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Cyclic and blending strategies for using nonsaline and saline waters for irrigation

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Summary. Large quantities of saline water frequently exist in irrigated areas of the world. Various strategies have been proposed to use these saline waters. Blending involves mixing saline water with good quality water to an acceptable salinity and then using this water to irrigate crops. The cyclic strategy uses waters of various salinities separately either during one season or in a crop rotation as a function of the crop's salt tolerance. A multi-seasonal transient state model, known as the modified van Genuchten-Hanks model, was used to investigate the effects of cyclic or blending application of irrigation waters of two salinity levels on alfalfa (*Medicago sativa* L.), and on a corn (*Zea mays* L.) and cotton (*Gossypium hirsutum* L.) crop rotation. Simulated alfalfa yields were similar for the cyclic and blending strategies that applied the same amount of salt and water. The cyclic strategy produced higher simulated yields of salt-sensitive corn than the blending strategy, whereas the simulated salt-tolerant cotton yield was not affected by the two strategies. The beneficial effects of the cyclic strategy on corn production decreased under deficit irrigation.

High quality irrigation water is a limited natural resource in semiarid areas of the world. However, large quantities of saline water frequently exist, often as ground water. Potentially, these saline waters can be used to supplement high quality irrigation water. Use of saline water for irrigation may also provide a means of partially disposing of drainage water. Drainage water disposal often creates problems. For example, in the San Joaquin Valley, California drainage water has been disposed of in evaporation ponds or discharged into streams. Placement in evaporation ponds has lead to the concentration of trace elements contained in the drainage water to toxic levels. Elements such as selenium have been linked to wildfowl deaths and deformation (Ohlendorf 1989). Evaporation ponds also take productive crop lands out of service.

Various strategies have been proposed to use saline waters. One approach blends the saline water with good quality water to an acceptable salinity as characterized by electrical conductivity (EC) and then uses this water to irrigate crops (Rains et al. 1987; Rolston et al. 1988). Choice of EC would be based upon the salt tolerance of the specific crop and availability of the water supplies. A second method uses a cyclic irrigation strategy to initially irrigate a crop with high quality irrigation water when the crop is more sensitive to salinity and then uses a lower quality water for later irrigations when the crop is more tolerant to salinity (Rhoades 1984, 1987). A third strategy cycles waters of various salinities in a crop rotation scheme as a function of the crop's salt tolerance. This strategy allows osmotic stress to be applied to the crop which is most tolerant to this stress (Rhoades et al. 1988).

The goal of this paper was to examine strategies which use saline water as a supplemental source of irrigation water. To do this, a multi-seasonal transient state model was used to simulate crop production under various irrigation management regimes. Simulations were run to examine the effects of the cyclic and blending irrigation schemes of alfalfa (*Medicago sativa* L.) and on a corn (*Zea mays* L.) and cotton (*Gossypium hirsutum* L.) crop rotation. The corn-cotton rotation was selected to illustrate the rotation of salt sensitive (corn) and salt tolerant (cotton) crops rather than a common agronomically practiced rotation. The model used for these simulations is known as the modified van Genuchten-Hanks model (V-H model) (Cardon and Letey, 1992b).

Description of the model

Cardon and Letey (1992a, b) compared the merits of two soil-plant-atmospheric continuum models; one developed by M. Th. van Genuchten and another by R. J. Hank and colleagues (van Genuchten 1987; Nimah and Hanks 1973; Childs and Hanks 1975; Torres and Hanks 1989). Based upon the relative merits of the van Genuchten and the Hanks model, Cardon and Letey (1992b) formulated

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the modified van Genuchten-Hanks (V-H) model which was used in this study. The modified V-H model is one-dimensional in space and assumes uniform irrigation. It can not simultaneously simulate nonuniform irrigation over a cropped field.

The V-H model uses van Genuchten's plant water uptake term. When matric and osmotic potential effects are present this term is:

$$S(z,t) = \frac{S_m(z,t)}{1 + \left[\dfrac{a \cdot h + \pi_{50}}{\pi_{50}}\right]^3} \tag{1}$$

where $S_m(z,t)$ is the potential uptake rate,

$$S_m(z,t) = \frac{T_p(t)}{L(z,t)}. \tag{2}$$

$T_p(t)$ is potential transpiration, $L(z,t)$ is rooting length, π is osmotic potential, h is matric potential, π_{50} and h_{50} are potentials at which 50% reduction in yields occur for a specific crop and "a" is the ratio of π_{50} and h_{50}. $S_m(z,t)$ is adjusted at varying depths to account for root distribution.

$S_m(z,t)$ in (Eq. 2) is affected by root distribution and depth of root growth. The V-H model as used assumed a root density distribution of 40%, 30%, 20%, 10% per quarter of root depth from top to bottom of the rooting depth (L). L as a function of time is specified by the modeler. The model allows feedback whereby L is adjusted to account for matric and/or osmotic stress, as well as being restricted to the height of the water table. Bingham et al. (1970) demonstrated that zonal salinization in the root zone caused preferential root growth and water uptake to occur in areas of low salinity. The model can accommodate any root distribution but does not account for preferential root growth other than specified by the modeler.

Jury et al. (1980) found that the electrical conductivity in the saline part of the root zone can be reduced when calcium rich irrigation waters precipitate calcium carbonate or gypsum. In contrast, dissolution of soluble salts can add salts to the root zone and drainage waters. The V-H model assumes that the effects of precipitation and dissolution are negligible.

The total plant water uptake is the summation over time and depth, $\Sigma S(z,t)$, and is related to crop yields in a linear relationship as proposed by Hanks (1974) and consistent with results of a review by de Wit (1958):

$$\frac{\Sigma S(z,t)}{\Sigma S_m(z,t)} = \frac{Y}{Y_m} \tag{3}$$

where Y is the dry matter production and Y_m is the maximum dry matter production without salt or water stress. Marketabale yields are of primary concern to growers. For crops which have a linear relationship between dry matter production and marketable yields, Eq. (3) is valid for computing relative marketable yield. The relationship between dry matter and marketable yields must be known for crops in which the two yields are not linearly related.

The V-H model uses a soil hydraulic properties function developed by Hutson and Cass (1987) which can be used over the entire soil water content range, including saturation. The V-H model predicts that evaporation during the non-crop season decreases as the soil surface dries; which is consistent with observation. The numerical implementation of the V-H model was found to converge and provide mass balance for all conditions during infiltration.

The V-H model calculates relative dry matter production (based on Eq. (2)), evapotranspiration, deep percolation, and the salt and water distributions over the course of the simulation. Cardon and Letey (1992b) reported reasonably good agreement between simulated relative dry matter yields and observed yields available from experimental data where the Willmott's index of agreement (Willmott 1981) equaled 0.79.

Input data for the simulations

The initial soil water and salt contents must be specified at the beginning of a simulation. Amount, time, and salinity of irrigation water application and/or rainfall are input variables for the V-H model. The value of $S_m(z,t)$ (Eq. (2)) must be specified for a given time period. $S_m(z,t)$ equals potential transpiration, but potential ET (PET) rather than transpiration is usually estimated so the computations are based on PET values and represents one deficiency of the model. PET is the ET value when the plant is not exposed to water or salt stress. The PET was taken as the climatic reference evapotranspiration (ET_0), which is the ET associated with climatic conditions, times a crop coefficient K_{cr} which varies with crop and stage of plant growth. Values of K_{cr} must be empirically established.

The simulations in this study were done for climatic and cropping conditions typical of the San Joaquin Valley, California. The seasonally variable ET_0 and crop coefficient values were taken from Letey and Vaux (1985). Averages of these values were used for each transpiration period between irrigations and are listed in Tables 1 and 2. Rainfall, which occurs mostly in the winter months, was chosen to be equal to the long-term average between Mendota and Westside, California. During the winter, monthly average precipitation was applied in one event. During the growing season, precipitation was assumed to be negligible.

Parameters used in the Campbell (1974) and Hutson and Cass (1987) hydraulic property functions are presented in Table 3. The saturated hydraulic conductivity (K_{sat}) and the saturated volumetric water content (θ_{sat}) chosen for the simulations are also shown.

Both π_{50} and h_{50} must be specified for each crop and the values can be varied to simulate time differential response to salinity and matric potential. For the simulations presented in this paper constant π_{50} and h_{50} values with the time were assumed. The salt tolerance of these crops is cotton greater than alfalfa greater than corn and the respective π_{50} values were -0.96, -0.64, and -0.425

Table 1. ET_0, K_{cr}, and rooting depth of cotton and corn for various simulated transpiration periods

Transpiration period (dates)	ET_0 (cm day^{-1})	K_{cr}	Root depth max (L) (cm)
Cotton			
April 15 – June 15	0.540	0.36	101
June 16 – July 11	0.660	1.00	131
July 12 – August 4	0.625	1.19	141
August 5 – September 6	0.511	1.05	166
September 7 – October 15	0.448	0.93	180
Corn			
April 15 – May 27	0.511	0.32	90
May 28 – June 14	0.660	0.89	100
June 15 – June 29	0.664	1.12	120
June 30 – July 13	0.668	1.20	120
July 14 – July 27	0.642	1.18	120
July 28 – August 13	0.577	0.99	120
August 14 – September 6	0.520	1.05	120

Table 2. ET_0, K_{cr}, and rooting depth of alfalfa for various simulated transpiration periods

Transpiration period (dates)	ET_0 (cm day^{-1})	K_{cr}	Root depth max (L) (cm)
March 1 – March 31	0.265	1.00	150
April 1 – April 30	0.410	1.00	150
May 1 – May 14	0.510	1.00	150
May 15 – June 1	0.570	1.00	150
June 2 – June 15	0.630	1.00	150
June 16 – June 30	0.665	1.00	150
July 1 – July 15	0.670	1.00	150
July 16 – July 30	0.655	1.00	150
July 31 – August 13	0.615	1.00	150
August 14 – August 28	0.565	1.00	150
August 29 – September 12	0.515	1.00	150
September 13 – September 27	0.440	1.00	150
September 28 – October 10	0.365	1.00	150
October 11 – November 11	0.230	1.00	150
November 12 – December 11	0.080	1.00	150
December 12 – January 12	0.070	1.00	150
January 13 – February 13	0.110	1.00	150
February 14 – February 28	0.160	1.00	150

Table 3. Parameter values of soil hydraulic properties used in the simulations

Name	Symbol	Value
Campbell parameters:	b	3.26
	B	8.45
	ψ_e	−1.40 kPa
Hutson and Cass parameters:	θ_i	0.42
	ψ_i	−2.23 kPa
	K_{sat}	0.89 cm/h
	θ_{sat}	0.48

MPa. The π_{50} values for alfalfa and corn were derived from Maas and Hoffman (1977) and for cotton from Letey and Dinar (1986). Experimental data for h_{50} are not available so it was assumed that h_{50} equals π_{50}. Cardon and Letey (1992b) did a sensitivity analysis and found that the results were not very sensitive to changes in the value of h_{50}.

For the two annual crops the unstressed rooting length was varied according to Table 1. Alfalfa was assumed to be established so that its rooting depth remained constant at a depth of 150 cm.

The amount of water applied for a given irrigation was based on the PET during the transpiration cycle between irrigations. Water transpired during the final transpiration period of the growing season is not replenished by irrigation until the beginning of the next growing season and is referred to as preirrigation for annual crops. This preirrigation serves the purpose of replenishing the water lost during the final transpiration period of the previous year and the non-cropping period and leaching the salts that have accumulated at the surface. For alfalfa the amount of irrigation on March 1 was equal to the potential evapotranspiration (PET) between October 10 and March 1 minus the precipitation.

Blending and cyclic schemes with alfalfa

In this section the effects of the cyclic and blending irrigation strategies on alfalfa production are examined. The soil was initially at a volumetric water content of 0.26 and salinity of 0.4 dS/m throughout the profile. A constant matric potential equal to −10 kPa was imposed at the bottom boundary layer set at 2.5 m.

Irrigations were simulated to replenish water lost by 1.2-, 1.0- and 0.8 PET between irrigations. Alfalfa received its first irrigation on March 1. Successive irrigations were applied on April 1 and May 1 and every to weeks thereafter until October 10 (Table 2). Precipitation was applied as one event monthly for the rest of the year.

The following simulations applied the same amount of water and salt during the year using different salinity schedules. The first strategy (strat. 1) applied irrigation water blended to an EC of 1.0 dS/m. The second strategy (strat. 2) applied irrigation water equal to 0.4 dS/m for the odd numbered irrigations and water equal to 1.53 dS/m for the even-numbered irrigations. The third strategy (strat. 3) applied irrigation water of 1.53 dS/m for the first three and the eighth through eleventh irrigations, and 0.4 dS/m irrigation water for the fourth through seventh and the last three irrigations. A fourth strategy (strat. 4) applied the same amount of water and salts during two years that the previous strategies did using irrigation water equal to 0.47 dS/m on odd-numbered years and irrigation water equal to 1.53 dS/m on the even-numbered years. This fourth strategy had an additional simulation which applied irrigation equal to 0.6 PET.

A second group of simulations that applied higher amounts of salinity were run using similar salinity addition strategies. One strategy applied irrigation water blended to an EC of 2.3 dS/m. Another strategy applied irrigation water equal to 0.4 dS/m for the odd-numbered irrigations and water of 4.0 dS/m for the even-numbered irrigations.

The simulated relative alfalfa dry matter yields for the cyclic and blending strategies except strat. 4 are presented in Table 4. Note that no significant difference in yields occurred between the blending and cyclic strategies when the same amount of salt and water were applied. Steady state yields are approached after one year of irrigating with saline waters.

Figure 1 illustrates the salt distributions for strat. 1 simulations at the end of each year. The EC values were standardized to saturated soil water conditions (EC_{sat}). The salt distributions at the end of the year for strat. 2 and 3 are almost the same as strat. 1, so they are not presented. The salt distribution at less than 10 cm depth remained unchanged after the first year. Salt concentration at greater depths continued to increase in successive years, but these increases in salinity at greater depths did not affect crop yield. For a given crop, assuming no change in salinity tolerance with age, it does not matter whether waters are blended or cycled during one year as long as the same amount of salt and water are added. This conclusion is consistent with experimental results of Meiri (1984) and Shalhevet (1984) where plants responded to weighted average of the EC of various waters applied during the season. Letey and Dinar (1986) compared yields from experimental plots to yields computed using a steady state model. The weighted average EC of the irrigation waters was used in the model for an experiment where waters of different salinities were used on a given plot. The good agreement between model predictions and experimental observations suggested that the use of a weighted average irrigation water EC was appropriate in the steady state model. Using the weighted average irrigation water EC in the steady state model is equivalent to blending the waters in the transient state model. Since the transient state model simulated similar results for cyclic and blending strategies, it explains why the steady state model produced results comparable to experimental results even though the experiment was not done under steady state conditions.

The simulated relative dry matter yields for six years when the two water qualities were cycled on an annual basis are given in Table 5. For all simulations, yields were highest the first year because of the low soil salinity initial conditions. Note that after the first year, simulations which received 1.2 PET or 1.0 PET had yields which fluctuated annually but out of phase with the imposed irrigation water salinity. Higher yields were achieved in years when irrigation with the higher irrigation water salinity. The simulations which received 0.8 or 0.6 PET had yields which approached a constant value with time.

The EC_{sat} distributions on October 9 for the strat. 4, 1.0 PET simulation are shown in Fig. 2. These salt distributions closely represent the distributions at the beginning of the growing season in succeeding years. A transition in root zone salinity occurs during the growing season. Irrigation with EC of 1.53 dS/m increases the root zone salinity during the season which is carried over to the beginning of the next year. The opposite occurs when irrigating with 0.47 dS/m water. The results indicated that the high salinity at the beginning of the season had greater impact on yield than salinity at the end of the season. Significantly this result was achieved even though no different salt sensitivity of crop with time was imposed.

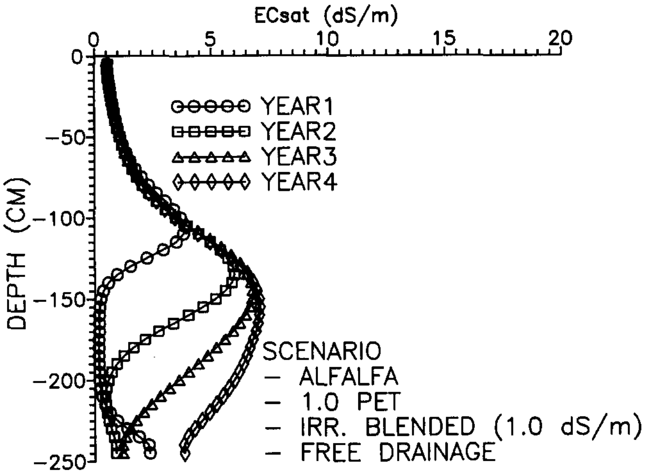

Fig. 1. The saturated electrical conductivity at the end of the season for the specified conditions

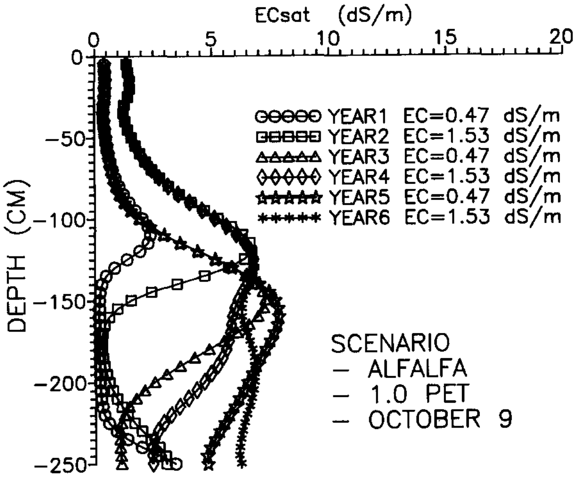

Fig. 2. The saturated electrical conductivity at the end of the season for the specified conditions

Table 4. The relative dry matter yields for the salinity addition schemes with alfalfa

Irrigation schemes	PET	Y1	Y2	Y3	Y4
1.0 dS/m	1.2	100	98	98	98
0.4 and 1.53 dS/m (*)	1.2	100	98	98	98
1.53 and 0.4 dS/m (**)	1.2	99	98	98	98
1.0 dS/m	1.0	99	89	90	90
0.4 and 1.53 dS/m (*)	1.0	99	90	90	90
1.53 and 0.4 dS/m (**)	1.0	98	90	91	90
1.0 dS/m	0.8	86	73	75	74
0.4 and 1.53 dS/m (*)	0.8	86	73	76	74
1.53 and 0.4 dS/m (**)	0.8	86	73	76	74
2.3 dS/m	1.2	97	89	91	90
0.4 and 4.0 dS/m (*)	1.2	97	89	91	90
2.3 dS/m	1.0	94	80	84	82
0.4 and 4.0 dS/m (*)	1.0	94	80	84	82
2.3 dS/m	0.8	83	67	71	69
0.4 and 4.0 dS/m (*)	0.8	83	67	71	69

* Alternating irrigations
** 1.53 dS/m for first 3 and 8 through 11 irrigations
0.4 dS/m for 4 through 7 and last 3 irrigations

Table 5. Relative yields from simulations which used strat. 4 to apply salinity

PET	Y1*	Y2**	Y3*	Y4**	Y5*	Y6**
1.2	100	99	96	99	96	99
1.0	100	94	87	94	87	94
0.8	87	74	75	75	73	76
0.6	67	54	60	57	58	57

* Irrigated with water of EC = 0.47 dS/m

** Irrigated with water of EC = 1.53 dS/m

Clearly initial soil salinity conditions are important as well as the salinity of the irrigation water used during the growing season.

Blending and cyclic strategies with crop rotation

Cyclic and blending strategies for waters of differing salinity were simulated for six years in a corn and cotton crop rotation. Initial salt and water distributions and boundary conditions were the same as those used in the alfalfa simulations.

The crop rotation was corn and cotton on alternating years. Irrigation to replenish water loss equal to 1.2, 1.0 and 0.8 PET between irrigations were simulated. The blending strategy had irrigation water EC of 1.9 dS/m for all irrigations, including preirrigation. The cyclic strategy simulated irrigation water of 0.4 dS/m for all irrigations to corn and preirrigation for cotton and water of 4.0 dS/m for in-season cotton irrigations. The same amount of salt and water were applied to a given rotation for the cyclic and blending strategies.

The yields for the corn/cotton rotation simulations are illustrated in Fig. 3. The cyclic strategy had consistently higher yields of corn than the blending strategy but cotton yields were relatively unaffected. The differences between the blending and cycling strategies on corn yields decrease with decreasing amount of applied water. Figure 4 shows the EC_{sat} distribution with depth for the years that corn received 1.2 PET using the cyclic and blending strategies. Note that the blending strategy has higher salinity in the rooting zone than the cyclic strategy. The higher salinity associated with the blending was sufficient to cause reduction in yield of the salt-sensitive corn. The EC_{sat} distribution with depth for the years that cotton received 1.2 PET using the cyclic and blending strategies are shown in Fig. 5. In this case the blending strategy had lower salinity in the rooting zone than the cyclic strategy. Cotton is tolerant to salinity, so yields were the same for both strategies even though the cyclic strategy caused a higher level of soil salinity in the root zone. The cyclic strategy separates the salt stress so that the salt sensitive crop (corn) receives less salt than the more salt-tolerant crop (cotton).

The soil salinity for 0.8 PET was concentrated to higher levels and at shallover depths than the 1.2 PET simulations (detailed data not presented). This difference is due to the decreased leaching associated with deficit irrigation. Here separation of salt stress on corn to cotton

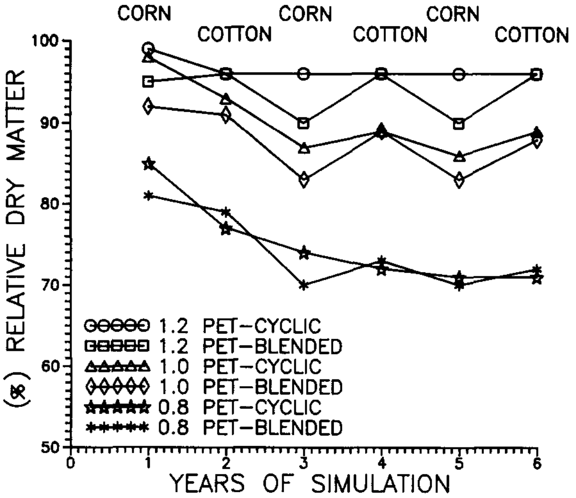

Fig. 3. Relative dry matter yields for corn-cotton rotation simulations for the specified conditions

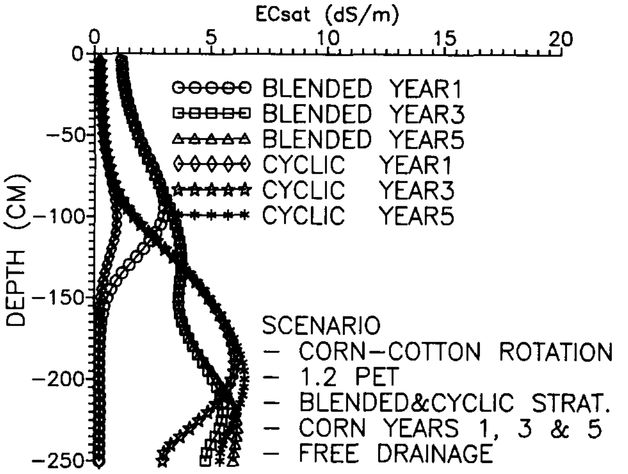

Fig. 4. The saturated electrical conductivity for the years corn was grown with the specified conditions

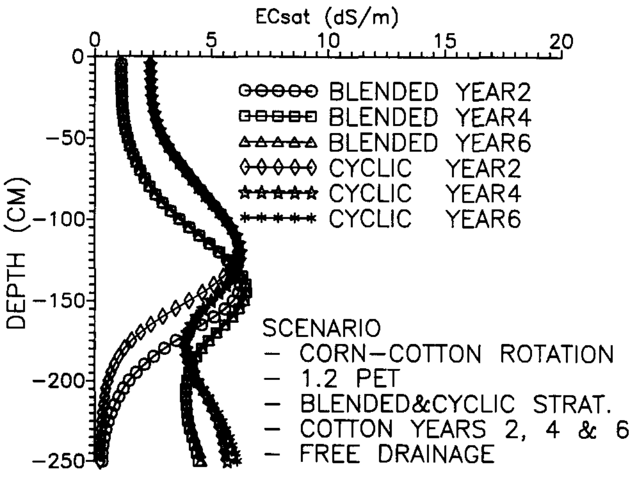

Fig. 5. The saturated electrical conductivity for the years cotton was grown with the specified conditions

does not help either crop significantly. The cyclic strategy did provide lower salinity than the blending strategy near the soil surface for corn production, but the high salt buildup deeper in the profile tended to nullify this effect on yields. Apparently the beneficial effects of the cyclic strategy are enhanced by ample water application which is typical of crop production.

The value of the cyclic strategy is in a crop rotation system which includes salt sensitive and salt tolerant crops. There was little benefit when only one crop is used as illustrated from the alfalfa results.

The simulated results are consistent with the concept of cyclic strategy proposed by Rhoades (1984, 1987) that both salt sensitive and salt tolerant crops can be grown in a rotation if the nonsaline and saline waters are kept separate and strategically used on specific crops. This concept was further verified in a field experiment (Rhoades et al. 1988) even though that experiment did not specifically compare cyclic to blending strategies. The simulated results also are consistent with observations that low salinity in the initial stages is more important than at latter stages of plant growth. This result was achieved even though the specific sensitivity of crop to salinity was the same throughout the growth cycle in the simulations. Bradford and Letey (1992) reported similar results in simulated effects of irrigation scheduling and water table on cotton production.

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