Water and Solute Movement under Conventional Corn in Central Spain. II. Salt Leaching

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ABSTRACT

Leaching of salts under field conditions may be addressed through a combination of the soil water balance and the drainage and concentration of salts in the soil profile. A field experiment was conducted in the 1991 growing season on a Typic Xerofluvent soil planted to corn (*Zea mays* L.) to assess the leaching pattern of Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, SO_4^{2-}, CO_3H^{-}, and NO_3^{-} under conventional cropping. River and well irrigation water were used with salinities of 680 and 1580 mg L^{-1}, respectively. Sampling of the soil water solution throughout the growing season was done for soil profile layers using a permanent ceramic-candle extraction system. Neutron probes and tensiometers allowed seasonal measurements of soil water content and water movement in the profile. Leaching of salts was calculated as the product of deep drainage amounts times the salt concentrations at the 1.4-m soil depth. Total salt drainage for river and well was 0.34 and 0.38 kg m^{-2}, respectively. Accumulation of salts to a depth of 1.4 m in the soil profile showed values of 0.02 and 0.21 kg m^{-2} in plots irrigated with river and well water, respectively. Soil water balance and concentration of salts in the soil solution indicated discharge of salts to the groundwater table with conventional cropping practices. Groundwater pollution was addressed by matching irrigation to the evapotranspiration and by minimizing the concentration of salts in irrigation water.

THE DANGER OF SALINIZATION of soils with a shallow groundwater table and flooding irrigation practices is very high (Boteva et al., 1986). A combination of soil texture, shallow groundwater table, and conventional irrigation practices (furrow with high irrigation rates) in the corn cropping area of the mid-Jarama River basin in Spain causes seepage of irrigation water to the aquifer. Nitrogen fertilizer rates unrelated to the available soil N increase the risk of NO_3^{-}-N leaching to groundwater. Losses of applied N fertilizers of up to 30% have been recorded (Díez et al., 1994). In other areas, N losses of 50% have been found (Exner and Spalding, 1979).

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In Spain, research work has been carried out with the purpose of minimizing the risk of NO_3^{-}-N leaching to groundwater (Ramos et al., 1989; Vallejo et al., 1993).

Although NO_3^{-}-N is considered the most important risk factor for human health, leaching of salts beyond the cropping system boundary can contribute to groundwater salinization.

Roman et al. (1996) developed and tested an experimental approach to calculate the soil water balance of undisturbed soils under field conditions. The focus of that study was the methodology of measuring water movement and its direction, water storage, and evapotranspiration (ET) and drainage below the root zone. In this study, the fate and transport of salts in the soil profile above and to the groundwater table was addressed using the soil water balance approach and measurements of drainage and salt concentration throughout the soil profile. The main objectives of this research were to: (i) determine if different patterns of salt regimes existed in relation to the salinity of two sources of irrigation water, and (ii) test if seasonal fluctuations of salt concentration of the soil water solution are related to seasonal changes in drainage below the root zone.

MATERIALS AND METHODS

The experimental field is located at the La Poveda Field Station (30 km southeast of Madrid, Spain). The soil particle-size distribution characteristics of the profile have been described by Roman et al., 1996. Two sets of 12 plots (9 by 11 m) were randomly irrigated with two waters (river and groundwater) of different quality. Each plot was instrumented with three sets of tubes (i.d. 63 mm) with porous ceramic tips (Nardeux, Humisol, Les Ulis, France) placed at soil depths of 0.5, 0.9, and 1.4 m. These depths corresponded to the topsoil, middle, and deep drainage zones, respectively. The depths of the ceramic tips were those of the previous sampling for the determinations of soil particle-size distribution and the depth to the gravel layer. To calculate drainage, a set of tensiometers and neutron probes were placed within the plots. Seasonal sampling of the soil water solution was performed

Abbreviations: ET, evapotranspiration; EC, electrical conductivity.

Table 1. Mean salt concentrations of groundwater and river irrigation water throughout the corn growing season.

Source†	Ca^{2+}	Mg^{2+}	Na^+	K^+	Cl^-	SO_4^{2-}	CO_3H^-	NO_3^-	Conductivity	pH
	mg L^{-1}								S m^{-1}	
Groundwater well	242 ± 25	68 ± 3	127 ± 8	14 ± 1	70 ± 8	557 ± 31	473 ± 15	35 ± 6	0.19 ± 0.04	7.5 ± 0.3
River	95 ± 12	23 ± 3	72 ± 13	10 ± 2	63 ± 17	193 ± 35	227 ± 20	9 ± 7	0.09 ± 0.01	7.6 ± 0.3

† Mean evaporation residue = 1540 ± 85 and 650 ± 50 mg L^{-1} for well and river water, respectively.

as described by Roman et al. (1996) for determinations of soil water storage and water movement.

Experimental work was carried out from 5 Apr. 1991 (t = 0) to 11 March of the following year, the dates of the first and last measurements of water potential gradients and water storage, respectively. Corn cv. Prisma 800 XL 72AA was planted at a density of 7 plants m^{-2} on 24 April with row spacing of 0.75 m.

The first irrigation with both waters was applied 75 d after planting. Soil water samples were extracted at 98, 115, 129, 146, 158, and 181 d after t = 0. The first sampling was at t = 98 d when the water had infiltrated such that deep drainage did occur (Roman et al., 1996). The last sampling at t = 181 d was done 30 d before corn harvest. The last measurements of flow direction and water storage were made 340 d after t = 0. Low rainfall during the winter of 1991-1992 (90 mm from December to March) precluded water draining into the groundwater (Roman et al., 1996) and thus, water samples were not taken during this period. Irrigation management was described by Roman et al. (1996). Total irrigation plus rainfall was 513 mm for all plots. Sampling both sources of irrigation water was performed on the same dates that the soil water solutions were sampled.

All plots received 800 kg ha^{-1} of a mineral fertilizer 8-6.55-12.45 (N-P-K) at seedbed preparation and 294 kg N ha^{-1} at the six-leaf stage (t = 60 d) following conventional farming practices in the area (Rodríguez, 1986; Bratos, 1990). Mean available N in the soil as measured by an electro-ultrafiltration technique before corn planting was 300 kg ha^{-1} (Díez et al., 1994). Mean harvest index was 0.6 ± 0.05 and mean grain yield (14% water content) was 14 500 ± 750 kg ha^{-1}.

Salt leaching was calculated seasonally as the product of soil water drainage times the concentration of salts in the soil water solution of the deepest soil layer (1.4 m). It was assumed that water reaching the 1.4-m soil depth, near the gravel layer (drainage discharge) would leach into the groundwater table (mean depth 4.5 m) in a short time because of the large hydraulic conductivity of the gravel layer (Smith and Mullins, 1991). Seasonal drainage volumes entering the gravel layer were calculated and have been given by Roman et al., 1996.

Salt balance was performed by comparing the total amount of salts contributed by irrigation water and the total amount of salts drained into the groundwater during the experimental time. Because variations of salt concentrations in the irrigation waters were small (Table 1), the total amount of salts contributed by irrigation was calculated as the product of the irrigation water volume times the mean salt concentration. However, since drainage volume fluctuated, cumulative amounts of individual salts drained were calculated seasonally as the product of the drainage volume times the salt concentration during this same period in the soil water solution of the deepest layer.

Analyses for NO_3^-, SO_4^{2-}, and Cl^- were performed by ionic chromatography (Dionex 100 equipment, Hucoa-Erlös, Madrid). Determinations of Ca^{2+}, Na^+, and K^+ were made by flame photometry (Elex 6361, Igoda, Barcelona). Determination of Mg^{2+} was made by atomic absorption spectrophotometry (Perkin Elmer 403, Perkin Elmer Hispania, Madrid). The CO_3H^- ion was measured by alkalymetric titration. Electrical conductivity and pH were measured with a Crison 525 conductimeter and a Crison 217 pH meter (Crison, Barcelona), respectively.

Standard deviations of ion concentrations at any given soil water sampling time were calculated within an irrigation source to assess the spatial variation of these parameters throughout the experimental field.

RESULTS AND DISCUSSION

Salt Content of Irrigation Water and Soil Water Solution

River and groundwater sources of irrigation showed mean total salt values of 690 and 1580 mg L^{-1}, respectively. In both irrigation waters, the main ions were SO_4^{2-}, CO_3H^-, Ca^{2+}, and Na^+. A high concentration of Mg^{2+} was also found in the groundwater. Mean NO_3^- contents were 9 and 35 mg L^{-1} in river and groundwater sources, respectively. This fairly high NO_3^- concentration in groundwater shows nonpoint sources of NO_3^- pollution to the aquifer. Low standard deviations for most salt concentrations and EC indicated small variations for both irrigation waters throughout the growing season (Table 1).

Mean EC values of 0.09 and 0.19 S m^{-1} and pH of 7.6 and 7.5 were found in river and groundwater, respectively. Mean EC values of 0.36 and 0.44 S m^{-1} and pH of 8.0 and 8.1 were found in the soil water solution of plots irrigated with river and groundwater, respectively. For most ions, except Na^+, concentration

Table 2. Salt concentrations of the soil water solution as a function of soil depth and irrigation water.

Source	Soil depth	Observations†	Ca^{2+}	Mg^{2+}	Na^+	K^+	Cl^-	SO_4^{2-}	CO_3H^-	NO_3^-	Conductivity	pH
	m		mg L^{-1}								S m^{-1}	
Well water	0.50	n = 32	608 ± 242	176 ± 92	359 ± 154	12 ± 4	403 ± 410	1297 ± 569	990 ± 279	406 ± 260	0.43 ± 0.18	8.1 ± 0.2
	0.90	n = 29	639 ± 257	197 ± 104	413 ± 225	11 ± 6	650 ± 580	1377 ± 618	1040 ± 346	394 ± 428	0.49 ± 0.23	8.0 ± 0.3
	1.40	n = 20	553 ± 261	159 ± 109	320 ± 182	6 ± 2	513 ± 421	1093 ± 705	871 ± 379	350 ± 161	0.39 ± 0.22	8.2 ± 0.4
River water	0.50	n = 23	441 ± 153	118 ± 41	270 ± 103	11 ± 7	300 ± 119	887 ± 351	683 ± 251	306 ± 159	0.33 ± 0.10	7.9 ± 0.3
	0.90	n = 26	473 ± 207	138 ± 58	338 ± 155	11 ± 5	371 ± 192	1047 ± 506	791 ± 367	391 ± 282	0.38 ± 0.14	8.0 ± 0.3
	1.40	n = 40	460 ± 179	138 ± 65	309 ± 164	12 ± 3	359 ± 173	984 ± 443	761 ± 352	500 ± 355	0.37 ± 0.14	8.1 ± 0.3

† Maximum number of data points = 72.

Table 3. Seasonal variations of salt concentrations in the soil water solution at the 1.4-m depth during the corn growing season.

Source of irrigation water	Sampling date†	Available data‡	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	SO_4^{2-}	CO_3H^{-}	NO_3^{-}	Conductivity	pH
	d		mg L^{-1}								S m^{-1}	
Well water	98	$n = 4$	475 ± 248	129 ± 109	272 ± 182	7 ± 4	423 ± 427	901 ± 856	748 ± 440	378 ± 128	0.33 ± 0.22	8.2 ± 0.4
	115	$n = 3$	543 ± 274	155 ± 116	324 ± 204	4 ± 2	411 ± 377	1126 ± 851	885 ± 451	411 ± 207	0.40 ± 0.26	8.0 ± 0.6
	129	$n = 3$	658 ± 303	168 ± 131	336 ± 211	5 ± 2	489 ± 443	1153 ± 220	905 ± 439	404 ± 212	0.41 ± 0.26	8.5 ± 0.5
	146	$n = 3$	559 ± 363	166 ± 160	321 ± 244	6 ± 3	606 ± 496	1015 ± 954	827 ± 527	345 ± 253	0.39 ± 0.38	8.3 ± 0.4
	158	$n = 4$	553 ± 285	163 ± 122	308 ± 204	10 ± 3	553 ± 449	1083 ± 597	894 ± 363	274 ± 131	0.40 ± 0.23	8.2 ± 0.5
	181	$n = 4$	640 ± 333	181 ± 116	377 ± 214	3 ± 1	632 ± 533	1348 ± 768	999 ± 373	316 ± 129	0.46 ± 0.45	8.1 ± 0.4
River water	98	$n = 6$	383 ± 99	110 ± 24	256 ± 62	14 ± 3	266 ± 85	892 ± 175	609 ± 153	496 ± 174	0.31 ± 0.6	8.0 ± 0.2
	115	$n = 5$	490 ± 81	140 ± 32	301 ± 83	15 ± 4	364 ± 98	1034 ± 238	799 ± 177	580 ± 411	0.38 ± 0.07	7.9 ± 0.3
	129	$n = 8$	394 ± 218	111 ± 70	237 ± 167	15 ± 4	282 ± 167	892 ± 534	629 ± 403	495 ± 583	0.31 ± 0.16	8.2 ± 0.3
	146	$n = 7$	448 ± 187	150 ± 85	313 ± 190	10 ± 1	376 ± 182	991 ± 492	755 ± 404	450 ± 425	0.37 ± 0.15	8.2 ± 0.3
	158	$n = 8$	538 ± 203	168 ± 76	386 ± 195	9 ± 1	443 ± 204	1180 ± 504	916 ± 406	514 ± 453	0.43 ± 0.16	8.2 ± 0.2
	181	$n = 6$	506 ± 201	145 ± 67	359 ± 201	10 ± 2	408 ± 206	1062 ± 501	837 ± 400	484 ± 303	0.40 ± 0.15	8.2 ± 0.1

† Days after first measurement of hydraulic head. Planting date (t = 19). Harvesting date (t = 211).
‡ Maximum number of data points = 12.

differences were found in drainage water from the two sources of irrigation water. Salt distribution in the soil profile was relatively uniform although the salt concentration at the intermediate (0.9-m) soil layer was slightly higher than at the upper- (0.5-m) and lowermost (1.4-m) levels (Table 2).

Mean total salt content of the soil water solution was >3500 mg L^{-1}, with slightly higher values in plots irrigated with groundwater than those irrigated with river water. For most salts, lower values were found at the beginning of the season. These values increased during the growing season with a corresponding increase in the EC. The NO_3^- ion was the exception to this trend, with slightly lower values at the initial and final sampling date of the season than at the intermediate dates (Table 3).

Series of salt concentrations in the soil water solution were analyzed using linear correlation. A significant relationship between SO_4^{2-} and both Ca^{2+} and Mg^{2+}, and between these two elements, was calculated, indicating a common source and a similar leaching trend. A high and expected correlation was also determined between Cl^- and Na^+. Electrical conductivity was highly correlated with the most dominant ions except CO_3H^-. The latter ion showed generally lower values in the deep drainage water than in the soil water solution of the uppermost level. Nitrate ion concentrations were unrelated to those of other ions or EC, indicating that application of N fertilizers masked the NO_3^- contents in sources of irrigation water (Table 4).

Seasonal fluctuation of EC values were not related to daily changes in drainage below 1.4 m. This finding was observed in plots irrigated with both well and river water and mean values are shown in Fig. 1. Electrical conductivity values tended to increase from 0.3 to 0.4 S m^{-1} as the growing season progressed. However, drainage reached peak values at about t = 115 d and thereafter decreased. This unrelated trend indicated that both seasonal and cumulative measurements of salt concentrations and volume of drainage must be made to estimate amounts of salt discharge. Seasonal and cumulative calculation of drainage was of real value only in plots no. 25 and 32 due to nonuniform distribution of surface water application within plots (Roman et al., 1996). The number of observations for each soil depth and sampling time are shown in Tables 2 and 3.

Salt Balances

Salt concentrations in the soil profile indicated salt movement but were poor indicators of pollution risk. Salt concentrations and salt discharge to the groundwater can be unrelated (Rhoades, 1973, 1974; Jury and Pratt, 1980).

When river water was used, the balance showed that total intake of salts in the irrigation water and total salt discharge were similar. Nevertheless, in plots receiving well water, 40% of total salt intake was retained in the soil profile (Table 5). In spite of differences in the total salt intake, the salt amounts drained to the groundwater during the corn growing season was similar for both types of irrigation water. With a total salt intake of 0.32 and 0.60 kg m^{-2} in river and well irrigation waters, respectively, salt amounts in the drainage discharge were

Table 4. Correlation matrix.†

	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	SO_4^{2-}	CO_3H^{-}	NO_3^{-}	Conductivity
Ca^{2+}	0.919***	0.765***	0.337**	0.790***	0.953***	0.806***	0.152	0.932***
Mg^{2+}		0.888***	0.282*	0.883***	0.935***	0.857***	0.108	0.954***
Na^{+}			0.320**	0.919***	0.809***	0.745***	0.154	0.867***
K^{+}				0.266*	0.332**	0.428**	0.189	0.385**
Cl^{-}					0.704***	0.626***	0.119	0.923***
SO_4^{2-}						0.730***	0.019	0.914***
CO_3H^{-}							0.065	0.691***
NO_3^{-}								0.108

† Ionic concentration was reported as mg L^{-1} and conductivity as S m^{-1}.
*,**,*** Significant at probability levels of 0.05, 0.01 and 0.001, respectively (n = 57).

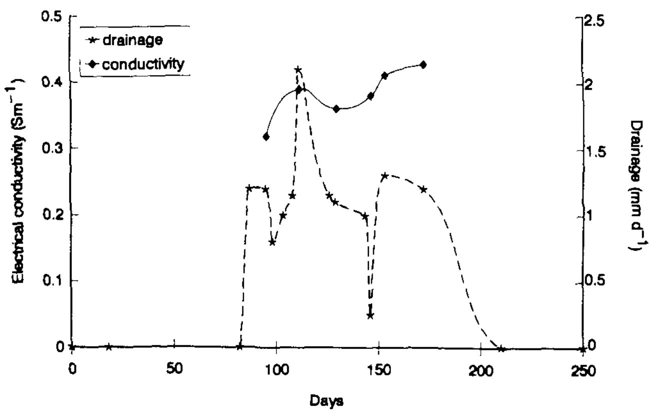

Fig. 1. Seasonal variation of electrical conductivity and drainage of soil water in Plots 25 through 32.

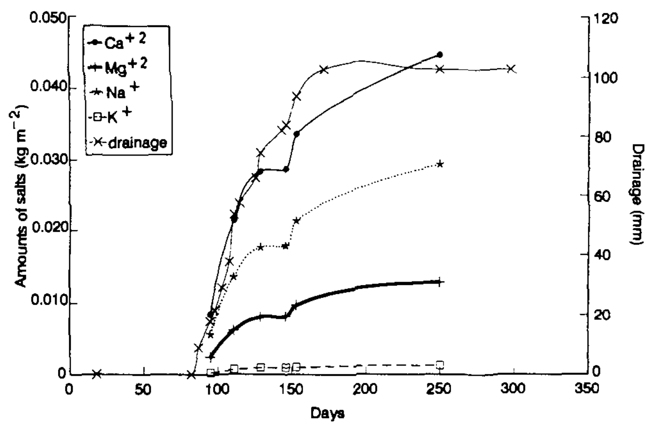

Fig. 2. Accumulated amounts of cations and drainage in plots irrigated with river water.

0.34 and 0.38 kg m^{-2}, respectively (Table 5). This balance did not include the salt amounts applied by the N-P-K corn fertilization. On the other hand, these amounts were similar in plots receiving both sources of irrigation water. Furthermore, no difference in plant uptake of salts was found between plots receiving river or well irrigation water. Although most ions are of nutritional value to corn, the total uptake by plants was negligible (0.0252, 0.0064, and 0.0043 kg m^{-2} for K^+, Ca^{2+}, and Mg^{2+}, respectively) relative to quantities measured in the soil profile. Uptake of K^+ had little impact relative to the total salt balance.

These results illustrate that losses of salts through leaching showed a ,different trend than those suggested by the total salt concentration in different sources of irrigation water. Jury and Pratt (1980) reported that the ratio of volume (irrigation to drainage) and the ratio of total salt concentration (drainage discharge to irrigation water) were similar. Our results suggested that this proportional model fitted the lower but not the high salinity concentrations of irrigation water. In the latter case, most complex models involving ionic exchange reactions between the soil and soil water solution can be applied. Examination of observed solute concentrations indicates solubility reactions of calcite ($CaCO_3$), anhydrite ($CaSO_4$), or dolomite [$(CO_3)_2CaMg$] may govern soil solution concentrations of Ca^{2+}, Mg^{2+}, CO_3H^-, and SO_4^{2-} ions, depending on the effective activity coefficients (Sposito, 1989). In the time interval under consideration, conventional irrigation practices, and the textural properties of our soil (Roman et al., 1996), a steady state must be difficult to achieve and, thus, dynamic exchange reactions must be operative (Jury and Pratt, 1980).

For irrigation from well water, accumulated salts in the soil profile during the growing season can be leached to the groundwater after the corn has been harvested, especially in high-rainfall winters. Low rainfall during the winter following corn production did not allow sampling for deep drainage.

Cumulative seasonal losses of individual salts are shown in Fig. 2 through 5. These curves show that the majority of the drainage volume occurred approximately 100 d after the first irrigation, with mean values fluctuating between 1 to 2 mm d^{-1} (Fig. 1). As little seasonal differences of individual salt concentrations were observed (Table 3), trends in the amounts of individual salt discharge and drainage were related. Cumulative seasonal nutrient losses were compared between plots with different sources of irrigation water. Again, wide differences were observed between individual salts and little differences were related to source of irrigation water.

SUMMARY

Results of this experiment showed that conventional corn cropping practices on farms of the middle basin of the Jarama River (central Spain) led to total salts discharge of 0.34 to 0.38 kg m^{-2} to the aquifer.

Total or individual salt concentrations in the soil solution at the 1.4-m soil depth increased by two- to threefold compared with those in the irrigation water. Relative increases were higher in river water with low salt concentration than in well water with high salt concentration. Small differences were observed between low-salt river and high-salt groundwater well sources of irrigation. Nitrate showed much higher rates of increase than other nutrients, irrespective of the source of irrigation water.

Table 5. Saline balance throughout the corn growing season with two sources of irrigation water.

Source	Ca^{2+}	Mg^{2+}	Na^+	K^+	Cl^-	SO_4^{2-}	CO_3H^-	NO_3^-	Total
	kg m^{-2}								
Well water									
Intake	0.049	0.028	0.052	0.006	0.028	0.227	0.193	0.014	0.597
Discharge	0.056	0.015	0.032	0.001	0.048	0.110	0.087	0.036	0.385
River water									
Intake	0.045	0.011	0.032	0.004	0.026	0.094	0.103	0.005	0.320
Discharge	0.045	0.013	0.028	0.001	0.034	0.095	0.073	0.051	0.340

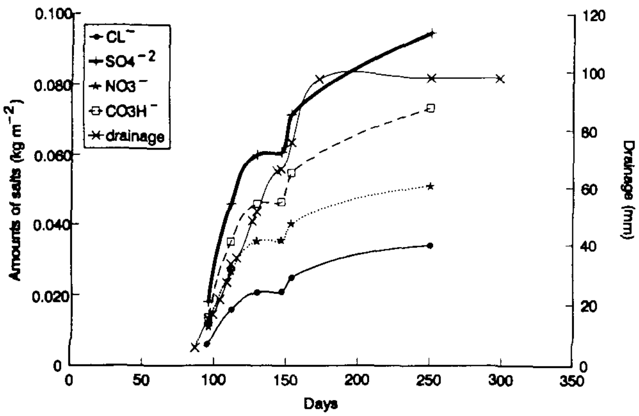

Fig. 3. Accumulated amounts of anions and drainage in plots irrigated with river water.

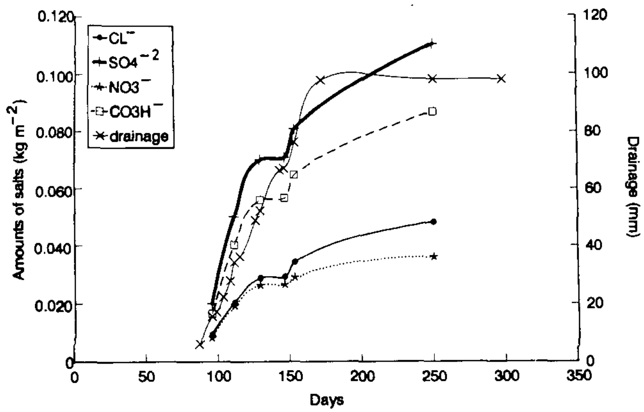

Fig. 5. Accumulated amounts of anions and drainage in plots irrigated with well water.

Despite differences in salt concentration between the two sources of irrigation water, drainage water concentrations were basically the same. Storage of nutrients in the soil profile increased as the irrigation water became more enriched. Seasonal losses of individual nutrients during the corn growing season were related to seasonal volumes of deep percolation.

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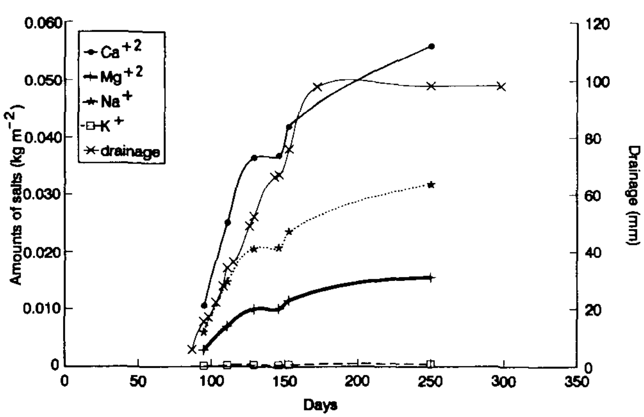

Fig. 4. Accumulated amounts of cations and drainage in plots irrigated with well water.

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