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Irrigation Management and Investment under Saline, Limited Drainage Conditions

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Abstract
A dynamic optimization model for soil salinity is formulated which includes crop rotations, spatially variable irrigation and soil salinity, and investment in irrigation systems. Optimal decision rules are concave in mean soil salinity; soil salinity state variables converge to a rotation averaged steady state.

Introduction

Optimal intertemporal irrigation management of an individual field under saline conditions is considered in Yaron and Olian (1973), Matanga and Marino (1979), and Knapp and Dinar (1986). This paper extends these studies by considering exogenous crop rotations, spatially-variable soil salinity and applied water infiltration, investment in improved irrigation systems, and the environmental and disposal costs associated with drainage. Applications include efficient management, cost of reduced irrigation and drainage volumes, cost of increased salinization of water sources, and grower response to regulatory instruments.

Model

To specify the mathematical model, it is convenient to use an alternate coordinate system for time based on the crop rotation number and year within the rotation. If there are n years in the given crop rotation, then $t = (i - 1) n + j$ defines a unique relation between year t and rotation number i and year within the rotation j. The notational convention $ij+1 = i,j+1$ if $j < n$, and $ij+1 = i+1,j$ if $j=n$ will be used later.

There are m possible irrigation systems available for use. Let x_{ij} denote investment in a new irrigation system, where $x_{ij} = 0$ denotes no new investment and $x_{ij} = k$ denotes investment in a new irrigation system of type k. Investment is subject to the constraint that irrigation systems must be replaced at or before the end of their physical life. Straightforward accounting identities provide the equations of motion for type (z_{ij}) and age (a_{ij}) of irrigation system respectively.

At a given point in the field, crop yield y_{ij}, deep percolation d_{ij}, and ending soil salinity s_{ij+1} are given by $g_j(s_{ij},q_{ij})$, where s_{ij} is soil salinity at the beginning of the year, q_{ij} is quantity of water infiltrating at that point in the field, g_j is a three-component vector function, i is the rotation number and j is the year within the rotation. In general, yield is decreasing in initial salinity and increasing in infiltrated water. Ending soil salinity level is increasing in initial soil salinity, increasing in infiltrated water when infiltrated volumes are low, and decreasing in infiltrated water when the infiltrated volume is sufficiently large.

The quantity of water infiltrating at each point in the field is $q_{ij} = \beta_{ij} \bar{q}_{ij}$ where β_{ij} is the water infiltration coefficient, and $\bar{q}_{ij}$ is the average applied water depth for the field as a whole. Thus the depth of water infiltrating at each point in the field is some positive fraction of the average applied depth for the entire field. In a given year, the water infiltration coefficients and beginning soil salinity levels are assumed to be spatially distributed according to the density function $f(s,\beta;\Gamma_{ij})$ where Γ_{ij} is a vector of parameters describing the joint distribution of salinity and water infiltration coefficients over the field with the existing irrigation system at the beginning of the jth year in the ith rotation. Integrating the density function with limits of (a,b) and (c,d) for s and β respectively gives the fraction of the field with $s_{ij} \epsilon [a,b]$ and $\beta \epsilon [c,d]$. It is straightforward to show that mass balance implies that $E[\beta] = 1$. Field-level yields ($\bar{y}_{ij}$) and drainage flows ($\bar{d}_{ij}$) are calculated by integration over the spatial density function.

To complete the problem, it remains to specify how the spatial density function changes over time. Here s and β are assumed to be spatially distributed according to a lognormal distribution. Thus the parameter vector Γ consists of the mean and variance of ln s, the mean and variance of ln β, and the correlation coefficient for ln s and ln β. $E[\beta] = 1$ from above and the standard deviation of β is a function of the irrigation system type; together these determine the mean and variance of ln β. The three remaining parameters can be calculated using the following general formula:

$$(1) \quad {}^{k,l}\theta_{ij+1} = \int_0^\infty \int_0^\infty [\ln g_{j3}(s, \beta\, \bar{q}_{ij})]^k \, [\ln \beta]^l \, f(s,\beta;\Gamma_{ij}) \, ds \, d\beta$$

where in the period corresponding to ij+1, the mean of s is given by (1) with (k,l)=(1,0), the variance of ln s is (1) with (k,l)=(2,0) minus the mean squared, and the correlation coefficient for ln s and ln β with the existing irrigation system at the beginning of the crop year is (1) with (k,l)=(1,1). Thus equation (1) effectively becomes the equation of motion for three of the parameters describing the spatial density function. Finally, the actual correlation coefficient during the year is assumed to be equal to the existing coefficient at the beginning of the year if there is no new investment in irrigation systems or if the same type of system is installed. If there is investment in a new type of irrigation system, then the actual correlation coefficient during the year equals zero.

Annual net benefits (profits) are crop revenue net of harvest, irrigation system and water costs, nonwater production costs, and environmental damages/disposal costs associated with drainage flows. The optimization problem is to maximize discounted net benefits over an infinite horizon subject to the equations of motion and definitions noted above and upper and lower bounds on the q_{ij}. The control variables are x_{ij} and q_{ij}, and the state variables are z_{ij}, a_{ij}, the mean and variance of ln s_{ij}, and the correlation coefficient for ln s_{ij} and ln β_{ij} at the beginning of the period. The solution algorithm is dynamic programming.

Data

The analysis is conducted for conditions representative of areas in the San Joaquin valley of California with existing or potential salinity and drainage problems. The field is assumed to be 129.5 ha, but most results are reported on a per-unit area basis.

The crop rotation is two years of cotton followed by one year of tomatoes. The base year for price and cost calculations is 1988 and the real rate of return is assumed to be 5%.

Five alternate irrigation systems are considered. These are given in table 1, along with the maximum system life. Point-level production functions are based on the Letey et al (1985) model with modifications for dynamic soil salinity relations. Standard deviations for β are computed from the CUC values reported in table 1.

Crop prices are $1757.36/Mg for cotton and $56.35/Mg for tomatoes; adjustments are made for harvest costs. Irrigation system and non-water production costs are reported in table 1. Water costs are computed as the sum of fixed and variable pumping costs plus the cost of water. Annualized drainage system costs are assumed to be $78.12/ha. Except where noted, the price of irrigation water is $1/(ha cm), environmental/disposal costs per unit of drainage flows are $2/(ha cm), and electrical conductivity (salinity) of the irrigation water is .67 dS/m.

Optimal Management and Investment

Optimal investment and water applications in each rotation year are functions of the five state variables. Figure 1 displays a portion of the optimal decision rules. These show optimal water applications as a function of mean soil salinity holding the standard deviation constant at .6 dS/m, the correlation coefficient at -.8, and a furrow (1/2 mile) irrigation system which is one year old. For first year cotton, optimal water applications are increasing in mean soil salinity. For second-year cotton and tomatoes, optimal water applications first increase as mean soil salinity increases, then decrease in general. The decreasing portion of the optimal decision rule is explained by the fact that, at higher salinity levels, crop evapotranspiration is less so that a given level of water applications results in increased leaching and hence lower ending salinity levels. Also noteworthy is that optimal applications are higher for second-year cotton in comparison to first-year cotton. This results in lower soil salinity levels for the more salt-sensitive tomato crop and illustrates the necessity of accounting for rotations in dynamic soil salinity models.

Under the specified conditions and an initial mean soil salinity of 4 dS/m, the optimal irrigation system is furrow with 1/2 mile runs. Figure 2 displays the optimal time path for mean soil salinity. Large initial water applications drive down the mean soil salinity levels within the first four years. After that, mean soil salinity follows a cyclical pattern, reaching a low point following the tomato crop and then increasing over the two cotton crops. Following the initial transition period the system is in steady state in the sense that each rotation is identical to the preceeding one. Analagous results apply to water quantities and the other salinity state variables.

The significance of spatial variability can be assessed by comparing these results to the case where irrigation and hence soil salinity are completely uniform. Under perfect uniformity and an average soil salinity of 4 dS/m, optimal water applications are 73,93 and 80 cm/yr for the three rotation years. These represent reductions of 26-40 percent compared to optimal water applications under nonuniformity, illustrating that accounting for spatial variability and nonuniformity in irrigation is essential for obtaining realistic results.

Water Policy

Empirical estimates of agricultural water demands are necessary for a wide range of water policies. Examples include allocation of available supplies between alternate uses, evaluating the benefits from developing new supplies, and calculating efficient groundwater management policies. Table 2 gives rotation-averaged values for optimal applied water depths, irrigation systems, and annualized net benefits in the steady-state for a range of water prices. Here, increasing the price of water from $1/(ha-cm) to $4/(ha-cm) decreases applied depths from 132 cm/yr to 104 cm/yr or 21%, and returns to land and management by $346/(ha-yr) or 25%. Arc elasticity of water demand for an increase in price from $1/(ha-cm) to $2/(ha-cm) is -.18; the elasticity declines in absolute value as water prices increase. These calculations suggest, therefore, that agricultural water demand for the crops considered is quite inelastic. It did not pay to install an improved (more uniform) irrigation system for any of the water prices considered.

Deep percolation (drainage) water is an inevitable consequence of irrigated production, and can result in high water tables encroaching the rootzone and degraded quality of surface and ground water bodies. Table 2 also gives results for alternate drainage disposal fees. Increasing the drainage fee from zero to $2/(ha cm) decreases optimal rotation-averaged water depths by only 19 cm/yr or 14%; however, an increase from zero to $4/(ha cm) implies a more substantial decrease of 52 cm/yr or 40%. Arc elasticities are -.04 and -.51 for zero to 2 and 2 to 4 $/(ha-cm) drainage fees respectively. Thus environmental/disposal costs associated with drainage water can have very significant impacts on optimal water use. It is also interesting to note that reduced water applications with the higher drainage fee are achieved solely through investment in an improved irrigation system; yields are either the same or higher in comparison to the lower drainage fee.

Surface and groundwater supplies in some areas of the west are experiencing increased salinization. From table 2, an increase in EC of the irrigation water from .67 dS/m to 2dS/m increases the rotation-averaged soil salinity in the steady-state by 148%, increases optimal water applications by 10% on average, and reduces returns to land and management by 15%. Similar figures for an increase from 1 to 2 dS/m are a 40% increase in soil salinity, a slight (3%) decrease in applied water, and a 18% decrease in returns. There is no change in the irrigation system. Thus the increased irrigation salinity did not result in large changes in management, but does have significant income effects.

Drought

California is entering the fifth year of a drought; with recent announced cutbacks by state and federal water authorities, water supplies will be tight. To simulate possible response, the model is run with three alternate upper limits to maximum water availability. This is only an approximation since in the model the constraint applies to all years but in actuality restricted water supplies presumably apply only to current and possibly near future years.

With 90 cm/yr a linear move system is used after an initial transition period. Investment follows a limit cycle after an initial transition period for the other two runs. With 100 cm/yr, the limit cycle consists of two five-year periods of furrow 1/2-mile followed by a five-year period of furrow 1/4-mile. Mean soil salinity levels trend upwards under the less efficient irrigation system but fall under the more efficient one. With 80 cm/yr, the optimal limit cycle consists of 12 years of linear move, 1-2 years of furrow 1/2-mile, 12 years of linear move, and finally 8 years of subsurface drip. Reductions in annualized net benefits range from 2-6 percent in comparison to the unconstrained case. Availability of alternate irrigation systems appears to mitigate the impact of reduced supplies.

Conclusions

The model developed here extends previous work in several directions including crop rotations, irrigation system investment, and spatial variability in water applications and soil salinity. Optimal water applications are generally concave in mean soil salinity; in the absence of binding constraints on water applications the system converges to a steady-state in the sense that each rotation is identical to the preceeding rotation after some initial transition period. Nonuniformity implies substantially greater water applications than uniform irrigations.

Irrigation water demand is inelastic within the range of prices considered, but is more responsive to drainage effluent fees. Small increases in the salinity of irrigation water imply large reductions in net returns. Installation of improved irrigation systems in the face of constrained water supplies is profitable.

References

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Table 1. Data

System Type	Capital Cost ($/ha)	O & M ($/[ha-yr])	Life (years)	CUC	Production Costs Cotton ($/[ha-yr])	Production Costs Tomatoes ($/[ha-yr])
Furrow, 1/2-mile	190	6	5	70	879	1231
Furrow, 1/4-mile	249	7	5	75	919	1299
Linear move	1495	75	12	90	834	1156
LEPA	1493	75	12	85	853	1176
Subsurface drip	2334	117	8	90	665	959

Source: UC Committee of Consultants (1988) and UC Cooperative Extension
Field size = 129.5 ha with 125.5 cropped area
CUC = Christiansen Uniformity Coefficient (dimensionless)

Table 2. Optimal soil salinity, water applications, irrigation systems, and net benefits under alternate conditions.

Pw	e	ECi	E[ECe]*	q*	z*	ANB*
1	0	0.67	1.47	132	1	1394
2	0	0.67	1.64	117	1	1270
3	0	0.67	1.75	109	1	1155
4	0	0.67	1.87	104	1	1048
1	2	0.67	1.70	113	1	1290
1	4	0.67	2.16	80	3	1218
1	2	2.00	4.23	124	1	1092
1	2	3.00	5.94	120	1	897

Pw = Price of water [$/(ha-cm)], e = environmental/disposal costs of DW [$/(ha-cm)], ECi = EC of irrigation water (dS/m), q* = Rotation-average field-level applied water depth in steady-state (cm/yr), z* = Optimal irrigation system in steady-state (1=furrow, 1/2-mile, 3=linear move), ANB* = Rotation average return to land and management in steady-state [$/(ha-yr)]

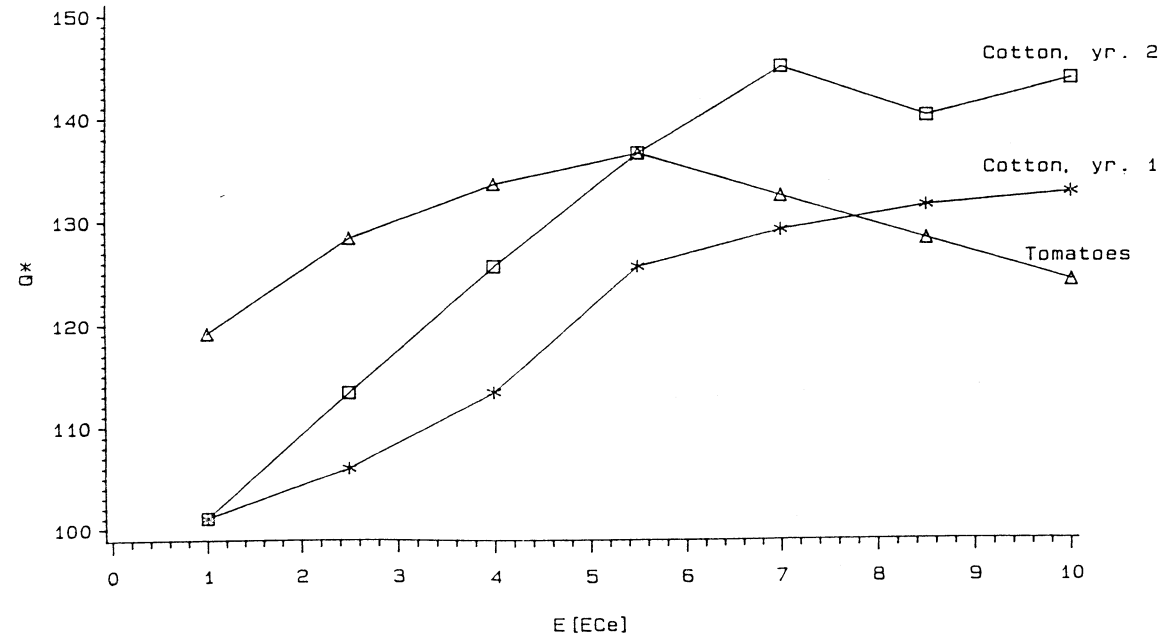

Figure 1. Optimal water applications as a function of field-level average soil salinity holding other state variables constant.

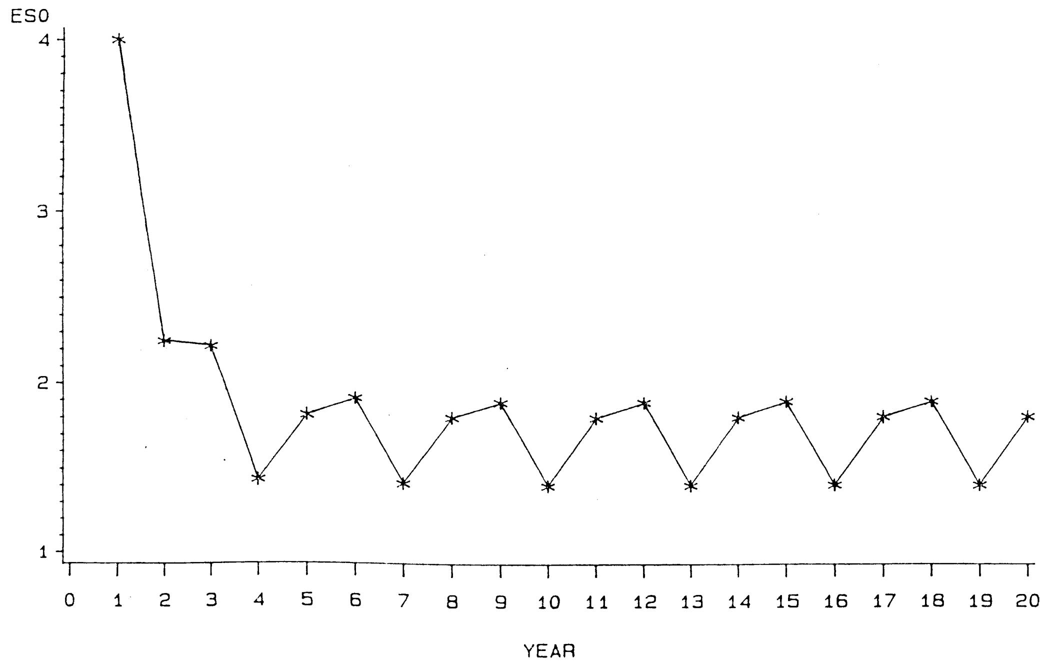

Figure 2. Time series plot for field-level average soil salinity under optimal management.