment relative to the bare soil experiment. These differences maybe attributed to the large number of roots in all treatments of the cropped soil experiment. However, the clay soil had a slightly higher bulk density in the cropped experiment.

Table 23. ANOVA model summary statistics and F-test significance levels for both main effects and specific SAR contrasts for the disturbed soil infiltration experiment

	Clay		**Loam**	
Statistic	**Irrigation**	**Rain**	**Irrigation**	**Rain**
R-square	0.9007	0.9760	0.9526	0.9362
Root MSE	0.3209	0.1182	0.0423	0.0523
	F-test significance levels associated with specific tests:			
Overall	0.0969	0.0123	0.0094	0.0167
EC	0.1871	0.2985	0.0770	0.2501
SAR	0.0850	0.0093	0.0075	0.0124
	F-test significance levels associated with SAR contrasts:			
2 vs 4	0.7108	0.0817	0.5166	0.5298
2 vs 6	0.4361	0.0588	0.0327	0.0542
2 vs 8	0.1311	0.0089	0.0101	0.0234
2 vs 10	0.0194	0.0019	0.0016	0.0025

Table 24. SAR and EC parameter estimates (with standard errors), corresponding t-test values and significance levels for the disturbed soil ln(infiltration) data (by soil type and event)

Soil-type	Event	R-square	Variable	Estimate	Std.Error	Pr > | t |
Clay	**Irrigation**	0.7762	SAR	-0.1719	0.0393	0.0047
			EC	0.3847	0.2294	0.1446
	Rain	0.8968	SAR	-0.1442	0.0200	0.0004
			EC	0.1395	0.1168	0.2773
Loam	**Irrigation**	0.9223	SAR	-0.0402	0.0046	0.0001
			EC	0.0634	0.0259	0.0443
	Rain	0.8836	SAR	-0.0428	0.0060	0.0002
			EC	0.0444	0.0338	0.2297

Alfalfa yield data

The cumulative fresh weight yield as related to irrigation water treatment is presented in Figure 28 for both the loam and clay soil. Yields were relatively uniform for all treatments, trending around 150 g/container for the clay soil and 115 g/container for the loam soil. The lower yield of the loam soil is explained by the lower water holding capacity of the soil and thus increased water stress caused buy the irrigation regime. As explained earlier the soil is relatively shallow and thus we irrigated the cropped containers every 3-5 days. We maximized the interval between irrigations to allow for maximum soil drying at the surface, and observed the alfalfa in the loam containers to be water stressed before numerous irrigations.

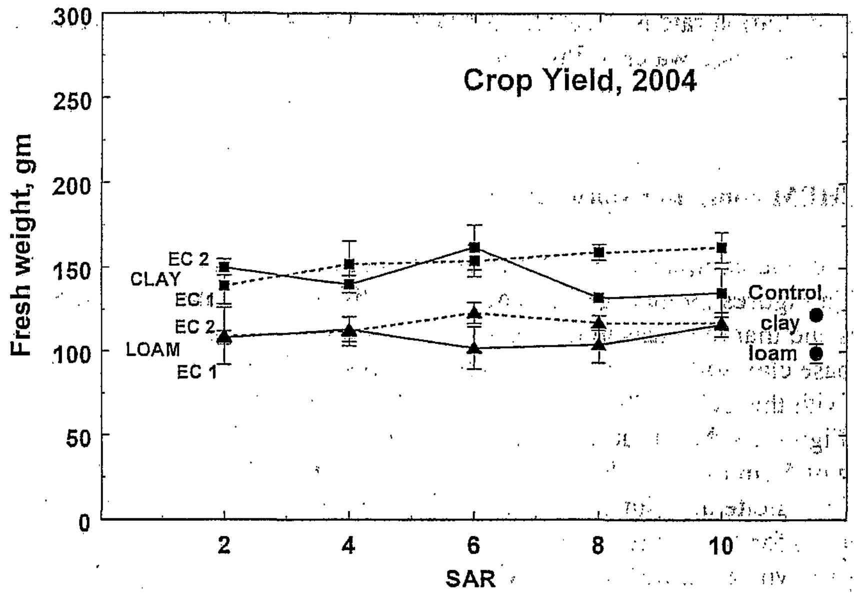

Figure 28. Alfalfa fresh yield data as related to EC and SAR or irrigation water. All plots had equal quantities of applied water.

We analyzed the total alfalfa yield data from the cropped soil experiment using a 2-way ANOVA without interaction, where the data were data analyzed separately by soil type. Table 25 presents the relevant statistical results.

Table 25. ANOVA model summary statistics and F-test significance levels (overall model effect, EC, SAR, and EC x SAR interaction): 2004 fresh-weight yield data

Statistic	Clay	Loam
R-square	0.1560	0.0926
Root MSE	17.80	15.36
F-test significance levels associated with specific tests:		
Overall	0.5049	0.7806
EC	0.6689	0.9232
SAR	0.1649	0.2239

It is clear from these ANOVA results that neither the changing EC nor SAR levels affected the final, fresh-weight crop yields. The lack of a decrease in yield with increasing SAR indicates that the soil physical properties did not directly impact yield in this one year experiment. As noted above, 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 will result in decreased yield if the crop is water limited.

UNSATCHEM computer simulations

The results of the computer simulations of the impact of rain on soil water SAR are presented in Figures 29 through 32. These simulations utilize the fact that both soils are calcareous and that the measured CEC of the Glendive loam soil is 58 mmol/kg and that of the Kobase clay soil 208 mmol/kg. In this analysis we first equilibrated the soils by irrigating with the EC 1.0 dS/m water and SAR 10 of composition given in Table 1. As shown in Figure 29 the EC at the surface decreased to below 0.5 dS/m at the surface after infiltration of 5 cm of rain. The soil water EC is maintained above the rainfall EC (0.016 dS/m) due to calcite dissolution. Calcite dissolution is further enhanced by the exchange of solution Ca for Na on the exchange sites (thus causing a reduction in the ESP with time). As shown in Figure 30, the SAR also decreased but is still at SAR=6 at the surface despite 5 cm of rain. The decrease in SAR is not sufficient to compensate for the decrease in EC thus the sodium hazard is increased.

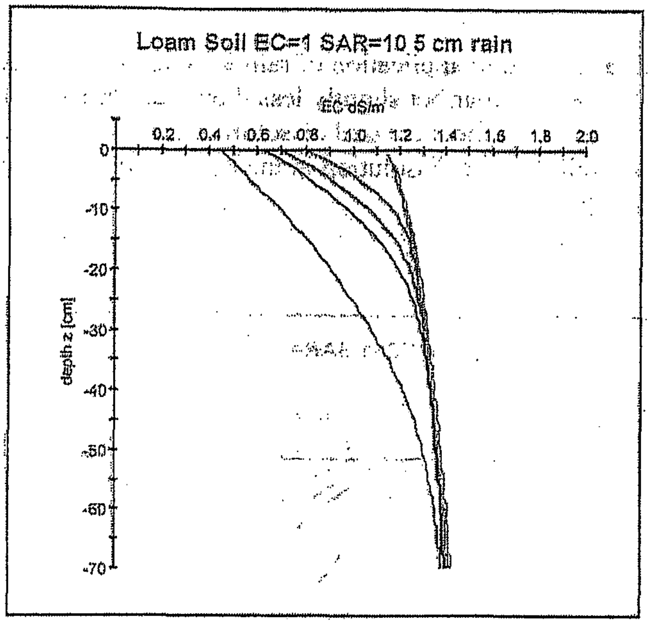

Figure 29. Predicted relationship of EC with depth and quantity of rain infiltrated for Glendive loam soil. The initial condition was EC=1.0 dS/m and SAR 10. Each curve represents addition of 1 cm of rain.

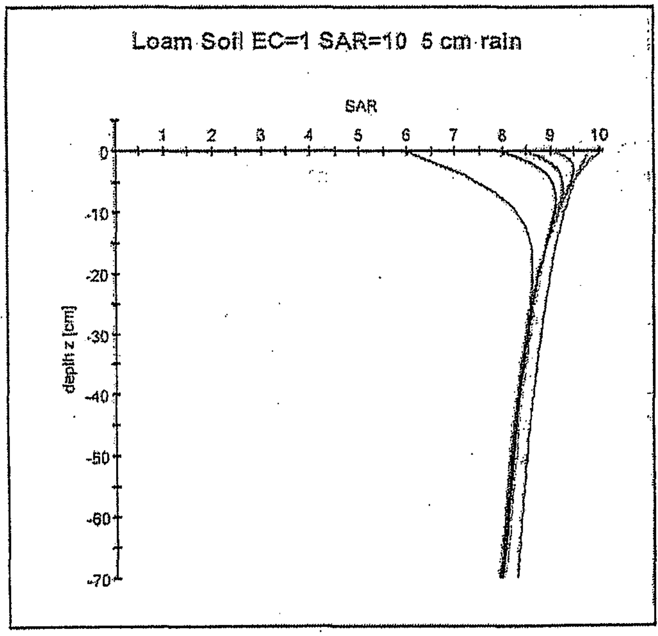

Figure 30. Predicted relationship of SAR with depth and quantity of rain infiltrated. The initial condition was EC=1.0 dS/m and SAR-10. Each curve represents addition of 1 cm of rain.

The decrease in EC as related to application of rain is simulated in Figure 31. Note that the decrease in EC is very similar but slightly less than that observed for the loam soil (Figure 29). This is caused by the increased dissolution of calcite with increased cation exchange in the clay soil. Calcite dissolution in the absence of exchange would result in an EC of about 0.15 dS/m.

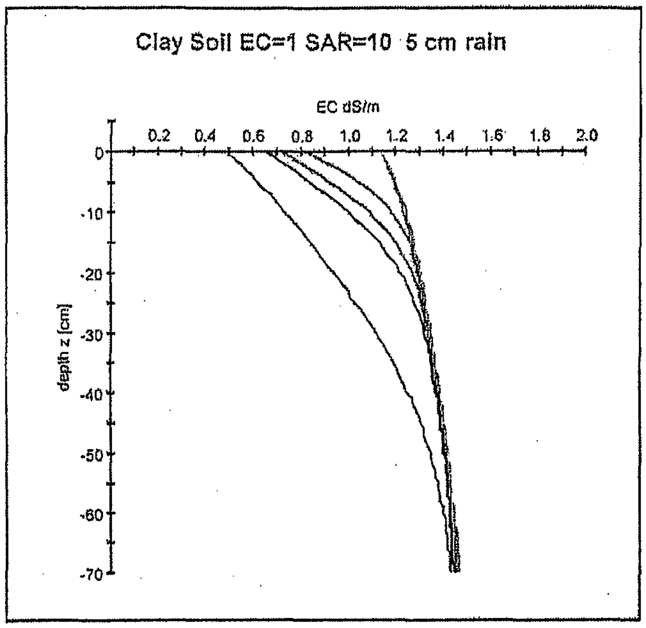

Figure 31. Predicted relationship of EC with depth and quantity of rain infiltrated into the clay soil. The initial condition was EC=1.0.dS/m and SAR 10. Each curve represents addition of 1 cm of rain.

As shown in Figure 32, the SAR of the clay soil was only slightly affected by the infiltration of 5 cm of rain. The higher cation exchange capacity of the clay soil as comapared to the loam soil means that the soil exchange sites are able to buffer the solution SAR. The soil surface at the end of the rain event is thus at low EC with almost no decrease in SAR relative to the irrigation condition.

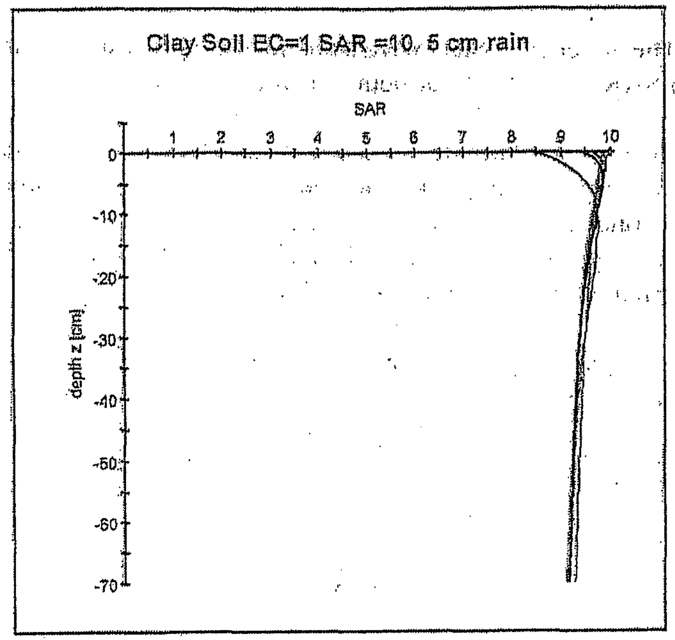

Figure 32. Relationship of SAR with depth and quantity of rain infiltrated into clay soil. The initial condition was SAR=10. Each curve represents addition of 1 cm of rain.

Conclusions

The increase in SAR of the irrigation water had an adverse impact on water infiltration for both the cropped and bare (uncropped) soils. For the bare clay soil even an increase from SAR 2 to SAR 4 resulted in a significant increase in infiltration time (decrease in infiltration rate), while for loam soil the increase in infiltration time was significant at the SAR 6 level. For cropped soil the variance was higher and differences were statistically significant at SAR 6 when paired tests were made. However, the fitted regression model showed decreases in infiltration are predicted for both bare and cropped clay soil and for cropped loam soil as the SAR increased from 2 to 4. For bare loam soil the model was non linear and the decrease in infiltration rate starts above SAR 4.

The decreased infiltration rate in the field can be expected to result in increased surface runoff and thus decreased availability of water to the crop. In conditions where water is limiting, this may result in decreased crop yield. The lack of an adverse impact of irrigation water SAR on yield in the present experiments is likely the result of having confined containers, where the total water infiltrated must be constant for all treatments.

The laboratory measurements of saturated hydraulic conductivity of undisturbed bare soil cores taken from the infiltration experiment also showed a trend of decreasing hydraulic conductivity with increasing SAR. The trend was statistically significant for the loam soil but not the clay soil. The adverse impacts were statistically significant in bare loam soil when increasing from SAR 2 to SAR 6 for both rain and irrigation water.

For cropped soil the changes in hydraulic conductivity as related to SAR were significant for loam soil under both irrigation and rain. The linear regression model predicts decreases in hydraulic conductivity as the SAR is increased from 2 to 4. The SAR trends were not significant for clay soil, due in part to increased variance. The ability to detect changes in SAR is limited by the experimental uncertainties.

Replicated disturbed soil cores under saturated conditions provide information comparable to more time consuming field infiltration studies. Adverse impacts of SAR on infiltration were statistically significant when increasing SAR from 2 to 6 for loam soils with both irrigation water and rain water and clay soils with rain water.

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Appendix A: 2003 & 2004 Experimental Data

Experimental Data: Bare soil (2003)

Obs	Sampling Period	Rain pass	Soil type	EC	SAR	Infiltration time (3 reps) y1	y2	y3
1	1	7	Loam	1	2	72.0	91.0	27.0
2	1	7	Loam	1	4	39.0	92.0	28.0
3	1	7	Loam	1	6	91.0	69.0	115.0
4	1	7	Loam	1	8	71.0	115.0	136.0
5	1	7	Loam	1	10	39.0	91.0	135.0
6	1	7	Loam	2	2	22.0	91.0	28.0
7	1	7	Loam	2	4	41.0	28.0	28.0
8	1	7	Loam	2	6	72.0	28.0	71.0
9	1	7	Loam	2	8	70.0	92.0	114.0
10	1	7	Loam	2	10	71.0	72.0	69.0
11	1	7	Clay	1	2	153.0	136.0	92.0
12	1	7	Clay	1	4	152.0	152.0	137.0
13	1	7	Clay	1	6	154.0	206.0	136.0
14	1	7	Clay	1	8	152.0	153.0	166.0
15	1	7	Clay	1	10	201.0	152.0	152.0
16	1	7	Clay	2	2	70.0	71.0	92.0
17	1	7	Clay	2	4	137.0	92.0	136.0
18	1	7	Clay	2	6	92.0	166.0	155.0
19	1	7	Clay	2	8	168.0	91.0	152.0
20	1	7	Clay	2	10	155.0	153.0	155.0
21	2	5	Loam	1	2	24.0	12.0	14.0
22	2	5	Loam	1	4	25.0	24.0	23.0
23	2	5	Loam	1	6	25.0	25.0	21.0
24	2	5	Loam	1	8	37.0	38.0	56.0
25	2	5	Loam	1	10	25.0	60.0	36.0
26	2	5	Loam	2	2	10.0	11.0	10.0
27	2	5	Loam	2	4	10.0	5.0	11.0
28	2	5	Loam	2	6	24.0	25.0	23.0
29	2	5	Loam	2	8	26.0	25.0	36.0
30	2	5	Loam	2	10	24.0	31.0	31.0
31	2	5	Clay	1	2	37.0	48.0	58.0
32	2	5	Clay	1	4	58.0	48.0	57.0
33	2	5	Clay	1	6	37.0	49.0	49.0
34	2	5	Clay	1	8	67.0	59.0	50.0
35	2	5	Clay	1	10	81.0	81.0	67.0
36	2	5	Clay	2	2	48.0	50.0	36.0
37	2	5	Clay	2	4	49.0	56.0	48.0
38	2	5	Clay	2	6	49.0	59.0	81.0
39	2	5	Clay	2	8	66.0	66.0	49.0
40	2	5	Clay	2	10	80.0	80.0	50.0
41	3	4	Loam	1	2	8.2	4.5	9.5
42	3	4	Loam	1	4	10.5	7.7	9.7
43	3	4	Loam	1	6	17.8	17.0	32.7
44	3	4	Loam	1	8	19.2	20.2	17.3
45	3	4	Loam	1	10	30.5	16.5	18.5
46	3	4	Loam	2	2	6.9	18.4	6.7
47	3	4	Loam	2	4	5.5	4.0	9.5
48	3	4	Loam	2	6	21.2	10.0	8.5
49	3	4	Loam	2	8	17.7	21.5	17.4
50	3	4	Loam	2	10	19.1	19.5	17.0
51	3	4	Clay	1	2	32.0	30.5	5.4
52	3	4	Clay	1	4	32.5	30.5	31.2
53	3	4	Clay	1	6	19.5	19.0	29.0
54	3	4	Clay	1	8	32.5	38.2	38.0
55	3	4	Clay	1	10	28.6	38.3	32.0
56	3	4	Clay	2	2	16.2	20.0	16.7
57	3	4	Clay	2	4	19.0	30.6	30.0
58	3	4	Clay	2	6	6.0	38.0	37.7
59	3	4	Clay	2	8	19.6	18.5	18.3
60	3	4	Clay	2	10	30.5	18.9	32.5

						Infiltration time (3 reps)		
Obs	Sampling Period	Rain pass	Soiltype	EC	SAR	y1	y2	y3
61	4	8	Loam	1	2	24.0	20.0	22.0
62	4	8	Loam	1	4	25.0	23.0	33.0
63	4	8	Loam	1	6	29.0	33.0	50.0
64	4	8	Loam	1	8	65.0	50.0	78.0
65	4	8	Loam	1	10	47.0	83.0	87.0
66	4	8	Loam	2	2	27.0	15.0	37.0
67	4	8	Loam	2	4	30.0	20.0	31.0
68	4	8	Loam	2	6	26.0	36.0	21.0
69	4	8	Loam	2	8	35.0	50.0	32.0
70	4	8	Loam	2	10	93.0	50.0	90.0
71	4	8	Clay	1	2	18.0	29.0	24.0
72	4	8	Clay	1	4	10.0	48.0	37.0
73	4	8	Clay	1	6	53.0	60.0	14.0
74	4	8	Clay	1	8	67.0	80.0	81.0
75	4	8	Clay	1	10	85.0	50.0	75.0
76	4	8	Clay	2	2	28.0	43.0	43.0
77	4	8	Clay	2	4	58.0	70.0	55.0
78	4	8	Clay	2	6	17.0	40.0	29.0
79	4	8	Clay	2	8	49.0	60.0	76.0
80	4	8	Clay	2	10	65.0	75.0	24.0
81	5	4	Loam	1	2	10.0	13.0	13.0
82	5	4	Loam	1	4	16.0	11.0	13.0
83	5	4	Loam	1	6	16.0	20.0	5.0
84	5	4	Loam	1	8	23.0	23.0	25.0
85	5	4	Loam	1	10	27.0	24.0	24.0
86	5	4	Loam	2	2	10.0	6.0	9.0
87	5	4	Loam	2	4	10.0	8.0	9.0
88	5	4	Loam	2	6	17.0	15.0	11.0
89	5	4	Loam	2	8	19.0	17.0	16.0
90	5	4	Loam	2	10	28.0	10.0	20.0
91	5	4	Clay	1	2	20.0	15.0	25.0
92	5	4	Clay	1	4	23.0	20.0	30.0
93	5	4	Clay	1	6	23.0	23.0	7.0
94	5	4	Clay	1	8	17.0	7.0	25.0
95	5	4	Clay	1	10	15.0	23.0	28.0
96	5	4	Clay	2	2	18.0	17.0	16.0
97	5	4	Clay	2	4	17.0	16.0	30.0
98	5	4	Clay	2	6	17.0	30.0	12.0
99	5	4	Clay	2	8	23.0	18.0	24.0
100	5	4	Clay	2	10	15.0	24.0	24.0
101	6	7	Loam	1	2	10.0	7.0	10.0
102	6	7	Loam	1	4	9.0	12.0	12.0
103	6	7	Loam	1	6	20.0	20.0	20.0
104	6	7	Loam	1	8	30.0	30.0	31.0
105	6	7	Loam	1	10	30.0	29.0	31.0
106	6	7	Loam	2	2	8.0	7.0	9.0
107	6	7	Loam	2	4	10.0	7.0	9.0
108	6	7	Loam	2	6	20.0	20.0	20.0
109	6	7	Loam	2	8	30.0	35.0	30.0
110	6	7	Loam	2	10	43.0	43.0	32.0
111	6	7	Clay	1	2	60.0	60.0	75.0
112	6	7	Clay	1	4	95.0	95.0	110.0
113	6	7	Clay	1	6	130.0	130.0	61.0
114	6	7	Clay	1	8	110.0	110.0	130.0
115	6	7	Clay	1	10	130.0	130.0	160.0
116	6	7	Clay	2	2	61.0	60.0	60.0
117	6	7	Clay	2	4	95.0	95.0	75.0
118	6	7	Clay	2	6	130.0	160.0	130.0
119	6	7	Clay	2	8	95.0	255.0	160.0
120	6	7	Clay	2	10	240.0	275.0	180.0

Experimental Data: Year 2004

Obs	Sampling Period	Rain pass	Soiltype	EC	SAR	Infiltration time (3 reps) y1	y2	y3
1	1a	12	Loam	1	2	3.0	10	10.0
2	1a	12	Loam	1	4	10.0	4	10.0
3	1a	12	Loam	1	6	7.0	10	2.0
4	1a	12	Loam	1	8	8.0	15	7.0
5	1a	12	Loam	1	10	15.0	15	15.0
6	1a	12	Loam	2	2	7.0	2	7.0
7	1a	12	Loam	2	4	8.0	10	2.0
8	1a	12	Loam	2	6	9.0	7	15.0
9	1a	12	Loam	2	8	6.0	10	7.0
10	1a	12	Loam	2	10	15.0	10	15.0
11	1a	12	Clay	1	2	3.0	7	2.0
12	1a	12	Clay	1	4	2.0	2	2.0
13	1a	12	Clay	1	6	2.0	3	3.0
14	1a	12	Clay	1	8	3.0	3	3.0
15	1a	12	Clay	1	10	3.0	8	3.0
16	1a	12	Clay	2	2	2.0	3	2.0
17	1a	12	Clay	2	4	3.0	7	8.0
18	1a	12	Clay	2	6	2.0	2	2.0
19	1a	12	Clay	2	8	2.0	2	3.0
20	1a	12	Clay	2	10	2.0	3	3.0
21	1b	12	Loam	1	2	9.0	7	4.0
22	1b	12	Loam	1	4	7.0	5	8.0
23	1b	12	Loam	1	6	8.0	10	5.0
24	1b	12	Loam	1	8	10.0	10	8.0
25	1b	12	Loam	1	10	8.0	7	12.0
26	1b	12	Loam	2	2	7.0	7	7.0
27	1b	12	Loam	2	4	5.0	10	4.0
28	1b	12	Loam	2	6	5.0	7	7.0
29	1b	12	Loam	2	8	8.0	10	8.0
30	1b	12	Loam	2	10	10.0	10	10.0
31	1b	12	Clay	1	2	10.0	8	7.0
32	1b	12	Clay	1	4	5.0	8	7.0
33	1b	12	Clay	1	6	5.0	7	7.0
34	1b	12	Clay	1	8	10.0	5	10.0
35	1b	12	Clay	1	10	7.0	10	5.0
36	1b	12	Clay	2	2	7.0	5	7.0
37	1b	12	Clay	2	4	7.0	7	8.0
38	1b	12	Clay	2	6	6.0	5	7.0
39	1b	12	Clay	2	8	5.0	10	7.0
40	1b	12	Clay	2	10	8.0	7	10.0
41	2a	12	Loam	1	2	5.0	10	10.0
42	2a	12	Loam	1	4	5.0	10	10.0
43	2a	12	Loam	1	6	10.0	10	5.0
44	2a	12	Loam	1	8	5.0	5	5.0
45	2a	12	Loam	1	10	10.0	10	10.0
46	2a	12	Loam	2	2	5.0	10	5.0
47	2a	12	Loam	2	4	5.0	5	5.0
48	2a	12	Loam	2	6	5.0	5	5.0
49	2a	12	Loam	2	8	5.0	5	5.0
50	2a	12	Loam	2	10	5.0	5	10.0
51	2a	12	Clay	1	2	14.0	5	14.0
52	2a	12	Clay	1	4	14.0	27	10.0
53	2a	12	Clay	1	6	14.0	25	31.0
54	2a	12	Clay	1	8	5.0	12	14.0
55	2a	12	Clay	1	10	13.0	25	14.0
56	2a	12	Clay	2	2	10.0	10	10.0
57	2a	12	Clay	2	4	5.0	10	14.0
58	2a	12	Clay	2	6	11.0	10	10.0
59	2a	12	Clay	2	8	20.0	20	31.0
60	2a	12	Clay	2	10	10.0	10	14.0

```
         Sampling   Rain                               Infiltration time (3 reps)
  Obs    Period     pass     Soiltype     EC     SAR      y1        y2        y3

   61      2b        12        Loam        1       2     15.0       20       25.0
   62      2b        12        Loam        1       4     25.0       17       25.0
   63      2b        12        Loam        1       6     25.0       25       17.0
   64      2b        12        Loam        1       8     25.0       25       25.0
   65      2b        12        Loam        1      10     25.0       25       25.0
   66      2b        12        Loam        2       2     15.0       25       20.0
   67      2b        12        Loam        2       4     15.0       25       25.0
   68      2b        12        Loam        2       6     17.0       25       17.0
   69      2b        12        Loam        2       8     25.0       25       15.0
   70      2b        12        Loam        2      10     17.0       25       25.0
   71      2b        12        Clay        1       2      6.0        2        6.0
   72      2b        12        Clay        1       4     15.0       25       17.0
   73      2b        12        Clay        1       6     15.0       17       14.0
   74      2b        12        Clay        1       8      6.0       17       25.0
   75      2b        12        Clay        1      10     14.0       25       15.0
   76      2b        12        Clay        2       2      2.0       25        2.0
   77      2b        12        Clay        2       4     25.0       14        6.0
   78      2b        12        Clay        2       6     15.0       19        2.0
   79      2b        12        Clay        2       8     15.0       14       30.0
   80      2b        12        Clay        2      10      6.0       25        4.0
   81      3a        12        Loam        1       2     20.0       20       10.0
   82      3a        12        Loam        1       4     20.0       15       20.0
   83      3a        12        Loam        1       6     20.0       20       20.0
   84      3a        12        Loam        1       8     20.0       20       20.0
   85      3a        12        Loam        1      10     20.0       20       20.0
   86      3a        12        Loam        2       2     15.0       15       30.0
   87      3a        12        Loam        2       4     20.0       20       20.0
   88      3a        12        Loam        2       6     20.0       20       20.0
   89      3a        12        Loam        2       8     20.0       20       20.0
   90      3a        12        Loam        2      10     20.0       20       20.0
   91      3a        12        Clay        1       2     30.0        5       20.0
   92      3a        12        Clay        1       4     30.0       50       30.0
   93      3a        12        Clay        1       6     30.0       30       30.0
   94      3a        12        Clay        1       8     20.0       50       50.0
   95      3a        12        Clay        1      10     20.0       50       20.0
   96      3a        12        Clay        2       2     10.0       20        5.0
   97      3a        12        Clay        2       4     30.0       20       20.0
   98      3a        12        Clay        2       6     50.0       30       20.0
   99      3a        12        Clay        2       8     30.0       50       50.0
  100      3a        12        Clay        2      10     30.0       20       20.0
  101      3b        12        Loam        1       2     10.0       10       10.0
  102      3b        12        Loam        1       4     10.0       10       10.0
  103      3b        12        Loam        1       6     10.0       10       10.0
  104      3b        12        Loam        1       8     10.0       10       10.0
  105      3b        12        Loam        1      10     10.0       10       10.0
  106      3b        12        Loam        2       2     10.0       10        6.0
  107      3b        12        Loam        2       4     10.0       10       10.0
  108      3b        12        Loam        2       6     10.0       10        6.0
  109      3b        12        Loam        2       8     10.0       10       10.0
  110      3b        12        Loam        2      10     10.0       10       20.0
  111      3b        12        Clay        1       2     10.0        5       20.0
  112      3b        12        Clay        1       4     20.0       20       85.0
  113      3b        12        Clay        1       6     10.0        5       90.0
  114      3b        12        Clay        1       8     20.0       85       45.0
  115      3b        12        Clay        1      10     20.0       30       95.0
  116      3b        12        Clay        2       2     20.0       10        5.0
  117      3b        12        Clay        2       4      5.0       10       30.0
  118      3b        12        Clay        2       6     95.0       95       10.0
  119      3b        12        Clay        2       8     95.0       60       95.0
  120      3b        12        Clay        2      10     90.0       95       95.0
```

	Sampling	Rain				Infiltration time (3 reps)		
Obs	Period	pass	Soiltype	EC	SAR	y1	y2	y3
121	4a	12	Loam	1	2	13.0	1	5.0
122	4a	12	Loam	1	4	7.0	11	6.0
123	4a	12	Loam	1	6	10.0	11	8.0
124	4a	12	Loam	1	8	12.0	14	15.0
125	4a	12	Loam	1	10	10.0	10	15.0
126	4a	12	Loam	2	2	6.0	4	6.0
127	4a	12	Loam	2	4	8.0	8	6.0
128	4a	12	Loam	2	6	10.0	4	10.0
129	4a	12	Loam	2	8	8.0	11	6.0
130	4a	12	Loam	2	10	11.0	8	11.0
131	4a	12	Clay	1	2	2.0	1	2.0
132	4a	12	Clay	1	4	4.0	1	2.0
133	4a	12	Clay	1	6	6.0	2	1.0
134	4a	12	Clay	1	8	4.0	2	4.0
135	4a	12	Clay	1	10	1.0	6	4.0
136	4a	12	Clay	2	2	6.0	2	1.0
137	4a	12	Clay	2	4	4.0	4	1.0
138	4a	12	Clay	2	6	6.0	2	1.0
139	4a	12	Clay	2	8	6.0	4	4.0
140	4a	12	Clay	2	10	6.0	2	4.0
141	4b	14	Loam	1	2	15.0	14	14.0
142	4b	14	Loam	1	4	16.0	18	15.0
143	4b	14	Loam	1	6	16.0	18	17.0
144	4b	14	Loam	1	8	17.0	18	18.0
145	4b	14	Loam	1	10	18.0	19	18.0
146	4b	14	Loam	2	2	12.0	14	12.0
147	4b	14	Loam	2	4	12.0	14	14.0
148	4b	14	Loam	2	6	17.0	16	17.0
149	4b	14	Loam	2	8	16.0	17	14.0
150	4b	14	Loam	2	10	17.0	17	17.0
151	4b	16	Clay	1	2	23.0	18	14.0
152	4b	16	Clay	1	4	27.0	39	28.0
153	4b	16	Clay	1	6	24.0	60	70.0
154	4b	16	Clay	1	8	25.0	100	45.0
155	4b	16	Clay	1	10	95.0	110	90.0
156	4b	16	Clay	2	2	17.0	20	19.0
157	4b	16	Clay	2	4	24.0	37	38.0
158	4b	16	Clay	2	6	30.0	90	35.0
159	4b	16	Clay	2	8	30.0	130	140.0
160	4b	16	Clay	2	10	90.0	80	80.0
161	5a	16	Loam	1	2	27.0	23	23.0
162	5a	16	Loam	1	4	27.0	29	24.0
163	5a	16	Loam	1	6	24.0	31	29.0
164	5a	16	Loam	1	8	32.0	29	26.0
165	5a	16	Loam	1	10	30.0	25	27.0
166	5a	16	Loam	2	2	27.0	23	26.0
167	5a	16	Loam	2	4	26.0	24	24.0
168	5a	16	Loam	2	6	24.0	25	27.0
169	5a	16	Loam	2	8	25.0	29	26.0
170	5a	16	Loam	2	10	32.0	32	26.0
171	5a	16	Clay	1	2	65.0	74	5.4
172	5a	16	Clay	1	4	37.0	154	16.0
173	5a	16	Clay	1	6	43.0	32	154.0
174	5a	16	Clay	1	8	12.0	79	65.0
175	5a	16	Clay	1	10	154.0	205	84.0
176	5a	16	Clay	2	2	2.1	65	138.0
177	5a	16	Clay	2	4	11.0	138	125.0
178	5a	16	Clay	2	6	11.0	149	201.0
179	5a	16	Clay	2	8	43.0	211	211.0
180	5a	16	Clay	2	10	74.0	139	79.0

Obs	Sampling Period	Rain pass	Soiltype	EC	SAR	Infiltration time (3 reps)		
						y1	y2	y3
181	5b	18	Loam	1	2	5.0	5	5.0
182	5b	18	Loam	1	4	10.0	12	5.0
183	5b	18	Loam	1	6	10.0	10	5.0
184	5b	18	Loam	1	8	6.0	10	10.0
185	5b	18	Loam	1	10	10.0	7	10.0
186	5b	18	Loam	2	2	5.0	7	5.0
187	5b	18	Loam	2	4	5.0	20	5.0
188	5b	18	Loam	2	6	5.0	15	5.0
189	5b	18	Loam	2	8	15.0	10	10.0
190	5b	18	Loam	2	10	20.0	18	30.0
191	5b	18	Clay	1	2	125.0	210	195.0
192	5b	18	Clay	1	4	345.0	315	10.0
193	5b	18	Clay	1	6	345.0	15	125.0
194	5b	18	Clay	1	8	375.0	375	375.0
195	5b	18	Clay	1	10	315.0	375	345.0
196	5b	18	Clay	2	2	125.0	285	70.0
197	5b	18	Clay	2	4	5.0	165	165.0
198	5b	18	Clay	2	6	125.0	315	195.0
199	5b	18	Clay	2	8	10.0	285	225.0
200	5b	18	Clay	2	10	125.0	5	375.0
201	6a	12	Loam	1	2	27.0	25	14.0
202	6a	12	Loam	1	4	26.0	14	24.0
203	6a	12	Loam	1	6	25.0	26	28.0
204	6a	12	Loam	1	8	27.0	27	25.0
205	6a	12	Loam	1	10	24.0	25	26.0
206	6a	12	Loam	2	2	25.0	21	25.0
207	6a	12	Loam	2	4	14.0	25	25.0
208	6a	12	Loam	2	6	28.0	25	29.0
209	6a	12	Loam	2	8	25.0	27	26.0
210	6a	12	Loam	2	10	27.0	27	28.0
211	6a	12	Clay	1	2	80.0	80	40.0
212	6a	12	Clay	1	4	170.0	140	60.0
213	6a	12	Clay	1	6	70.0	90	140.0
214	6a	12	Clay	1	8	170.0	220	215.0
215	6a	12	Clay	1	10	140.0	215	150.0
216	6a	12	Clay	2	2	70.0	95	80.0
217	6a	12	Clay	2	4	70.0	80	80.0
218	6a	12	Clay	2	6	70.0	140	80.0
219	6a	12	Clay	2	8	95.0	155	220.0
220	6a	12	Clay	2	10	140.0	70	230.0
221	6b	12	Loam	1	2	10.0	3	10.0
222	6b	12	Loam	1	4	3.0	20	20.0
223	6b	12	Loam	1	6	20.0	25	9.0
224	6b	12	Loam	1	8	20.0	20	3.0
225	6b	12	Loam	1	10	30.0	20	10.0
226	6b	12	Loam	2	2	20.0	3	20.0
227	6b	12	Loam	2	4	15.0	20	20.0
228	6b	12	Loam	2	6	15.0	20	20.0
229	6b	12	Loam	2	8	10.0	20	20.0
230	6b	12	Loam	2	10	20.0	20	20.0
231	6b	12	Clay	1	2	3.0	3	7.0
232	6b	12	Clay	1	4	3.0	3	7.0
233	6b	12	Clay	1	6	3.0	7	10.0
234	6b	12	Clay	1	8	7.0	20	15.0
235	6b	12	Clay	1	10	3.0	25	3.0
236	6b	12	Clay	2	2	3.0	7	3.0
237	6b	12	Clay	2	4	7.0	3	3.0
238	6b	12	Clay	2	6	7.0	7	3.0
239	6b	12	Clay	2	8	3.0	15	30.0
240	6b	12	Clay	2	10	3.0	7	7.0

Appendix B

Undisturbed core bulk density, g cm^3

Loam 2003		rep 1	rep 2	rep 3	ave	Loam 2004	rep 1	rep 2	rep 3	ave
EC	SAR									
1	2	1.41	1.39	1.39	1.40		1.33	1.34	1.37	1.35
1	4	1.40	1.42	1.38	1.40		1.33	1.33	1.31	1.32
1	6	1.40	1.41	1.41	1.41		1.34	1.37	1.35	1.35
1	8	1.42	1.40	1.44	1.42		1.37	1.31	1.38	1.35
1	10	1.43	1.43	1.43	1.43		1.35	1.34	1.36	1.35
2	2	1.39	1.40	1.39	1.39		1.38	1.37	1.33	1.36
2	4	1.40	1.38	1.37	1.38		1.33	1.33	1.35	1.34
2	6	1.41	1.36	1.36	1.38		1.36	1.34	1.39	1.36
2	8	1.39	1.39	1.38	1.39		1.35	1.35	1.35	1.35
2	10	1.35	1.35	1.41	1.37		1.37	1.36	1.35	1.36
control		1.42	1.36	1.36	1.38		1.36	1.35	1.37	1.36

Clay 2003		rep 1	rep 2	rep 3	ave	Clay 2004	rep 1	rep 2	rep 3	ave
EC	SAR									
1	2	1.23	1.18	1.18	1.20		1.25	1.32	1.26	1.28
1	4	1.26	1.22	1.26	1.25		1.24	1.17	1.32	1.24
1	6	1.18	1.23	1.19	1.20		1.22	1.18	1.22	1.21
1	8	1.17	1.17	1.18	1.17		1.27	1.27	1.31	1.28
1	10	1.20	1.17	1.19	1.19		1.25	1.18	1.24	1.22
2	2	1.30	1.24	1.32	1.29					
2	4	1.31	1.26	1.30	1.29					
2	6	1.29	1.30	1.32	1.30					
2	8	1.23	1.25	1.31	1.26					
2	10	1.31	1.32	1.30	1.31					
control		1.24	1.26	1.20	1.23					

Appendix C

Montana Undisturbed Core Data

Hydraulic conductivity, cm/day

2003		rep 1	rep 2	rep 3	ave
	SAR				
EC 1	2	127.20	108.96	79.44	105.20
sand	4	133.68	70.32	114.48	106.16
Irrig	6	64.32	85.20	54.24	67.92
	8	45.60	63.12	51.36	53.36
	10	31.68	74.88	55.20	53.92
EC 2	2	207.84	220.80	106.08	178.24
sand	4	124.32	178.56	165.36	156.08
Irrig	6	127.44	159.12	157.68	148.08
	8	83.52	121.68	199.68	134.96
	10	81.60	93.84	86.40	87.28
EC 1	2	84.96	104.64	78.24	89.28
sand	4	*126.00*	61.68	89.28	*92.32*
Rain	6	66.48	59.04	41.76	55.76
	8	49.68	47.52	58.08	51.76
	10	28.32	61.68	46.56	45.52
EC 2	2	154.08	174.00	75.60	134.56
sand	4	84.72	123.12	115.44	107.76
Rain	6	81.12	76.08	99.60	85.60
	8	41.04	58.08	75.36	58.16
	10	30.24	41.28	39.12	36.88
CONsand Irrig		122.88	124.56	140.16	129.20
CONclay Irrig		0.470	0.080	*43.100*	*14.550*

Hydraulic conductivity, cm/day

2004		rep 1	rep 2	rep 3	ave
	SAR				
EC 1	2	23.28	66.48	10.80	33.52
sand	4	19.44	68.16	44.88	44.16
Irrig	6	14.40	14.64	40.56	23.20
	8	17.28	26.88	7.92	17.36
	10	15.84	18.72	19.20	17.92
EC 2	2	16.32	66.48	65.04	49.28
sand	4	69.12	*95.52*	47.52	*70.72*
Irrig	6	39.12	76.32	40.08	51.84
	8	46.56	48.00	57.84	50.80
	10	27.60	24.96	33.60	28.72
EC 1	2	15.60	37.92	6.48	20.00
sand	4	7.92	31.92	21.12	20.32
Rain	6	7.44	5.52	15.12	9.36
	8	12.48	9.84	5.28	9.20
	10	4.56	7.92	25.20	12.56
EC 2	2	11.52	51.84	32.64	32.00
sand	4	54.72	*92.40*	20.40	*55.84*
Rain	6	16.80	46.08	25.68	29.52
	8	18.72	23.52	31.92	24.72
	10	12.24	16.32	18.96	15.84
CONsand Irrig		19.20	24.96	30.72	24.96
CONclay Irrig		1.20	0.89	0.00	0.70

2003					
EC 1	2	1.89	0.04	0.05	0.66
clay	4	1.27	5.73	1.40	2.80
Irrig	6	0.96	0.19	5.72	2.29
	8	7.81	0.05	0.44	2.77
	10	1.68	3.25	0.05	1.66
EC 2	2	1.87	12.25	5.61	6.58
clay	4	0.22	0.74	9.94	3.63
Irrig	6	0.01	5.15	3.72	2.96
	8	4.94	0.02	5.28	3.41
	10	1.27	1.53	1.18	1.33
EC 1	2	0.78	0.00	0.03	0.27
clay	4	0.44	0.74	0.48	0.55
Rain	6	0.03	0.02	0.88	0.31
	8	0.63	0.04	0.07	0.24
	10	0.08	0.68	0.01	0.26
EC 2	2	3.64	0.67	0.35	1.55
clay	4		2.06	0.98	1.01
Rain	6		1.64	0.92	0.85
	8	3.71	0.02	0.55	1.43
	10	0.06	0.05	0.29	0.13
CONsand Rain		81.36	103.44	129.12	104.64
CONclay Rain			0.04	2.50	0.85

2004					
EC 1	2	*13.49*	2.06	1.78	*5.78*
clay	4	0.74	*22.92*	2.09	*8.58*
Irrig	6	6.29	6.26	3.17	5.24
	8	6.65	0.86	0.79	2.77
	10	7.22	2.45	1.87	3.85
EC 2	2				
clay	4				
Irrig	6				
	8				
	10				
EC 1	2	*6.00*	0.77	0.86	*2.54*
clay	4	1.37	*9.10*	1.06	*3.84*
Rain	6	0.60	1.68	1.13	1.14
	8	1.99	0.53	0.50	1.01
	10	2.38	0.91	0.62	1.30
EC 2	2				
clay	4				
Rain	6				
	8				
	10				
CONsand Rain		13.68	15.36	19.68	16.24
CONclay Rain					

(Values in italics omitted from graphs but included in statistical analysis)