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Economics of Agroforestry Production in Irrigated Agriculture

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A dynamic optimization model for agroforestry management is developed where tree biomass and soil salinity evolve over time in response to harvests and irrigation water quantity and quality. The model is applied to agroforestry production in the San Joaquin Valley of California. Optimal water applications are at first increasing in soil salinity, then decreasing, while the harvest decision is relatively robust to changes in most of the underlying economic and physical parameters. Drainwater reuse for agroforestry production also appears promising: both net reuse volumes and the implied net returns to agroforestry are substantial.

Key words: agroforestry, drainwater reuse, dynamic optimization, irrigation, salinity

Introduction

Agroforestry is a potential cropping system in arid region irrigated agriculture. Agroforestry arose as a means for commercial supply of various products including hardwood for furniture manufacture, other forestry products such as pulp, and as a potential new fuel source in response to the energy crisis of the 1970s (Lohr). Lohr performed an extensive and insightful analysis of agroforestry in this context. A market analysis was conducted for California identifying likely prices received and other demand-related factors for various agroforestry products. Data were collected from a variety of experimental plots, and these were used to estimate tree growth as a function of age and other factors. An economic analysis then identified efficient rotation levels, how they varied with distance from a market center, and the spatial extent of the market over which agroforestry could maintain positive returns.

More recently, agroforestry has been proposed as one way of managing drainage waters in irrigated areas [San Joaquin Valley Drainage Program (SJVDP); Tanji and Karajeh]. Saline high water tables emerge when deep percolation flows from crop production accumulate on relatively impervious geologic strata. These occurrences can impact yields by reducing aeration and increasing salinity in the crop rootzone. Historically, salinity and drainage problems were solved by installation of tile drainage systems with effluent disposal to the ocean or inland lakes, but this is increasingly circumscribed in recognition of the environmental contaminants contained in the drainage waters.

In the agroforestry approach to drainage management, saline drainage water generated from production of other crops is used to irrigate eucalyptus trees. Because these

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trees are considerably more salt tolerant than most other crops, reasonable growth can still be attained. A portion of the irrigation water is transpired by the trees and the remainder then becomes drainage flows from eucalyptus production. In the original conception of this approach, agroforestry drainage flows are intended to be used to irrigate an even more salt-tolerant crop; however, suitable crops for this purpose are still the subject of active investigation.

In any event, deep percolation flows which are not reused (regardless of source) require some sort of final disposal. In the region of interest here (the westside area of the San Joaquin Valley, California), disposal options are currently quite limited, and many operations must rely on evaporation ponds. Unfortunately, evaporation ponds are not a desirable solution. They generally utilize prime farmland, they are somewhat expensive to construct, and they must be operated in a manner that mitigates possible hazards to birds and other wildlife—an objective which has been difficult to achieve to date. In these circumstances, the potential value of agroforestry is clear: it allows production of a commercial crop (eucalyptus trees) while reducing the total volume of drainage flows, and thereby reduces the necessity of evaporation ponds or other disposal methods.[1]

In this study, we analyze the microeconomics of agroforestry production at the stand level in the context of irrigated agriculture, with the primary motivation of agroforestry as a solution to salinity and drainage problems in irrigated agriculture. Our analysis draws upon two separate literatures. In the irrigation economics literature, several studies have developed dynamic soil salinity models at the field level; however, these have been either for field crops (Matanga and Marino; Dinar and Knapp) or for perennial crops such as citrus (Yaron and Olian) where tree growth and harvest rotations are not an issue. The forestry economics literature has extensively addressed the optimal rotation problem of when to harvest growing trees (e.g., Hanley, Shogren, and White; Montgomery and Adams, among many others). Minimal attention (if any) has been addressed to forestry management with endogenous annual management inputs and dynamic soil quality. Our analysis combines elements from both of these literatures. We consider biological growth and optimal rotations as in the forestry economics literature, but we also incorporate irrigation and dynamic soil salinity over time as in the salinity and drainage economics literature. Thus the approach developed here represents a synthesis and extension of these two previously disparate literatures.[2]

Agroforestry Production with Saline Irrigation Water

For this analysis, we examine the management of a single stand of eucalyptus trees in the San Joaquin Valley of California. A fixed land area is considered; for convenience in reporting results, this is taken to be one acre. Decision variables in the model are:

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[1] Agroforestry has other potential applications in developing countries where it provides food and fuel for households and contributes to erosion control and soil fertility on adjacent cropland (Scherr; MacDicken and Vergara). While a number of papers have addressed various issues relating to agroforestry economics from a conceptual viewpoint, there appears to be relatively little work based on quantitative modeling and analysis (aside from Lohr).

[2] Montgomery and Adams consider choice of a variable management input at the beginning of a rotation, which only affects tree growth during that rotation. In the agroforestry problem of interest here, the variable inputs affect soil quality as well as tree growth during the rotation, and hence potentially affect tree growth during subsequent rotations.

q_{it} = annual applied water from irrigation source i in year t $\{i = 1, 2\}$ [acre-feet/year (af/yr)]; and h_t = a binary tree harvest variable, with 0 indicating no harvest and 1 indicating that the stand is harvested. The two state variables are: s_t = soil salinity measured as the electrical conductivity of a saturated paste extract (dS/m), and b_t = tree biomass (10^3 ft^3). Other key variables are identified as follows: e_t = annual tree evapotranspiration (af/yr), d_t = deep percolation flows from the stand during the year (af/yr), and y_t = yield when the trees are cut (bdt/yr), where bdt refers to bone dry tons or 0% moisture. All prices and costs are measured in real terms with 1996 as the base year.

Annual Net Benefits

Annual net benefits are denoted π_t and are defined as

$$\pi_t = \left[(p^c - \gamma^h)y_t - \gamma^e\right]h_t - \sum_{i=1}^{2} p_i^w q_{it} - \gamma^p - p^d d_t, \tag{1}$$

where p^c = the price of harvested wood (\$/bdt), γ^h = harvest and transport costs (\$/bdt), γ^e = tree establishment costs (\$/yr), p_i^w = the price of water from source i (\$/af), γ^p = production costs (\$/yr), and p^d = deep percolation disposal costs (\$/af). At harvest time ($h_t = 1$), the producer receives the output price net of harvest costs per unit of (dry) yield, and then immediately replants the trees with a given establishment cost. In years with no harvest ($h_t = 0$), revenue received and establishment costs are zero. The producer incurs costs associated with irrigation water, deep percolation water, and other production inputs in all years.

Lohr identifies the main uses for eucalyptus production in California as fuel chips, pulp chips, and residential firewood. An extensive analysis of the market potential for each of these products was conducted by Lohr. This included surveys of current prices paid and projected quantities consumed by end-use at a variety of locales in California, along with consideration of other factors influencing projected demand such as seasonality, packaging, plant capacity constraints, and other items. Based on her research, Lohr estimated expected prices paid in 1987–88 of \$40/bdt, \$65/bdt, and \$107/bdt for eucalyptus fuel chips, pulp chips, and residential firewood, respectively.

While Lohr's analysis of the California market is extensive, it covers only a single year, and timber product prices have exhibited substantial year-to-year variability.[3] Accordingly, we also collected data on woodpulp prices for 1975–96 from various annual publications of the U.S. Department of Agriculture's *Agricultural Statistics*. After deflation, a regression analysis suggested that U.S. woodpulp prices in 1987 were close to an estimated trend line, and that (real) woodpulp prices from this point forward exhibited a slight U-shaped pattern. Under the assumption that the structural factors considered by Lohr are little changed over this period, this regression analysis (and the associated inflation factors) was combined with Lohr's original estimates to calculate expected 1996 prices as \$55/bdt, \$90/bdt, and \$148/bdt, respectively, for the three eucalyptus products of fuel chips, pulp chips, and residential firewood. Because our emphasis here is the application of eucalyptus production as a reuse system for agricultural drainage, and less so for commercial production of various timber products, we estimate the output

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[3] Thanks to an anonymous reviewer for stressing this point.

Table 1. Economic and Irrigation Water Parameter Values for a One-Acre Stand of Eucalyptus (*E. Camaldulensis*) Production in the San Joaquin Valley, California

Parameter	Description	Value/Unit[a]
p^c	Output price	\$101.50/bdt
γ^h	Harvest cost	\$23.98/bdt
γ^e	Establishment costs	\$416.51/yr
γ^p	Production costs[b]	\$200.60/yr
c^1	Freshwater salt concentration	0.67 dS/m
p_1^w	Freshwater price	\$54.63/af
c^2	Drainwater salt concentration	10 dS/m
γ^r	Reuse pumping cost	\$3.03/af
γ^g	Gypsum cost[c]	\$17.50/af
p^d	Deep percolation disposal costs	\$47.73/af

Notes: Price and cost data are in \$1996 (data sources are discussed in the text); one-acre stand = 1,210 eucalyptus trees.

[a] Unit definitions include: bdt = bone dry ton (0% moisture); dS/m = deciSiemens per meter (a measure of electrical conductivity, and hence salt concentration); and af = acre-foot.

[b] Production costs (γ^p) include irrigation and drainage system costs as well as fertilizer, herbicide, and other miscellaneous costs.

[c] Gypsum costs (γ^g) are per acre-foot of 10 dS/m saline drainwater used in agroforestry irrigation.

price p^c (see table 1) as just the average of the fuel chip and firewood prices, and employ sensitivity analysis to address variability issues.

Economic and irrigation water parameter values used in this study are identified in table 1. Several of the cost parameters (as well as tree biomass parameters) depend on planting density for the stand. This is assumed here to be 1,210 trees per acre. Harvest and transport costs, establishment costs, and production costs (after adjustment for inflation) are derived from data in Lohr; River Basin Planning Staff; University of California Committee of Consultants; and Weinberg and Wilen. Tree harvests (if any) occur at the end of the year. In this instance, yield is given by

$$y_t = 17.65 b_t^e, \tag{2}$$

where b_t^e denotes tree biomass at the end of the year after accounting for growth during the year. This equation converts tree biomass when cut to dry matter production for sale, and was estimated from the unit conversions given in Lohr. Calculation of end-of-year biomass will be discussed after first developing the salinity and biological growth models.

Irrigation and Drainage Variables

The two sources for irrigation water are fresh water ($i = 1$) and saline drainage water ($i = 2$). The first source is normal irrigation supplies available for crop production in the area, while the second is drainwater generated by other crops, for which agroforestry is the reuse or volume-reduction strategy. The salt concentration of each irrigation source is exogenous and denoted as c^i. With these definitions, the total quantity of irrigation water applied for tree production in year t is defined by

$$q_t = q_{1t} + q_{2t}, \tag{3}$$

or simply the sum of the quantities from the individual sources. Likewise, the salt concentration of applied water in year t is given by

$$c_t = \frac{c^1 q_{1t} + c^2 q_{2t}}{q_{1t} + q_{2t}}, \tag{4}$$

which is a weighted average of salt concentrations from the individual sources. Deep percolation of water below the rootzone is calculated as

$$d_t = q_t - e_t, \tag{5}$$

or the difference between annual irrigation flows and tree evapotranspiration as calculated below.

Irrigation water price and salinity data, as reported in table 1, are derived from several sources. The salinity data are from Letey and Knapp, while the price of fresh water is typical for the area under consideration. Estimation of the saline drainwater price (p_2^w) is somewhat more complex; discussion of it and the associated salt concentration are deferred until later in the article. Deep percolation disposal costs (p^d) were estimated by assuming that deep percolation emissions from agroforestry production are disposed in an evaporation pond. With an evaporation rate of 5.32 af/yr (Oster et al.), 0.19 pond acres are required to dispose of one af/yr of agroforestry drainage emissions. Annualized pond construction costs are estimated from Summers, with adjustment for inflation. There is also an opportunity cost of land used for the pond since this land can no longer be used for crop production. Land opportunity costs were estimated from land price data reported in the *1997 Census of Agriculture* (U.S. Department of Commerce). Combining these data results in the estimated deep percolation disposal costs (p^d) of \$47.73/af reported in table 1. Various alternative values for deep percolation disposal costs will also be considered given uncertainty over the actual magnitude of these costs and their likely spatial variability. There is also an upper bound on total applied water of 7.6 af/yr. This reflects a hydrologic limit on infiltration into the soil and is consistent with findings reported by Letey and Knapp.

Salinity and Biomass Dynamics

A dynamic model of tree growth with soil salinity and irrigation is constructed by combining a dynamic soil salinity/water-use model for agroforestry production developed in Letey and Knapp with eucalyptus growth data reported in Lohr. The general conceptual process can be summarized as follows. Maximum tree evapotranspiration (ET) is determined by climatic conditions (taken as given here) and tree size. Tree evapotranspiration during the year can be reduced below maximum levels by soil moisture deficiencies or by high soil salinity levels. At irrigation time, irrigation water replenishes soil water up to the maximum water-holding capacity of the soil; excess water above that level then becomes deep percolation flows below the rootzone. The salt concentration of deep percolation flows depends on the soil salinity before irrigation and the salt concentration of applied water. Soil salinity after irrigation is then calculated by mass balance accounting for incoming salts in the irrigation water and outgoing salts in the deep percolation flows. The following development quantifies these relations.[4]

Maximum ET under nonstressed (no salinity and nonlimiting water applications) conditions is a function of biomass:

$$(6) \qquad e_t^{\max} = \begin{cases} 1.21 + 3.84\left(\dfrac{b_t}{0.53}\right) & \text{if } b_t < 0.53, \\ 5.05 & \text{if } b_t \geq 0.53, \end{cases}$$

where climatic conditions are taken as given. Under full canopy closure, maximum ET for the region under consideration is estimated at 5.05 af/acre per year (Letey and Knapp). Full canopy closure is reached in two years (Lohr), which corresponds to a biomass of 0.53 10^3 ft^3/acre. Maximum ET is assumed to increase linearly up to the full canopy value for biomass values less than 0.53 10^3 ft^3/acre starting from an initial rate ($b_t = 0$) of 1.21 af/yr.

Tree stress (reduction of ET and growth below maximum levels) may occur from lack of sufficient water, excessive soil salinity, or both. Following Letey and Knapp, ET with moisture stress but without salinity stress is denoted e_t' and is defined by

$$(7) \qquad e_t' = \mathrm{Min}\left(e_t^{\max}, q_t\right),$$

i.e., the smaller of applied water or maximum possible ET. Following the work of Maas and Hoffman, Letey and Knapp compute the proportionate reduction in tree ET due to soil salinity by

$$(8) \qquad \frac{e_t}{e_t'} = \begin{cases} 1 & \text{if } \hat{s}_t \leq \underline{s}, \\ \dfrac{\bar{s} - \hat{s}_t}{\bar{s} - \underline{s}} & \text{if } \underline{s} \leq \hat{s}_t \leq \bar{s}, \\ 0 & \text{if } \bar{s} \leq \hat{s}_t, \end{cases}$$

where e_t is actual ET, $\hat{s}_t = (s_t + s_{t+1})/2$ is average soil salinity over the irrigation season, and $\underline{s}$ and $\bar{s}$ are lower and upper limits, respectively, for soil salinity. The Maas and Hoffman relation in (8) is piecewise linear: ET occurs at the (moisture-stress adjusted) maximum rate for low salinity levels, is zero for salinity levels sufficiently great enough, and is linearly decreasing in soil salinity for levels between the bounds. The salinity bounds are estimated by Letey and Knapp as $\underline{s} = 9$ dS/m, and $\bar{s} = 23.3$ dS/m.[5]

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[4] Detailed theoretical and empirical developments on irrigation under saline conditions may be found in Bresler, McNeal, and Carter, and in Tanji (among many other sources).

[5] We are ignoring the potential contribution of soil moisture at the beginning of the horizon to ET. The volume of water stored in the rootzone and available for tree growth is relatively small compared to annual evapotranspiration rates. Over long time horizons, the average contribution to evapotranspiration of the initial soil moisture level is essentially negligible. Therefore, it is reasonable to assume (as here) that annual evapotranspiration comes solely from irrigation flows in a given year, with the excess going to deep percolation.

Letey and Knapp also develop and test a simulation model for soil salinity over the course of the irrigation season, which is used here. This model considers multiple soil layers, irrigations at equal moisture deficits, and salt transport under piston flow conditions. The simulation program gives soil salinity at the end of the season as a function of initial soil salinity, ET during the season, and applied water quantity and quality:

$$s_{t+1} = f(s_t, e_t, q_t, c_t). \tag{9}$$

While future salinity levels do not depend directly on tree biomass in this model, they do depend indirectly on it through the ET variable (e_t). Simultaneous solution of the recursive soil salinity model (9) and the ET model defined by equations (6)–(8) gives e_t and s_{t+1} as functions of initial soil salinity and biomass, and irrigation quantity and quality.

End-of-season tree growth is specified as

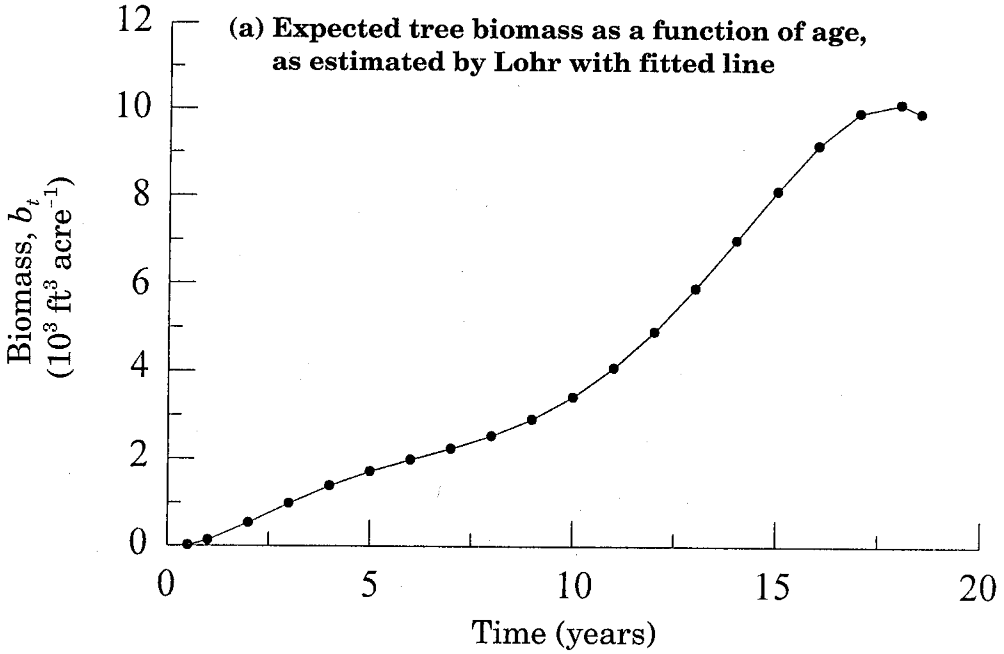
$$b_t^e = b_t + \frac{e_t}{e_t^{\max}} g(b_t), \tag{10}$$

where g is the nonstressed growth function. The nonstressed growth function gives tree growth during the year as a function of current biomass, assuming that water and salinity are not limiting. Relative ET is actual ET divided by the maximum ET. Relative ET is a measure of tree stress during the season; multiplying this by the maximum possible growth gives the actual increment in tree biomass. This follows the water production function literature for field crops where crop biomass (and often yield) is typically linearly increasing in ET up to the maximum level for a given set of climatic conditions. The equation of motion for tree biomass is then

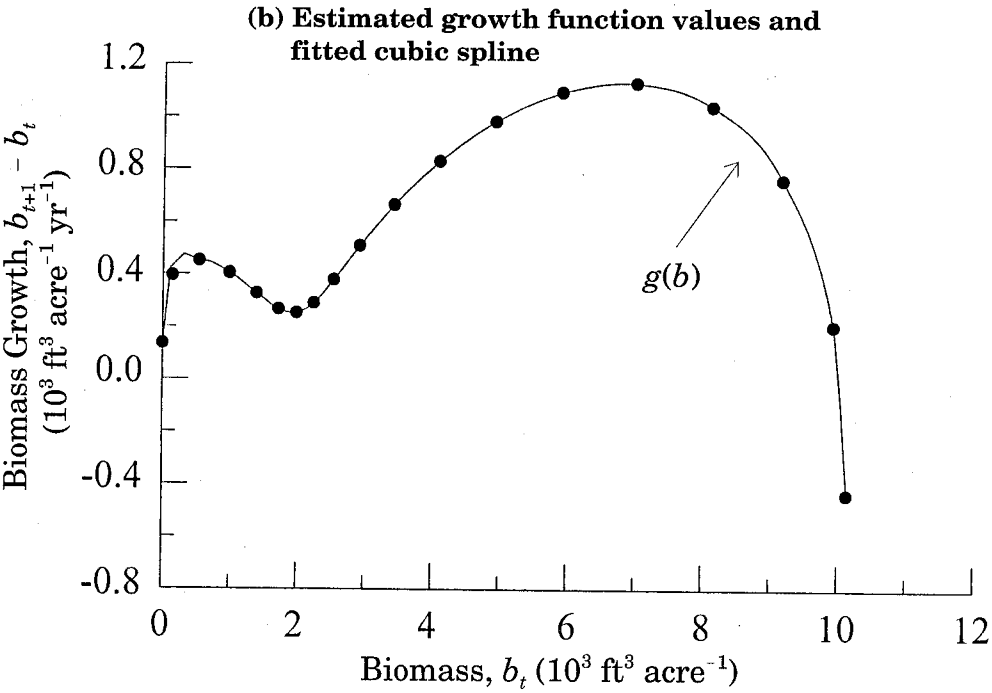
$$b_{t+1} = \begin{cases} b_t^e & \text{if } h_t = 0, \\ b_0 & \text{if } h_t = 1, \end{cases} \tag{11}$$

where b_0 is biomass of a new planting. This definition merely indicates that biomass at the beginning of year $t+1$ is end-of-year biomass as given by (10) with no harvest; otherwise trees are cut with immediate replanting and biomass equal to an initial value.

The nonstressed growth function was estimated from results in Lohr. Lohr collected experimental data on eucalyptus growth in California and then used regression analysis to estimate tree biomass as a function of age and a range of soil, climatic, and management variables. Expected biomass at various ages was estimated by Lohr from the regression analysis for conditions typical of the San Joaquin Valley. These values are illustrated in figure 1(a) for the specified planting density (a fitted line is added for clarity). The analysis for saline conditions as outlined above requires biomass growth in state-space form. Accordingly, growth function values were estimated from the biomass-age data in figure 1(a) by plotting the change in biomass ($b_{t+1} - b_t$) versus biomass at the beginning of each year (b_t), illustrated in figure 1(b). A cubic spline was then estimated which exactly fits the data with a smooth function while preserving shape. The cubic spline is also illustrated in the figure, and this is the nonstressed growth function $g(b)$ which is used in the dynamic programming model.



(a) Expected tree biomass as a function of age, as estimated by Lohr with fitted line



(b) Estimated growth function values and fitted cubic spline

Figure 1. Eucalyptus (*E. Camaldulensis*) growth in the San Joaquin Valley, California, under nonstressed conditions (planting density = 1,210 trees per acre)

Forestry Management and Endogenous Soil Quality

The optimal harvest/rotation problem in forestry economics is typically analyzed using a Faustmann-type model (e.g., Neher; Conrad and Clark; Hanley, Shogren, and White). In these models, individual rotations are independent of other rotations in that actions within an individual rotation do not affect other rotations (other than the start time). In addition, each rotation is identical to the other rotations in terms of parameter values. These assumptions imply that—under an infinite horizon—the optimal harvest age is the same for each rotation, and convenient analytical expressions can be readily derived for the present value of net benefits and the optimal rotation lengths. However, when we consider variable management inputs and endogenous soil quality, then these assumptions no longer apply. In this instance, management decisions within an individual rotation potentially affect future rotations, and there is no necessity that the rotation lengths be the same. This is because both the harvest time and annual management decisions will typically vary with soil quality, which itself evolves through time. Thus a more general approach seems necessary when there are variable management inputs which have dynamic effects on soil quality and tree growth rates.

For such an approach, the problem is cast in the form of a dynamic programming model. This allows for endogenous irrigation quantities and soil salinity dynamics in conjunction with the tree growth and harvest/replanting decision. The present value of net benefits is given by

$$\sum_{t=1}^{\infty} \alpha^t \pi_t, \tag{12}$$

with annual net benefits defined as in (1), and where the discount factor $\alpha = 1/(1 + r)$ and r is the interest rate. The problem is to find annual irrigation volumes (q_{it}) and harvest times (h_t) which maximize the present value of net benefits (12) subject to the equations of motion for soil salinity and tree biomass, the constraints and definitions in (2)–(5), and nonnegativity conditions for q_{it}. The initial condition when solving for optimal time-series values is a nonsaline soil profile ($s_1 = 0$) and a newly planted tree ($b_1 = 0$).[6]

Let $J(s, b)$ be the optimal value function defined as the value of the objective function (12) evaluated at the optimal solution given initial levels of the state variables. A dynamic programming algorithm for calculating $J(s, b)$ is specified as follows:

$$\begin{aligned} &J_0(s, b) = 0, \\ &J_{k+1}(s, b) = \underset{q_1, q_2, h}{\text{Max}}\ \pi(y, q_1, q_2, h, d) + \alpha J_k[\mathbf{v}(s, b, q_1, q_2, h)], \end{aligned} \tag{13}$$

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[6] Dynamic programming models have been developed to address several issues in optimal forestry management. Amidon and Akin consider the simultaneous selection of optimal thinning and rotation policies; Haight and Holmes, and Thomson evaluate stochastic prices; van Kooten, van Kooten, and Brown examine stochastic growth; and Lembersky and Johnson address both stochastic growth and stochastic prices. Lyon develops a dynamic programming model for forestry management with alternate age classes, and Max and Lehman include a recreation benefit function in an optimal harvest model. Additional citations as well as continuous-time optimal control models may be found in Williams, and also in Montgomery and Adams. The work here differs from these previous studies by including annual management decisions which influence the evolution of both tree biomass and soil quality over time.

where J_k is the value function after k iterations, π gives annual net returns as a function of the indicated variables, and $\mathbf{v}$ is a vector function mapping the current states and controls to the future state values. Annual net returns are defined by (1), while the vector function $\mathbf{v}$ is defined implicitly by (6)–(11). In the above optimization problem, the constraints and definitions in (2)–(5) and nonnegativity conditions on the controls also apply. As $k \to \infty$, then $J_k \to J$ (Bertsekas). This problem is solved numerically on the computer using the error bound calculations described in Bertsekas to determine convergence.

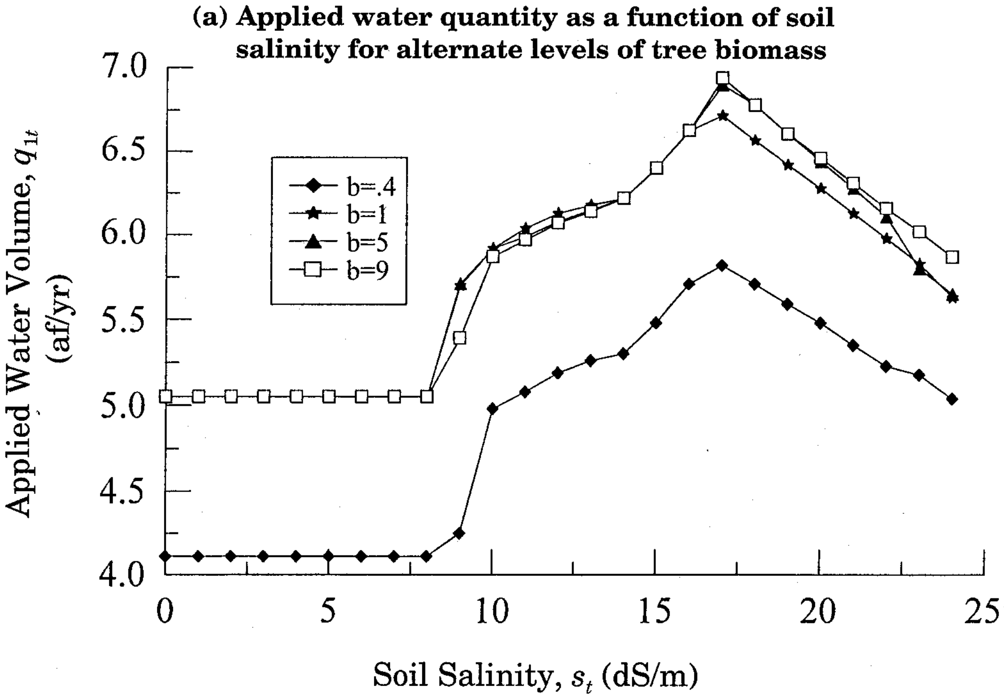
Optimal decision rules are calculated as the solution to the right-hand side of the lower relation in (13) for given values of soil salinity and tree biomass after substituting the optimal value function J for J_k. These rules give optimal water applications and harvests as functions of the soil salinity and tree biomass state variables. The interpretation is that in a given year, one first observes the current values for the state variables, then applies the optimal decision rules to determine the economically efficient course of action. Since the problem is time-autonomous and an infinite horizon is being considered, the same decision rules apply in every year. We also consider the optimal values for the state and control variables over time. The optimal time series for the variables of interest are computed by simulating the optimal decision rules forward in time along with the equations of motion and other relations as needed.

The interest rate is generally an important parameter in forestry economics. Since the analysis is in real terms (constant \$1996), r should be set equal to the estimated real rate of return in the economy (Hanke, Carver, and Bugg). Here, we typically assume an interest rate of 4%; however, alternative values will also be considered in view of uncertainty over long-run real rates of return. Higher values for the interest rate can also be interpreted as an approximate way of allowing for uncertainty associated with agroforestry production.

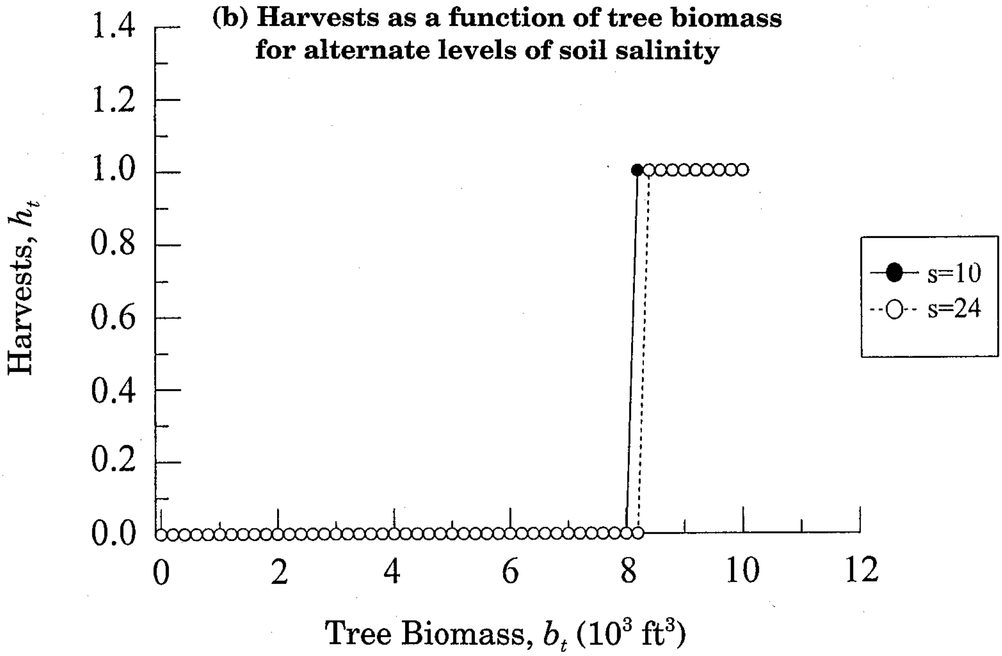
Irrigation Management and Harvests

We begin by considering management of agroforestry production as a commercial crop but with no special attention to either drainwater reuse or the disposal costs associated with deep percolation flows from agroforestry. More specifically, we consider only irrigation with fresh water ($q_{2t} = 0$) and no costs associated with deep percolation flows ($p^d = 0$). This problem is of independent interest as noted in the introduction, and also illustrates the qualitative and quantitative dynamics of the problem in a somewhat simplified setting. Most of the qualitative dynamics will carry over to the more general model with drainwater reuse and deep percolation costs (which is taken up in the next section). Sensitivity analysis is used to identify the direction and magnitude of various parametric changes on the optimal solution in this setting.

The optimal decision rule for water applications is illustrated in figure 2(a) under the base parameter values of table 1. This decision rule shows how the efficient level of water applications in any given year depends on soil salinity and tree biomass at the beginning of that year. As can be seen, efficient water applications are largely independent of tree biomass, with the only exception being for the very small biomass levels when the tree is quite young. This is due to reduced maximum ET in the early years followed by a constant rate of maximum ET after the trees reach full canopy closure. Efficient water applications are, however, quite dependent on soil salinity. The threshold concentration at which soil salinity begins to affect tree ET, and hence growth, is



(a) Applied water quantity as a function of soil salinity for alternate levels of tree biomass



(b) Harvests as a function of tree biomass for alternate levels of soil salinity

Figure 2. Economically efficient eucalyptus (*E. Camaldulensis*) production in the San Joaquin Valley, California, with fresh-water irrigation and no deep percolation costs

9 dS/m. Water applications are approximately equal to ET for soil salinity below this level. As salinity increases, however, additional water is applied to leach salts below the rootzone and maintain high growth levels. At a sufficiently high salinity level (approximately 17–18 dS/m in the figure), tree ET levels are inevitably depressed, implying that reduced water applications are needed to accomplish a given amount of leaching. As a consequence, applied water levels are declining in soil salinity after that point.

The optimal harvest decision rule is illustrated in figure 2(b). In principle, optimal harvests are also a function of soil salinity and tree biomass at the beginning of the year—but, in effect, the decision is somewhat simpler. Generally harvests occur at a biomass of 8.1–8.4 10^3 ft^3 over the range of salinities considered in this analysis. For soil salinities below 17 dS/m, harvests occur at the lower end of this range, while higher salinity levels imply cutting at somewhat greater biomass levels. Nevertheless, the effect is small and, as seen below, soil salinities remain below this level when starting out with a relatively nonsaline soil profile; thus the decision rule is effectively to cut when the tree biomass equals or exceeds 8.1 10^3 ft^3, more or less irrespective of soil salinity.

Time-series values for tree biomass, soil salinity, and water applications under optimal management are depicted in figure 3 starting from newly planted trees in an initially nonsaline soil profile. Biomass exhibits a constant cycle over the period with little or no transition period. Harvest occurs at biomass levels of 8.1 10^3 ft^3 as noted above, or every 16 years. Soil salinity levels are maintained below the threshold level of 9 dS/m in all years. There is an initial transition period which is relatively short (15–18 years), after which soil salinity exhibits cyclical behavior. Some cyclical behavior is also observed with applied irrigation water. Irrigation water is generally at maximum ET most of the time during a typical rotation, with the exception of small quantities when the trees are first starting out, and three periods of short duration in which additional irrigation water is applied to leach out salts and drive down soil salinities which are rising during the periods of irrigation just sufficient to meet maximum ET.

The explanation for the cyclical behavior in irrigation is that a given volume of leaching water is more effective (removes more salts) when soil salinity is high. Since irrigation water is expensive, it pays to let soil salinity climb somewhat and then reduce it at one time to lower levels than would actually be needed to maintain maximal growth. This theory was tested by running the model with an upper limit on irrigation water just sufficient to maintain soil salinity at the threshold level with equal annual leaching. In this instance, soil salinity climbed to a steady-state value at the threshold level and then remained constant thereafter, as did irrigation volumes for all but the youngest trees; however, net returns were somewhat reduced in comparison to the cyclical optimum solution.

The optimal limit cycle or steady-state rotation can be defined as that rotation which is reached after an initial transition period for the soil quality variable. As a practical definition, we calculate this as the last full rotation in the 100-year simulations of the optimal decision rules. The effects of various parametric changes on the optimal limit cycle are explored in table 2. Increasing the interest rate tends to emphasize current-period returns relative to future returns. As a consequence, soil salinity tends to increase under an interest rate increase, although the effect is limited. A decrease in the interest rate increases the rotation length consistent with theory, but only by one year, and has minimal impact on management inputs. Since returns from agroforestry are

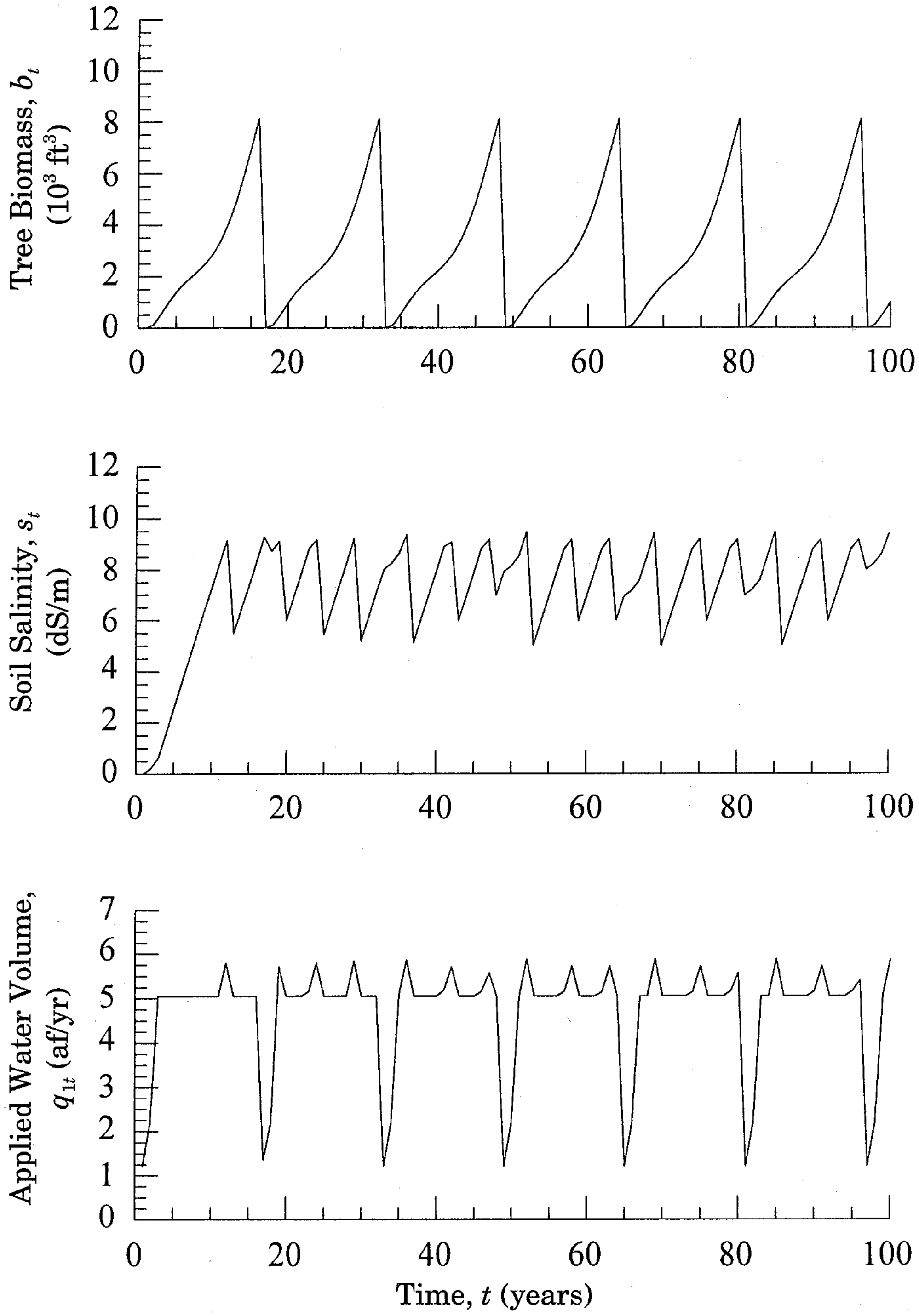


Figure 3. Economically efficient eucalyptus (*E. Camaldulensis*) production in the San Joaquin Valley, California, with fresh-water irrigation and no deep percolation costs: Time-series values for tree biomass, soil salinity, and irrigation volume

Table 2. Agroforestry Production with No Drainwater Reuse and No Disposal Costs: Sensitivity of the Optimal Solution in the Limit Cycle to Changes in Various Parameter Values

Parameter Values	Rotation Time, t^* (years)	Applied Water, q^* (af/yr)	Deep Percolation, d^* (af/yr)	Soil Salinity, s^* (dS/m)	Annualized Net Returns, π^* (\$ acre^{-1} yr^{-1})
Base	16	4.76	0.13	7.65	67.21
Interest rate (r):					
0.02	17	4.77	0.11	6.66	176.86
0.07	16	4.78	0.15	8.76	-58.59
Water price of primary irrigation source (p_1^w):					
\$25/af	16	4.77	0.14	7.72	204.10
\$85/af	16	4.77	0.14	7.60	-74.47
Output price (p^c):					
\$50/bdt	40	1.98	0.06	9.28	-265.18
\$150/bdt	16	4.77	0.14	7.72	426.14
Salt concentration of primary irrigation source (c^1):					
5 dS/m	16	5.84	1.21	9.00	-39.84
10 dS/m	20	5.64	1.92	11.91	-199.97
Drainage disposal cost (p^d):					
\$30/af	16	4.74	0.11	7.41	65.14

Notes: Production area = 1 acre. There is no reuse ($q_{2t} = 0$) and parameter values are as in table 1, except deep percolation costs (p^d) generally = 0 (and as noted above). Gypsum costs are included for irrigation water with higher salt concentrations, as discussed later in the text. The optimal limit cycle is computed as the last full rotation in a 100-year simulation. Tabular values represent averages over the limit cycle, except net returns which are annualized.

preceded by several years of only costs, an increase in the interest rate also decreases the attractiveness of the investment. Changing the price of irrigation water has essentially no impact on the management variables, although the effect on net returns is significant. An increase in irrigation water salt concentration also tends to increase water use, deep percolation flows, and salt concentration as would be expected. Also expected is that increasing deep percolation costs decrease applied irrigation water and deep percolation flows.

The results in table 2 suggest that the timing of the harvest decision is relatively stable across a fairly wide range of parameter values. One exception occurs for the relatively low output price. Here the crop value is so low that only the minimal amount of water is applied, and tree growth is so delayed that harvest occurs relatively late. Another exception is the high irrigation salt concentration which delays tree growth, and hence the harvest time. Likewise, biomass at harvest time typically occurs at 8.1 10^3 ft^3/acre for most parameter values. The main exceptions are the low output price and high irrigation salt concentrations with biomass at harvest of 8.5–8.6 10^3 ft^3/acre, and the low interest rate with harvest biomass equal to 9.2 10^3 ft^3/acre.

The general forestry economics literature emphasizes the theoretical effect of economic parameters on the optimal rotation time. In this problem, however, these effects appear to be fairly small over plausible ranges of the parameter values. The sensitivity analysis also suggests that, with the exception of the low output price, water use is little affected by changes in the economic parameters, but is significantly affected by salt concentration of the irrigation water. It should be noted, however, that the analysis here is for a relatively uniform distribution of water over the field. Under nonuniform conditions, water demand could be more elastic.

While the various management variables are reasonably robust to the various parametric changes, the same is not true for net returns (table 2). These are highly variable depending on the parameter values. Under the base parameter values, there is a positive level of annualized net returns, but these are modest and probably substantially less than traditional crop production in the area. This is consistent with observed practice where agroforestry is not grown commercially, but instead interest has arisen in the research community as a solution to the drainage problem. However, when more adverse conditions are encountered (e.g., lower output price, higher irrigation salt concentrations), net returns are negative, whereas the more beneficial conditions (e.g., higher output price, lower water price) make agroforestry production potentially quite profitable. These conclusions regarding net returns will be somewhat modified in the next section when the possibility for drainwater reuse is considered. Here, net returns will generally be positive, and in many instances significantly so when the value of reusing drainage water generated by other crops is factored in.

Drainwater Reuse and Disposal Costs

This section considers agroforestry production as the reuse component in an integrated system for managing and disposing drainage water. As described at the outset of the article, this means that drainwater generated by other crops is used for agroforestry production and that deep percolation emissions from agroforestry are subject to disposal costs. Thus we are considering here the full model as outlined earlier: irrigation water comes from either or both sources, and deep percolation flows from agroforestry production incur disposal costs (p^d) as given in table 1.

Salt concentration of drainwater in the valley varies substantially depending on location, crop, and time of the year; however, a typical value is 10 dS/m (Tanji and Karajeh) which is used here as a base value. The cost of using the secondary (saline drainwater) source for irrigation is calculated as

$$p_2^w = \gamma^r + \gamma^g + p^r, \tag{14}$$

where γ^r = the cost of lifting water from a drain sump or shallow water table (\$/af), γ^g = gypsum amendment costs (\$/af), and p^r = the shadow value of drainwater reuse on the farm or in the region (\$/af). The definition in (14) implies that there are three components to estimating the price or cost of drainwater reuse. First, some costs are incurred by the grower in lifting water out of drainage sumps or a shallow water table before it can be used for irrigation. Second, the use of saline water for irrigation can result in soil crusting and water penetration problems (Rhoades). The application of gypsum as a soil amendment is typically recommended to counteract these effects.

Third, there is a shadow value to the farm or region for reusing drainwater generated by other crops, and this shadow value is external to agroforestry production. In the case of low-quality drainage water, drainwater reuse in agroforestry avoids disposal costs incurred elsewhere in the system—so this "cost" is typically negative and, as a result, p_2^w may be negative as well.

Pumping costs (γ^r, table 1) are estimated assuming a 20-foot pumping lift and energy costs of \$0.13 per acre-foot of lift. Although gypsum requirements are subject to some uncertainty, typical recommendations range from 1–5 tons/acre annually. Gypsum costs (γ^g, table 1) are calculated assuming an annual application rate of 3 tons/acre and gypsum costs of \$35/ton (Oster et al.). These estimates are for 10 dS/m irrigation water. Since the gypsum is required to counteract the effect of salts in the drainwater, these costs are adjusted proportionally when irrigation water of other salt concentrations is considered.

In the region under consideration, drainwater emissions from other crops are disposed of in the same manner as deep percolation emissions from agroforestry. Therefore, for economic efficiency, $p^r = -p^d$ since reuse is resulting in avoided costs elsewhere in the system. Where agroforestry production is part of a farming operation which incurs all disposal costs, the shadow value p^r is implicit. When drainage flows are disposed regionally, then p^r represents a subsidy which needs to be paid to agroforestry producers to induce efficiency. Combining estimates for the three components of p_2^w results in $p_2^w = -\$27.20$/af, implying a net benefit to the farm or region for drainwater reuse in agroforestry production.

Results for the last full rotation in a 100-year horizon are reported in table 3. Following the analysis of the previous section, this is interpreted as the limit cycle or "steady-state" rotation for the system as a whole. Under the base conditions as just developed, the optimal strategy is to irrigate continuously with low-quality drainwater. Average soil salinity in the limit cycle is approximately 10 dS/m, which is somewhat higher than the no-reuse case analyzed in the previous section. This higher salinity slightly limits growth, resulting in an 18-year rotation. The use of lower-quality water also implies higher irrigation volumes for salt leaching, and hence larger deep percolation values (2.88 ft/year). Nevertheless, the reduced irrigation costs far outweigh the reduced returns from lower growth rates and imposition of drainage charges. This results in annualized net returns in the limit cycle of \$326/acre, assuming that the reuse shadow value is being paid as a subsidy to agroforestry producers.

We also explored the possibility of alternate pricing strategies and drainage concentrations for drainwater reuse. One possibility is where (as now) there is no subsidy being paid for drainwater reuse ($p^r = 0$). In this instance, optimal irrigation volumes are a mix of both fresh and drainage waters. Thus, while the reuse volume does go down as would be expected, agroforestry producers would still have an incentive to use at least some drainage water generated elsewhere, even absent the subsidy or other management plan, such that the reuse shadow value is in effect. Also to be noted is that agroforestry net returns are somewhat larger than the equivalent no-reuse case, reflecting the availability of cheaper water. It is also theoretically possible (although empirically unlikely in this region) that the saline drainage water could have a positive shadow value, reflecting water scarcity and an overall beneficial value as an irrigation source to the farm or region. In this instance, even a nominal \$15 positive shadow value results in no drainwater reuse, as demonstrated in table 3.

Table 3. Agroforestry Production with Drainwater Reuse and Disposal Costs: Sensitivity of the Optimal Solution in the Limit Cycle to Prices and Salt Concentrations

Parameter Values	Rotation Time, t^* (years)	Applied Water, Source i: q_1^* (af/yr)	q_2^* (af/yr)	Deep Percolation, d^* (af/yr)	Soil Salinity, s^* (dS/m)	Annualized Net Returns, π^* ($/yr)
Reuse shadow value (p^r):						
-$47.73/af	18	0	7.18	2.88	10.01	325.54
$0/af	17	3.14	2.23	0.71	8.61	73.40
$15/af	17	4.79	0	0.14	7.87	59.71
Salt concentration of secondary irrigation source (c^2):						
5 dS/m	17	0	5.89	1.24	8.87	470.85
15 dS/m	19	1.77	4.94	2.60	10.40	128.23
Deep percolation disposal costs (p^d):						
$0/af	18	0	7.60	3.29	9.83	477.84
$100/af	18	0.18	6.73	2.64	10.18	179.97

Notes: Production area = 1 acre. Parameter values are $p^r = -\$47.73$/af and as in table 1, except as noted. The optimal limit cycle is computed as the last full rotation in a 100-year simulation. Values are averages over the limit cycle, except π^* which is annualized.

With a drainwater (second source) concentration of 5 dS/m, the optimal strategy in the limit cycle is to use all drainwater for irrigation. Total irrigation volumes are increased somewhat over the no-reuse case for increased salt leaching, and this implies greater deep percolation volumes, but irrigation volumes are reduced in comparison to those under the original reuse concentration (10 dS/m), as would be expected. Results for a salt concentration of 15 dS/m are also given in table 3. In comparison to the original salt concentration, this increase reduces secondary source water use and results in a blended irrigation strategy which mixes fresh and drainage waters for irrigation. Soil salinity is slightly higher and deep percolation flows slightly less; net returns are considerably reduced due in large part to the reduction in subsidy payments.

Changes in deep percolation disposal costs are also considered in table 3. Here, an increase in disposal costs tends to reduce irrigation volumes and deep percolation levels, increase soil salinity levels, and reduce net returns. The effect is significant for the range of parameter values being considered.

The shadow value of drainwater, both in reuse (p^r) and as the cost of deep percolation flows from agroforestry (p^d), depends on a number of factors external to agroforestry. For instance, if reduction of drainage flows from other crops is easy or if there are marginal, unproductive lands available for drainwater disposal, then this value may be low. Where source reduction is relatively expensive or drainage disposal would have to occur on productive lands (as in the region under consideration), then the shadow value is relatively high. Furthermore, for regional drainwater management, the relevant outcome from agroforestry is not just the amount reused, but rather the difference between reuse and the deep percolation flows generated, since the latter are incurring costs external to agroforestry.

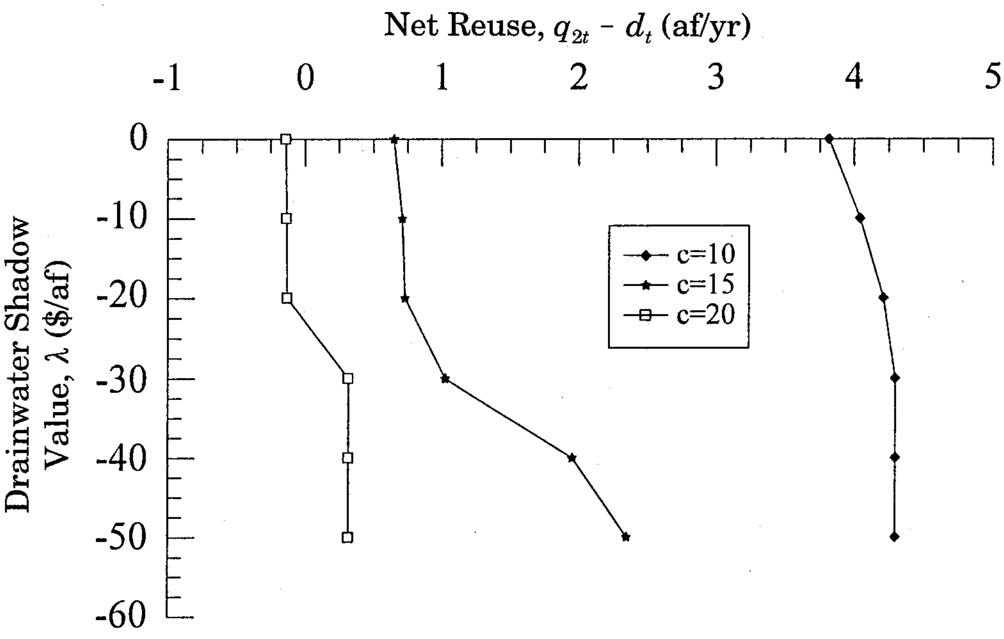


Figure 4. Net reuse in agroforestry production as a function of the drainwater shadow price for three different salt concentrations of the secondary, low-quality/low-cost irrigation source

Regional drainwater management and policy analysis therefore requires knowledge of how net reuse, defined as $q_{2t} - d_t$, varies with the shadow value of drainwater (which we denote as λ). Accordingly, the dynamic programming model is used to derive a series of demand curves showing how net reuse in agroforestry depends on the shadow value of drainwater. In the simulations, we set $p^r = -p^d = \lambda$ for various values of λ. Also, as the previous analysis shows, there are transition dynamics, both between rotations and within a rotation. Here we ignore these and instead calculate long-run demand curves where net reuse is calculated as the average of values over the last full rotation in the 100-year simulations.

Derived demand curves for net reuse are illustrated in figure 4 for several different salt concentrations of the secondary source. At the low concentration ($c_2 = 10$ dS/m), net reuse is already quite substantial even when the shadow value is zero. This is due to the fact that the eucalyptus trees are relatively salt tolerant and reuse saves on the use of expensive fresh water. As the shadow value declines (e.g., drainwater disposal becomes more expensive), net reuse increases by approximately 0.5 af/yr. Net reuse is much more responsive to price at the next higher concentration (15 dS/m), where there is fairly minimal net reuse at $\lambda = 0$; however, as the shadow value falls, net reuse increases from 0.7 af/yr to 2.3 af/yr. At the highest salt concentration (20 dS/m), net reuse demonstrates some response to price; however, net reuse remains at fairly small levels over the range of shadow values considered here. Thus it may not make sense to consider agroforestry (or at least the species considered here) as a reuse system for drainwater salt concentrations of this magnitude unless shadow values are considerably higher.

Conclusions

Interest in agroforestry as a potential cropping system in irrigated agriculture has arisen as a possible solution to salinity and drainage problems (SJVDP) as well as a commercial source of pulp and energy products (Lohr). This study analyzes the microeconomics of agroforestry production relevant to these issues. A dynamic programming model is developed with managed inputs, endogenous harvests, and dynamic soil quality and tree biomass. Fundamental to the empirical model is a dynamic production function which is formulated by combining growth functions as typically used in forestry economics with the relevant concepts from the crop water-use literature. The model is applied in two settings: (*a*) commercial agroforestry production with a single high-quality source of irrigation water and no deep percolation charges, and (*b*) agroforestry production as the reuse component in an integrated system for drainwater management. In the latter instance, irrigation from multiple sources is considered, and deep percolation flows are subject to an emissions charge.

Simulation of the computed decision rules shows how optimal decisions for irrigation management, harvests, and the state variables evolve over time. Here we find that, starting from a nonsaline rootzone and using the base parameter values, soil salinity generally reaches an approximate steady state fairly quickly (typically less than 20 years), and tree harvests generally occur on a regular basis of 16–18 years depending on the particular parameter values. It should be emphasized that under other circumstances this need not be the case; changes in soil quality over time could induce rotations of differing length in the optimal solution. Cycling was also found in some instances, but this was relatively small, likely due to lower average leaching costs at higher salinities, and probably of minimal consequence in actual operating environments.

The optimal rotation proved to be fairly stable with respect to changes in economic and physical parameters. Outside of an output price low enough to make production noneconomic, the main influence is the salt concentration of irrigation water. This reduces tree growth and prolongs the harvest decision, although the effect is not large in absolute terms. Other studies in forestry economics have found that the optimal rotation length may vary significantly with the interest rate and other parameters. The relative stability of the optimal rotation in this problem (across alternate parameter values) is likely due to the relatively quick growth of eucalyptus, combined with a growth function which rapidly declines after reaching the maximum level. Tree species in traditional forestry economics studies typically have much longer rotations, and hence the interest rate becomes more important.

In contrast, irrigation management was found to be sensitive to the salt concentration of irrigation water and to the reuse price. With commercial production and a single irrigation source, increasing irrigation salt concentration implies significantly greater irrigation quantities in order to leach salts from the soil profile and maintain high rates of growth for tree biomass. In the reuse case with multiple irrigation sources, salt concentration of the secondary source greatly affects the optimal mix of irrigation water. With salt concentrations typically found in the study area and base parameter values, all irrigation comes from the secondary, low-quality source. However, when this concentration increases, then use of the secondary source is reduced. Over the range of parameter values considered, irrigation management was found to be relatively unresponsive to the other parameters, aside from circumstances where agroforestry would be very unprofitable to begin with. In particular, irrigation volumes are relatively unresponsive to water price in the single-source case. This is likely a result of the relatively high rate of water uniformity considered here; in other circumstances, the water price responsiveness will likely be higher.

As a commercial crop with no drainwater reuse, the results suggest that agroforestry is a relatively unprofitable investment in the region under consideration. While net returns are positive under base parameter values, they are fairly small, likely considerably less than other crops which could be grown, and they can easily turn negative with unfavorable parameter values. This corresponds with observed production in the region where agroforestry is not practiced commercially; however, this conclusion could be altered in the future if forestry or energy prices increase substantially.

In contrast, the economics of agroforestry as a reuse system for drainwater management appears favorable under the estimated parameter values. In this instance, net reuse of drainwater is high and the implied net returns to agroforestry are substantial. The analysis does demonstrate sensitivity of the management variables and net returns to some parameters. For instance, development of a market for agroforestry products with a reasonable price is clearly a prerequisite for agroforestry to make economic sense, and the shadow value of drainwater is also a key parameter. While it cannot be concluded that agroforestry production should be adapted as a management strategy at this time, it certainly appears promising as a mechanism for helping to mitigate salinity and drainage problems in irrigated agriculture.

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