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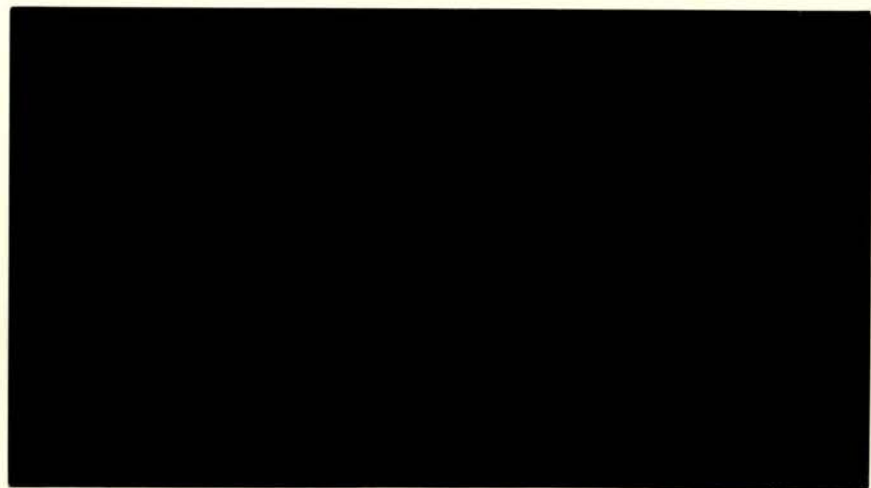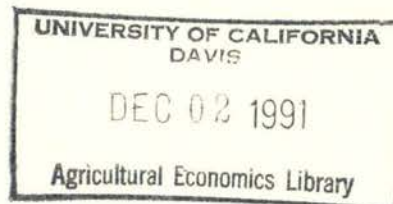
WORKING PAPER SERIES

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A DYNAMIC MODEL OF MULTI-CROP IRRIGATED
AGRICULTURE UNDER CONDITIONS OF POOR RESOURCE
QUALITY AND LIMITED DRAINAGE

by
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A Dynamic Model of Multi-crop Irrigated Agriculture Under Conditions of Poor Resource Quality and Limited Drainage

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Abstract. This paper presents a dynamic model of irrigated agriculture under saline soil and limited drainage conditions. The model allocates land and water inputs based on an intertemporal profit maximization objective function and a soil salinity accumulation process. Functional specifications for crop yield, soil salinity and drainage generation that are econometrically-derived from lysimeter field tests are incorporated in the modeling framework. The model is applied to conditions in the San Joaquin Valley of California, where environmental degradation from drainage has become a policy issue. Findings indicate that, in the absence of regulation, drainage volumes increase over time before reaching a steady state as larger amounts of water are allocated to leaching soil salts. The model is used to evaluate alternative drainage abatement scenarios involving drainage quotas and taxes, water-supply quotas and taxes, and irrigation technology subsidy. Of the instruments evaluated, drainage quotas may be the most efficient means of controlling drainage. In general, direct drainage policies are more efficient than drainage reduction policies operating indirectly through surface water use, and quota-based policies are more efficient than tax-based policies. In some cases, efforts to control drainage may result in increased soil salt-buildup, with implications for long-term cropland productivity. The paper's results demonstrate the need for a dynamic framework with interdependence of water use, soil salinity, and drainage in analysis of irrigated agriculture.

Key words. Dynamic model, irrigation, water quality, soil salinity, drainage, technology, policy evaluation

1. Introduction

Critical resource supply and quality affect irrigated agriculture in many parts of the world. The problems include short- and long-term production effects of reduced water quality and soil productivity; competition for fixed water supplies; and management of irrigation drainage residuals that may create negative externalities.

In this setting, the decision-making framework for analysis of irrigated agriculture requires several elements. First, the model should incorporate dynamic, intertemporal effects of resource quality. This ensures that current decisions affect future resource conditions and, consequently, future returns. Second, the model's set of production choices should involve multiple input and output decisions. Thus, soil salinity and drainage residual can be controlled by alternative producer responses involving adjustments in cropping patterns, crop rotations, water quality (i.e., mix of fresh and saline water), water application rates, irrigation technology, and irrigated cropland. Finally, the model should provide for exogenous, policy-imposed incentives or regulations to demonstrate the effect of externality controls on production decisions, resource quality, and farm returns.

Research on the dynamic nature of irrigated agriculture under saline and poor drainage conditions has been limited due to lack of information on physical relationships among the state and decision variables mentioned earlier. Much of the previous empirical research used crop production functions to evaluate the relationship between yield and water quantity, water quality, and soil salinity (e.g., Yaron et al., 1980; Dinar and Knapp, 1986; Knapp and Dinar, 1988; Knapp and Wichelns, 1990). These studies, however, do not account for drainage. More recently, Knapp 1991, modified a steady state model by incorporating the dynamics of soil salinity into a comprehensive modeling framework that considers salinity of applied water, drainage quantity, and spatial variability of soil properties. The model was used also to evaluate irrigation investment decisions under limited drainage. The results, based on a normative crop-water relationships, suggest that crop rotations and irrigation technologies are important model elements, in addition to the standard consideration of water quantity and quality mix. However, use of a dynamic programming algorithm restricted the analysis to only a few decision variables in each period, involving a two-crop fixed rotation.

Lack of information on physical-agronomic relationships are compounded by variation in production and environmental conditions across sites. General models applied to specific locales have been found less robust than expected (e.g., Imhoff, 1991). Many of the above studies, in particular, were limited in their applicability and transferability across sites. Calibration to on-site conditions was found to be time and resource consuming.

In this paper, analysis of irrigated agriculture under saline and limited drainage conditions at the farm level incorporates three elements that have not been combined

previously: (a) application of crop production functions from field lysimeter data, based on soil salinity and water quantity-quality variables, (b) a dynamic multi-year, multi-crop model of a production enterprise, and (c) exogenous regulatory policies that reduce irrigation water supply, restrict off-farm drainage residuals, and/or impose limits on the extent of land quality (salinity) degradation.

Crop production functions estimated from lysimeter experiment data (Dinar et al., 1991) are the central element of the production model. They include relationships between crop yield and water quantity, water quality, soil salinity and drainage volume. Reliance on regional lysimeter experiments allows the modeling approach to be applied more readily to different sites, thereby removing a major limitation of previous research. Lysimeter experiments are much less expensive, more controlled, and can be completed in fewer years than conventional field experiments. (For further discussion, see Dinar et al., 1991.)

The opportunity to adjust multi-crop decisions over time offers more realistic input-output combinations to the production framework. Relatively saline water (from the ground water source) can be applied to salt-tolerant crops, while fresh water (from the surface water source) may be reserved for other crops (Rhoades and Dinar, 1991). Similarly, soil salinity can be managed at varying levels, according to salt tolerance levels of the crops.[1]

Finally, alternative economic or regulatory policies can be analyzed within the modeling framework. With non-linear functional relationships for drainage and salinity and a linear cost function for drainage abatement, the modeling framework can analyze both responses to and impacts of various drainage regulations. The framework also can analyze incentives to reduce irrigation water use and policy-imposed thresholds on the level of both drainage and soil salinity. Pollution from irrigation drainage, productivity effects of soil salt accumulation and conservation of irrigation water supplies are important water policy issues (e.g., Caswell and Zilberman 1986; Caswell et al. 1990), and have emerged most acutely in California's San Joaquin Valley (National Research Council, 1989; Moore, 1991).

Section 2 presents the model equation system. In section 3, an empirical application of

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[1] While our model allows for differences in soil salinity by crop over the course of the year, average soil salinity over the cropland base at year end serves as starting salinity level in the subsequent period.

the model is presented based on representative production conditions in the San Joaquin Valley of California. Section 4 demonstrates the use of the model for policy analysis.

2. The Model

The analytical framework involves a dynamic mathematical programming model that incorporates non-linear functions for crop production, soil salinity, and drainage generation. Water and cropland allocation decisions directly affect the levels of soil salinity and drainage water generated. The dynamic nature of irrigation and salinity management is captured in the path of soil salinity accumulation and in the intertemporal decisions on land and water allocations.[2]

The objective function of the farm operation (or regional authority) is to choose land and water allocations, land retirement levels, and water marketing activity for a given time horizon so that the following is maximized

$$[1] \ \text{Max} \sum_t [\frac{1}{(1+r)^t}] \{ \sum_i [(P_i - H_i) \cdot y_{ti} - V_i - K] \cdot x_{ti} - \sum_h w_t^h \cdot W^h - D_t \cdot G - xI_t \cdot K + xR_t' \cdot R$$

$$+ \sum_j m_t^j \cdot M \}$$

where t is year (t=1,2,...,T); i is crop; r is discount rate, P_i is crop price; H_i is harvest cost per unit yield; y_{ti} is crop yield; V_i is non-water variable cost per acre of crop i; K represents per acre amortized cost of irrigation technology applied to both cropped and idled acres. x_{it} is crop area; w_t^h represents total water use by supply type h, and W^h is per unit water cost; D_t represents total drainage volume; and G is unit cost of drainage disposal; xI_t is acreage idled; xR_t' is acreage retired (with compensation), and R is compensation per acre; m_t^j represents a permanent sale of water rights from water source j, and M is the market price for a water right per unit water. All prices and costs (r, P, H, V, W, K, G, R and M) are exogenous to the farm or region. The model assumes one irrigation technology applied on all acres. In order to analyze irrigation technology effects on yield, soil salinity, drainage generation and profit, technology coefficients are adjusted and the model is run separately for each technology.

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[2] The current model is to be modified to provide for endogenous technology adoption paths over time.

The intertemporal problem in [1] is maximized subject to production function relationships, resource and regulation constraints, and initial conditions. Production functions for crop yield, soil salinity accumulation, and drainage production are

$$[2]\ y_{ti}=y_{ti}(\sum_{j} a^j_{ti}, C_{ti}, sL_{ti}) \qquad t=1,...,T;\ i=1,...,n,$$

$$[3]\ s_{ti}=s_{ti}(\sum_{j} a^j_{ti}, C_{ti}, sL_{ti}) \qquad t=1,...,T;\ i=1,...,n,$$

and

$$[4]\ d_{ti}=d_{ti}(\sum_{j} a^j_{ti}, C_{ti}, sL_{ti}) \qquad t=1,...,T;\ i=1,...,n$$

The three dependent variables -- yield, soil salinity at season's end (s_{ti}), and per acre drainage (d_{ti}) -- each depend on per acre applied water over the growing season ($\sum a^j_{ti}$), salt concentration of applied water over the growing season (C_{ti}), and soil salinity following preseason leaching (sL_{ti}). The state variable for the problem is soil salinity by crop, s_{ti}.

The land and water resource constraints are

$$[5]\ \sum_{i} x_{ti}+xI_t+xR'_t=X-\sum_{k} xR'_k \qquad t=1,...,T;\ k=0,...,t-1,\ \forall\ t \geq 1$$

and

$$[6]\ \sum_{i} [x_{ti}(a^j_{ti}+aL^j_{ti})]+m^j_t \leq A^j_t-\sum_{k} m^j_k \qquad j=1,2;\ t=1,...,T;\ k=0,...,t-1,\ \forall\ t \geq 1$$

where X sets a constraint on the total area in agricultural production; A^j_t sets a constraint on total water use from source j for crop production, leaching, and market sales in year t; and aL^j_{ti} is leaching application rate per acre.

Finally, initial conditions in the base year (t=1) are fixed for salinity concentration by water source, aggregate soil salinity, cropland base, and water supply:

$$[7]\ c^j_1=\overline{c}^j;\ SI_1=\overline{SI};\ \text{and}\ A^j_1=\overline{A}^j \qquad j=1,2.$$

The model differentiates between water supply by "source" j and "type" h. Total water

supply available to the farm or region is specified for surface water (j=1) and groundwater (j=2) sources. Surface water supply is based on water allotments while groundwater supply reflects the effective pumping capacity of the farm or region. Water quality parameters (salinity) are also provided by water source. Water supply "type" represents a further disaggregation of surface water and groundwater sources to reflect different water prices. Three water supply types are defined to represent base surface water (h=1), supplemental surface water (h=2), and groundwater (h=3). Water supply types are used to compute total water cost to the farm or region; water costs are charged to aggregate water use by supply type in the objective function. Use of distinct water supply permits analysis of water pricing options, in addition to water allocation and marketing policies. Equations [8] and [9] balance water use by supply type h with use by source j across crop acres.

$$[8] \; w_t^{h=1}+w_t^{h=2}=\sum_i [x_{ti}(a_{ti}^{j=1}+aL_{ti}^{j=1})]+m_t^{j=1} \qquad t=1,...,T$$

$$[9] \; w_t^{h=3}=\sum_i [x_{ti}(a_{ti}^{j=2}+aL_{ti}^{j=2})]+m_t^{j=2} \qquad t=1,...,T$$

Idled land (xI_t) refers to cropland fallowed in a given year, which may be returned to production in subsequent years. With idled land, fixed costs are incurred although some irrigation systems are not in use. Idles land retains salinity levels of the previous year (t-1), as reflected in aggregate salinity of cropland base (SI_t). Retired lands (xR_t') refer to cropland permanently removed from the cropland base.[3] Irrigation system costs on retired lands are no longer borne (i.e., systems that are economically obsolete or sold at salvage value). Soil salinity levels on these lands are not considered in the aggregate salinity calculation.

Equation [10] ensures a reasonable cropping pattern based on endogenous apportionment of acres across crop-mix alternatives. The product of acres by crop-mix alternative u in year t (xF_{tu}) and fixed crop acreage share by crop-mix alternatives (f_{ui}) is set equal to crop i in year t:

$$[10] \; \sum_u xF_{tu}f_{ui}=\sum_i x_{ti} \qquad t=1,...,T; \; i=1,...,n.$$

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[3]While water rights also could be reduced as a part of permanent land retirement, the model does not link water and land as resource use rights.

Salinity of applied irrigation water is computed as a weighted average of concentrations (c^j) across sources used to irrigate crop i. The model assumes that ground and surface water may be mixed to control salinity concentration of water applied, that salinity concentration may vary by crop, and that the mix for leaching application (CL_{ti}) may differ from that for applied irrigation water (C_{ti}). The related equations are

$$[11] \quad C_{ti} = \frac{\sum_j c^j \cdot a_{ti}^j}{\sum_j a_{ti}^j} \qquad t=1,...,T; \ i=1,...,n,$$

and

$$[12] \quad CL_{ti} = \frac{\sum_j c^j \cdot aL_{ti}^j}{\sum_j aL_{ti}^j} \qquad t=1,...,T; \ i=1,...,n.$$

Changes in soil salinity over time are affected by the distribution of crops, the level and quality of preseason leaching application, and seasonal irrigation applications by crops. Measures of soil salinity include initial soil salinity by year t (SI_t), post leaching soil salinity by crop i and year t (s_{ti}), and aggregate post season soil salinity by year t (SE_t), which serves as initial salinity for the following period (SI_{t+1}).

Soil salinity is the critical dynamic element of the model. Initial soil salinity in year t represents a weighted average of salinity over all cropped and idled fields at the end of the preceding year

$$[13] \quad SI_{t+1} = \sum_i \frac{s_{ti} \cdot x_{ti}}{x_{ti}} \cdot \frac{x_{ti}}{X_t} + SI_t \cdot \frac{xI_t}{X_t} \qquad t=1,...,T.$$

Three related equations follow. Equation [14] is leaching application balance. It includes initial soil salinity (SI_t), soil salinity after leaching (sL_{ti}), salinity concentration of leach water (CL_{ti}), and leaching coefficient (L). Equation [15] calculates the amount of drainage generated in the preseason leaching (dL_{ti}), based on applied water by source, field root-zone capacity (RC), and wilting point (WP). Equation [16] defines total drainage generated

on the farm (D_t) as the sum of per acre drainage from preseason leaching and seasonal irrigations.

[14] $\sum_j aL_{ti}^j \geq L \cdot \dfrac{SI_t - sL_{ti}}{SI_t - CL_{ti}}$ $\qquad$ t=1,...,T; i=1,...,n,

[15] $dL_{ti} = \sum_j aL_{ti}^j \cdot (RC - WP)$ $\qquad$ t=1,...,T; i=1,...,n,

and

[16] $\sum_i x_{ti} \cdot (d_{ti} + dL_{ti}) = D_t$ $\qquad$ t=1,...,T.

In addition, three non-negativity constraints apply for the salinity component of the model:

[17] $sL_{ti} - CL_{ti} > 0$ $\qquad$ t=1,...,T; i=1,...,n.

[18] $SI_t - sL_{ti} \geq 0$ $\qquad$ t=1,...,T; i=1,...,n.

and

[19] $s_{ti} - sL_{ti} \geq 0$ $\qquad$ t=1,...,T; i=1,...,n.

To assure model convergence at a reasonable solution, upper and lower bounds (beyond the range of observed values) were specified for the values of applied water, soil salinity, drainage volume, and yield:

[20] $a^l \leq \sum_j a_{ti}^j \leq a^u$ $\qquad$ t=1,...,T; i=1,...,n,

[21] $aL^l \leq \sum_j aL_{ti}^j < aL^u$ $\qquad$ t=1,...,T; i=1,...,n,

[22] $s^l \leq s_{ti} \leq s^u$ $\qquad$ t=1,...,T; i=1,...,n,

[24] $sL^l \leq sL_{ti} \leq sL^u$ $\qquad$ t=1,...,T; i=1,...,n,

[25] $d^l \leq d_{ti} \leq d^u$ $\qquad$ t=1,...,T; i=1,...,n,

[26] $dL^l \leq dL_{ti} \leq dL^u$ $\qquad$ t=1,...,T; i=1,...,n,

and

[27] $y_i^l \leq y_{ti} \leq y_i^u$ $\qquad$ t=1,...,T; i=1,...,n.

The equation system [1]-[27] defines an intertemporal multi-crop profit maximization

problem. The system is solved first for the status quo production environment, based on current water prices, water allotments, and given irrigation technology. Then, adjustments are made in baseline assumptions to reflect a modified policy environment. Comparisons between baseline and policy solutions provide insight into the effectiveness of proposed policies at achieving desired resource goals.

3. Empirical Application

The model is applied to conditions prevailing on the west side of the San Joaquin Valley, California. The region is considered to be the most productive agricultural area in California, producing a wide array of field and specialty crops under irrigation. However, severe drainage and salinity problems jeopardize the region's long-term production potential. The proposed modeling framework is designed to evaluate efficiency and distributional impacts of alternative policy instruments for drainage and salinity management.

DATA AND EMPIRICAL SPECIFICATIONS

A field-crop farm operation with a representative 500 acres of irrigable cropland is defined based on data in Dinar and Campbell, 1990. Irrigable cropland is assumed net of acreage set-aside for federal commodity programs. Irrigation is required for crop production on the farm.

Cropping alternatives include wheat, sorghum, and wheatgrass.[4] While cropping rotations for a given field are not explicitly defined in the production alternatives, endogenous apportionment of acreage by crop-share alternative (Eq. 10) ensures a mix of crops by period. Crop-share alternatives include: (a) 20% wheat - 80% wheatgrass, (b) 17% wheat - 17% sorghum - 66% wheatgrass, and (c) 80% wheat - 20% sorghum.

Commodity prices represent observed market prices adjusted for commodity-program deficiency payments. Market price is based on average seasonal market price over the 1980-1987 period, expressed in constant 1987 dollars. Market prices for wheat, sorghum

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[4]Crop activities were based on published yield, drainage and salinity functions (Dinar et al, 1991). Efforts are underway to collect data for production function analysis of other major field crops in the region.

and wheatgrass are $133, $109 and $94 per ton, respectively. While farm program participation is not explicitly addressed in the model, an acreage-weighted deficiency payment is added to market prices to more accurately reflect returns to program crops. The deficiency payment adjustment are $89/acre for wheat and $23/acre for sorghum.[5]

The California State Water Project and U.S. Bureau of Reclamation's Central Valley Project supply surface water for irrigation use in the San Joaquin Valley. Ground water is a supplemental water source for many farms of the region. The baseline model assumes an annual surface water entitlement of 1500 acre-feet (af). Surface water charges are based on a multi-tiered pricing system, with the first 1000 af priced at $10/af and an additional 500 af available at $15/af. Ground water supplies reflect an annual pumping capacity of 1500 af at a pumping cost of $35/af (Dinar and Campbell, 1990). Drainage disposal costs are estimated at $7/af (SJVDP, 1990). For purposes of this analysis, it is assumed that opportunities for marketing irrigation water supplies are not available (i.e., market price for water is set to zero).

Salt concentration in surface water is set at 0.7 EC (Electrical Conductivity measured in deciSiemens per meter (dS/m)), based on typical salt levels for surface water deliveries (Dinar et al., 1991). Ground water is assumed to be of lower quality, at 2.0 EC (Quinn, 1991). Initial soil salinity was fixed at 1.5 EC across all fields (Dinar et al., 1991).

Irrigation technology costs are based on a survey of representative technologies in the region (CH2M HILL, 1989). Irrigation cost components include labor cost by crop; pressurization, maintenance, and amortized fixed costs of the system; and irrigation scheduling and implementation costs. For purposes of this paper, two irrigation technologies were considered: an improved gravity system (.25 mile run, with tailwater pumpback system), which serves as the baseline technology, and a linear-move sprinkler system. Systems are assumed to be operated under medium-level management. Annual capital cost was $25.00/acre for the gravity system and $70.00/acre for the linear-move sprinkler system.

Production function coefficients for crop yield, drainage and salinity are provided in Dinar et al., 1991. The effect of alternative irrigation technologies is reflected in the model through slope adjustments for yield, drainage and salinity functions. Slope adjustments by

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[5]Program payment adjustments were calculated based on per acre deficiency payments for irrigated wheat ($115) and sorghum ($52), adjusted for percent acreage enrollment by irrigated wheat (77%) and sorghum (44%) in California, 1987 (USDA, 1990).

crop and technology are provided by Rhoades (1990). Leaching function coefficients were estimated based on a soil moisture capacity of 52 cm, a wilting point of 20 cm, and a leaching factor of 0.5 for Arlington soils (Dinar et al., 1991).

Non-irrigation production costs were obtained from crop budget reports for central California, 1986-87 (University of California Cooperative Extension). Non-irrigation cost categories include preharvest variable costs, variable harvest cost per unit yield, and stand establishment cost for wheatgrass. Non-irrigation fixed costs include fixed equipment cost, other depreciation costs, interest on investments, and office overhead.[6]

The present value of farm returns for baseline and policy scenarios are calculated over a 15-year planning period, using a 4 percent discount rate.

The model was programmed using GAMS modeling software (version 2.21/MINOS 5.2), which allows concise model expression and flexibility in structural and data assumptions.

BASELINE SCENARIO EVALUATION

The baseline scenario represents farm income, production, and input use under observed conditions. This section provides a brief discussion of the baseline model results, highlighting features of the proposed modeling framework. In the following section, baseline results serve as a benchmark for comparison of alternative policy scenarios.

The baseline scenario demonstrates the dynamic nature of the salinity management problem. Under the baseline, soil salinity (the state variable) increases steadily from an initial setting of 1.5 EC to a steady-state level of 3.0 EC by the end of the fourth year. Such increases in soil salinity commonly occur in many irrigated soils due to the salt loading and concentrating effects of irrigation, particularly where water supplies are saline or where limited drainage conditions restrict leaching practices. Figures 1 and 2 show the change in soil salinity over time under the baseline scenario and alternative surface water and drainage discharge quotas. (Section 4 includes an analysis of quotas and other policy instruments.)

Farm returns decline significantly over the first several years of production, before

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[6]Non-irrigation fixed costs are not included in the model's objective function, although farm returns net of fixed cost are calculated in the solution report.

stabilizing at a steady-state level. Annual net income falls from $29,590 in year 1 to $13,160 in year 4 in current-value terms. Strong returns in year 1 reflect low leaching requirements and higher crop yields under less saline soil conditions. Declining returns in subsequent years reflect increased water application costs and reduced productivity with increasingly saline soils. The present value of farm returns over the 15-year planning horizon is $162,500.

Soil-salt accumulation has the potential to motivate several adjustments in producer decisions within the modeling framework. Output substitution, involving changing crop selection and crop shares, is one such possibility. In this example however, a cropping pattern of 80% wheat - 20% sorghum remains constant over the planning period. The predominance of wheat reflects high market returns and deficiency payments, and a relative tolerance for saline water applications. Sorghum enters the solution under the minimum acreage share requirement, while wheatgrass does not enter at all due to low returns. Output substitution may be more important in the model where changes in baseline parameters (such as commodity prices or water quality) alter relative commodity returns, and production alternatives more fully reflect the range of cropping opportunities available to producers.

Land retirement, an additional land-use decision, also was invariant to salt accumulation. The land base was planted to capacity over the entire planning period due to the relatively abundant water supply and positive marginal value of irrigable land under the baseline conditions.

The baseline scenario does illustrate potential for input substitution in response to increasing soil salinity. Water use for leaching and consumptive purposes increased from 1816 af in year 1 to 2118 af in the steady state (an additional 17%). The resulting average application per unit land increased from 3.6 to 4.2 af/acre. At the same time, the productivity of irrigation applications declined with increasing salinity. Yield per unit water fell by roughly 10% for sorghum and 20% for wheat.

The mix of water use by water source also changed over the planning period. Surface water as a share of total water use increased from 55% to 63%, reflecting increased use of higher-quality water for salt leaching on wheat acreage. The share of total water use attributable to leaching increased from 28% to 38%. As base surface-water allocations were fully used, additional leaching water was drawn from the more expensive second tier

of surface supply. Wheat used water from both ground and surface water supplies, while sorghum, reflecting more salt sensitivity, used surface water only.

The opportunity to allocate water for salt-reduction purposes means that soil quality is modeled as a renewable resource. This adds realism to the modeling framework, as producers in California and other irrigated areas do mitigate soil-salt accumulation with pre-season water applications.

Finally, the model demonstrates the effect of soil-salt accumulation on drainage production over time. Annual drainage volume increased from 158 af in year 1 to 439 af at the end of year 4. Increased volumes are attributable primarily to greater preseason leaching; drainage from preseason leaching rose from 30% of total drainage in year 1 to 70% in the steady state. Drainage generation is highest for sorghum, with 1.2 af/acre, as compared with 0.8 af/acre for wheat. However, wheat production accounts for most soil salt contamination due to reduced preseason leaching applications, reduced leaching from seasonal crop-water applications, and increased use of lower-quality ground water.

This last result has serious ramifications for evaluating environmental degradation from irrigated agriculture. Economic incentives for waterand cropland use, combined with the physical procwss of salt accumulation, may increase drainage volumes over time. Without some form of drainage regulation, drainage-induced environmental problems may worsen as drainage flows increase to a steady-state level. This would not be revealed if evaluation of agriculture's potential for environmental degradation was conducted at the beginning of the planning period in a static framework.

4. Use of the Model for Policy Analysis

INDEPENDENT ANALYSIS OF SELECTED POLICY INSTRUMENTS

The baseline model can be modified to evaluate the effect of pollution abatement policies on input use, production, drainage, and salinity. Policy provisions may take a variety of forms: taxes levied directly on polluting outputs or indirectly on contributing inputs; quotas applied to polluting outputs or contributing inputs; and public cost-sharing for improved input or pollution management technologies. Five policy instruments that have been proposed to address drainage and salinity problems in central California are evaluated

briefly in this paper. These include: (a) surface water tax, (b) drainage tax, (c) surface water quota, (d) drainage quota, and (e) irrigation technology cost-sharing.

Tax and quota policies are evaluated based on the baseline gravity irrigation system. Cost-sharing is evaluated assuming conversion from the gravity system to an improved sprinkler system that is considered more efficient. Under the cost-share scenario, amortized fixed system costs are reduced by a 40% cost-share subsidy (with no annual payment limit per farm operator). A 40% reduction in sprinkler cost (from $70/acre to $27.40/acre) yields a present value of farm returns ($162,500) that is roughly equivalent to baseline returns. At this level of subsidy, a farmer is indifferent to system conversion, while society gains from water conservation and pollution reduction benefits that may justify the social subsidy for improved irrigation technologies. A 40% cost-sharing rate falls within the range of reported levels used in federal soil and water conservation programs (USDA, 1990).

Table 1 shows present value of farm returns for selected scenario levels by policy instrument. Total farm income over the planning horizon declines under all policies evaluated, with the exception of the cost-share scenario. In general, income reductions are small for marginal changes in taxes and quotas, as farmers adjust inputs to minimize income reductions. As tax and quota levels become more restrictive however, income reductions are increasingly significant. Income reductions are generally greater for water use policies than for drainage policies, under a given percent increase in tax or quota level.

Total social net income is defined in Table 1 as private farm returns, adjusted for public revenues or costs.[7] In California and other jurisdictions, revenue from water and drainage taxes are redistributed locally, e.g., for reinvestment in improved water-use efficiency. From a "social accounting" perspective, these taxes may be regarded as regional income transfers, although they represent real costs to farm decision makers. The distribution of program costs between public and private sectors varies by policy. In general, tax policies generate public revenue, thereby increasing social net revenues above private farm returns. Quota-based policies are neutral with respect to public revenue and costs. Under cost-share programs, social net returns are reduced below private farm returns as society assumes a share of the cost of pollution abatement and improved water-

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[7]Estimates of social net income do not account for offsite benefits of drainage reduction and water conservation.

use efficiency.

Notable among return estimates are negative social returns associated with the technology cost-share policy. This result suggests that technology subsidies do not represent an attractive public investment under base empirical assumptions. Low-valued field crops and adequate supplies of relatively low-cost irrigation water limit the potential for enhanced returns under water-conserving technologies. Findings of a similar nature have been cited in other technology adoption studies (e.g., Caswell and Zilberman, 1986; Caswell et al., 1990; and Dinar and Zilberman, 1991). Nevertheless, the model does not account quantitatively for unmarketed benefits associated with drainage reduction and water conservation. A technology cost-share can be socially justified if these benefits exceed the technology subsidy.

Alternative resource policies occasionally alter the length of time in which a steady-state solution is achieved. Convergence to a steady state was reached after 4 to 6 years for most policy scenarios. Increasing restrictions in the form of taxes or quotas tended to lengthen convergence time. Convergence time was particularly sensitive to surface water quotas; a reduction in surface water supply from 1500 af to 500 af resulted in convergence of approximately 13 years. In contrast, cost-sharing for improved technology reduced convergence time to 3 years.

The steady-state level of soil salinity increased under the tax and quota scenarios evaluated. Surface water policies resulted in relatively small increases in soil salinity, although convergence time to a steady-state was extended (Figure 1). Soil salinity increases were somewhat more significant under drainage policies, increasing with more restricting policy levels; however, convergence times to steady-state levels were roughly the same as in the baseline case (Figure 2). Cost-sharing for improved technologies resulted in a substantially reduced soil salinity level relative to the baseline steady-state level.

Land in production was relatively stable over the policy scenarios evaluated. However, land retirement does become a viable alternative under more restrictive quotas and taxes. The most significant reductions occurred in the case of surface water quotas, indicating that water supply places an effective constraint on size of farming operation. By contrast, drainage tax and quota policies encourage less intensive water use over a broader acreage base. Technology cost-sharing would have the effect of maintaining land base in

production, as the marginal value of the fixed land asset is increased. The baseline cropping pattern of wheat-sorghum (80%-20%) was unaffected by policy adjustments evaluated, as wheat returns remained dominant.

Total water use varied substantially under alternative policy instruments. Aggregate water use was most significantly affected by direct quotas and taxes on surface water. It is notable that significant drainage restrictions resulted in relatively small reductions in water use. Per acre application rates declined at a lesser rate, as reductions in water use are offset to some extent by reduced acreage irrigated. In general, tax-based policies were more effective in reducing per-acre applications than quota-based policies. Cost-sharing for improved water-use efficiency reduces per acre applications most significantly, although aggregate water use is less affected due to reduced acreage retirement.

Alternative policy instruments had varying impacts on the mix of surface and ground water sources. As in the baseline, surface water use generally increased over time due to increased leaching requirements under more saline soils. Ground water use declined under all scenarios evaluated, although ground water as a share of total water use generally exceeded baseline levels. Not surprisingly, substitution of ground for surface water was greatest for direct surface water taxes and quotas.

ALTERNATIVE POLICIES TO ACHIEVE DRAINAGE REDUCTION

Management of irrigation drainage has emerged as a critical issue in central California (National Research Council, 1989). Drainage flows containing agricultural residuals (e.g., pesticides, nitrates), natural salts (e.g., sodium) and trace elements (e.g., selenium), have reduced the productivity of cropland soils and damaged water supplies for downstream agricultural, municipal, wildlife, and recreation uses. As evidence mounts on the extent of drainage impacts, pressures will intensify to restrict irrigation drainage flows.

Alternative policies may be implemented to reduce drainage resulting from irrigated crop production. Direct policies involve taxes or quotas on drainage produced at the farm or regional level. Indirect policies restrict drainage by discouraging inefficient water use, either through taxes or quotas on purchased water, or cost-sharing for water-conserving technologies. Alternative policies may have varying impacts on input and output allocation mix, with differences in the efficiency of achieving drainage control and distributional

effects throughout the economy.

A simple empirical example demonstrates the relative efficiency of alternative policy instruments for drainage control under baseline conditions. Assume a drainage reduction goal of 30% of the baseline steady-state level, or 307 acre-feet of drainage. As shown in Table 1, each of the policy instruments alone may by used to achieve the drainage goal, although reductions in returns vary significantly. The drainage goal is achieved with the highest level of social returns under a drainage quota of 307 af ($157,500), followed by a drainage tax of $8.40/af ($157,200, including $26,900 in tax revenue), a surface water quota of 1104 af ($152,200), and a surface water tax of $6.36/af ($147,300, including $72,300 in tax revenue). In general, direct policies targeting drainage can achieve drainage goals more efficiently (in terms of reductions in social returns) than indirect policies targeting water use that contributes to drainage. Quota-based policies appear more effective in achieving drainage goals than tax policies, even where private returns are adjusted to include public tax revenues.

5. Discussion

This paper develops and applies a dynamic model of irrigated agriculture under saline and limited drainage conditions. The model allocates land and water inputs, based on an intertemporal profit maximization objective function and resource availability over time. Production relationships include crop yield functions as well as functions for drainage generation and soil-salinity accumulation.

The proposed model provides a framework to evaluate intertemporal effects of water conservation and drainage abatement policies on income, cropping patterns, input use and resource quality. Policies may be evaluated independently (e.g., a drainage quota) or in combination (e.g., a drainage quota with technology cost-share). Policies may be evaluated relative to a single criterion (e.g., drainage reduction) or multiple criteria (e.g., drainage reduction, with limits on salt accumulation). The model permits examination of tradeoffs inherent in agricultural water policies. For example, drainage reduction policies may contribute to increased soil salinity, with implications for long-term productivity of soils. Water tax and quota policies may result in reduced irrigated acreage and farm income, with impacts on local economies. On the other hand, technology subsidies may

result in maintenance of irrigated cropland base, with implications for aggregate water use and drainage generation.

Model results are presented for a representative baseline condition and a set of policy scenarios affecting water use and drainage reductions. The empirical analysis generally supports findings of earlier dynamic modeling studies on irrigation drainage and salinity (e.g., Knapp, 1991). The most significant response to policy adjustments in this analysis involves reduced irrigation applications per unit land, with adjustments in surface and ground water shares. Land allocations are relatively stable, both over time and across policy scenarios. The steady-state solution is reached, in the majority of applications, relatively early in the planning period. Thus in many cases, steady-state models can reasonably approximate values derived in a dynamic framework. However, for certain parameter settings (e.g., initial soil salinity) or policy instruments (e.g., water quotas, in our analysis), a single-period, static analysis may yield substantially different results than a multi-period, dynamic analysis.

The sensitivity of model decision and output variables to variation in soil and water quality parameters (across regions and over time) underscores the need for accurate agronomic response data over a range of observed conditions. Use of lysimeter tests is an efficient means of developing essential field-level data used in estimating yield, drainage and salinity functions. Lysimeter tests, which can be conducted for a range of regions and conditions at relatively low cost, increase the reliability and transferability of the modeling framework.

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Table 1: Steady-state levels of selected variables by policy scenario

	TOTAL PRESENT VALUE				****************VALUE AT STEADY STATE***************						
	Private farm income	Public revenue or cost	[a]Total social income	Steady state achieved	Annual income	Total land use	Total water use	Surface water use	Ground water use	Drainage water	Soil salinity
	($000)	($000)	($000)	(year)	($000)	(acre)	(AF)	(AF)	(AF)	(AF)	(EC)
Baseline	162.5	0	162.5	4	13.2	500	2118	1326	792	439	3.00
Surface water tax[b] ($/AF)											
5	93.0	67.1	160.1	4	6.8	500	2021	1234	787	357	3.01
10	34.7	110.6	145.3	6	1.5	412	1648	1000	648	278	3.01
Drainage tax ($/AF)											
10	125.4	30.1	155.5	4	9.6	500	1965	1183	782	288	3.02
20	100.3	41.1	141.4	4	7.2	500	1868	1096	772	194	3.04
30	83.3	41.7	125.0	5	5.6	500	1798	1035	763	129	3.05
50	57.8	62.7	120.5	6	3.3	500	1743	1000	743	115	3.05
70	32.8	86.9	119.7	5	1	489	1743	1000	743	115	3.05
Surface water quota (AF/yr)											
1250	161.1	0	161.1	4	13.0	500	2038	1250	788	371	3.01
1000	145.5	0	145.5	6	11.5	412	1648	1000	648	278	3.01
750	113.7	0	113.7	8	8.6	310	1236	750	486	208	3.01
500	81.1	0	81.1	13	5.8	207	825	500	325	137	3.01
Drainage quota (AF/yr)											
350	160.4	0	160.4	4	12.9	500	2027	1241	786	350	3.01
300	156.9	0	156.9	4	12.6	500	1976	1193	783	300	3.02
250	151.3	0	151.3	4	12.0	500	1925	1147	778	250	3.03
200	143.1	0	143.1	4	11.2	500	1874	1102	772	200	3.03
100	109.5	0	109.5	6	7.8	500	1753	993	760	100	3.11
Technology cost share (%)											
40	162.5	-237.0	-74.5	3	13.4	500	2098	1298	800	411	2.64

[a] Social income estimates do not include offsite benefits.

[b] Water tax added to both base and supplemental surface water supplies.

Figure 1

**Soil Salinity over Time under Baseline Conditions
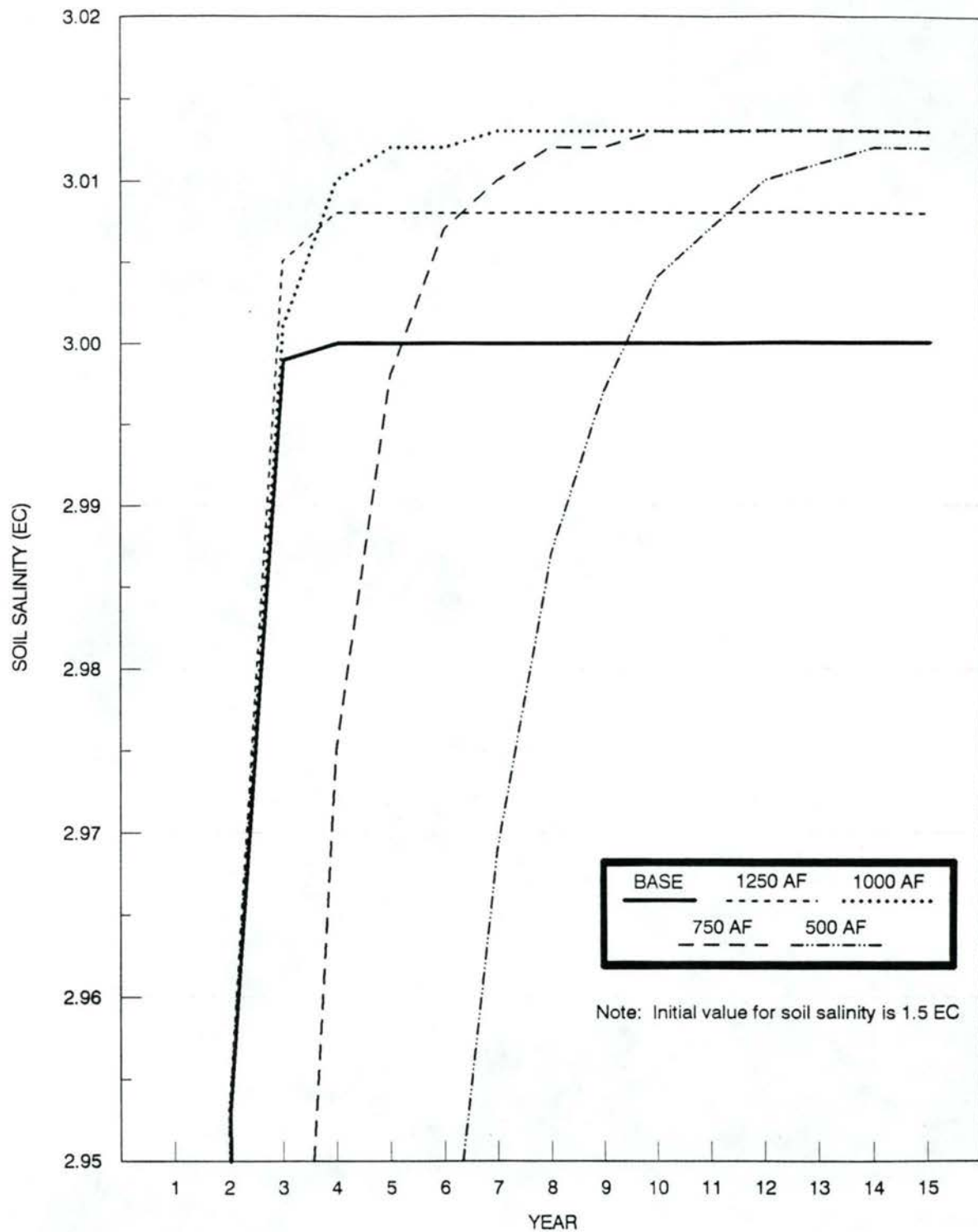and Selected Surface Water Quotas**

Figure 2

**Soil Salinity over Time under Baseline Conditions
and Selected Drainage Water Quotas**

Note: Initial value for soil salinity is 1.5 EC