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# An Economic Analysis of Farm Forestry as a Means of Controlling Soil Salinisation

by

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## Abstract

Dryland salinity emergence is an important land degradation problem in Australia. Large areas of agricultural land where conventional crops and pastures are produced are at risk. The salinisation problem can be controlled by planting trees in conjunction with crops, but a disadvantage of growing trees as a farm enterprise is the long lag between planting and harvest. When farm forestry enterprises are evaluated with conventional discounting techniques they do not generally rank as an attractive alternative to annual crops on productive land. In this paper, a dynamic model that explicitly accounts for decline or improvement in land quality over a period of 40 years is presented. The model is solved for a hypothetical farm on the Liverpool Plains of NSW. The optimal area planted to trees and the optimal groundwater table trajectory through time are determined under a variety of scenarios. Implications of the results for policy design are discussed.

Key Words: soil salinity, farm forestry, dynamic modelling

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# An Economic Analysis of Farm Forestry as a Means of Controlling Soil Salinisation

## Introduction

Dryland salinisation is a land degradation problem that affects many regions across Australia. As deep-rooted native vegetation is replaced with European-style cropping and grazing systems, more water recharges the groundwater systems, resulting in rising groundwater tables. In the process, salts from the bedrock are mobilised and brought towards the land surface. Plant growth on saline soils is impaired through various chemical effects (Greiner 1997). Conventional annual crops are particularly salt sensitive and land affected by soil salinity may eventually become unusable for their production.

Arguably, salinity control in agricultural land will have to be based on biological methods as engineering techniques are too costly. Agronomists have shown that trees and deep-rooted crops are characterised by high and year-round transpiration and are therefore effective biological control tools for the emergence of dryland salinity (e.g. Davidson 1993). However, some of these crops may not be considered economically efficient alternatives by landholders. A disadvantage of growing trees as a farm enterprise is the long lag between planting and harvest. Consequently, when evaluated with conventional discounting techniques, farm forestry does not generally rank as an attractive alternative to crops on productive land.

The question then arises: under what conditions are tree crops profitable enough to encourage producers to change their land use patterns? This question has important social and economic dimensions and has implications for the efficient allocation of public resources between competing activities such as extension, research, subsidies and tax incentives. If society deems it desirable that soil salinity be reduced or further salinisation prevented, and if farm forestry is a profitable alternative but has not been adopted because of lack of knowledge by producers, then extension should be a priority. However, if the problem is one of low profitability of tree crops, then policy makers have the option of introducing incentive instruments such as subsidies and tax credits, or they may prefer to finance research aimed at producing higher yielding and/or faster growing trees for Australian conditions. The challenge facing policy makers is to develop incentives that help prevent large-scale land degradation while maintaining the economic viability of farms.

To develop an analytical tool to study these issues, we must account for the effect of land degradation in the long run. Long-run static economic models are not designed to study problems such as dryland salinisation where changes in the depth of groundwater table caused by trees and annual crops, and the effect of these changes on crop yields, must be taken into account. Thus, a dynamic model that explicitly accounts for decline or improvement in land quality over a suitably long time period must be used.

In this study we estimate the conditions under which agroforestry is an attractive alternative on farms where dryland salinity is liable to emerge under conventional crops. The analysis is based on a multi-period non-linear programming model with five crops: two annual crops which produce a steady flow of income but cause salinity to emerge; one annual crop which does not cause salinity but is less profitable; and two tree crops which may reduce salinity emergence but produce income far into the future and require considerable capital investment early on.

Using parameter values based on the Liverpool Plains, a well researched catchment in the north-west slopes of New South Wales, it is shown for a typical'farm how the profit-maximising level of salinity is affected by prices, costs, yields, discount rates and the initial depth of the groundwater table.

# The Model

### *Salinity Emergence*

Annual crops with shallow root systems, such as wheat and sorghum, and their requirement for fallow periods generate high recharge rates to the groundwater system because they use only a proportion of the water received as rain. Given the hydrogeological conditions over vast areas in Australia this causes groundwater tables to rise. In the process historic salts are being mobilised and cause soil salinisation once a critical depth of groundwater table is exceeded. In contrast, deep-rooted perennial crops have much higher transpiration rates and may even be able to tap into a shallow aquifer, thereby causing the depth of the groundwater table to increase.

There is an obvious trade-off between present and future profits when the crops that are more profitable are also the ones that contribute to salinity emergence. Crop growth and hence farm profits are negatively affected by salinity, while the level of salinity is indirectly affected by the choice of land use, through the effect of the various crops on the groundwater table.

When we conceptualise the groundwater system under a farm as isolated from the catchment, changes in the depth of groundwater table in a given year depend on the recharge balance of the farm. The recharge balance depends on annual rainfall, the recharge rates associated with individual crops and the areas that they cover. As the depth of groundwater table declines below a critical level, crop yields are reduced because soluble salts accumulate in the crops'root zone and adversely affect plant growth. If the depth of groundwater table continues to decline and approaches the soil surface, the land will eventually become useless for crop production.

As the extent of soil salinity and depth of groundwater table are correlated, the effects of salinity on crop growth (*G*) can be represented as a function of the depth of groundwater table (*W*). It is convenient to express *G* as a 'yield multiplier'with a value between zero and one. The value of *G* for crop *j* is represented by the equation:

$$G_j = 1 - be^{-jW} \tag{1}$$

The parameters $b$ and $j$ can be determined algebraically once two critical points are identified (Fig. 1). If $W$ is sufficiently large yields are not affected and $G_j$ has a value of one. However, if groundwater levels rise and $W$ declines below the critical point $W_{crit}$, yields will be increasingly adversely affected (Fig. 1) until a point is reached where a crop can no longer grow. This minimum depth of groundwater table required by a crop to produce some yield is termed $W_{min}$. Crop yields are consequently defined as:

$$Y_j = \overline{Y}_j \cdot G_j \tag{2}$$

where $\overline{Y}_j$ represents the expected yield of crop $j$ in the absence of salinity. The dynamic behaviour of the groundwater system is captured as a difference equation:

$$W_t = W_{t-1} + \Delta W_t \tag{3}$$

where:

$$\Delta W_t = \frac{-\mathbf{r_t} \cdot \mathbf{x}'_t}{q \cdot L} \tag{4}$$

Here, the numerator is the product of two vectors. Vector $\mathbf{r_t} = [R_{1t}, R_{2t}, , R_{kt}]$ contains recharge rates associated with each crop, vector $\mathbf{x_t} = [X_{1t}, X_{2t}, , X_{kt}]$ contains the area planted to each crop (hectares) during any given year of the planning period $t$. $L$ is total area of land on the farm and $q$ is a coefficient that translates the farm's recharge balance into a change of groundwater level. We assume that there is no lateral groundwater flow into or out of the farm and adopt the estimate provided by Greiner (1994) for this parameter, whereby 150 mm mean annual recharge cause the groundwater level to rise by one metre. If the farm achieves a discharging water balance through the extensive use of perennial crops, the groundwater level will decline and *W* will increase.

The actual recharge associated with a given crop in a given year depends on a range of factors including rainfall, land topography, soil type, and crop management practices. This complexity is irrelevant for the principal question that we examine in this modelling exercise. We assume average rainfall conditions over the planning period and uniform land, soil and cropping practices across the farm. In our deterministic model the crop-specific recharge rates for annual crops can be taken as constant and time-independent. In contrast, annual recharge rates of tree crops depend on the age of the crop. Thus, the recharge rate associated with crop *j* is defined as:

$$R_j = \max\{a_j + g_j A_j, R_{\min}\} \tag{5}$$

Where $A_j$ is the crop age and $R_{min}$ is the minimum level of (negative) recharge achieved when trees reach maturity. The rate of recharge of trees declines significantly as they mature and thus for trees $g_j < 0$ whereas for annual crops $g_j = 0$.

### *The Economic Model*

Assuming that the representative producer maximises profits over a planning horizon (*1,T*), the problem is:

Max: $$\underset{x_t}{NPV} = \sum_{t=1}^{T} p_t(x_t)e^{-rt} + FV\left(W_T(x_t)\right)e^{-rT} \tag{6}$$

subject to:

$$p_t = \sum_j GM_{jt} X_{jt}, \quad \textit{for } j = 1,,.k \tag{7}$$

$$GM_{jt} = Y_{jt} P_j - C_j \tag{8}$$

$$Y_{jt} = \overline{Y}_j G_{jt} \tag{9}$$

$$G_{jt} = 1 - be^{jW_t} \tag{10}$$

$$W_t = W_{t-1} + \Delta W_t(x_t) \tag{11}$$

$$\sum a_{ijt} X_{jt} \le b_{it}; \quad \textit{for } i=1,..., n; j=1,..., k \tag{12}$$

Where *r* is the discount rate; *FV* is the value of the land at the end of the planning horizon and is a function of land quality, as represented by $W_T$; $GM_{jt}$ is the gross margin obtained from crop *j* in year *t*; $P_j$ is the price per unit and $C_j$ is the cost per hectare of crop *j*; $a_{ijt}$ are technical coefficients relating the requirements of resource *i* by crop *j* during period *t*, and $b_{it}$ are resource constraints. All other variables have been previously defined and $DW_t$ is estimated as in (4) and (5).

## The Empirical Model

Five enterprises where included in the model: wheat (*Wht*) and sorghum (*Sor*) are the dominant crops in the dryland cropping areas of the Liverpool Plains and represent a winter and summer crop based rotation, respectively. Lucerne (*Luc*) is treated as an annual but deep-rooted crop. Eucalyptus woodlot (*EWL*) and eucalyptus oil (*EOil*) are the two farm forestry options under consideration. Model parameters were based on estimates by Greiner (1997) and Fulloon (1996) for the Liverpool Plains of NSW. Parameter values and other assumptions are presented in Tables 1 and 2. Crop names *Wht* and *Sor* represent summer-based and winter-based rotations rather than single crops, more detailed simulation of actual rotations was not undertaken as it would have increased the complexity of the model unnecessarily given the objectives of this study.

Given the critical depth of groundwater table ($W_{crit}$) and the minimum depth at which crops can grow ($W_{min}$) the parameters of equation (1) were estimated algebraically as: $b$=3.7 and $j$=-2.61.

Applying the simulation model APSIM (McCown *et al.*, 1996), Greiner (1997) estimated that in the establishment year a eucalyptus-woodlot in the Liverpool Plains generates recharge at a rate of 20 mm/m$^2$. By year five, the tree roots tap into a high groundwater table and the woodlot transpires more water than it receives from rain, resulting in a negative recharge (discharging) rate of -122 mm/m$^2$. By year twenty the water consumption of the tree crop has further increased with an associated recharge rate of -300 mm/m$^2$. Recharge parameter values are presented in Table 2.

Assumed yields, prices and costs are presented in Table 2. Only two linear constraints for each time period were included in equation (12): land and credit limit on overdraft.

The model was solved for a period of 40 years, resulting in a total of 200 decision variables (40 years for each crop). The model (6) to (12) was solved in two stages. In the first stage the terminal value of the land was ignored in the objective function (*FV*=0) and the model was solved for different initial levels of land quality ($W_0$). The present value of profit obtained from each optimal solution was taken as an approximation to land value under perfectly competitive land markets (e.g. Samuelson, 1976; Comolli, 1981). In the second stage, this information was used to estimate $FV(W_T)$ and the objective function (6) was maximised using this value. The assumptions in the base scenario are summarised in Tables 1 and 2. Table 3 describes the changes to parameters that constitute the other scenarios. The scenarios cover various policies that could be used to encourage adoption of farm forestry, such as low interest loans, planting or harvesting subsidies and development of high-yield trees. The consequences of an initially low level of land quality and the exclusion of trees from the farm were also analysed (Table 3).

## Results

### *First Stage Results*

In the first stage the model was run for four different levels of initial depth of groundwater table (1, 2, 4 and 6 meters). The results are summarised in Table 4. In all cases the optimal solution included trees as a means of managing the groundwater level and maintaining some level of land productivity. The final depth of groundwater table ($W_T$) ranged from 1.02 to 1.53 m and was directly related to $W_0$ (Table 4). The area planted to tree crops ranged from 41 to 59 hectares, representing 8.2 to 11.8 per cent of farm area. Both farm forestry options entered the optimal solution, but *EWL* was the preferable option, with only a minor proportion of the forested land being planted to *EOil*. The fact that the area of farm forestry varied little despite large differences in $W_0$ suggests two things. Firstly, the proposed forms of farm forestry are part of a favourable diversification strategy for the long-term viability of farms and secondly, farm forestry plays an important component in any economically efficient and long-term recharge control strategy.

The requirement for immediate effective recharge control in the scenarios with shallow initial depth of groundwater table is reflected in the large proportion of land planted to lucerne over the first ten years of the planning period, averaging 64.7 per cent (324 ha) and 37.9 per cent (189 ha) for $W_0$ values of 1 and 2 respectively. Lucerne did not enter the optimal solution at higher $W_0$ values.

The economic rationale for and effectiveness of introducing recharge control measures quickly in the scenarios with shallow initial depth of groundwater table is further reflected in Figure 2. Figure 2A shows the optimal eucalyptus woodlot area trajectories while the corresponding trajectories of $W_t$ are depicted in Figure 2B. For the two scenarios with shallow $W_0$, the full extent of tree planting occurs in the first five years of the planning period, with the highest immediate effort for $W_0$ = 1 m. For this scenario, the immediate recharge control effect of lucerne is reflected in a stagnant $W_t$ before the recharge effect of farm forestry kicks in an leads to a gradual decline in groundwater level (increase in depth) until the trees are harvested. The rapid increase in groundwater level (decrease in depth) towards the end of the planning period, which is also visible in two other scenarios, can be interpreted as an edge effect of the optimisation exercise, whereby no more trees are planted because their financial and hydrological benefits cannot be realised before the end of the optimisation period. The optimal $W_t$ trajectory for $W_0$ = 6 m shows that the 55 hectares of eucalyptus woodland planted are not quite sufficient for complete recharge control on the farm if the remainder of the area is kept under wheat and sorghum. If trees are the only recharge control measure, between 11 and 13 per cent of land have to be planted to trees to achieve a zero water balance.

Estimated land values ranged from $2,077/ha to $4,246/ha, while ABARE (1996) survey data suggest land values are around $1000 for fully productive dryland farming land in the Liverpool Plains. The disparity between *FV* estimated values and actual survey values suggest that the assumption of competitive land markets implicit in the estimation of *FV* does not hold. By assuming that the land has no value when $W_t$=$W_{min}$, the value of the land as a function of *W* was estimated by nonlinear regression, the resulting formula (Fig 3) for land value was:

$$FV = 2046 \cdot \left(1 - 1.66 \cdot e^{-1.07 W_T}\right) \tag{13}$$

this function was incorporated into the objective function (6) to obtain the second-stage solution.

### *Second Stage Results*

Taking account of the productive capacity of the land beyond the planning period, by valuing the land resource at the end of the planning horizon, effectively eliminated the edge effect and resulted in a larger depth of groundwater table at the end of the planning horizon. In the base case ($W_0$ = 4m) $W_T$ increased from 1.18 m (Table 4) to 1.80 m (Table 5). The land-use strategy remained unchanged for the first 25 years, but additional land was planted to eucalyptus woodlot later in the planning period (Fig 4A) and also two per cent of land (Table 5) was planted to lucerne to assist recharge control. These results correspond with Greiner's (1998) findings that the salinisation trajectory is sensitive to end-of-optimisation-period land values. The economically efficient area of salt-affected land in a catchment declines (and the corresponding level of recharge control increases) for higher land values.

The sensitivity of the optimal final depth of groundwater table ($W_T$) and the area planted to farm forestry was tested for a number of assumptions in the base scenario. Assumptions in each scenario are presented in Table 3.

The economically efficient land status at the end of the planning period is highly sensitive to the discount rate (scenario 2). Reducing the discount rate from 12 to 6 per cent leads to a significantly higher level of recharge and salinity control even though the area planted to trees is increased by less than one percentage point of land area. The implementation of farm forestry is undertaken faster in this scenario than in any other scenario with the same initial state of the groundwater table (Figure 5A). In fact $W_T$ is 2.21 metres, which is above the critical depth and therefore salinity is not permitted to develop at all.

If farm forestry is rejected as an option (scenario 3), lucerne is the only recharge control option. However, even if 71 per cent of farm land is planted to lucerne (Table 5) it is impossible to achieve a zero water balance and prevent the rise in groundwater level. The optimal value of $W_T$ under this scenario was 1.38m, indicating a considerable level of land salinisation.

If the establishment costs associated with farm forestry are reduced (scenario 4), a slightly larger proportion of land is planted to trees (Table 5). Interestingly, the start of farm forestry is delayed by a couple of years in comparison to the base scenario but then implementation rates are higher (Figure 5A). This results in a slightly higher level of recharge and salinity control and also the NPV of the optimisation is marginally improved.

High timber yields (scenario 5) had virtually no effect on the optimal solution as compared with the base case. The optimal *EWL* planting trajectory under this scenario was practically the same as in the base case and is not shown in Figure 5A. A slightly larger average area of *EWL* planted at the expense of *Sor* (Table 5) resulted in a small increase in the optimal value of $W_T$ (1.83m vs 1.80m).

As seen before, an initially low water table depth (scenario 6) causes early corrective reaction consisting of planting lucerne and trees (Table 5), with approximately 70 ha of trees planted by year 5 (Figure 5A). By comparing the NPV obtained under this scenario with that obtained in the base case we see that, under optimal management, the cost of a two-meter difference in the initial water table depth is $467,108 over the whole property.

It appears that, under the assumed economic parameters, the optimal water table depth tends to a value of approximately 1.8 m (Figure 5B). This is consistent with results obtained from farm-level optimisation (Greiner, 1996) and catchment-level optimisation (Greiner, 1998) results.

## Summary and Conclusions

The results obtained in the study suggest that farm forestry may have an important role to play in the management of dryland salinity.

The present average depth of the groundwater table across the Liverpool Plains is around 4 meters. The results obtained in this study indicate that under assumed prices and costs, the optimal level from a micro-economic perspective is around 1.8m. This means that it is not economically efficient for individual farms to prevent dryland salinisation completely (unless discount rates were substantially below current capital costs). It is, however, economically efficient to control salinity to a large degree.

Farm forestry in the form of eucalyptus-oil plantations may be very profitable and, after an initial five-year establishment period, returns gross margins greater than wheat and sorghum. However, this high revenue earning enterprise does not come without price risks. Large capital outlays are required and its ability to control the emergence of dryland salinity is lower than for eucalyptus woodlots.

As an enterprise, eucalyptus-woodlots are not equally profitable but they have the greatest impact on recharge control. It is this ability to manage and even lower groundwater tables and therefore maintain land productivity that sees eucalyptus-woodlots implemented in the optimal solution on 10 to 11 per cent of land area, a result that is very robust across a wide range of scenarios.

The results of the study also indicate that commonly applied policy instruments such as tax incentives and subsidies for tree planting may not be very effective in encouraging the adoption of farm forestry, unless they can generate a psychological momentum that exceeds their economic impetus. If people vehemently object to planting trees on their land, they cannot make a contribution to catchment-scale efforts of recharge and salinity control. In this instance, regulatory instruments that force them into participating in joint action may be necessary to limit (a) the negative externalities their land use imposes on other farmers in the catchment and (b) the positive externalities they may capture from having surrounding farmers engage in recharge control activities.

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**Table 1. Model Assumptions and parameter values.**

| Variable | Value | Units |
|---|---|---|
| Land area *(L)* | 500 | ha |
| Initial depth of groundwater table $(W_0)$ | 4 | m |
| $W_{crit}$ | 2 | m |
| $W_{min}$ | 0.5 | m |
| Discount rate (r) | 12 | % |
| Credit on overdraft | 100,000 | $ |

**Table 2. Crop parameters.**

| | | | | | Recharge: | | |
|---|---|---|---|---|---|---|---|
| Crop | Year | Yield | Price | Cost | $a$ | $g$ | $R_{min}$ |
| | | (ton/ha) | ($/ton) | ($/ha) | | | |
| Luc | 1 | 3 | 120 | 100 | 0 | 0 | 0 |
| Wht | 1 | 4.5 | 140 | 140 | 40 | 0 | 40 |
| Sor | 1 | 4.5 | 120 | 100 | 40 | 0 | 40 |
| | | | | | | | |
| EWL | | (m3/ha) | ($/m3) | ($/ha) | 55.6 | -35.6 | -300 |
| | 1 | | | 1920 | | | |
| | 5 | | | 175 | | | |
| | 10 | 60 | 21 | 95 | | | |
| | 30 | 90 | 70 | 210 | | | |
| | | | | | | | |
| EOil | | (ton/ha) | ($/ton) | ($/ha) | 38.9 | -18.9 | -300 |
| | 1 | | | 7367 | | | |
| | 5-10 | 2.5 | 8000 | 10500 | | | |

**Table 3. Scenarios used in second-stage analysis**

| Scenario | Variable values | | | | |
|---|---|---|---|---|---|
| | $W_0$ | $r$ | $\bar{Y}_{EWL}$ | $C_{0,EWL}$ | $C_{0,EOil}$ |
| 1. Base | 4 | 0.12 | 90 | 1920 | 7367 |
| 2. Low discount rate | 4 | 0.06 | 90 | 1920 | 7367 |
| 3. No trees | 4 | 0.12 | 0 | 0 | 0 |
| 4. Low tree planting cost | 4 | 0.12 | 90 | 960 | 3684 |
| 5. High timber yield | 4 | 0.12 | 180 | 1920 | 7367 |
| 6. Degraded land | 2 | 0.12 | 90 | 1920 | 7367 |

**Table 4**. **Results of first-stage analysis.**

| | Average crop area (ha) | | | $W_T$ | Land value |
|---|---|---|---|---|---|
| $W_0$ | *EWL* | *EOil* | *Luc*[1] | (m) | ($/ha) |
| 1 | 55.7 | 3.3 | 323.7 | 1.02 | 2077 |
| 2 | 53.2 | 3.4 | 189.7 | 1.01 | 3004 |
| 4 | 48.0 | 3.2 | 0.0 | 1.18 | 3942 |
| 6 | 38.1 | 2.9 | 0.0 | 1.53 | 4246 |

1. Average lucerne area was calculated for the first 10 years only. Averages for other crops were calculated over 40 years.

**Table 5. Results of second-stage analysis.**

| Scenario | Average Crop Mix (%) | | | | | NPV | $W_T$ |
|---|---|---|---|---|---|---|---|
| | EWL | EOil | Luc | Wht | Sor | ($) | (m) |
| 1. Base | 10.51 | 0.52 | 2.05 | 79.42 | 7.50 | 1,983,229 | 1.80 |
| 2. Low discount rate | 10.96 | 0.85 | 0.00 | 79.95 | 8.24 | 3,720,295 | 2.21 |
| 3. No trees | 0.00 | 0.00 | 71.28 | 28.72 | 0.00 | 1,826,656 | 1.38 |
| 4. Low tree planting cost | 10.52 | 0.63 | 2.37 | 86.47 | 0.00 | 2,034,620 | 1.94 |
| 5. High timber yield | 10.53 | 0.52 | 2.08 | 80.55 | 6.32 | 1,991,406 | 1.83 |
| 6. Degraded land | 10.83 | 0.69 | 15.94 | 71.70 | 0.84 | 1,516,121 | 1.78 |

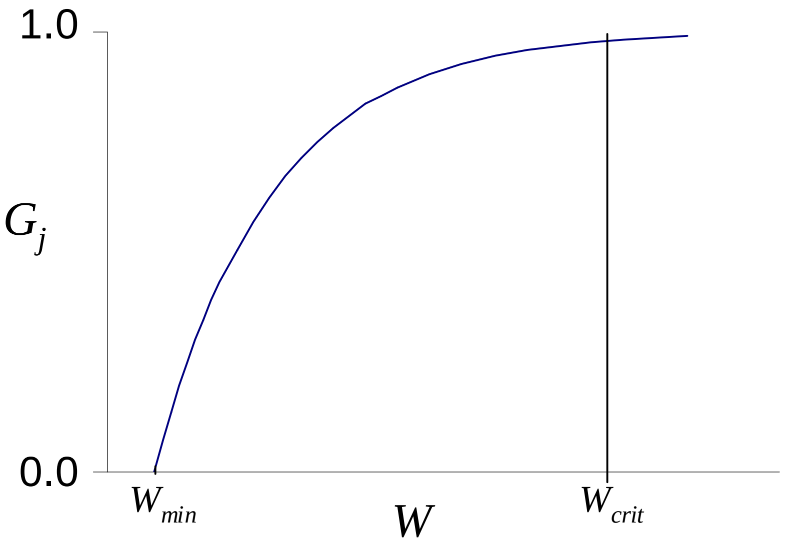


Figure 1. Effect of depth of the groundwater table on crop yield

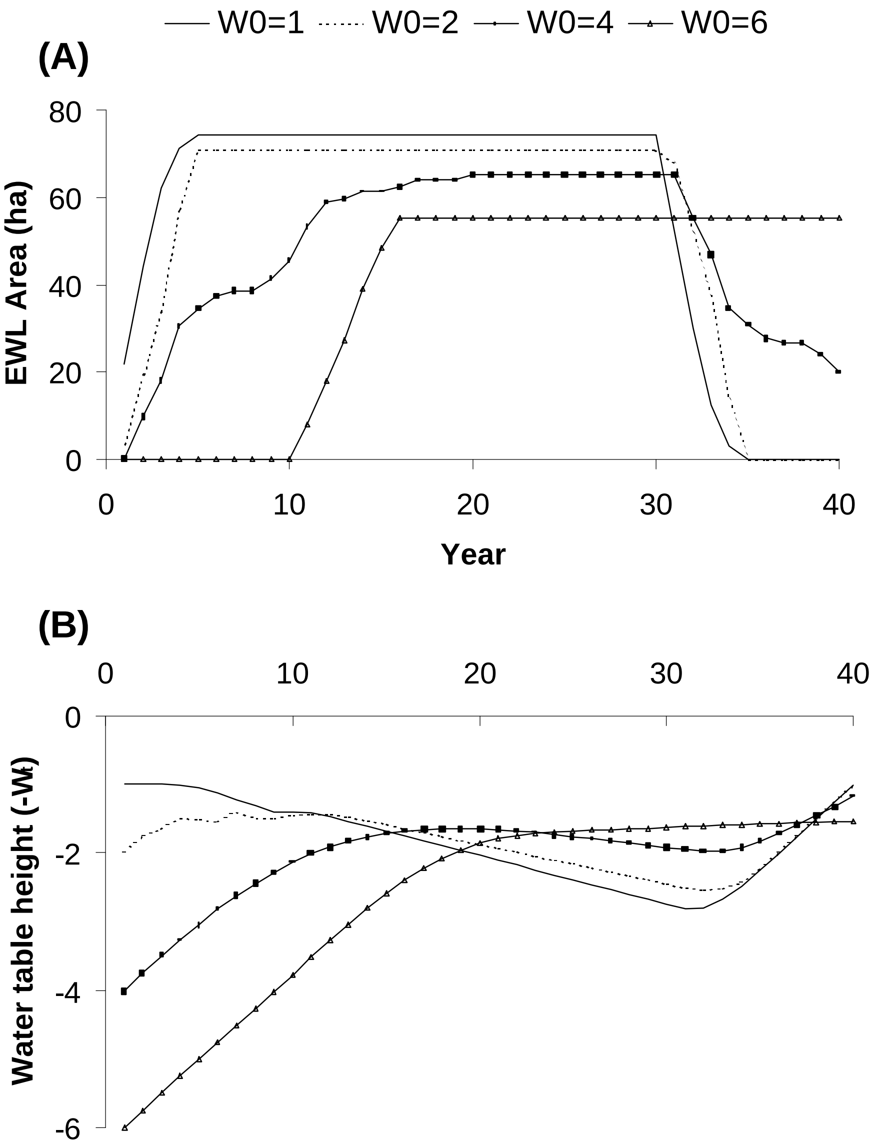


Figure 2. Optimal area planted to eucalyptus woodlot (A) and optimal water table time trajectory (B) as affected by the initial state of the water table ($W_0$) in the first-stage analysis.

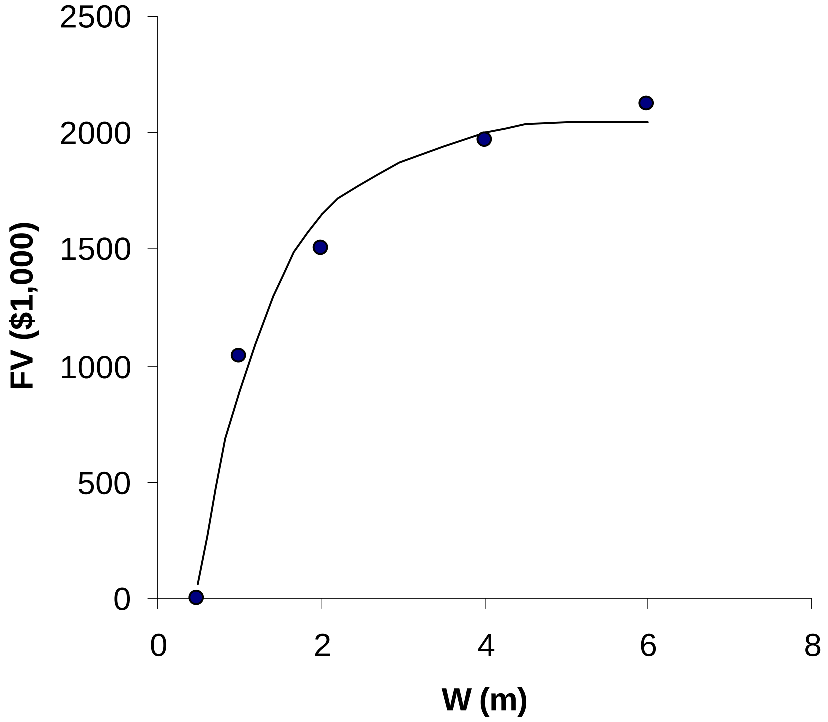


Figure 3. Estimated final value of the land as a function of water table depth

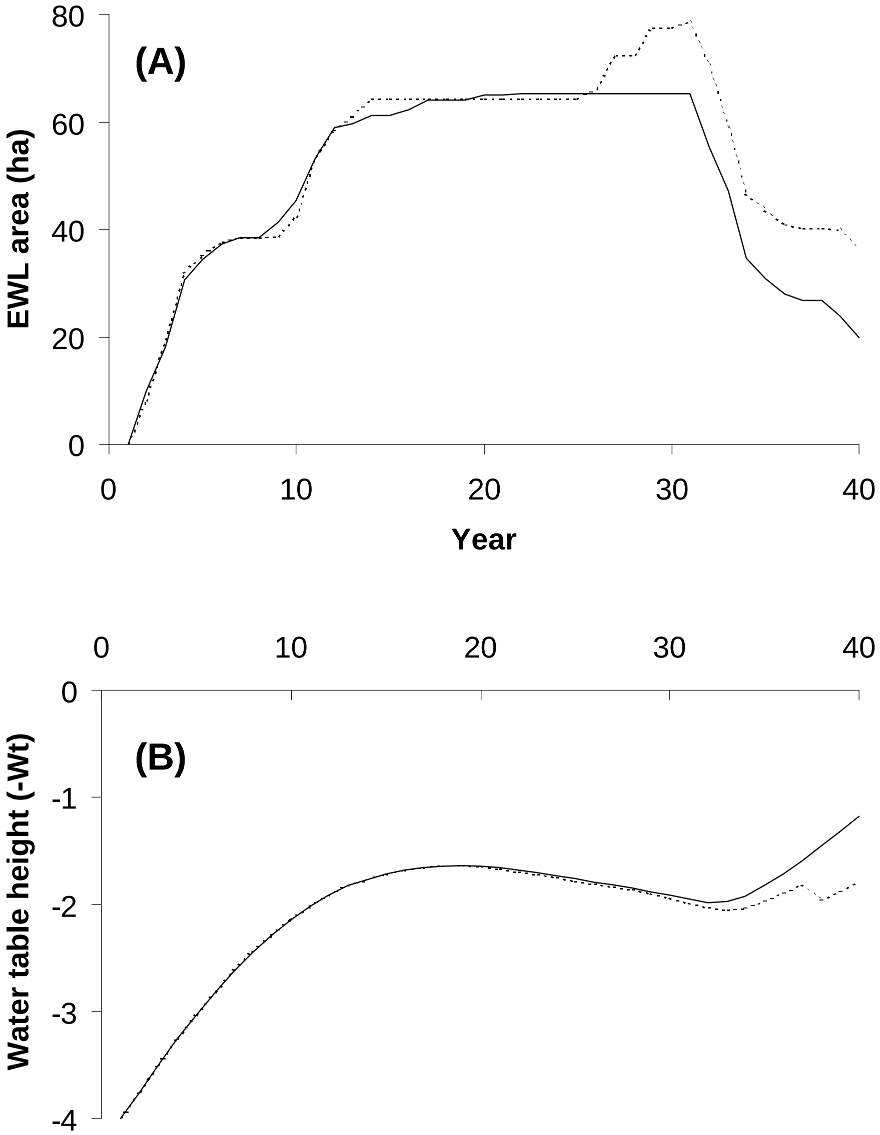


Figure 4. Optimal area planted to eucalyptus woodlot (A) and optimal water table time trajectory (B), with either $FV$=0 (solid line) or $FV=FV(W_T)$ (dotted line).

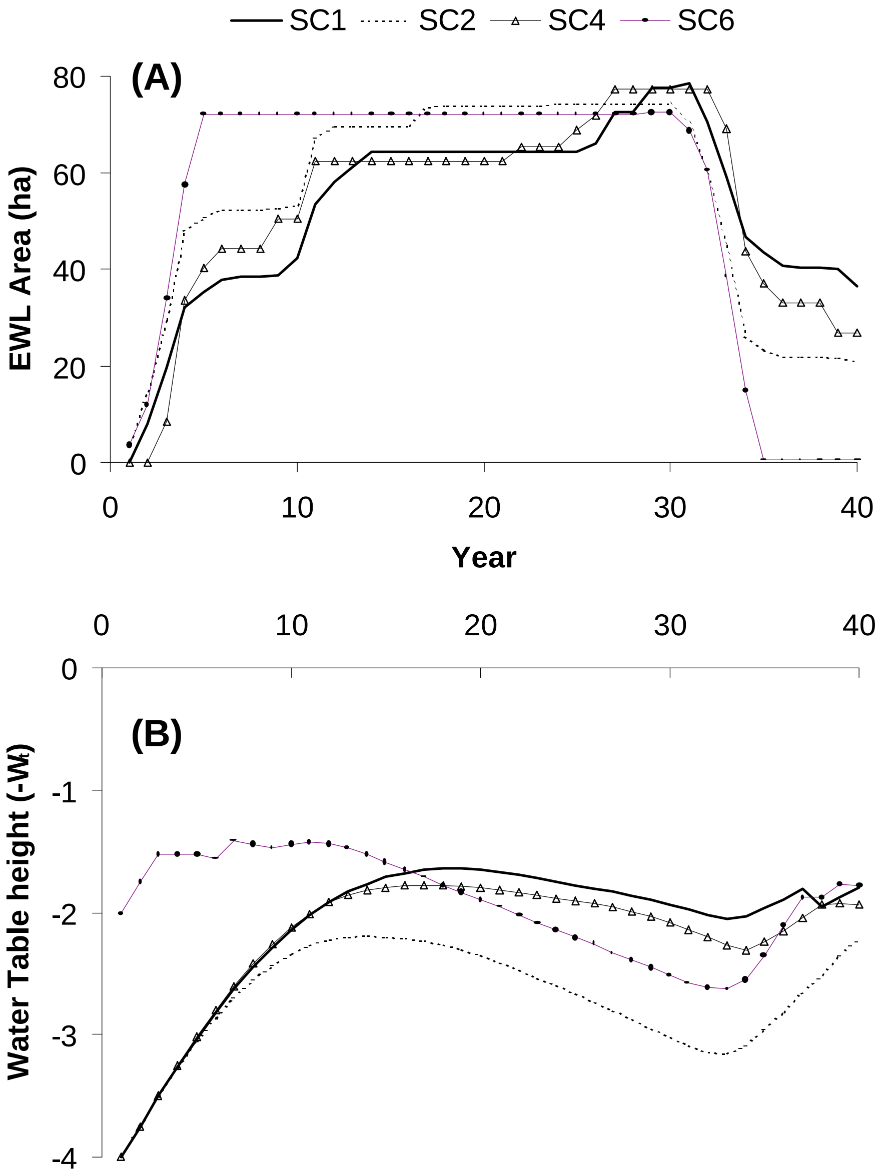


Figure 5. Optimal area planted to eucalyptus woodlot (A) and optimal water table time trajectory (B) under selected scenarios.