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A Dynamic Analysis of Optimal Water Use under Saline Conditions

Ariel Dinar and Keith C. Knapp

Irrigation with saline waters is a major problem in many parts of the world. Economic questions have usually been addressed using synthesized production functions and theoretically based soil salinity relations. The purpose of this paper is to estimate functions relating crop yield and salt accumulation in the soil to initial soil salinity and water quantity and quality. Crop response functions and dynamic salt balance relations are estimated from experimental data for alfalfa and cotton. The estimated functions are then used in a dynamic programming model to determine optimal water applications for different levels of initial soil salinity and crop and water prices.

Key words: crop response, dynamic programming, irrigation, saline water.

Salinity is a severe problem for irrigated agriculture in many parts of the world. Farmers face economic questions such as optimal water applications for given irrigation water quality, reuse of drainage water, reduction in profits from using saline waters, and rate of mixing good with saline water. Answering these questions requires knowledge of crop-yield response to water quantity and quality. Because salt may accumulate in the soil over time, it is also necessary in many cases to consider the impact of current actions on future production.

One common approach is to divide the overall system into two subsystems, water-soil and soil-crop yield. The water-soil relations are often treated using theoretically based models of water and salt transport in soils (Bresler; Childs and Hanks; Bresler, McNeal, and Carter). Crop yields are then estimated from the calculated salinity levels using experimentally determined relations, such as in Maas and Hoffman. Although this approach is potentially quite useful, the assumptions in the theoretical soil models restrict their applications. Another difficulty is that the relations in Maas and Hoffman were estimated under conditions where water is not limited (Hoffman, Jobes, and Alves, p. 454). This causes problems in economic analysis where profit maximization may imply water quantities less than those necessary for maximum yields or where water inputs are otherwise limited. In many cases, the production functions generated by this approach are not verified by actual data.

An alternative approach is to estimate crop response functions and dynamic salt balance relations using data from field experiments. This approach estimates direct relations between quantity and salinity of applied irrigation water and either yield or salt accumulation in the soil given local conditions and technologies. Many production functions have been estimated for non-saline water (see the comprehensive analytical and empirical work by Hexem and Heady, and a general review by Vaux and Pruitt). However, it appears that very few direct estimates of crop response functions to water have been made under saline conditions (e.g., Selassie and Wagenet). We are not aware of previous attempts to estimate dynamic salt balance relations using actual field data.

The purpose of this paper is to provide econometric estimates of crop-water response functions under saline conditions and func-

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tions for salt accumulation in the soil and to apply them to economic decision problems. Response functions are estimated for alfalfa and cotton using data from two field experiments in the western part of the United States. Also estimated are dynamic relations which give soil salinity at the end of the growing season as a function of initial soil salinity and quantity and quality of irrigation water used during the season. These relations are necessary for determining optimal water applications over several irrigation seasons under saline conditions. In the past they usually have been based on theoretical soil salinity models (Yaron and Olian). The estimated relations are used in a dynamic programming model to determine optimal water applications for different levels of initial soil salinity and crop and water prices.

Framework of the Analysis

Crop yields and soil salinity levels depend on a number of man-controlled and exogenous variables. These include quantity and quality (salinity) of irrigation water, initial soil salinity level, and climatic conditions. Other factors influencing crop yields and soil salinity, such as soil types, fertilizers, irrigation systems, and irrigation management, are treated as constants here.

The most general relations to be estimated are

$$Y = f(Q, C, S_0, E_p | X) \tag{1}$$

$$S_1 = g(Q, C, S_0, E_p | Z) \tag{2}$$

where Y = crop yield per unit area (kg/ha); Q = quantity of rainfall and applied irrigation water during the growing season (cm); C is salt concentration of the irrigation water expressed by the electrical conductivity (EC) of the water (millimhos/cm); S_0 is soil salinity of the root zone at planting time measured as the EC of a saturated paste extract (millimhos/cm); S_1 is soil salinity at the end of the growing season measured as the EC of a saturated paste extract (millimhos/cm); E_p = pan evaporation during the growing season as a measure of the climatic conditions (cm); X is vector of all the constant factors influencing yield; Z is vector of all the constant factors influencing soil salinity. Not all variables are reported in each experiment, so special versions of the general relations are used in some cases.

Table 1. Range of Values for the Variables in the Regressions

Variable	Units	Crop	
		Alfalfa	Cotton
Y	kg/ha	15,800–23,100	1,560–5,928
Q	cm	154–237	61–100
S_0[a]	mmhos/cm	2.37–13.07	3.87–13.10
S_1	mmhos/cm	6.55–13.35	5.53–17.68
C	mmhos/cm	1.35	0.67–7.96
E_p	cm	251–254	127–161

[a] S_0 and S_1 are computed as a simple average of the reported layers.

Two different functional forms are used in the analysis. These are the quadratic and the power function (Cobb-Douglas). A general description of these functions is found in Hexem and Heady. The power function was estimated through a linear transformation with logarithms. A logit model was also used to estimate relative crop yield functions; however, the results were poor and are not reported.

Holding other variables constant, we expect yield to increase as water quantity increases, decrease as initial soil salinity levels increase, and decrease as the salt concentration of the irrigation water increases. Likewise, we expect ending soil salinity levels to decrease as water application levels increase, increase as initial soil salinity levels increase, and increase as the salt concentration of the irrigation water increases. The behavior of ending soil salinity may be different in the case when the field is irrigated with low water quantities. If no leaching occurs, then salt accumulates in the soil and ending salinity levels will increase as water quantities increase until the point where leaching begins. The extent to which these a priori expectations are met will be discussed in the empirical analysis.

Data were collected from two four- to five-year field experiments. In the following sections we briefly describe the field experiments and then present the estimated functions. For convenience, the ranges of the reported variables are summarized in table 1.

Alfalfa

The experiment was located near Tacna in southern Arizona during 1975–78 (U.S. Salinity Laboratory Staff). The experiment was designed to determine the potential for mini-

Table 2. Yield Response Functions and Soil Salinity Relations for Alfalfa

Estimated Equation	R^2	df[a]	F^2[b]
$Y = 110{,}259 + 1{,}053Q - 2.1Q^2 + 4{,}734S_0 - 56.99S_0^2 - 16.87Q \cdot S_0 - 881E_p$ $(592{,}957)\quad(1{,}136)\quad(2.4)\quad(8{,}511)\quad(180)\quad(27.42)\quad(1{,}815)$	.88	5	6.6
$\log Y = 128.5 + 1.005 \log Q - .0681 \log S_0 - 22.37 \log E_p$ $(49.30)\quad(.22)\quad(.060)\quad(9.00)$	.78	8	9.6
$S_1 = -240.1 - .078Q - 6.4 \cdot 10^{-5}Q^2 - 1.777S_0 + .077S_0^2 + .006Q \cdot S_0 + 1.056E_p$ $(370.1)\quad(.70)\quad(.001)\quad(5.31)\quad(.11)\quad(.017)\quad(1.13)$	.92	5	10.9
$\log S_1 = -228.6 - 1.146 \log Q + .394 \log S_0 + 42.68 \log E_p$ $(84.3)\quad(.37)\quad(.10)\quad(15.39)$	.74	8	7.8

Note: Figures in parentheses are estimated standard errors of the coefficients.

[a] Degrees of freedom.

[b] F-test value.

mizing salt loads in irrigation return flows by decreased leaching. Alfalfa was irrigated with Colorado River water (1.3 millimhos/cm) and three leaching treatments (5%, 10%, 20%) with five replications. The irrigation system was a lateral move sprinkler. The soil was well drained, and the texture varied from very fine sandy loam to silty clay loam. Rainfall during the experiment was negligible, and the crop was harvested several times a year.

The regression results for alfalfa are presented in table 2. They explain .78–.88 of the yield variation and .74–.92 of the soil salinity.

The log yield response functions and the log soil salinity relations behave as expected. The quadratic yield response function shows increasing yield as water quantity increases. However, for a wide range of water quantities, yield increases as initial soil salinity increases, holding water quantity constant. The quadratic soil salinity relations also exhibit some unexpected behavior: while ending salinity decreases as water quantity increases (as expected), for very low water applications and some initial soil salinities, ending salinity decreases as initial soil salinity increases, holding water quantity constant. These results were also noted in the original field experiment report (U.S. Salinity Laboratory Staff); however, no explanation was given. A possible explanation can be given using the approach of Letey, Dinar, and Knapp. They suggested plant size adjustment to stress situation: high initial salinity causes a smaller plant with lower evapotranspiration. Such a plant is associated with higher leaching as less of the water applied is utilized by the plant and the result is lower ending salinity. The pan evaporation coefficient has a negative sign in the yield equations and a positive sign in the soil salinity equations. This implies that an increase in pan evaporation decreases yield and increases soil salinity at the end of the season holding other variables constant.

One difficulty with alfalfa is that it is a perennial crop. Therefore, treatments in one year may influence the level of yield in the following years. The estimated equations do not include this interstage dependency.

Table 3. Description of Treatments in the Lost Hills Cotton Experiment

Water Source	EC of Water (mmhos/cm)	Leaching Fraction	
		Low	High
		(%)	
Aqueduct water	.7	.03	.15
Well water	8	.15	.30
Mixed water	4	.08	.16

Cotton

The experiment was located in Lost Hills, California (Rhoades). The experiment was designed to test the hypothesis that cotton can be grown using drainage water with very high salinity levels. Complete information was provided for twelve plots out of sixty. Data for the years 1979–81 were used to estimate the functions. Furrow irrigation was used, and there was no effective rainfall during the year. Treatments are described in table 3 (note that yield is defined as lint plus seed weight).

Regression results are reported in table 4.

Table 4. Estimated Yield Response Functions and Soil Salinity Relations for Cotton

Estimated Equation	R^2	*df*	*F*
$Y = \underset{(8,860.5)}{1,064.14} + \underset{(176.61)}{100.96}Q - \underset{(1.20)}{.536}Q^2 + \underset{(558.12)}{345.32}S_0 - \underset{(23.10)}{42.46}S_0^2 - \underset{(362.51)}{288.76}C$ $+ \underset{(16.22)}{.648}C^2 + \underset{(4.39)}{1.82}Q \cdot S_0 + \underset{(13.09)}{36.68}C \cdot S_0 - \underset{(3.55)}{3.97}Q \cdot C - \underset{(31.03)}{10.37}E_p$	.82	23	10.2
$\log Y = \underset{(4.65)}{15.80} + \underset{(.427)}{.335} \log Q - \underset{(.219)}{.439} \log S_0 - \underset{(.041)}{.198} \log C - \underset{(1.07)}{1.635} \log E_p$	.52	29	7.95
$S_1 = \underset{(35.51)}{-23.40} + \underset{(.71)}{.30}Q - \underset{(.005)}{.00281}Q^2 - \underset{(2.23)}{1.649}S_0 + \underset{(.09)}{.0869}S_0^2 - \underset{(1.45)}{.73}C$ $+ \underset{(.07)}{.02}C^2 + \underset{(.018)}{.00587}Q \cdot S_0 - \underset{(.05)}{.02}C \cdot S_0 + \underset{(.014)}{.01}Q \cdot C + \underset{(.12)}{.20}E_p$	.61	23	3.6
$\log S_1 = \underset{(4.25)}{-8.716} - \underset{(.39)}{.029} \log Q + \underset{(.2)}{.141} \log S_0 + \underset{(.038)}{.103} \log C + \underset{(.979)}{2.176} \log E_p$	.51	29	7.6

Note: Figures in parentheses are estimated standard errors of the coefficients.

The quadratic yield response function has an R^2 value of .82 while the reported log response function has an R^2 value of .52. The log and quadratic functions also provide reasonable estimates of the soil salinity relations with R^2 values between .51–.61. The role of the pan evaporation variable in the cotton case is important. Including this variable improves the R^2 value by almost 0.1 in the quadratic and log equations. (Results without pan evaporation are not presented.)

Implications of the Results

The results presented earlier show that variation in yields is substantially explained by soil-water relations when other production inputs are constant. More specifically, we found that 52%–83% of the yield variation is explained by variation in initial salinity of the root zone and water quantity and quality. Generally, the quadratric relations give the best fit and the log equations give a poor fit.

The empirical response functions have several implications for economic analysis. The soil salinity, water quantity, and water quality coefficients in the log functions have an absolute value less than one. This implies decreasing marginal productivity with respect to these variables. Water quantity has negative values in the nonlinear term of the quadratic function which also implies decreasing marginal productivity.

The marginal rate of substitution (*MRS*) between quantity and quality of water can be calculated from the marginal productivities using the relation

$$MRS_{C,Q} = -\frac{\partial Y/\partial C}{\partial Y/\partial Q}.$$

The *MRS* is useful in determining the crop sensitivity to saline irrigation water. Since Q and C are independent of each other and the other variables in the yield function, the *MRS* relation is valid. Table 5 gives marginal products of quantity (MP_Q) and quality (MP_C) of irrigation water for cotton and alfalfa based on the chosen estimations. The *MRS* between quality and quantity of irrigation water is also presented in table 5. The results imply that cotton needs only 14.2 cm of water to maintain the same yield when the salinity of the water increases from 2 to 3 millimhos/cm at a soil salinity of 8 millimhos/cm. The results reported here are consistent with those in Letey and Dinar.

As noted earlier, several previous studies on the economics of soil salinity have used Maas and Hoffman relations and either a simplified version of Bresler's soil salinity model or steady-state relations to synthesize production functions and soil salinity relations. Those relations are not directly comparable to the relations here for several reasons. First, Maas and Hoffman relations were estimated under conditions where water was not limiting, and this condition does not apply to all treatments in the experimental data used here. A procedure which applies Maas and Hoffman rela-

Table 5. Marginal Product (MP) and Marginal Rate of Substitution (MRS) between Quantity (Q) and Salt Concentration (C) of the Irrigation Water (based on quadratic response functions)

	Alfalfa[a]	Cotton
	(Range of Marginal Products)	
MP_Q (kg/cm)	−163–366	−31–57
MP_C (kg/mmhos/cm)		−543–−40
	(Experimental Means)	
Q (kg/ha)		80
C (mmhos/cm)		2
S_0 (mmhos/cm)		8
	(Marginal Product at the Mean Values)	
MP_Q (kg/cm)		21.8
MP_C (kg/mmhos/cm)		−310.2
$MRS_{C,Q}$ (mmhos/cm^2)		14.2

[a] For alfalfa there is only a single value of C in the experiment.

tions to cases where water is limiting is developed in Letey, Dinar, and Knapp. However, their analysis assumes steady-state conditions and cannot be compared to the results here. Second, Bresler's soil salinity model and the steady-state soil relations require knowledge of evapotranspiration (ET). ET data were not available for some of the experiments used here. More important, ET is itself dependent on initial soil salinity and quantity and salinity of the irrigation water. Because functions relating ET to these variables are not available, it would not be possible to apply these soil salinity models independently of the experimentally determined ET values. For these reasons we have not attempted to compare our estimates with relations used in other works.

Applications of the Estimated Yield-Water Salinity Relations to Efficient Water Use

The estimated response functions and soil salt relations are incorporated in an economic decision model. The model assumes a one hectare crop plot which can be irrigated with two sources of irrigation water (relatively good and saline). The objective is to determine water applications for any given set of prices and initial soil salinities which maximize the net present value of profits from the plot. The decision variables are the quantities of good and saline water, and the state variable is the root zone soil salinity at the beginning of the year.

The optimization problem is formulated as

$$\begin{aligned} \text{Max } \pi = \sum_{t=0}^{\infty} \frac{1}{(1+r)^t} [P_y \cdot Y(t) - P_1 \cdot Q_1(t) \\ - P_2 \cdot Q_2(t)] \end{aligned}$$

$$\begin{aligned} \text{s.t. } Y(t) &= f[Q(t), C(t), S_0(t) \mid E_p, X] \\ S_0(t+1) &= g[Q(t), C(t), S_0(t) \mid E_p, Z] \\ Q(t) &= Q_1(t) + Q_2(t) \\ C(t) &= \frac{C_1 \cdot Q_1(t) + C_2 \cdot Q_2(t)}{Q(t)} \\ q \le\ &Q(t) \le \bar{q} \\ s \le\ &S_0(t) \le \bar{s} \\ &Q_1(t), Q_2(t) \ge 0 \end{aligned}$$

where π is present value of crop revenues net of water and variable harvest costs ($/ha); r is interest rate; P_y is crop price net of marketing and variable harvest costs ($/kg); $Q_i(t)$ is quantity of irrigation water from source i, $i = 1, 2$, applied in year t (cm); P_i is price of irrigation water from source i ($/ha-cm); C_i is salt concentration of irrigation water from source i (millimhos/cm); q, $\bar{q}$, s, $\bar{s}$ are limits based on the experimental data for $Q_i(t)$ and $S_0(t)$, respectively.

Table 6. Parameter Values for the Dynamic Optimization Problem

Crop and Location	s	$\bar{s}$	q	$\bar{q}$	C_1	C_2	P_y	P_1	P_2	E_p
	(mmhos/cm)		(cm)		(mmhos/cm)		($/kg)	($/ha-cm)		(cm)
Alfalfa/Yuma AZ[a]	2.3	13.0	150	237	.2		.055	1.34		252
Cotton/Lost Hills CA[b]	4.0	14.0	61	110	.7	8.0	.49	1.71	.09	150

[a] Alfalfa was irrigated with a single water quality. All monetary values in 1984 dollars. Alfalfa crop and water prices from Barry Tickers, Farm Advisor, Cooperative Extension, Yuma AZ, 1984.

[b] Cotton prices from Kern County Agricultural Commissioner, 1984. Cotton water prices from Vaux, and Knapp and Dinar with adjustment for inflation. Other parameters, see text.

We assume that the water qualities, prices, and weather conditions are constant throughout the analysis. We do not consider crop rotations and assume that the same crop can be grown on the plot through the analysis horizon. The problem solved here can be viewed as an approximate solution to a problem with rotations where the approximation is with respect to the value of the soil salinity at the end of the first rotation for the crop being considered (alfalfa or cotton). The salt relations and the appropriate annual yields are calculated using the quadratic regression equations. The state variable (S_0) and the decision variables (Q_1, Q_2) were bounded to be within the limits of the experimental data (see table 6).

The optimization problem is solved using a dynamic programming procedure. For comparison purposes we also consider the case where optimal water applications in each year are determined only by maximizing current profits (1-year decision rule). Sensitivity analysis with respect to crop and water prices is also performed. Parameter values used in the analysis are presented in table 6.

Results from the Economic Analysis

Optimal decision rules from the dynamic programming model for the base case (actual prices) are reported in table 7 for alfalfa and cotton. These show the optimal quantities of water applications for various initial soil salinity levels. Under the optimal decision rules it does not pay to use poor quality water. For cotton, water quantities increase as initial soil salinity levels increase. The behavior of the optimal decision rule in the case of alfalfa is unexpected: water quantities first decrease, then increase as initial soil salinity levels increase. This behavior stems from the characteristics of the estimated yield and ending soil salinity relations which were discussed earlier.

The one-year decision rules are also reported in table 7. As before it does not pay to use poor quality water for cotton. For alfalfa and cotton, water quantities in the one-year decision rule for the low initial soil salinity levels are higher than in the optimal decision rule; and for the high initial soil salinity levels, water quantities in the one-year decision rule are less than or equal to those in the optimal decision rule.

Sensitivity analysis of the optimal and the one-year decision rules with respect to crop and water prices shows that increasing the price of good water by 20% does not significantly change the decision rules for cotton. Neither was it changed by increasing the price of cotton by 20% or by decreasing saline water price by 70%. The optimal decision rule for alfalfa is also not sensitive to increasing good water price by 20% or decreasing saline water price by 70%. However, increasing the crop price by 20% affects the optimal decision rule for the low initial soil salinities (EC $\leq$ 7.7). In this case applied water increases by 2–4 ha-cm.

Table 7. Optimal Decision Rule and One-Year Decision Rule for Alfalfa and Cotton in the Base Case

	Alfalfa[a]				Cotton			
	1-year		Optimal		1-year		Optimal	
S_0	Q_1	Q_2	Q_1	Q_2	Q_1	Q_2	Q_1	Q_2
	(cm)							
2.30	235.22		213.92					
4.00	228.12		208.59		95	0	96	0
6.00	221.02		203.27		99	0	97	0
8.00	212.14		199.71		102	0	98	0
9.00	208.59		199.71		104	0	100	0
10.00	203.26		201.49		105	0	103	0
11.00	199.71		210.37		107	0	106	0
12.00	196.16		224.57		109	0	110	0
13.00	229.89		237.00		110	0	110	0
14.00					110	0	110	0

Notes: S_0 is initial soil salinity (mmhos/cm); Q_1 is good water quantity (cm); Q_2 is poor water quantity (cm).

[a] Alfalfa was irrigated with a single water quality.

One surprising result from this analysis is that the solution does not include poor quality water at the chosen prices and water qualities. Reuse of low quality drainage water is of increasing interest in arid and semiarid regions where high quality water is becoming increasingly scarce and harmful accumulations of drainage water pose potential problems. To investigate this issue further we made additional runs with higher prices for good water and lower prices for the poor quality water. The results indicate that it pays to use poor quality water only when very substantial changes are made in water prices. For cotton, we found that a price of \$8/ha-cm for good quality water was sufficient to introduce poor quality water into the optimal decision rule. The implied price is well above the typical price paid by agricultural water users in California. These results imply, therefore, that use of the poor quality water considered here (table

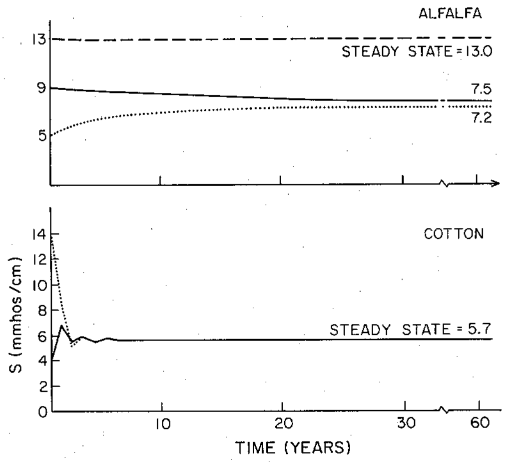

Figure 1. Time paths for soil salinity under the one-year decision rule

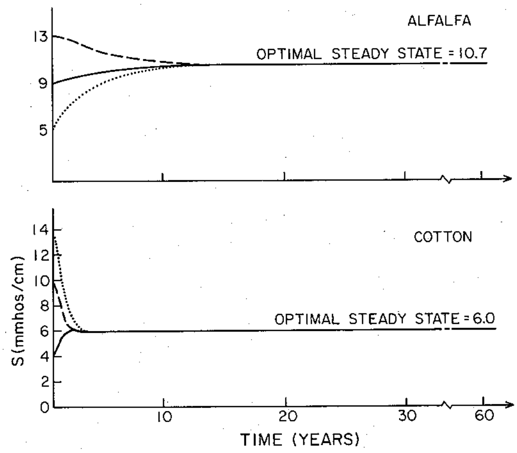

Figure 2. Time paths for soil salinity under the optimal decision rule

6) is not currently justified. (Disposal of drainage water by reuse may have other benefits in some situations. If accounted for, these might alter the conclusions reached here.)

The time paths of soil salinities are presented in figures 1 and 2. Figure 1 presents the time paths for the one-year decision rule for different initial salinities, while figure 2 shows paths under the optimal decision rule. In each case the time paths converge to a steady-state value. A steady-state solution to a dynamic optimization problem is defined as the value for the state variable (soil salinity in this case) which, once achieved, will be maintained forever under the optimal policy. For the optimal decision rule there is a unique optimal steady state for each crop (10.7, 6.0 for alfalfa and cotton, respectively). In the one-year decision rule there is a unique steady state only for cotton (5.7) but multiple steady states for the alfalfa case. Sensitivity analysis shows that under the optimal decision rule the optimal steady-state values do not change as a result of the price changes which were made. For the one-year decision rule only alfalfa was affected. In this case an increase in the price of good water increased the steady-state value for initial soil salinities less than 13 millimhos/cm. An increase in the price of alfalfa decreases the steady-state values for initial soil salinities less than 13 millimhos/cm.

Yaron et al. present time paths of soil salinities for fruit groves in Israel, using a modification of the salt accumulation model proposed by Bresler. With initial soil salinities of 1.3–2.5 millimhos/cm and electrical conductivity of irrigation water ranging from 1.6–2.2 millimhos/cm, they report that the salinity of the soil converges within three to five years to a steady state. The analysis is related to a subhumid region with mean rainfall values of 35 cm per year before the irrigation season, which leaches salt from the root zone. Although the time to convergence depends on the initial soil salinity levels, the results obtained here are generally consistent with those obtained by Yaron et al.

Present values of profits over an infinite horizon are reported in table 8. As expected, profits generally increase as crop prices increase, decrease as good water prices increase, and decrease as initial soil salinity increases. For alfalfa over a range of salinity between 4–7 millimhos/cm, profits increase as initial soil salinity increases. This is a consequence of the characteristics of the estimated yield and ending salinity relations which were discussed earlier. Net present values are higher when using the optimal decision rule compared to the one-year decision rule by 9%–26% for alfalfa and negligible for cotton. The percentage increase in profits will be greater after other production costs are subtracted out.

Summary and Conclusions

In this paper we use field experiment data to estimate crop-water-soil relations and apply them to the problem of determining profit-

Table 8. Present Value of Crop Revenues Minus Water Costs under Optimal and One-Year Decision Rules for Different Crops, Initial Soil Salinity Levels, and Prices

		Optimal Decision Rule			One-year Decision Rule		
			20% increase			20% increase	
Crop	S_0	Base	P_1	P_y	Base	P_1	P_y
	(mmhos/cm)	($1,000/ha)					
Alfalfa	3.0	19.24	18.55	30.61	17.58	16.85	26.68
	5.0	19.33	18.65	30.70	17.22	16.93	25.55
	13.0	18.89	18.18	30.20	15.01	14.23	24.39
Cotton	6.0	51.0	50.4	62.1	50.9	50.3	62.0
	10.0	50.8	50.1	61.8	50.7	50.1	61.7
	14.0	49.9	49.2	60.7	49.7	49.1	60.6

Notes: Monetary values are constant 1984 dollars; an infinite time horizon is assumed.

maximizing water applications. Yield response functions and soil salinity relations were estimated for alfalfa and cotton. Quadratic estimations gave the best fit and have R^2 values of .82–.88 for yield and .61–.92 for soil salt relations. Generally, the estimations show that yield increases as water quantity increases, initial soil salinity decreases, and water concentration decreases. Likewise, ending soil salinity increases as water quantity decreases, initial soil salinity increases, and water concentration increases. However, contradictory results were obtained in some instances.

A dynamic programming procedure was used to solve the optimization problem for each of the crops for given initial soil salinity levels and water and crop prices. A decision rule was provided for the range of conditions which were derived from the experimental data. The decision rules are characterized by no use of poor water and generally increasing good water quantities as initial soil salinity increases. The exception is over some initial soil salinity values for alfalfa. Water quantities in the one-year rule exceed those in the optimal rule for low initial salinity levels and are less than or equal to those in the optimal rule for high initial salinity levels.

Soil salinities converge over time to steady-state values under both the one-year and optimal decision rules. In the case of the one-year decision rule for alfalfa, multiple steady states were found. Steady-state values are generally higher under the optimal decision rule compared to the one-year decision rule. We also found that the present value of profits can be significantly higher under the optimal decision rule than under the one-year decision rule. This implies that a dynamic analysis may be warranted in regions where winter rains do not significantly leach salts.

This paper provides direct estimates of crop yield to initial soil salinity and water quantity and quality. This is in contrast to previous economic studies where production functions have usually been synthesized from separate models of soil salinity and crop response to soil salinity. In addition, we estimate dynamic soil salinity relations. Most previous studies have either ignored the dynamics by assuming steady-state conditions or have used relations based on theoretical soil models. The advantage of the approach presented in this paper is that direct relations for a given region are provided without any calibration of theoretical models. Some disadvantages of this approach are the necessity of finding appropriate field experiments, the possibility of finding estimations which are in contradiction to the theory, and difficulties in transferring the relations to other regions. Further research is needed to estimate production functions which account for irrigation timing as well as quantity and quality of water applied throughout the growing season.

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