Agricultural Water Management, 19 (1991) 51-66
Elsevier Science Publishers B.V., Amsterdam

Production functions relating crop yield, water quality and quantity, soil salinity and drainage volume

A. Dinar[a,1], J.D. Rhoades[b], P. Nash[c] and B. L. Waggoner[b]
[a]*Department of Soil and Environmental Sciences, University of California, Riverside and San Joaquin Valley Drainage Program, 2800 Cottage Way, Sacramento, CA 95825 (USA)*
[b]*United States Salinity Laboratory, USDA-ARS 4500 Glenwood Dr., Riverside, CA 92501 (USA)*
[c]*Department of Soil and Environmental Sciences, University of California, Riverside, CA 92521 (USA)*

(Accepted 8 June 1990)

ABSTRACT

Dinar, A., Rhoades, J.D., Nash, P. and Waggoner, B.L., 1991. Production functions relating crop yield, water quality and quantity, soil salinity and drainage volume, Agric. Water Manage., 19: 51-66.

Data from a long-term lysimeter experiment were used to estimate a set of production functions describing relationships between yield, water quantity and quality, soil salinity and drainage volume. The experiment simulated a variety of conditions prevailing in the San Joaquin and Imperial Valleys of California currently suffering salinity and drainage problems. Coefficients for the various estimated functions are statistically significant and the functions describe the relative effects of input water quality and quantity on yield, soil salinity, and drainage volumes for wheat, sorghum and tall wheatgrass. Possible use of these functions for decision making is discussed.

INTRODUCTION

Irrigated agriculture occasionally suffers from problems related to high levels of salinity in irrigation water and soil (Messer, 1982), especially in locations with shallow groundwater tables and poor or restricted drainage. Irrigation in excess of crop evapotranspiration is necessary to prevent excess salts from accumulating in the soil. This necessarily results in deep percolation and the ultimate need for the discharge of saline (and sometimes toxic) drainage waters. If an impermeable layer restricts deep percolation, a perched water table will form and the soil can develop excessive secondary salinity levels in the root zone thus reducing plant yield. Actions to control salinity, reduce

---

[1] To whom correspondence should be addressed. Currently at Department of Agricultural Economics, University of California, Davis, CA 95616, USA.

drainage, and prevent yield loses are associated with costs. Therefore, decisions about optimal water quantities and qualities must consider economic factors as well as agricultural and environmental issues. Soil–crop–water relationships, which relate crop yield, soil salinity, drainage volume and quantity and quality of the applied irrigation water, are needed to make such decisions. Use of such functions would facilitate optimizing the use of limited soil and water resources while minimizing long-term deleterious impacts of irrigation on the environment.

It is unfortunate that such important information as water–yield–salinity–drainage relationships required for decision making is so scarce. Only a few filed observations (e.g. Wichelns and Nelson, 1989; Dinar and Hatchett, 1989) and experiments (Hoffman et al., 1986; Bingham et al., 1987, 1988) designed to investigate relationships between quantity and quality of applied water and the resulting yields, soil salinity and drainage volume, have been reported in the literature. This is probably because of their relatively high cost and complexity to design and execute.

Hexem and Heady (1978), and Vaux and Pruitt (1983) reviewed normative* and positive** studies on crop–water production functions. Their review did not include salinity aspects. Letey et al. (1990) reviewed the recent literature on crop–water production functions, including the effects of soil and water salinity and drainage volumes. However, there is still lack of empirical information and inference.

The purpose of this paper is to provide statistical estimates of crop–water response functions which include dynamic relationships for salt accumulation in the root zone and drainage volume during the growing season. These relationships are expressed in terms of the quantity and quality (salinity) of the applied irrigation water and the level of initial root zone salinity present at the beginning of the growing season. The analysis is based on data from a four-year lysimeter experiment (Bingham et al., 1987, 1988) involving wheat, sorghum and tall wheatgrass production with use of fresh and saline irrigation waters. The positive relationships are compared, where possible, to the normative model results of Letey and Dinar (1986), and their possible uses for decision making are discussed. Although the applicability of the results is limited in a strict sense, to conditions similar to those of the experiment, it is felt that they are valuable for predicting relative crop response due to salinity and irrigation management under more general conditions, as well.

FRAMEWORK FOR THE ANALYSIS

The appraoch undertaken in this paper is similar to that of Dinar and Knapp (1986); crop yield, soil salinity and agricultural drainage water volume are

---

*Based on concept, rather than data.

**Based on experimental or observed data.

related to several man-controlled variables – quantity and quality of the irrigation water (here only the salinity component of quality is considered) and the initial level of soil salinity. Other factors that may affect yields, soil salinity or drainage volumes are considered constant for the purpose of our analysis.

The implicit relationships to be estimated are:

$$Y=f^{1}(Q, C, S_0 \mid \boldsymbol{R}) \tag{1}$$

$$S_1=f^{2}(Q, C, S_0 \mid \boldsymbol{X}) \tag{2}$$

$$D=f^{3}(Q, C, S_0 \mid \boldsymbol{Z}) \tag{3}$$

where Y is the crop yield, Q is the quantity of seasonal applied water, C is the average salt concentration of the applied irrigation water, S_0 and S_1 are the levels of root zone soil salinity at the beginning and the end of the growing season, respectively, and D is the volume of drainage water produced by the crop. $\boldsymbol{R}$, $\boldsymbol{X}$ and $\boldsymbol{Z}$ are vectors of all other unconsidered variables affecting crop yield, soil salinity and drainage volume, respectively, such as various soil properties, weather conditions, irrigation method, fertilizer usage, etc. These latter variables are assumed to be constant in this analysis.

Based on previous studies (Vaux and Pruitt, 1983) on the use of production functions for decision-making purposes, the analysis here was undertaken using quadratic and log–log functional forms. The quadratic forms imply that (while holding all other variables constant) an increase in the level of one of the man-controlled variables (hereafter referred to as a decision variable) results in a change (increase or decrease – depending on the relationship) in the level of the dependent variable up to a certain point. Any further increase in its level results in an opposite response (decrease or increase, respectively) in the dependent variable level.

For example, for the case of yield and water application, after some minimum application there is a positive effect of further increases in water application on yield production, but the effect becomes smaller as more water is applied (this is usually defined as the positive-diminishing marginal-productivity zone on the production surface). Eventually, however, as more water is applied it may cause aeration and salinity problems (in the case of over-irrigation and if drainage is restricted*) and loss of yield (the zone where this occurs is characterized by a negative marginal productivity). Such behavior has been observed in many biological experiments (Vaux and Pruitt, 1983) and is also explained by the classical theory of production (Russell and Wilkinson, 1979). This relationship has also been found by Letey and Dinar (1986) and Dinar and Knapp (1986) to work well for relating yield and water quality and quantity, and for relating the final level of soil salinity and water

---

*These limitations do not necessarily exist in a lysimeter experiment setup.

quality and quantity. Economic theory assumes that the rational producer, if free to choose, will not produce in the zone of negative marginal productivity.

The log–log functional forms cannot be used to describe relations which first increase and then decrease (or vice versa); they can be used to portray relations which either increase or decrease toward an asymptotic value. For this reason the use of log–log forms for describing yield production functions restricts the analysis to zones on the production function where positive responses occur. Log–log functional forms are therefore not used for predicting final levels of soil salinity since negative marginal productivity (with respect to applied water) occurs in this case and can not be captured using this form.

From our knowledge of soil–plant–water relations it is expected that, while holding other variables constant, plant yield increases as water quantity increases beyond some minimum value (with the exception of a possible decrease in the zone where excessive quantities are applied); the yield decreases as the initial level of soil salinity in the root zone and as the salt concentration in the applied irrigation water increase beyond some minimum values. In the same way, it is expected that the final level of root zone soil salinity will decrease with increasing irrigation water quantities (except for a possible increase where relatively insufficient water quantities are applied*), increasing initial level of soil salinity and decreasing salt concentration of the irrigation water. Likewise, it is expected that the quantity of drainage water increases as water quantity increases, as initial level of root zone soil salinity will increase, and as salt concentration in the irrigation water increases. This behavior implies that increased salt concentration in the irrigation water results in smaller plants with decreased evapotranspiration rates, and hence, in greater deep percolation for a given irrigation amount (Letey and Dinar, 1986, p. 2).

THE EXPERIMENTAL DATA AND EMPIRICAL SPECIFICATIONS

Data from a four-year experiment (Bingham et al., 1987, 1988) were used to determine the effects of irrigation and crop management on the build-up and distribution of boron and salts in the root zone and the corresponding crop yields. The crops used were relatively tolerant to boron so that crop yield should have been dominated by salinity. Therefore, the analysis in this paper is concerned only with the relationships between crop yield, quantity and salinity of applied irrigation water, salinity level in the root zone, and drainage water volumes that were produced as a result of irrigation.

Wheat and sorghum were grown in rotation in some 100 cm deep lysimeters, and tall wheatgrass (hereafter called wheatgrass) was grown continu-

---

*For example, when the initial levels of soil salinity and salt concentration in the irrigation water are high, water quantities needed might be much more than under conditions of low levels of soil salinity and salt concentration in the irrigation water.

ously in others over the four-year period (1983–1986). The soil used was Arlington loam (Table 1). The irrigation management included the use of waters of different salt concentrations and varying leaching fractions (Table 2). Other management practices such as fertilization were consistent from lysimeter to lysimeter. The lysimeters were covered, when necessary, with clear plastic roofs to prevent rainfall from entering the lysimeters. Each lysimeter was equipped with a drainage outlet and collector. An uncropped lysimeter was included as a control.

Soil salinity build-up was measured in only some of the lysimeters (12 for wheat sorghum, and 18 for wheatgrass). Therefore data from only these lysimeters were used in the development of the crop–water production functions. Data from three seasons were used for the case of wheat (total of 24 observations), from four seasons for sorghum (total of 30 observations), and from four years for wheatgrass (total of 40 observations). Salt concentrations of the irrigation waters were measured at the time of each application; and levels of salinity in the soil water at six depths in the root zone were measured following each irrigation. Ranges of the experimental values incurred for the variables under test are presented in Table 3.

The analyses reported in this paper were performed on an annual basis. Therefore, average values of salt concentration in the irrigation water and

TABLE 1

Selected properties of Arlington loam soil.

pH	Org. C (%)	Sand (%)	Silt (%)	Clay (%)	Bulk density (Mg/m^3)
7.0	0.2	48	38	13	1.6

TABLE 2

Chemical composition of the irrigation water and leaching fractions.

Water	Ca	Mg	Na	Cl	B (ppm)	EC (dS/m)	Leaching fractions[a] V_d/V_i
	------ (mmolc/l) ------						
(1) California aqueduct	2.2	1.3	3.1	2.2	0.3	0.7	0.05, 0.1, 0.3
(2) Colorado River	4.6	2.6	5.7	3.4	0.7	1.3	0.1, 0.2, 0.3
(3) Imperial Valley drainage	9.4	8.9	22.9	16.6	3.0	3.9	0.15, 0.3
(4) San Joaquin Valley drainage	25.7	13.9	49.1	47.7	6.0	8.0	0.2, 0.3, 0.4
(5) California aqueduct for germination and San Joaquin Valley drainage thereafter	Same as above for a given source						0.3
(6) Colorado River for germination and Imperial Valley drainage thereafter	Same as above for a given source						0.3

[a] V_i = volume of applied irrigation water; V_d = drainage volume.

TABLE 3

Range of values for the experimental variales used in the regression.

Variable	Crop		
	Wheat	Sorghum	Wheatgrass
Q (cm)	25–58	70–121	26–390
S_0 (dS/m)	1.99–14.62	1.64–14.65	1.26–18.26
S_1 (dS/m)	2.15–14.87	2.04–14.99	1.26–19.17
C (dS/m)	0.72–8.24	0.71–8.33	0.71–8.17
D (cm)	3.70–21.41	8.79–45.15	6.15–151.78
Y (ton ha)	0.23–3.54	1.10–6.33	0.53–13.11
S (dS/m)	2.10–14.82	1.70–15.11	1.55–19.74

average levels of salinity in the soil water for the 0–90 cm of the root zone (both expressed in terms of electrical conductivity, EC) were used. For each crop, the first and last measurements of soil salinity during each growing season were taken as the initial and final levels of soil salinity, respectively.

The following relationships were used to calculate several aggregated variables:

$$Q=\sum_i q_i \tag{4}$$

$$C=\sum_i c_i q_i / \sum_i q_i \tag{5}$$

$$S=[(1/J)\sum_j s_{tj}]\tau_t \tag{6}$$

$$\tau_t=(t_2-t_1)/\text{total number of days in the season} \tag{7}$$

where Q is the annual quantity of irrigation water, q_i is the quantity of water applied at the ith irrigation event during the season, C is the average salt concentration of the irrigation water, c_i is the salt concentration in the water applied at the ith irrigation event during the season, S is the average seasonal root zone salinity, J is the number of soil layers sampled, s_{tj} is the soil salinity level at depth j sampled at Julian day t, τ_t is the duration that this salinity level existed, in terms of fraction of the season, and t_1 and t_2 are first and last Julian days for a given level of soil salinity.

Regression equations were estimated separately for the wheat and sorghum crops assuming them to be independent of the previously grown crop. This assumption should hold because leaching was made at the beginning of each growing season. For the case of wheatgrass, it was also assumed that there was no serial correlation in the four-year time series (meaning that the values of the dependent variable over time are not correlated). An equation accounting for the time effect was also estimated for wheatgrass (by simply including a variable that accounts for year). We expected a quadratic relationship to exist between yield and time which is a typical behavior for perennial crops. But the results (not presented) indicated that the time effect was not significant. It is likely that irrigation water salinity and soil salinity effects on yield dominated the time effect so much that no time effect of yield could be observed.

RESULTS

The results of the regression analyses for the three crops without consideration of the time effect are presented in Tables 4–7. The regressions explain a high percentage of the observed variations in yield (0.88–0.92 using the quadratic equations, and 0.51–0.90 using the log–log equations), in final soil salinity levels (0.98–0.99 using the quadratic equations), and in drainage water

TABLE 4

Estimated quadratic yield response functions for wheat[a], sorghum and wheatgrass irrigated with water of various qualitites and at various initial soil salinity levels.

Variable	Wheat	Sorghum	Wheatgrass
Q	0.2064	0.0410	0.0121
	(1.64)[b]	(3.30)	(1.36)
Q^2	-1.4×10^{-3}	-3.3×10^{-5}	7.5×10^{-5}
	(−0.98)	(−0.50)	(2.86)
C	3.5553	0.1407	−0.0505
	(1.40)	(0.12)	(−1.10)
C^2	2.3261	−0.0752	-3.45×10^{-3}
	(4.05)	(−2.03)	(−1.06)
S_0	−2.0317	−0.1977	0.6860
	(−1.82)	(−2.10)	(1.23)
S_0^2	0.8234	−0.0151	-2.99×10^{-3}
	(3.75)	(−5.10)	(−0.08)
QC	−0.0716	0.0031	0.0025
	(−1.68)	(0.31)	(1.73)
QS_0	0.0338	−0.0040	-5.67×10^{-3}
	(1.29)	(−0.51)	(−3.60)
CS_0	−2.7540	0.0768	0.0115
	(−3.91)	(1.80)	(1.18)
Intercept	−3.3500	1.5714	−0.6138
	(1.21)	(0.24)	(−0.62)
R^2	0.88	0.86	0.92
F	11.4	14.0	39.6

[a] The equation for wheat should be read as follows:

$$\text{Yield} = -3.350 + 0.2064Q - 0.0014Q^2 + 3.555C + 2.326C^2 - 2.031S_0 + 0.823S_0^2 - 0.071QC + 0.033QS_0 - 2.754CS_0$$

[b] Values in parentheses are t-values.

TABLE 5

Estimated quadratic soil salinity relationships for wheat, sorghum and wheatgrass irrigated with water of various qualities and at various initial soil salinity levels.

Variable	Wheat	Sorghum	Wheatgrass
Q	0.1740	0.0480	0.0209
	(1.32)[a]	(3.40)	(3.12)
Q^2	-1.37×10^{-3}	$-2.44\times^{-4}$	-2.54×10^{-5}
	(−1.85)	(−3.40)	(−1.29)
C	−1.9010	2.0130	1.2150
	(−0.75)	(1.50)	(3.35)
C^2	−0.3270	4.47×10^{-3}	−0.0658
	(−0.57)	(1.10)	(−1.48)
S_0	2.0360	0.2530	2.6801
	(1.28)	(2.30)	(6.40)
S_0^2	−0.1560	−0.0242	−0.0611
	(−1.71)	(−0.79)	(−2.17)
QC	0.0465	-4.97×10^{-3}	6.03×10^{-3}
	(1.09)	(−0.43)	(5.490)
QS_0	−0.0242	0.0016	-9.68×10^{-3}
	(−0.93)	(1.80)	(−8.17)
CS_0	0.4507	0.0052	0.0393
	(0.64)	(1.10)	(0.80)
Intercept	−3.849	−2.335	−4.383
	(−1.39)	(−0.31)	(−5.92)
R^2	0.99	0.98	0.98
F	246.9	152.7	168.9

[a] Values in parentheses are t-values.

volumes (0.83–0.89 using the quadratic equations and 0.56–0.81 using the log–log equations). Levels of the F-statistic (a test for the overall significance of a multiple regression; Gujarati, 1988) indicate that the estimated regressions significantly ($p<0.05$) explain the variations in the levels of the various dependent variables. In most cases, the estimated coefficients of the various equations are statistically significant at a value of 5% or less. In most cases, the lowest t-values (a statistical measure for rejection of the null hypothesis that an estimated coefficient is not significantly different from zero; Gujarati, 1988) were obtained for the coefficients of the interacting variables (QC, QS_0, and CS_0).

Relatively high correlations (0.98, 0.73, 0.74 for wheat, sorghum and wheatgrass, respectively) were found (not presented) between the salt concentration in the irrigation water (C) and the initial level of soil salinity (S_0). Hence, problems in the estimation process may occur when these two variables are included in the same equation because of multicollinearity (correlation between independent variables appearing in the same equation). This multicollinearity is the result of the experimental design which did not in-

TABLE 6

Estimated quadratic drainage volume relationships for wheat, sorghum and wheatgrass irrigated with water of various qualities and at various initial soil salinity levels.

Variable	Wheat	Sorghum	Wheatgrass
Q	−0.2860	−0.526	−0.0875
	(−0.37)[a]	(−0.58)	(−0.88)
Q^2	5.52×10^{-3}	3.60×10^{-3}	3.38×10^{-4}
	(6.30)	(7.80)	(2.17)
C	−30.134	5.085	1.617
	(−2.20)	(6.00)	(3.30)
C^2	−7.047	−0.189	−0.0422
	(−2.27)	(−7.01)	(−6.06)
S_0	17.532	−0.775	−8.115)
	(2.04)	(−0.11)	(−1.32)
S_0^2	−2.787	0.282	−0.165
	(−2.35)	(1.44)	(−1.40)
QC	0.544	-5.36×10^{-3}	−0.0232
	(2.36)	(−2.07)	(−1.44)
QS_0	−0.270	0.0224	0.0682
	(1.91)	(0.39)	(3.91)
CS_0	8.822	−0.588	0.244
	(2.32)	(−1.89)	(0.34)
Intercept	2.537	25.018	20.412
	(0.18)	(0.53)	(1.87)
R^2	0.83	0.83	0.89
F	7.9	11.0	28.0

[a] Values in parentheses are *t*-values.

clude any treatments involving the use of low salt concentration irrigation waters on soils with high initial, soil salinity levels.

Regression equations relating seasonal average soil salinity and crop yield were also estimated for each crop. Results obtained in the current study were poor for both linear and log–log functional forms and are not presented. Previous studies (e.g. Maas, 1986) have indicated a relative yield decrease with increasing seasonal average soil salinity in excess of some threshold level for optimum values of irrigation and drainage. The results from our study suggest that yield is not simply related to average soil salinity but also to salinity and volume of water applied and to drainage volume.

The quadratic functions relating yield, final soil salinity and drainage to quantity and quality of irrigation water and to initial soil salinity for the case of wheat are presented in Figs. 1–3. (Plots of relations for other crops are not presented but are available upon request). The curves in these figures are extended beyond the limits of the experimental data for higher values of annual irrigation water quantities (the maximum value for wheat in the experiment was 58 cm and the upper limit exhibited in the figures is 100 cm). This

TABLE 7

Log–log estimated relationships for crop yield and drainage water volumes for wheat, sorghum and wheatgrass irrigated with water of various salinities and various initial soil salinity levels.

	Intercept	Q	C	S_0	R^2	F
Wheat						
Yield[a]	−8.593	2.485	−0.148	−0.094	0.51	6.9
	(−320)	(4.26)	(−0.82)	(−0.08)		
Drainage volume	−0.066	0.580	0.431	−0.132	0.56	8.7
	(−0.05)	(1.81)	(0.82)	(−0.20)		
Sorghum						
Yield	−1.647	0.765	−0.011	−0.445	0.83	44.4
	(−1.40)	(3.05)	(−0.021)	(−6.13)		
Drainage volume	−2.606	1.127	0.237	0.270	0.77	29.1
	(−2.07)	(4.19)	(3.94)	(3.47)		
Wheatgrass						
Yield	−3.784	1.073	−0.139	−0.468	0.90	115.4
	(−13.72)	(17.68)	(−1.89)	(−5.30)		
Drainage volume	−0.480	0.720	0.405	−0.026	0.81	53.5
	(−1.31)	(8.90)	(4.12)	(−0.22)		

[a] The equation for wheat should be read as follows:

$$\text{Yield} = e^{-8.593} Q^{2.485} C^{-0.148} S_0^{-0.094}$$

[b] Values in parentheses are t-values.

was done for several purposes: (1) to include the quantities of applied water commonly used in the west side of the San Joaquin Valley (between 75 to 90 cm (University of California, Cooperative Extension, 1987), and (2) to estimate the empirical range of applied water in which maximum levels of yield and ending soil salinity are obtained at various conditions of initial soil salinity and water quality. These procedures were also undertaken for sorghum and wheatgrass (results not shown). It should be noted that the experimental data do not exist beyond the solid lines in Figs. 1–3, and that the extrapolation was done assuming a quadratic behavioral pattern.

The quadratic functions obtained relating wheat and sorghum yield to the explanatory variables Q, C, and S_0 behaved as expected. In the case of wheatgrass no decreasing marginal productivity for water was observed. Apparently the irrigation quantities did exceed the plant needs but were inefficient under the existing conditions of soil salinity and irrigation water salinity levels*.

---

*Water quantities of 280–390 cm, of qualities ranging from 3.9 to 8 dS/m, were apparently not sufficient to leach salts when applied on soils with initial salinity levels ranging from 4 to 9 dS/m. As a result, ending soil salinity levels increased significantly (6 to 14 dS/m).

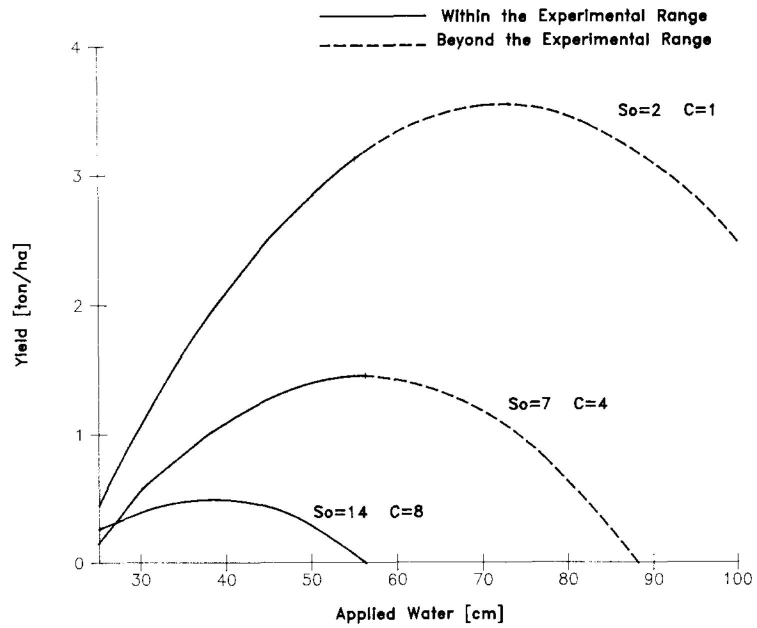

Fig. 1. Quadratic yield response function for wheat.

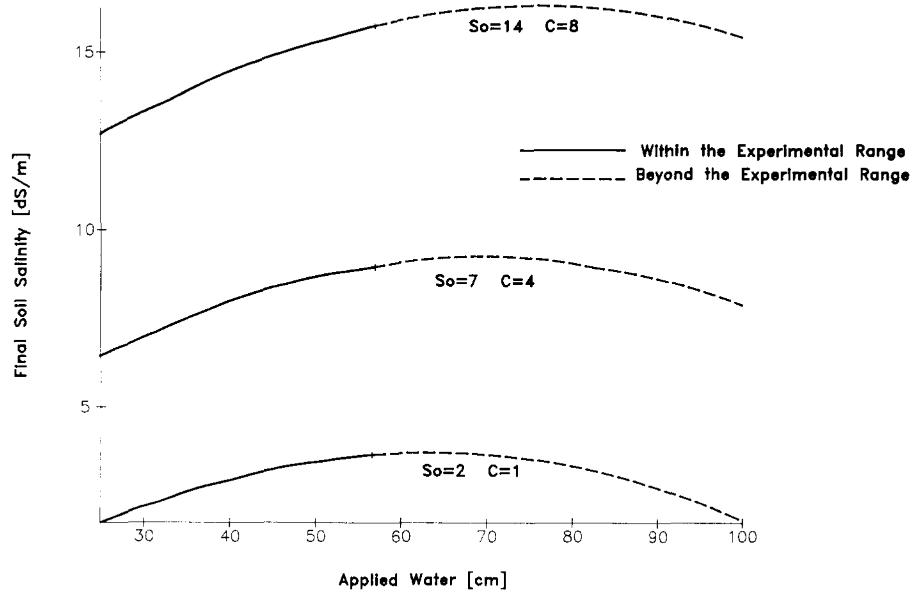

Fig. 2. Quadratic soil salinity relationships for wheat.

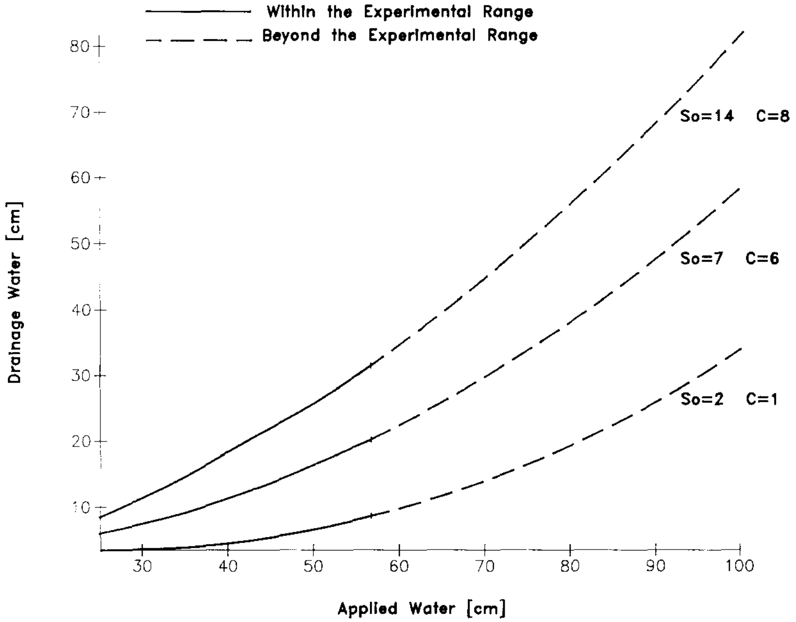

Fig. 3. Quadratic drainage water function for wheat.

Except for sorghum, the log–log yield relations did not behave as would be expected with regard to water quantity. In the case of wheat, the estimated coefficients for Q were greater than 1; this implies that any increase in water quantity would increase yield, with all other variables being constant. For wheatgrass this coefficient was very close to 1.

Relationships for seasonal soil salinity changes were obtained for all crops. For sorghum and wheatgrass, the final levels of soil salinity were found to be a decreasing function of the irrigation quantity. For wheat, final soil salinity increased as water quantity increased, up to 70 cm (for all initial conditions), and then decreased as water quantity increased further. This behavior is in agreement with the findings reported by Dinar and Knapp (1986, p. 59). The estimated drainage functions (both quadratic and log–log) for the three crops showed that drainage quantity increased as applied water increased, as initial soil salinity level increased, and as salt concentration in the irrigation water increased. This behavior also follows the pattern found by Letey and Dinar (1986) and was explained earlier in the text.

COMPARISON OF THE RESULTS OBTAINED FOR WHEAT WITH EXISTING LITERATURE

Normative models are usually used in cases where empirical information is absent. However, the applicability of such models to the variety of conditions is questionable. Verification of models should be carried out before they are used for such different conditions. In this section, our wheat results (the estimated quadratic regressions for yield and drainage volume) are compared to the results obtained using the normative model of Letey and Dinar (1986). Their normative model provides relative yield and quantity of drainage water as a function of the quantity and quality of the applied irrigation water. The model assumes implicitly that initial soil salinity levels are low enough to permit regular management. Therefore, we applied their model to our wheat data for the case of low initial soil salinity levels (<5 dS/m). Pan evaporation (PE) values measured throughout the different seasons were used for each crop. Salt concentration levels in the irrigation water were 0.7, 1.2, and 3.5 dS/m. Irrigation water quantities were in the range of 0.35PE to 0.85PE. Results showing the agreement between the normative model and the estimated functions are presented in Figs. 4 and 5. The solid lines in these figures are the regression lines, and the dashed lines represent the 45° angle starting from the origin. The correlation obtained between the estimated yields and the normative model-calculated yields is 0.96, and the correlation between the estimated drainage volumes and the model-calculated volumes is 0.69. The agreement in the case of the relative yield is better than in the case of drainage volumes. This can be seen also from the regression coefficients relating estimated and model-calculated yields and drainage volumes; in the case of yield, the slope is closer to 1 compared to the case of drainage volumes. Average absolute percent difference (AAPD) equal to 17 was calculated between indi-

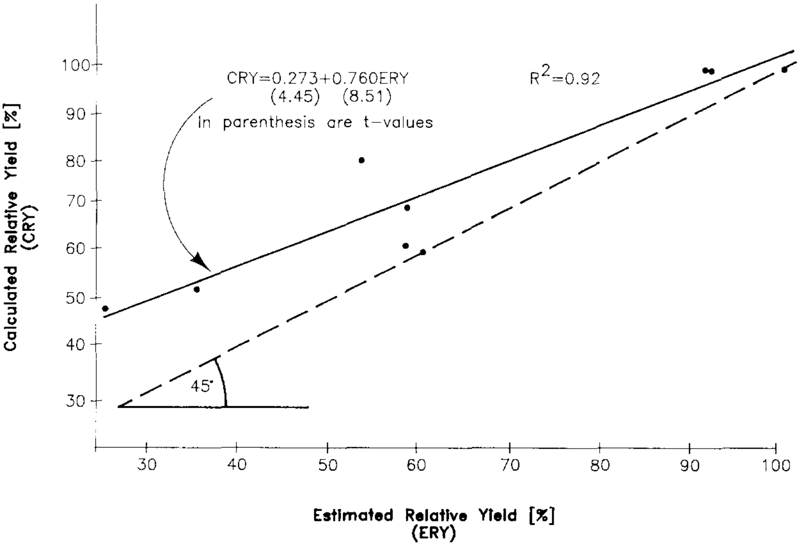

Fig. 4. Comparison between normative-calculated and positive-estimated relative yield for wheat.

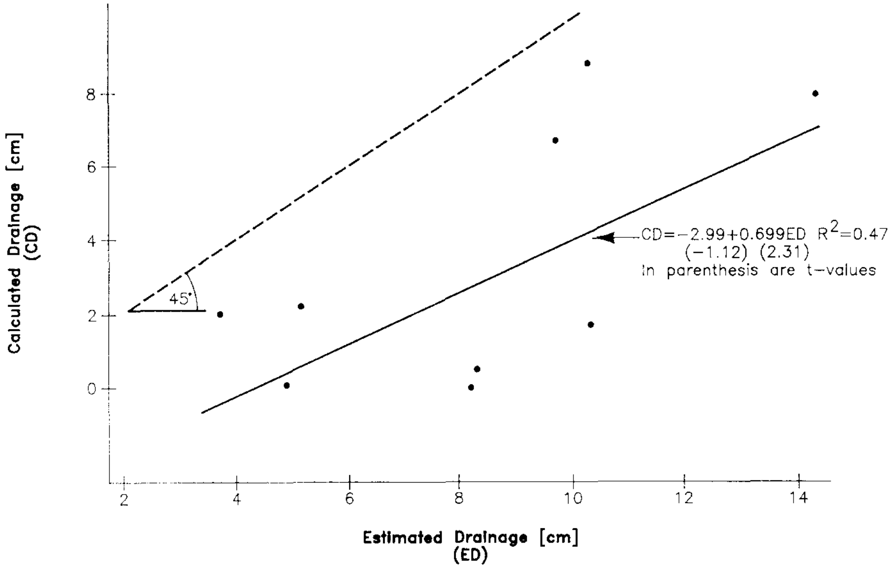

Fig. 5. Comparison between normative-calculated and positive-estimated drainage volumes for wheat.

vidual observed and model-calculated relative yield values. This value falls within the range (2 to 23%) of AAPD calculated in previous applications of that model (Letey et al., 1985; Letey and Dinar, 1986). An AAPD of 51 between model-calculated and observed drainage volume values was calculated, which means a lower agreement than in the case of relative yield. Therefore, using this comparison, the normative model provides reasonable predictions for yield, and less reasonable predictions for drainage volumes under the lysimeter conditions.

The equations comparing estimated to model-calculated values (Figs. 4 and 5) have relatively high R^2 values. This, and the results in Figs. 4 and 5 mean that for the lysimeter experiment conditions the normative model consistently overestimated yield and underestimated drainage. Therefore, in order to apply the model, one should simply calibrate it using an adjustment factor.

SUMMARY AND DISCUSSION

Lysimeter data were used to estimate relationships between yield, water quantity and quality, soil salinity and drainage volumes for a variety of conditions similar to those prevailing in the San Joaquin and the Imperial Valleys of California. Coefficients for the various estimated functions were found to be statistically significant and in most cases were also in agreement with findings provided by previous studies.

A major conclusion from this study is that a direct relation between yield and average seasonal soil salinity does not apply to conditions where several limiting factors are interrelated. For example, when soil and applied water salinity levels are high, and the quantity of applied water is not sufficient, average soil salinity itself will not explain yield reduction. Therefore, interrelated effects should be estimated as suggested in this paper.

The results imply that these lysimeter-based functions can also be used to develop information needed for decision making. For example, several on-farm practices have been recommended as a possible solution to reduce private and social damages from salinity and drainage water problems (National Research Council, 1989). For this purpose, one should have relationships that relate water quantity, water quality, yield, soil salinity, and drainage volume. These relationships should ideally be based on site-specific data. Unfortunately, such data are scarce.

Lysimeter experiments are relatively easy to control and can be used to simulate a variety of environmental conditions. The lysimeter results can verify normative predictions of the models, and if necessary to calibrate for local conditions. In the case of wheat, a reasonable agreement was achieved between the normative yield model results and the regression model results. Drainage predictions by the normative model were drastically, but consistently lower than those estimated by the regression model.

Relationships such as those presented here for wheat, sorghum, and wheatgrass, can be used to evaluate different alternatives of irrigation/drainage management on a field or farm level. A further application of the estimated relationships presented here is urged in order to assess economic and management aspects of different policies and solutions being advocated for reducing salinity and drainage related problems.

ACKNOWLEDGEMENTS

This study was supported in part by the San Joaquin Valley Drainage Program, Sacramento, California. The authors would like to acknowledge the assistance of David Ackerman in the stage of results verification, and the comments of two anonymous reviewers.

REFERENCES

Bingham, F.T., Rhoades, J.D. and Strong, J.E., 1987. A lysimeter study of boron distribution in relation to irrigation management. Progress Rep., US Salinity Laboratory, Riverside, CA, unpublished.

Bingham, F.T., Rhoades, J.D. and Strong, J.E., 1988. The effect of irrigation water management on the distribution of boron in lysimeters under wheat–sorghum cropping. Progress Rep., US Salinity Laboratory, Riverside, CA, unpublished.

Dinar, A. and Hatchett, S., 1989. Data on applied irrigation, drainage volumes, and yields for five crops and sixty fields for the period 1987–1988 in the west side of the San Joaquin Valley, California, unpublished.

Dinar, A. and Knapp, K., 1986. A dynamic analysis of optimal water use under saline conditions. W. J. Agric. Econom., 11(1): 58–66.

Gujarati, D.N., 1988. Basic Econometrics. McGraw-Hill, New York, 2nd ed.

Hexem, R. and Heady, E.O., 1978. Water Production Functions and Irrigated Agriculture. Iowa State University Press, Ames, IA.

Hoffman, G.J., Jobes, J.A. and Alves, W.J., 1986. Response of tall fescue to irrigation water salinity, leaching fraction, and irrigation frequency. Agric. Water Manage., 7: 439–456.

Knapp, K. and Wichelns, D., 1990. Dynamic optimization models for salinity and drainage management. In: K.J. Tanji (Editor), Agricultural Salinity Asessment and Management. American Society of Civil Engineers, New York.

Letey, J. and Dinar, A., 1986. Simulated crop-water production functions for several crops when irrigated with saline waters. Hilgardia, 54(1): 1–32.

Letey, J., Dinar, A. and Knapp, K., 1985. Crop-Water Production Function Model for Saline Irrigation Waters. Soil Sci. Soc. Am. J., 49(4): 1005–9.

Letey, J., Knapp, K. and Solomon, K., 1990. Crop-water production functions under saline conditions. In: K.K. Tanji (Editor), Agricultural Salinity Assessment and Management. American Society of Civil Engineers, New York.

Maas, E.V., 1986. Salt tolerance of plants. Appl. Agric. Res., 1(1): 12–26.

Messer, J., 1982. International development and trends in water reuse. In: E.J. Middlebrooks (Editor), Water Reuse. Ann Arbor Science Publishers, Ann Arbor, MI.

National Research Council, 1989. Irrigation Inducted Water Quality Problems. National Academy Press, Washington, DC.

Russell, R.R. and Wilkinson, M., 1979. Microeconomics – A synthesis of modern and neoclassical theory. Wiley, New York.

University of California, Cooperative Extension, 1987. Cost Budgets for Wheat and Sorghum in Fresno County, 1987.

Vaux Jr., H.J. and Pruitt, W.O., 1983. Crop-water production functions. Adv. Irrig. 2: 61–97.

Wichelns, D. and Nelson, D., 1989. An empirical model of the relationship between irrigation and the volume of water collected in subsurface drains. Agric. Water Manage., 16: 293–308.