Ion Partitioning among Soil and Plant Components under Drip, Furrow, and Sprinkler Irrigation Regimes: Field and Modeling Assessments

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ABSTRACT

Soil and water resources can be severely degraded by salinity when total salt input exceeds output in irrigated agriculture. This study was conducted to examine partitioning of Ca^{2+}, Na^{+}, and Cl^{-} between soil and soybean [Glycine max (L.) Merr.] plants under different irrigation regimes with both field and modeling assessments. In drip and sprinkler treatments, the irrigation water was salinized with NaCl and $CaCl_2$ salts to simulate a Cl^{-} and Na^{+} dominant saline drainage water. In the furrow irrigation treatment, the soil was salinized, prior to planting, with NaCl and $CaCl_2$ salts to simulate a Cl^{-} and Na^{+} dominant saline soil. A total of 756 soil and 864 plant samples were collected and analyzed for the salt ions to obtain ion partitioning and mass balance assessments. Modeling of salt ion uptake by plants and distribution in the soil profile was performed with a two-dimensional solute transport model for the three irrigation regimes. Results indicated that about 20% of the applied Ca^{2+} was recovered in harvested soybean biomass in all treatments. Plant uptake of either Na^{+} or Cl^{-} was less than 0.5% in the drip and furrow, and about 2% in the sprinkler irrigation treatment. Significant increases in soil salinity were found in the sprinkler plot that received the highest cumulative amount of salts. Simulated ion distributions in the soil were comparable with the measurements. Compared with the total seasonal salt input, mass balances between 65 and 108% were obtained. Most salt inputs accumulate in the soil, and need to be removed periodically to prevent soil salinization.

In irrigated agriculture, leaching is usually required to remove excessive amounts of soluble salts from accumulating in the soil to levels that inhibit plant growth. Agricultural drainage waters often contain high concentrations of salt ions (Ayars et al., 1993; Skarie et al., 1986). Land disposal of the saline drainage water can lead to serious environmental consequences since dissolved ion species such as sodium, calcium, and chloride may accumulate to extremely high levels, becoming toxic to plant growth. An alternative and sustainable method to disposal is to reuse saline drainage water for plant growth (Grieve and Suarez, 1997; Rhoades et al., 1988; Shennan et al., 1995).

To maintain soil and crop productivity, a critical question for saline drainage water reuse is to determine the fate of major and toxic salt ions, which is related to the potential effect on soil salinization, plant growth, crop quality, and yield. The rate of drainage water reuse and salt ion redistribution in the soil profile are directly related to irrigation method. Differences in the dynamics of salt transport among irrigation methods can be determined either experimentally with direct field measurements (Bernstein and Francois, 1973) or numerically with mathematical simulations (Annandale et al., 1999; Wang et al., 1997). In drip irrigation, the placement of drip lines relative to crop rows is important to the spatial distribution of soil salinity. For row crops, the drip emitters are often placed at the center of row beds, below which most salt loading or leaching would probably occur. In sprinkler irrigation, water is applied over the entire soil surface. A relatively uniform salt loading or leaching may be expected, which would result in similar salinity patterns either in the row or furrow locations of the field. Another conventional method of applying water is by furrow irrigation. However, it may not be very suitable for saline drainage water reuse because it may generate large quantities of runoff tail water. An option with furrow irrigation is to recirculate the tail water for irrigation of salt tolerant crops. Furrow irrigation with good quality (or low salt content) water in a saline soil can affect salt redistribution and salt ion uptake by plants. In furrow irrigation with good quality water, subsurface salt leaching should be more significant at the furrow locations. However, lateral water movement due to capillary effect may also generate sufficient leaching in the plant root zone below the field row beds. Surface evaporation would tend to reconcentrate the salts near the soil surface on the field row beds.

High levels of salinity can significantly reduce plant growth such as shoot and root development for many plant species including soybean (Shannon, 1997). A main concept in saline drainage water reuse is to use the brackish water as a partial or complete supplement of good quality irrigation water, without causing significant yield reductions. The extent and timing of drainage reuse in lieu of good quality water depend on the plant species or potential for salt tolerance (Francois et al., 1994) and soil properties. From a conservation perspective, it is imperative to know the partitioning of salt ions among soil and plant components when the salts originate from the reused saline drainage water. It is also important to determine the relative rate of leaching and plant uptake of salt ions from saline soil.

The objective of this study was to determine the partitioning of salt ions between soil and plants under different irrigation regimes. More specifically, the study was conducted to quantify the fate of calcium, sodium, and chloride when applied with the irrigation water under drip and sprinkler irrigation or applied to the soil prior to furrow irrigation with good quality water.

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Abbreviations: DAP, days after planting; EC, electrical conductivity; ET, evapotranspiration; TDR, time domain reflectometry.

MATERIALS AND METHODS

Field Assessment

A field experiment was conducted between June to October 1998 at a University of California Agricultural Experiment Station. Furrow beds at a 0.8-m center-to-center spacing were constructed at the beginning of the experiment for the drip, furrow, and sprinkler irrigation treatments. Each irrigation treatment contained a control plot irrigated with good quality water and a salinity plot irrigated with saline water (drip and sprinkler plots) or one in which the soil was salinized prior to the season (furrow-salinity plot). Soil salinization was achieved by applying a concentrated NaCl and $CaCl_2$ (1:1 weight ratio) solution uniformly across the plot with a sprinkler system, which increased the electrical conductivity of saturation extracts (EC_e) to 6 dS m^{-1} for the surface 10 cm of soil. The irrigation source water contained low salinity (EC_w = approximately 0.5 dS m^{-1}), hereafter referred to as good quality water. This water was used to irrigate both the control- and salinity-furrow plots for the duration of the experiment.

To determine plant uptake of salt ions, soybean [*Glycine max* (L.) Merr. cv. Manokin] was planted at the center of the row beds at about a 4-cm depth. Volumetric soil water content at the time of planting averaged 0.10 cm^3 cm^{-3} at the 0- to 5-cm depth range. A line of drip tape was placed on the soil surface directly above the planted soybean seeds in the drip irrigation plots. The drip system supplied water to the field plots at 0.62 L h^{-1} m^{-1} rate or 0.78 mm h^{-1} on an area basis. Application rate for the sprinkler system was 5.08 mm h^{-1}. In the first 40 days after planting (DAP), a sprinkler system was also installed in the furrow plots to help for soybean emergence and seedling establishment, and all irrigation plots received the good quality water during this time. The sprinkler system in the furrow plots was replaced with furrow irrigation at 40 DAP, and one each of the drip and sprinkler plots continued to receive the good quality water, hereafter called drip-control and sprinkler-control plot. The remaining drip and sprinkler plots started to receive saline water. Water salinization was achieved by injecting a concentrated NaCl and $CaCl_2$ solution (at 1:1 weight ratio) to the irrigation stream, simulating a Cl^- and Na^+ dominant saline drainage water. The degree of salinization was predetermined to produce a final saline irrigation water with an EC_w value of about 4 dS m^{-1}, which would result in an EC_e close to the threshold value for soybean salt tolerance (Maas and Hoffman, 1977). The relative ratio of the three salt ions or Ca^{2+} to Na^+ to Cl^- was 1:2:4 on a molar basis or 0.18:0.20:0.62 on a mass basis. Detailed information on irrigation scheduling and salt application is listed in Table 1.

Nine soybean plants were harvested from each irrigation and salinity treatment at 40, 60, 80, and 102 DAP. These harvest dates represented soybean maximum vegetative (40 DAP) and reproductive growth stages (flowering at 60, podding at 80, and seed filling at 102 DAP). After each harvest, the plant samples were separated into leaves, stems, roots, and pods (if present); thoroughly washed with deionized water; dried to a constant weight at 70°C in a forced-air oven; then weighed and ground to powders for chemical analyses. A total of 864 tissue samples were obtained during the course of the experiment. Concentrations of Ca^{2+} and Na^+ were determined for each plant sample on nitric–perchloric acid digests by inductively coupled plasma optical emission spectrometry (ICPOES). Chloride determinations were made on dilute nitric–acetic acid extracts by coulometric–amperometric titration. Total plant Ca, Na, and Cl contents were calculated for each harvest from the concentration measurements, plant dry weights, and plant density with a generic equation:

$$M_i = \rho \sum_{1}^{n=4} C_{ij}\, \mathrm{DW}_{ij} \qquad [1]$$

where M_i represents the total ion content (either Ca^{2+}, Na^+, or Cl^-) in a plant and subscript i designates irrigation method. The term ρ is plant density, C_{ij} is the ion concentration, and DW_{ij} is the dry weight for a plant part designated by subscript j. The total plant ion content is a summation of ions from all plant parts (n = 1 to 4) including leaf, pod, stem, and root. Calcium, Na, and Cl content from the last harvest (102 DAP) was used for the final mass balance assessment. Soybean leaves started to change color due to senescence soon after the last harvest and defoliation started to occur.

To determine changes of Ca, Na, and Cl content in the soil profile, soil samples were taken at the end of the experiment at three randomly selected locations from each irrigation and salinity treatment, including the control plots (18 locations in total). Three replicated cores were taken from each sample location at the center of both field row and furrow. Each core was separated into seven samples between 0-, 5-, 10-, 20-, 30-, 50-, 75-, and 100-cm depths. A total of 756 soil samples was taken for the mass balance assessment. Solution extracts were collected from saturation pastes made from each sample. Concentrations of Ca^{2+}, Na^+, and Cl^- in the solution extracts were analyzed with the ICPOES and coulometric–amperometric titration, respectively, following procedures similar to the plant analyses. Total soil Ca, Na, and Cl contents were calculated from the ion concentration, total soil volume from each sampling increment, and soil bulk density. The calculations were made with a formula similar to Eq. [1] in which ρ was replaced with soil bulk density and moved into the summation since it changed with soil depth. The term DW_{ij} was replaced with the soil volume of each depth increment designated by subscript j and n = 1 to 7. Changes of soil Ca, Na, and Cl content due to the salinity addition were determined as the difference between the salinity and control plot for each irrigation regime.

Time domain reflectometry (TDR) probes were installed in each plot to provide hourly measurements of soil water content and apparent electrical conductivity (EC_a). The frequent soil water content measurements were used for irrigation scheduling. Irrigation was initiated when soil water content in the plant rootzone dropped to about 0.12 cm^3 cm^{-3}. At this water content, soil water matric potential was about 50 kPa according to the soil retention data from Wang et al. (1998).

Modeling Assessment

Ion distribution in the soil and partitioning between soil and plants involve many complex processes including solute transport under different irrigation methods, root water uptake as functions of evapotranspiration (ET), and ion uptake or exclusion required for plant development. Model simulation provides a means of integrating these processes and exploring potential scenarios that are otherwise experimentally prohibitive to conduct. The numeric code CHAIN_2D (Simunek and van Genuchten, 1994) was used with boundary conditions similar to Wang et al. (1997) for simulation of salt ion transport and distribution in the soil considering root uptake of both water and salt ions. In the model, water flow was computed with the modified form of Richards' equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left[K(h, x, y)\frac{\partial h}{\partial y} + K(h, x, y)\right] - S \qquad [2]$$

where θ is the volumetric water content, h is the soil water matric potential, $K(h,x,y)$ is the unsaturated hydraulic conduc-

Table 1. Irrigation and salt application during the soybean field experiment.

Day of year	Irrigation† Drip	Irrigation† Furrow	Irrigation† Sprinkler	Rain	Salinization‡ Drip	Salinization‡ Furrow	Salinization‡ Sprinkler
	mm				g m^{-2}		
128		24				181	
132				12			
133				12			
162§							
163	5	25	17				
164		9					
167				2			
168	2	4	8				
171	1	2	5				
172		10					
174	5	14	29				
178	3	14	19				
182	2	8	15				
183	4	11	23				
186	2	6	14				
188	5	15	16				
190	3	10	20				
192	3	10	20				
195	2	7	13				
197	7	7	15				
199	4	14	28				
201				1			
204		172	30				41
205	6				14		
210	6				14		
211			30				41
212		141					
213		141					
217	8				14		
218		117	83				41
219		109					
220	9				14		
221				14			
223	7				14		
224			20				41
226	5	94			14		
227		188					
228		188					
229	6	70			14		
231			25				41
232	6				14		
236		94	33				41
237	6	94			14		
239			51				41
240	12				14		
241	7						
243	7				14		
244		43	33				41
245		145					
246	7				14		
247			25				41
251	6				14		
252		66	23				41
253		59					
254	7				14		
257	6				14		
258			20				41
259		94					
260	6				14		
261			22				41
264	6				14		
266	6	39			14		
267		133	22				41
268	6				14		
271	7				14		
272		94					
273	6	80			14		
274			22				41
275	6				14		
280	6				14		
Total	208	2357	681	41	322	181	574

† Irrigation rate was 0.78, 7.82, and 5.08 mm h^{-1} for drip, furrow, and sprinkler, respectively. Application rates for drip and furrow treatments were extrapolated to the whole surface area, and the rate for furrow irrigation was calculated from inflow rate, not excluding tail water.
‡ Salinization was accomplished by injecting a concentrate solution of NaCl and $CaCl_2$ at a 1:1 weight ratio through the irrigation systems.
§ Soybean seeds planted.

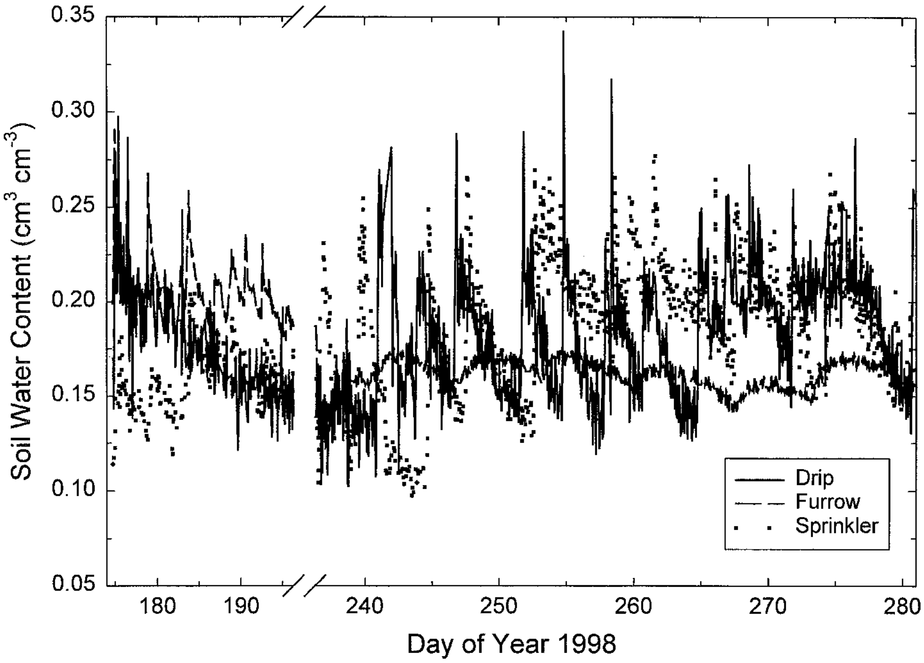

Fig. 1. Temporal variations of soil water content measured with time domain reflectometry (TDR) at 10 cm below the center of field rows under drip, furrow, and sprinkler irrigation.

tivity at potential h and location (x,y), t is time, and S a sink term to account for root water uptake. Based on Wang et al. (1998), soil physical properties used in the model input for water and solute transport were $\theta_r = 0.077$ cm^3 cm^{-3}, $\theta_s = 0.371$ cm^3 cm^{-3}, $n = 1.373$, $\alpha = 0.357$ cm^{-1}, $K_s = 41.9$ cm d^{-1}, and $\rho_s = 1.5$ g cm^{-3}, where θ_r and θ_s are residual soil water content and that at saturation, n and α are empirical parameters for the soil water retention function (van Genuchten, 1980), K_s is hydraulic conductivity at water saturation, and ρ_s is soil bulk density.

Transport and distribution of salt ions in the soil and uptake by plant roots were computed with the following equation:

$$\frac{\partial \theta\, C_s}{\partial t} = \frac{\partial}{\partial x}\left[\theta\, D_s \frac{\partial\, C_s}{\partial\, y}\right] - \frac{\partial\, q\, C_s}{\partial\, y} - SC_r \qquad [3]$$

where C_s is the solution salt ion concentration in the soil, D_s is the diffusion–dispersion coefficient for both x and y directions, q is the convective volumetric flux, and C_r is the solution salt ion concentration taken up by plant roots.

To generate input information for plant water use, a weather station was installed at the field site for measurements of net radiation (R_n), air temperature (T_a) and relative humidity (h_r), wind speed (u), and soil heat flux (G). Soybean plant height and leaf area index (LAI) was measured biweekly during the growing season, with LAI measured with an LAI-2000 Canopy Analyzer (LI-COR, Lincoln, NE), to facilitate ET computation and for partitioning ET into separate components of evaporation (E) and transpiration (T or the sink term S) required as separate input parameters in the simulation model. Estimation of ET was performed with the modified Penman–Monteith equation (Campbell and Norman, 1998):

$$\mathrm{ET} = \frac{s(R_n - G) + \gamma * \lambda\, g_v D_v/p_a}{s + \gamma *} \qquad [4]$$

where s = slope of the saturation mole fraction at apparent atmospheric pressure (p_a), γ^* = apparent psychrometer constant, λ = latent heat of vaporization of water, g_v = vapor conductance of the canopy, and D_v = vapor pressure deficit. Parameters s and D_v were determined with measurements of T_a and h_r and the Tetens formula for saturation vapor pressure:

$$s = \frac{abc}{p_a\,(c + T_a)^2} \exp\left(\frac{bT_a}{c + T_a}\right) \qquad [5]$$

$$D_v = a\,(1 - h_r) \exp\left(\frac{bT_a}{c + T_a}\right) \qquad [6]$$

where coefficients $a = 0.611$ kPa, $b = 17.502$, and $c = 240.97$°C.

Vapor conductance of the canopy (g_v) was computed from stomatal conductance (g_s) and boundary layer aerodynamic conductance (g_a):

$$g_v = \frac{1}{\dfrac{1}{g_s} + \dfrac{1}{g_a}} \qquad [7]$$

Whereas soybean stomatal conductance was assumed to be 0.2 mol m^{-2} s^{-1} (Kelliher et al., 1995; Coale et al., 1984), the aerodynamic conductance was calculated with:

$$g_a = \frac{k^2\, \hat{\rho}\, u(z)}{\left[\ln\left(\dfrac{z - d}{z_M}\right) + \Psi_M\right]\left[\ln\left(\dfrac{z - d}{z_H}\right) + \Psi_H\right]} \qquad [8]$$

where k = von Karman constant (0.4), $\hat{\rho}$ = molar density of air, z = height of wind measurement, d = zero-plane displacement height, and $z_{M,H}$ and $\Psi_{M,H}$ are roughness lengths and profile diabatic correction factors for momentum and heat, respectively. Separation of evapotranspiration (ET) into evaporation (E) and transpiration (T or S in Eq. [2] and [3]) was accomplished with the empirical equation of Campbell (1985):

$$E = \mathrm{ET}\, \exp(-0.82\mathrm{LAI}) \qquad [9a]$$

and:

$$T = \mathrm{ET} - \mathrm{ET}\, \exp(-0.82\mathrm{LAI}) \qquad [9b]$$

Table 2. Measured and simulated overall maximum (θ_{max}), average (θ_{avg}), and minimum (θ_{min}) soil water content at a 10-cm depth, and amount of leaching (L) below the rootzone.†

		Irrigation		
Method	Variable	Drip	Furrow‡	Sprinkler
Measured	θ_{max}, cm^3 cm^{-3}	0.27	0.17	0.26
	θ_{avg}, cm^3 cm^{-3}	0.18	0.16	0.19
	θ_{min}, cm^3 cm^{-3}	0.14	0.15	0.13
	L, cm	2.12	NA	33.56
Simulated	θ_{max}, cm^3 cm^{-3}	0.33	0.21	0.30
	θ_{avg}, cm^3 cm^{-3}	0.21	0.19	0.23
	θ_{min}, cm^3 cm^{-3}	0.15	0.17	0.17
	L, cm	1.06	NA	18.30

† Amount of measured leaching (L) = total irrigation + rain − evapotranspiration (ET); amount of simulated leaching (L) = cumulative flux across the lower boundary.

‡ No leaching assessment for furrow irrigation because of incomplete runoff measurements.

For a soil solution EC_e of about 4 dS m^{-1}, according to Coale et al. (1984), the relative ion accumulation in soybean is 61:33:1 for Ca^{2+} to Cl^- to Na^+. This relative ratio was used in the model input to simulate ion uptake (or C_r in Eq. [3]) by the soybean roots.

RESULTS AND DISCUSSION

Soil Water Content and Salinity over Time

During the growing season, volumetric soil water content measured with TDR at 10 cm below the center of field row fluctuated between about 13 to 27% for the three irrigation regimes (Fig. 1). Overall average soil water content was 18 to 19% for the drip and sprinkler irrigation, and 16% for the furrow irrigation (Table 2). The relative difference between the maximum, average, and minimum soil water content values predicted with model simulation were similar to that of the measured values. Simulated total amount of water leached below the lower boundary was also comparable with measured values for the drip and sprinkler regimes (Table 2). The water balance assessment was not feasible for the furrow irrigation treatment because runoff measurements were not complete.

Compared with the drip irrigation, the sprinkler plots received about three times as much water and the furrow treatment received more than 10 times as much water during the experiment (Table 1). In terms of water conservation and delivering water directly to the plants, drip irrigation clearly had an advantage over the sprinkler and furrow irrigation regimes. In all treatments, there should have been sufficient soil water to maintain the salt ions in the solution phase and for redistribution in the soil profile. The soil water also should have been sufficient for soybean consumptive use even without consideration of reduced uptake due to salt stress. The total soil water potential that plants were subjected to in the salinity plots should have been lower than those in the control plots due to increases in osmotic potential induced by the salinization.

After the initiation of irrigation with saline water, measured apparent soil electrical conductivity (EC_a) exhibited strong cyclic variation following each irrigation event in the drip and sprinkler plots (Fig. 2). On the average, soil EC_a fluctuated between about 4 to 9 dS m^{-1}. Peak EC_a values corresponded closely to the infiltration wetting front. This was reasonable because in both the drip and sprinkler irrigation treatments, vertical water movement would carry the resident soil salts past the TDR probe at a 10-cm depth creating a pulse of high EC_a. After the wetting front passes the probe, the high soil EC_a should gradually decrease to that of the salinized irrigation water or about 4 dS m^{-1}. In the furrow plots, however, soil EC_a at 10 cm below the row

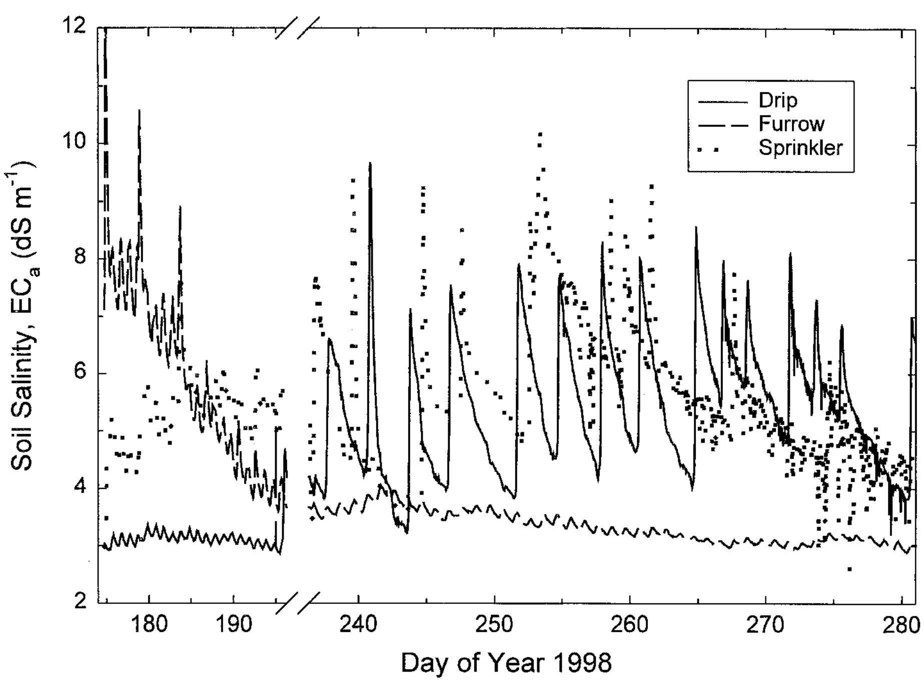

Fig. 2. Soil salinity measured as apparent electrical conductivity (EC_a) at 10 cm below the center of field rows under drip, furrow, and sprinkler irrigation.

center decreased drastically from about 8 to 4 dS m^{-1} in the first 40 d of the experiment. After this initial reduction, EC_a decreased very slowly from about 4 to 3 dS m^{-1} and did not respond to each irrigation cycle. Variations of soil salinity in the plant rootzone are important to plant growth. Whereas soybeans in the drip and sprinkler plots were subjected to periodic fluctuations in salinity ranging from about 4 to 9 dS m^{-1}, those in the furrow plot experienced high salinity during their seedling and initial vegetative growth, but low and relatively constant salinity in later development. The subsurface salinity history should have an integral effect on plant development and final salt ion uptake.

Ion Accumulation in Plants

Total Ca uptake by soybean plants increased over time in all irrigation systems (Fig. 3). In the drip and furrow irrigation treatments, plant Ca content started from approximately 30 mg $plant^{-1}$ at 40 DAP and rose to about 400 mg $plant^{-1}$ on 102 DAP. No significant difference was found between irrigation with either the saline or good quality water. In the sprinkler treatment, however, the amount of Ca started from about 40 mg $plant^{-1}$ and increased to 615 and 940 mg $plant^{-1}$ for irrigation with the saline or good quality water, respectively. A student t test for mean comparison further indicated that the Ca content in plants irrigated with the good quality water was significantly higher (P = 0.01) than plants irrigated with the saline water on both 80 and 102 DAP. Because Ca is an important structural component for higher plants, the reduction in Ca uptake in the sprinkler salinity plot was attributed to the retarded plant growth caused by salinity stress. The total plant dry weight (including leaves, stems, pods, and roots) was 82 and 46 g $plant^{-1}$ for the control and salinity plot, respectively. The 44% biomass reduction induced by salinity was in accordance with findings reported by Läuchli and Wieneke (1979).

Unlike Ca, the amount of Na taken up by the soybean plants was significantly less (Fig. 4). The amount of Na found on 102 DAP was only about 6.5 and 9.0 mg $plant^{-1}$ in the drip and furrow irrigation treatment, respectively. In the sprinkler treatment, however, more Na accumulated in the plants where Na concentration increased exponentially over time to 61 and 82 mg $plant^{-1}$ for the

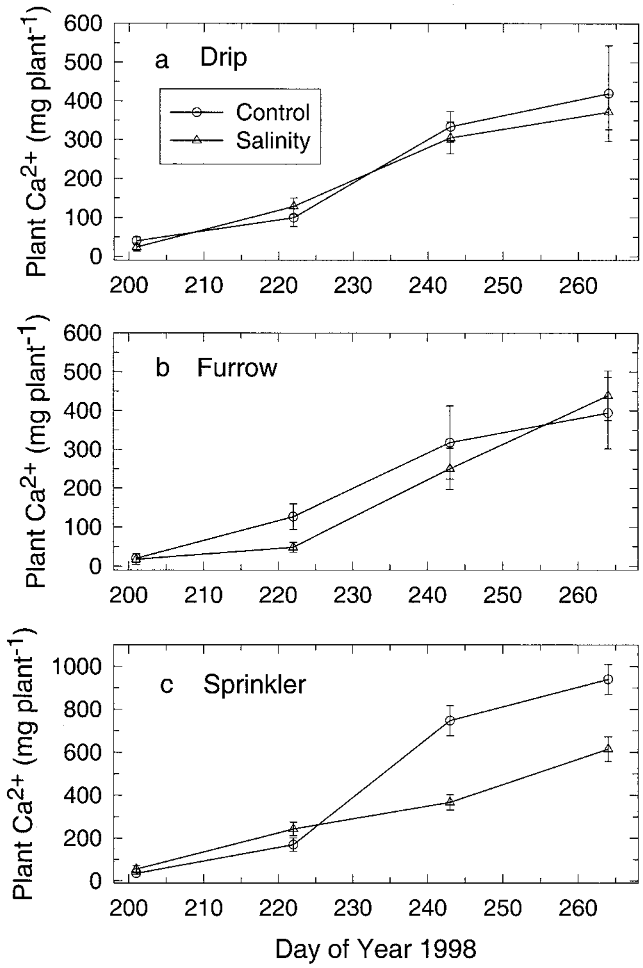

Fig. 3. Seasonal accumulation of calcium (Ca) in plant tissues under drip, furrow, and sprinkler irrigation with good quality (Control) and saline water (Salinity). Error bars = standard deviations (n = 9).

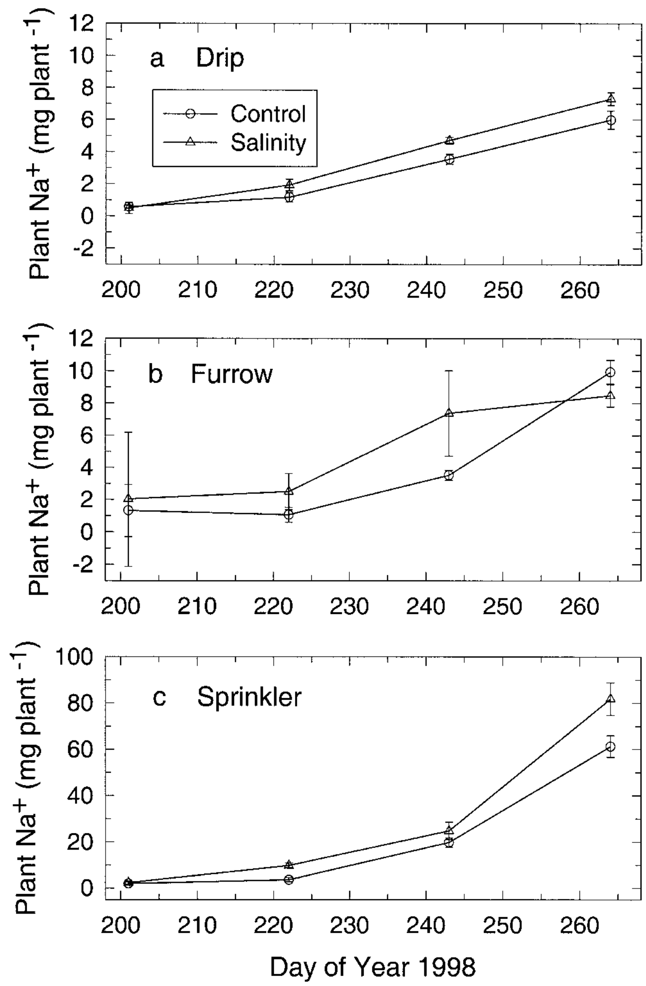

Fig. 4. Seasonal accumulation of sodium (Na) in plant tissues under drip, furrow, and sprinkler irrigation with good quality (Control) and saline water (Salinity). Error bars = standard deviations (n = 9).

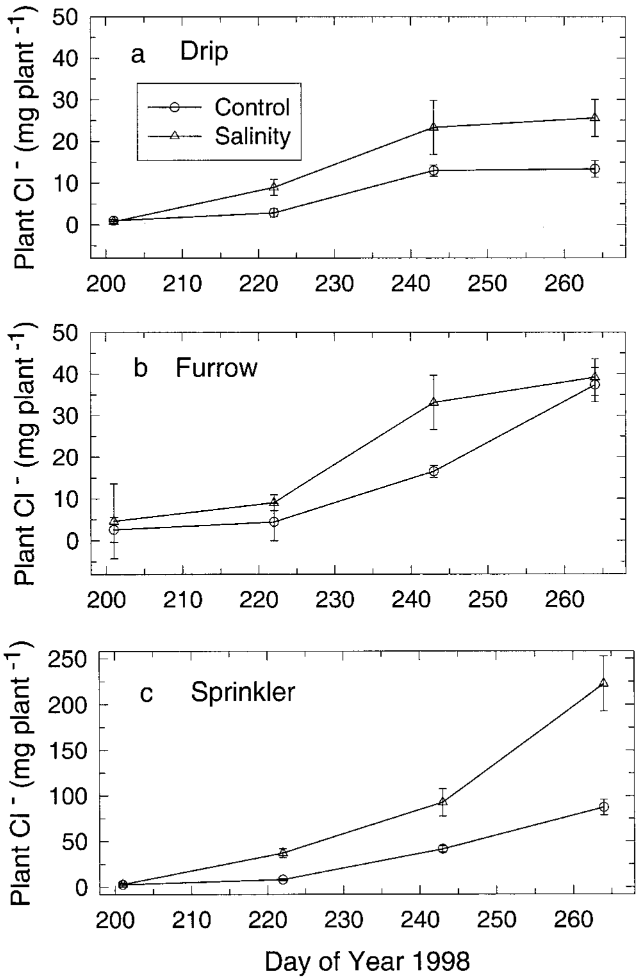

Fig. 5. Seasonal accumulation of chloride (Cl) in plant tissues under drip, furrow, and sprinkler irrigation with good quality (Control) and saline water (Salinity). Error bars = standard deviations (n = 9).

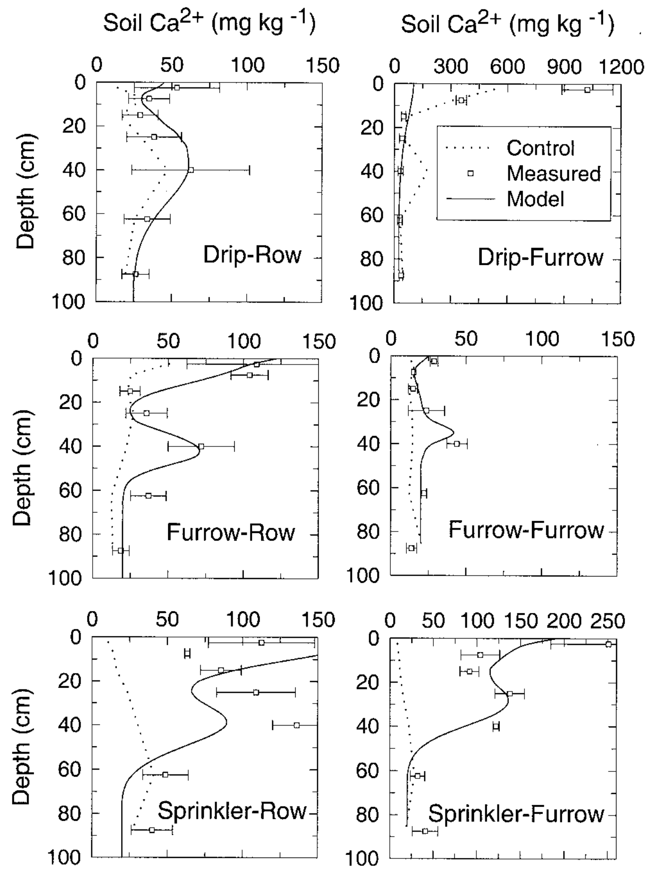

Fig. 6. Calcium (Ca) content under the row and furrow locations of the soil profile at the end of the growing season subjected to drip, furrow, and sprinkler irrigation with good quality (Control) and saline water (Measured ± SD and Model).

control and salinity treatment, respectively. The elevated Na accumulation in the sprinkler treatment was probably attributed to absorption by wetted leaves and stems. Foliar absorption of salt ions has been found to be a significant mechanism of salt accumulation in maize (*Zea mays* L.) and barley (*Hordeum vulgare* L.) (Benes et al., 1996). For soybean, ion absorption from the above-canopy sprinkler irrigation may be more pronounced because of the dense trichome hairs on leaves and stems. These trichomes can entrap the saline irrigation water allowing more time for ion absorption. Plants in the sprinkler control treatment also accumulated more Na because the good quality water contained about 40 mg L^{-1} Na^+.

The rate and ratio of chloride accumulation (Fig. 5) among irrigation and salinity treatments were similar to the sodium uptake. Under salinity, lower Cl content was found in the drip (26 mg $plant^{-1}$) and furrow (39 mg $plant^{-1}$) than in the sprinkler treatment (223 mg $plant^{-1}$) on 102 DAP. Chloride accumulation in the sprinkler control plot reached 87 mg $plant^{-1}$, which was higher than those in either the drip or the furrow control treatment. Again, the enhanced uptake was probably attributed to foliar absorption. Plants irrigated with the saline water in the drip and sprinkler treatment accumulated significantly more Cl (P = 0.01) than those irrigated with the good quality water. This was consistent with findings by Lessani and Marschner (1978) that higher substrate ion concentrations would translate to more uptake and accumulation in plant tissues. High Cl^- concentrations in soybean tissue can lead to leaf chlorosis and reduction in photosynthesis (Parker et al., 1983). In fact, leaf scorch was observed near the end of the growing season on the perimeter of the sprinkler plot irrigated with the saline water. Similar foliar damage was reported by Nielson and Cannon (1975) on edges of alfalfa irrigated with saline water.

Salt Ion Distribution and Buildup in the Soil

Since soil chemical processes of cation exchange and dissolution–precipitation were not considered, the discussion is limited to qualitative examination of the individual ion trends and predictions. Under drip irrigation, a small increase in Ca^{2+} was found under field rows by both soil sampling and model simulation, and model simulation slightly overpredicted the Ca buildup at a 10- to 40-cm depth (Fig. 6). Extremely high Ca^{2+} was measured near the soil surface at the furrow locations (to about 1000 mg kg^{-1}); however, no significant differ-

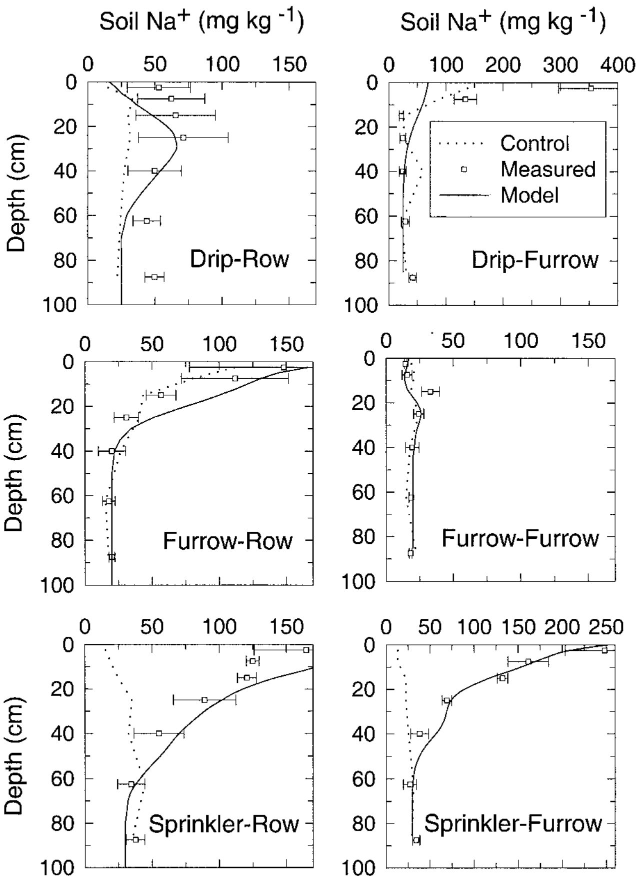

Fig. 7. Sodium (Na) content under the row and furrow locations of the soil profile at the end of the growing season subjected to drip, furrow, and sprinkler irrigation with good quality (Control) and saline water (Measured ± SD and Model).

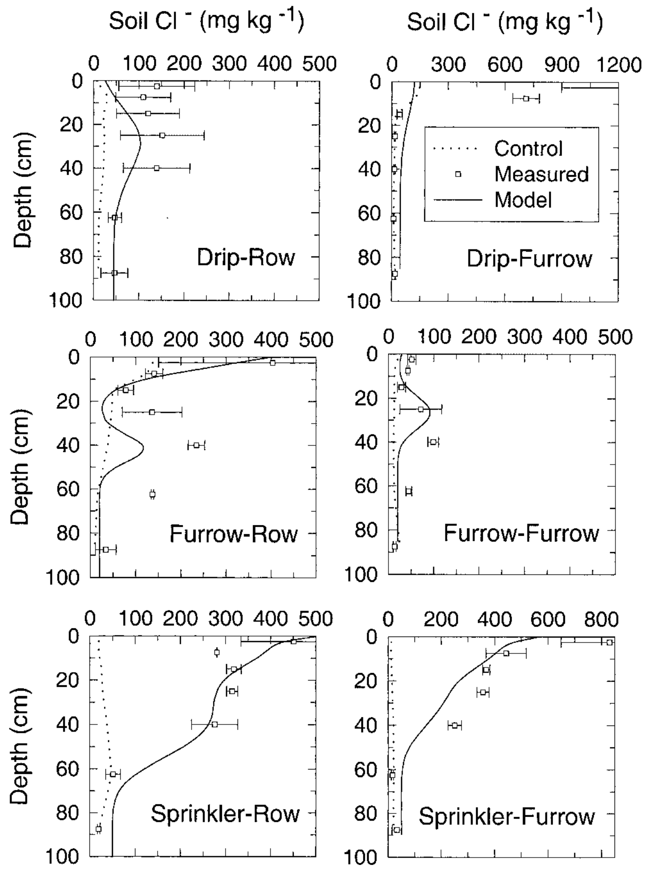

Fig. 8. Chloride (Cl) content under the row and furrow locations of the soil profile at the end of the growing season subjected to drip, furrow, and sprinkler irrigation with good quality (Control) and saline water (Measured ± SD and Model).

ence was found by either soil sampling or model simulation for subsurface concentrations. The distribution patterns were consistent with the drip irrigation method where saline water was applied at the row center. Under furrow irrigation, nonsaline water was applied through the furrows. Because of lateral flow and evaporation, more surface accumulation was found near the soil surface at the row than at the furrow locations. Significant Ca^{2+} buildup was also found in the subsurface at about a 40-cm depth because of the early season salinization and subsequent sprinkler irrigation with nonsaline water. Model simulation compared very well with the measured Ca profile. Application of fresh water caused removal of Ca from solution and onto the exchange sites. Consideration of cation exchange would have caused underprediction of Ca, consistent with the Cl predictions. Under sprinkler irrigation with saline water, significant Ca accumulation occurred throughout the top 60-cm soil profile. A similar distribution pattern was found for both the row and furrow locations because of the uniform water and salt application over the entire soil surface. Detailed interpretation of the Ca and Na profiles is not possible since the simulations did not consider the effects of cation exchange. For example, underprediction of Ca is in this case qualitatively consistent with the consideration that application of saline water caused Ca release from exchange sites.

The general trend of Na^+ and Cl^- distribution (Fig. 7 and 8) is derived from the processes of physical transport and concentration by evaporation and root water uptake. Plant requirements and uptake of Na^+ and Cl^- are relatively lower (Marschner, 1995). Concentration buildups were found for both Na^+ and Cl^- at the row locations under both drip and furrow irrigation, and at both the row and furrow locations under sprinkler irrigation. These results are consistent with limited plant uptake of Na and Cl and concentration of the solution by plant water uptake (Marschner, 1995). The average maximum concentration for Cl^- (about 500 mg kg^{-1}) was higher than either Na^+ (150 mg kg^{-1}) or Ca^{2+} (150 mg kg^{-1}). This was caused by the higher application rate for Cl than for Na or Ca (4:2:1 molar ratio) coupled with low plant uptake. The overall salt buildup was high in the sprinkler plot because about twice as much salt than the drip and three times as much than the furrow was applied during the season (Table 1). The results also indicated that more leaching with good quality water may be needed to remove the salt buildup from the plant rootzone. Model simulation compared well with the measured Na and Cl concentrations. Similar to predictions for Ca under drip irrigation at the furrow loca-

Table 3. Salt ion mass balance among soil and plant components: Field measurement.

Irrigation	Ion	Total amount† Added	Plant	Soil	Plant uptake	Mass balance‡
		g m^{-2}			%	
Drip	Ca^{2+}	56.7	11.9 (1.5)	46.3 (22.2)	21.0	102.6
	Na^{+}	65.0	0.2 (0.01)	46.1 (15.2)	0.3	71.2
	Cl^{-}	200.4	0.8 (0.1)	160.8 (9.6)	0.4	80.6
Furrow	Ca^{2+}	31.9	7.0 (1.0)	13.7 (11.3)	21.9	64.9
	Na^{+}	36.5	0.1 (0.01)	30.2 (7.3)	0.3	83.0
	Cl^{-}	112.6	0.6 (0.1)	108.6 (6.0)	0.5	97.0
Sprinkler	Ca^{2+}	101.0	17.2 (1.6)	91.8 (13.3)	17.0	107.9
	Na^{+}	115.8	2.3 (0.2)	111.3 (11.7)	2.0	98.1
	Cl^{-}	357.1	6.2 (0.8)	323.1 (6.5)	1.7	92.2

† Added = cumulative season input; plant = salts from whole plant including leaf, pod, stem, and root; soil = total increase in salt ion in the top 1-m soil profile. Standard deviations are in parentheses.
‡ Mass balance = (plant + soil)/added.

Table 4. Salt ion mass balance among soil and plant components: Model simulation.

Irrigation	Ion	Total amount† Added	Plant	Soil	Plant uptake	Mass balance‡
		g m^{-2}			%	
Drip	Ca^{2+}	56.7	8.7	47.1	15.3	98.4
	Na^{+}	65.0	0.1	41.3	0.2	63.7
	Cl^{-}	200.4	4.7	137.5	2.3	71.0
Furrow	Ca^{2+}	31.9	8.1	15.2	25.4	73.0
	Na^{+}	36.5	0.1	33.5	0.3	92.1
	Cl^{-}	112.6	4.4	97.9	3.9	90.9
Sprinkler	Ca^{2+}	101.0	10.5	85.4	10.4	95.0
	Na^{+}	115.8	0.2	110.1	0.2	95.3
	Cl^{-}	357.1	5.7	321.3	1.6	91.6

† Added = cumulative season input; plant = cumulative products of C_r and S; soil = difference of total ion between initial and final time steps within simulation domain (1-m depth).
‡ Mass balance = (plant + soil)/added.

tion, however, predicted Na and Cl concentrations in the surface 10 cm of soil were significantly lower than the measurements.

Ion Partitioning among Soil and Plants and Mass Balance Assessment

A reasonable mass balance was achieved for the salt ions under the three irrigation regimes from both the field measurements (65 to 108%, Table 3) and model simulation (64 to 98%, Table 4). Between 17 and 22% of the applied Ca accumulated as soybean biomass dry materials (Table 3). Because of the difference in application rates between irrigation regimes, the absolute amount of Ca uptake was the highest (17.2 g m^{-2}) in the sprinkler (lowest in percent of uptake, 17%) followed by the drip and furrow irrigation treatment. Tissue concentrations of Ca^{2+} in the same plant parts (i.e., either leaf, pod, stem, or root) were very similar among irrigation treatments; therefore, the difference in quantities of Ca uptake between treatments was attributed to differences in total plant biomass dry weight. Under salinity, total plant dry matter at 102 d after planting weighed 46, 33, and 37 g plant^{-1} for the sprinkler, drip, and furrow irrigation treatment, respectively.

Compared with Ca, a very small fraction of the applied Na and Cl ($\leq$2%) accumulated in plant tissues in all irrigation treatments (Table 3 and 4). Between the irrigation regimes, however, measured Na and Cl uptake in the sprinkler treatment were about seven and four times of that in the drip or furrow plot because of higher application rate and foliar absorption (Table 3). Unlike the field measurements, model simulation produced similar rates of Na or Cl uptake between sprinkler and drip or furrow irrigation treatments because of the absence of a mechanism to simulate foliar uptake (Table 4).

The low Na and Cl uptake may indicate that the mechanism of salt tolerance for this soybean cultivar (Manokin) is by avoiding Na and Cl. The general plant responses and adaptations to salinity are either through salt exclusion by plants called excluders or by ion accumulation in plants called includers (Greenway and Munns, 1980). Most halophytic plants are salt includers or accumulators since they can tolerate high internal Na^{+} and Cl^{-} concentrations. Glycophytic plants such as soybean are usually sensitive to Na^{+} and Cl^{-} accumulation in plant tissues and tend to develop mechanisms for ion exclusion (Drew and Dikumwin, 1985). The ability of a plant to accumulate salt is very variable among species and even among genotypes of the same species. For a species such as soybean, the adaptation to salt tolerance can be achieved through either including or excluding the salt ions. Yang and Blanchar (1993) surveyed 60 soybean cultivars, and found that includer types accumulated 1.8 g kg^{-1} Cl^{-} in the leaves. However, Cl^{-} concentrations in the excluder varieties reached only about 0.3 g kg^{-1}, a value that is consistent with the Cl^{-} concentrations in 'Manokin' leaves. By proportion, the overall Na^{+} and Cl^{-} uptake by a salt includer soybean would be about six times of what we found for the 'Manokin' cultivar. For other species, especially halophytes, the amount of salt removal by plants would probably be higher if no other factors adversely affected plant growth.

SUMMARY AND CONCLUSIONS

Agricultural drainage water is usually sufficiently saline to be detrimental to most crop species. Without a means of disposing saline drainage water, increasing amounts of farm land will become salt impaired, suffer declines in productivity, and be lost to agriculture. A more sustainable way of drainage disposal is to reuse the saline waste water for crop production. To evaluate the potential effect on soil and crop quality, a quantitative approach is to determine the fate of major salt ions from the saline drainage. This study was conducted to characterize the partitioning of Na^{+}, Ca^{2+}, and Cl^{-} both in the soil and to soybean plants through soil and plant sampling and model simulations.

The overall Na^{+} and Cl^{-} accumulation in plant tissues was very low because soybean (cv. Manokin) exhibited minimal root uptake of these salt ions. Foliar absorption under sprinkler irrigation resulted in more salt accumulation than by root uptake for this excluder type of soybean. Plant analyses showed that regardless of differences in salinity and irrigation method, large quantities of Ca^{2+} were required for soybean production.

Depending on irrigation scheduling and seasonal salt load, substantial salt can accumulate in the soil profile that would require leaching and generate secondary saline drainage. Therefore, the management method needs to be optimized in a way that minimal secondary drainage will be generated. The optimization would require the knowledge of salt transport and distribution in the soil under different irrigation methods, and partitioning between soil and plants. Model simulation may provide a means of optimizing application of saline drainage water to reduce salt buildups in the soil profile. The study provided a framework of evaluating the mass balance of salt ions under field conditions. Additional work is needed to include salt uptake by different plant species and under different soil and environmental conditions.

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