Modelling the Effects of Soil Moisture and Solute Conditions on Growth and Tree Water Use

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Abstract Planting trees has been advocated as an economic and environmentally sustainable method for solving problems of waterlogging and salinity. However, assessment of the likely success of these plantings in field situations is difficult. Modelling can assist our understanding of how the system works, and how the growth, and water uptake of a plantation may be affected by different environmental factors. TOPOG_Dynamic is an ecohydrological model, which simulates the 3-dimensional water and solute dynamics within a catchment, and couples these to plant growth and carbon allocation. It has been applied to a small (2 ha) 20 year old plantation growing over a shallow saline watertable in an irrigation area. The plantation has been the subject of an intensive monitoring programme, over 2 years, to assess the current status of the soil-water-solute system, how it changes with seasonal events, and how the soil-water-salt system has impacted on growth. The extent to which the trees can help the surrounding agricultural land through watertable control depends on the sustainability of this system. The sustainability may be limited by salt accumulation beneath the trees through concentrated water uptake. This paper discusses indications that after an initial period of drawdown, followed by a period of relatively stable level, the watertable under the plantation may begin to rise, coincident with a fall in leaf area, and reduction in growth rate. The impact of rising salinity levels in the plantation root zone is of particular concern, as it is likely to reduce tree water uptake. It is found that depth to the watertable is not especially significant in limiting growth. The salinity of the underlying groundwater has a significant impact on leaf development, but a lesser impact on water uptake, at least for the first 20 years of growth. The influence of sensitivity to salt concentration of a plantation may be the most controlling influence, especially if groundwater has salinity above 1500 mg/L.

1 INTRODUCTION

Large areas of Australia have become degraded as a result of agricultural practices and large scale land clearing. This degradation may take many forms from ecological and habitat damage, to soil erosion and rising watertables. It is the last of these, which concerns us in this paper.

When land is cleared for agriculture, the crops and pastures generally use water for a much shorter period, and overall at a lesser rate, than the native forest they replaced. This results in water accumulation in the soil and a rise in the watertable. In irrigation areas water is added to the surface at a rate exceeding that required by the plants. This is done to ensure that any salt that accumulates in the soil near the surface, as a result of evaporation and soil water extraction by roots, is leached below the root zone of the crops or pasture. In many areas, the rise in the watertable since agriculture began is 30 m or more, and the watertables are saline. When the watertable reaches the root zone of the plants, waterlogging can be a problem, and commonly salt is concentrated in the surface soil as surface evaporation drives capillary rise of water from the watertable. The problem is therefore one of too much water, in an environment often characterised as dry, and short of water.

Methods of addressing the problem generally revolve around exporting the water, and salt with it, away from the site. This can be done by deep drainage, or pumping to a drain or sacrificial stream or an evaporation basin, but these methods are expensive, and rely on suitable soil and aquifer properties for their efficacy.

Planting of large numbers of trees in areas with particular problems has been proposed as a means of achieving a similar level of "drainage". The trees are thought of as acting like pumps, lowering the water table by virtue of their deeper rooting capability, and creating small underground "sinks" into which water from surrounding areas can drain. Benefits of using trees rather than engineering works are several. If the trees chosen have commercial value, the "drainage" operation may be self-funding, or at least partially so, as financial return on the plantation can offset the cost of the work and overall be cheaper than an equivalent drainage exercise. There are benefits of shelter for stock, and windbreaks for crops, as well as the visual amenity of the trees being considerably greater than that of a drain, and the land-holder need not be concerned with difficulties of access to land around drainage works.

However, while the principles of using trees in this way are understood, the details of application of this scheme are still uncertain. Choice of the species for a given site, the influence of soil conditions and watertable depth and salinity, in addition to the area planted, the likely extent of benefit to the surrounding area, and the net environmental and economic benefit to the land-holder, are all considerations which require addressing. Of particular importance is the sustainability of the system. As the trees take up water they will concentrate salt in their root zone. This salt accumulation may limit the ability of the trees to use water and to grow. Ideally, a range of species would be planted experimentally at a range of sites with differing soils, salinity, and watertable depth, to test the likely success of such a scheme. Through the life of the plantations, detailed measurements would be taken of soil salt and watertable dynamics under the plantation and in the surrounding paddocks, as well as tree water use and growth. In practice, such experiments are not possible. They are too costly to repeat at more than a few sites and take far too long, as landholders and management authorities require some answers now.

As a means of addressing this, a modelling study has been undertaken. The advantages of this are clear: a modelling study can be done for a fraction of the cost and in a fraction of the time required for a field study. As well, if the model is well constructed the results may be generalised to a wide range of sites and conditions, and different planting and management strategies can be tested.

2 MODEL DESCRIPTION

TOPOG_Dynamic is an ecohydrological model, which simulates the 3-dimensional water and solute dynamics within a catchment, and couples these to plant growth and carbon allocation (Dawes, *et al.* 1997). The model uses a flow net defined by elevation contours, and lines of steepest descent (Dawes and Short, 1994). An automated terrain analysis system has been designed to build the flow net, and for each element, calculate terrain attributes (such as slope and aspect) which govern catchment water and carbon balances. Each element can have its soil profile, vegetation, and climate individually specified.

The model uses Richards' equation for vertical moisture flow, Darcy's Law for lateral saturated flow, the convection-diffusion equation for solute transport, and a surface energy balance based on the Penman-Monteith (Monteith, 1965) and Choudhury and Monteith (Choudhury and Monteith, 1988) models driving evapotranspiration, and soil evaporation, respectively. Soil water extraction is through a distributed root system from the multi-layered soil, and the soil profile is linked to an underlying aquifer system. Water flow and solute transport within the underlying aquifer system are given by the two-dimensional convection-diffusion equation, solved on a finite element mesh. The underlying finite element mesh is coregistered with the overlying catchment mesh, and the linkage between them is governed by a "potential flow" condition. If the piezometric level within a finite element differs from that in the overlying catchment element soil column, there is a flux between the finite element and the soil column at the rate of the saturated hydraulic conductivity, provided always that available storage and specific yield considerations can be satisfied.

A physiologically based plant growth module allocates carbon to roots, stems and branches, and leaf compartments, dependent on water, nutrient and light availability, ambient temperature, salinity and atmospheric CO_2 content. Vegetation growth is modelled by assuming CO_2 is assimilated at a rate (A_g) dependent on a maximum rate (A_{max}) and scaled by the relative availability of light (x_l), water (x_w) and nutrients (x_n) (Wu *et al.* 1994) as :

$$r_g = \frac{A_g}{A_{\max}} = \frac{1 + W + x_n}{\frac{1}{(x_l x_T)} + \frac{W}{(x_n x_w)} + \frac{w_n}{x_n}} \qquad \text{Eq. 1}$$

with W the ratio of mesophyll to gas phase conductances, and w_n is the relative waiting of nutrients to light. Canopy conductance (g_c) is as given by Ball *et al.* (1987) and Leuning (1990):

$$g_c = g_0 + \frac{g_1 A_g}{(C_s - \Gamma)\left(1 + {D_a}/{D_0}\right)} \qquad \text{Eq. 2}$$

with g_0 the minimum value of canopy conductance; g_1 the slope of the dependence of g_c on atmospheric vapour pressure deficit, D_a; C_s is the atmospheric CO_2 concentration, and Γ the CO_2 compensation point for leaves. Soil moisture extraction by roots at each soil node is weighted by root density within the soil interval, moderated by soil moisture availability as represented by the soil moisture potential, and moderated by the osmotic potential of the dissolved salts in the soil moisture. The osmotic potential can be weighted more heavily than soil moisture potential for plants that are more salt sensitive, if data indicate this should be the case.

The mechanism for coupling soil moisture, canopy conductance and root water uptake, represented by the parameter x_w, is critical to the performance of the model. This is made up of the combination of the average soil moisture potential and osmotic potential within the rooting depth of the vegetation, weighted by the proportion of roots within each soil interval:

$$x_w = \frac{1}{\psi_{lmax} z_r} \sum \rho_i \Delta z_i \min\left(\psi_{lmax} - \psi_i + \eta \pi_i, 0\right) \qquad \text{Eq. 3}$$

where ψ_{lmax} is the maximum leaf water potential (i.e. most negative) of the plants, z_r is the maximum rooting depth of the plants, ψ_i is the soil moisture potential and π_i is the osmotic potential due to salt in the soil moisture, within each depth interval i, of thickness z_i, and ρ_i is the proportion of roots within the depth interval, and η is the salt sensitivity factor. The salt sensitivity factor is used in the model to scale the osmotic potential of the groundwater relative to soil moisture potential. Generally it is set at 1; however, evidence is mounting through laboratory experiments which indicate that as soil dries, even slightly below field capacity, it could be much higher (Stirzaker and Passioura, 1996).

3 MODELLING EXPERIMENTS

Modelling experiments have been undertaken to assess the likely growth and water use of a plantation in an irrigation area. The model has been tested at a site, with a plantation surrounded by irrigated pasture.

3.1 Site Description

Kyabram, in northern Victoria, Australia, is within the Shepparton Irrigation Region of the Murray River Irrigation area. Prior to the commencement of agriculture in the district, it is estimated watertables were 30-40 m below the surface. They are currently 1-3 m below the surface through most of the region. The region is very flat, with only one major outflow, being the Murray River, approximately 40 km to the north, and at which point is 120 m above sea level, and flows about 2000 km to the sea.

Deep groundwater pumping is not an economic possibility due to the very low relief, the low permeability of the soils and low specific yield of the aquifer in the region.

In 1976, a 2 ha plantation of five Eucalyptus species was established near Kyabram, at a site with a watertable at about 2 m below the surface. The plantation was established to give information on tree growth under the conditions at this site, and to investigate the ability of the plantation to draw down the watertable, and the lateral extent of any drawdown into the surrounding paddocks. Several monitoring wells installed at the time of planting were destroyed, and 6 years later a network of piezometers was installed within the plantation and in the surrounding paddocks. The plantation was irrigated for the first six years (until a severe drought limited availability of irrigation water), and subsequently has received only rainfall, which falls at a mean annual rate of 480 mm. Rainfall is spread throughout the year with 60% falling in the six months May-October. Annual pan evaporation is 1400 mm, of which nearly 80% occurs in the period October-March. Soil at the site is classified as a Lemnos loam, a red-brown duplex soil which is the principal soil in the Shepparton Irrigation Region. Groundwater beneath the site has a salinity of around 500-1000 mg/L.

3.2 Field Observations and Model Testing

During a 2 year period (Feb. 1994-March 1996), the site was monitored intensively in order to acquire sufficient data to parameterise and test the model. The network of piezometers was added to, and soil moisture and salinity monitoring instruments were installed. Six sapflow instruments were installed in selected trees in the plantation, and the instruments were moved approximately every two weeks to other trees. Stand water use was determined by averaging the sapflow measurements and accounting for tree size distribution within the variable density planting. Figure 1 shows the measurement of daily total stand transpiration with model calculation of transpiration for the plantation, for the two years of intensive measurement. It can be seen that the model generally performs well, although it tends to over-predict in summer and under-predict in winter. The cause of this is still being investigated, however, the measured values of sapflow in winter are considered to be high, during these low flux periods, due to the low sensitivity of the instruments used.

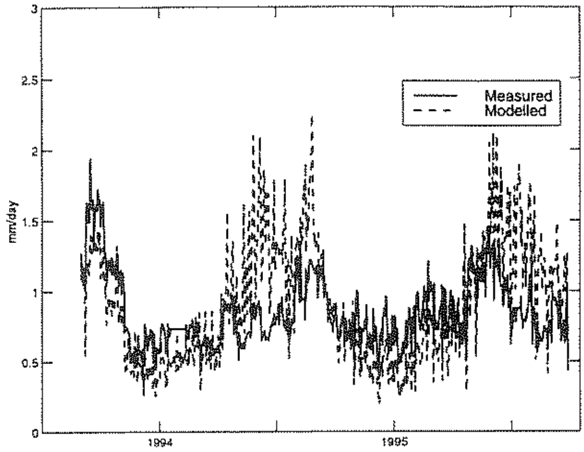

Figure 1: Measured and modelled daily transpiration of the plantation at Kyabram.

This test gives confidence we have captured the water balance of the site, which is the primary driving influence on salt accumulation and tree growth. It is the beginning of a more exhaustive process to ensure we capture as many of the critical processes as possible. It is not our aim in this paper to consider the detailed testing of the model but rather to explore the results of simulations which may indicate the important site and system properties which need to be considered.

3.3 Model Experiments

In order to examine how the plantation might perform over its life and to consider other site characteristics in which a similar plantation might be established, the model was used to simulate the growth from planting to age 30 years. Three scenarios were considered. First, the simulation was performed with groundwater initially at 1m, 2m, 4m, and 8m below the surface. Then, for each watertable depth the groundwater was given three levels of salinity, being 500, 1500 and 5000 mg/L. (The median salinity of water in the deep piezometers at the site is ~600 mg/L). In each case the soil column was initialised with no salt content. Finally, these 9 simulations were repeated for varied salt sensitivity factors, η, being 1, 3 and 9.

In the next section the results of the modelling experiments are reported. The time axis in all cases is given in calendar years, commencing with the date of planting of the trees at Kyabram, although care must be used in interpreting these literally. The simulations most closely resembling the situation at Kyabram are those with initial watertable at 2 m below the surface, and with groundwater salinity 500 mg/L (although at Kyabram it is a little higher than this). The soil moisture at Kyabram had a mean solute concentration of about 600 mg/L at the time of planting.

4 RESULTS

4.1 Variation of Initial Watertable Depth

Figure 2 shows the predicted leaf area index (LAI) for two different values of groundwater salinity and four different initial watertable depths. The first point to note is the rapid growth in the early years, which peaks around year 6. This marked the onset of a severe drought and the cessation of irrigation for the plantation in order to conserve water for other uses. It can be seen from the figure that the plantation over a watertable with 500 mg/L TSS appears to be able to maintain its leaf area index ~1.2 for at least 30 years. However, if the groundwater had a salinity of 5000 mg/L it would begin to go into decline at about its current age (20 years).

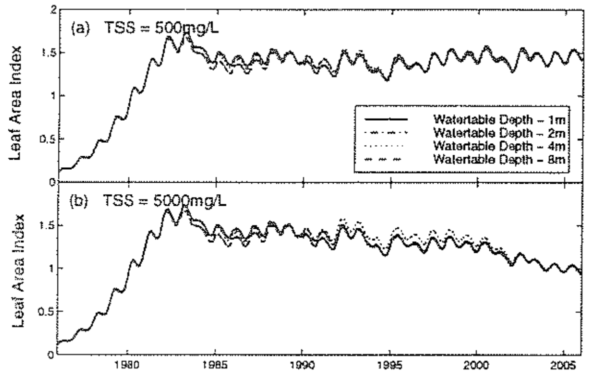

Figure 2: The effect on plantation leaf area of watertable depth at time of planting, for a) low salinity groundwater and b) high salinity groundwater.

Figure 3 shows a similar plot of LAI for the neighbouring pasture, which was assumed to have LAI=3 at the time the plantation was planted. The pasture growth was not affected by the watertable depth or groundwater salinity, as all curves plotted together. This is not surprising as the water added during irrigation is designed to give the pasture an optimum level of moisture within its root zone at all times. While the LAI of the pasture has remained much higher than the trees there is a clear downward trend, indicating the effect of salt accumulation within the shallow root zone. The figure shows that for the first 10 years or so, the pasture maintained a healthy leaf area, (LAI~2.8) but then started to decline. After a significant drop during the drought in 1994, LAI remains at an average value ~2.4. This is likely due to the increase in salt content.

Figure 4 shows the soil moisture storage under the plantation for this simulation set. Two trends appear, namely that at high salinities, the water storage is higher, as a result of lesser water use by the plantation (and lower LAI – see Figure 2). For the plantation over the high salinity groundwater, there is also the counter intuitive result, that the water storage in later years is highest when the initial watertable was at 4m. This is due to the less rapid accumulation of salt and hence greater activity of roots and water uptake, while still maintaining a higher moisture content than the 8m watertable.

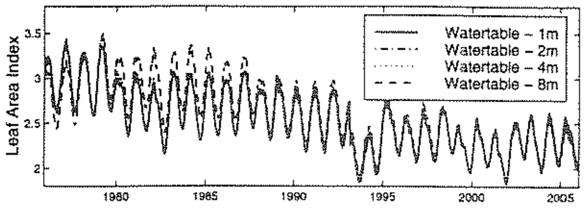

Figure 3: The effect on pasture leaf area of watertable depth at time of planting, for a) low salinity groundwater and b) high salinity groundwater.

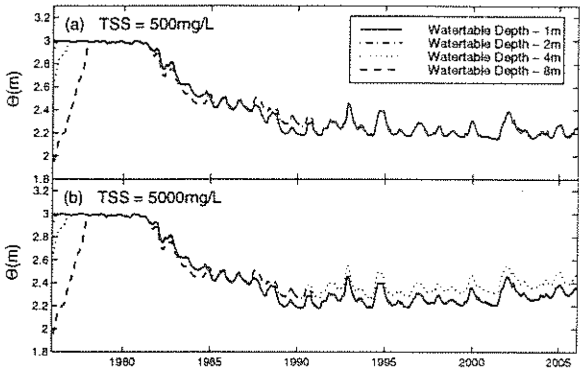

Figure 4: Soil moisture storage (θ)under the plantation for different initial watertable depths for a) low salinity groundwater and b) high salinity groundwater.

For the simulations discussed in the remainder of the paper, the initial watertable was set at 2m, being the field situation at the time of tree planting.

4.2 Variation in Groundwater Salinity

The impact of groundwater salinity on LAI is shown in Figure 5 for two values of the salt sensitivity factor, η. For $\eta=1$, salinity of groundwater does not appear to affect the growth of the plantation until about year 20 (1997), when leaf area starts to decline for the higher salinities. With $\eta=9$, the plantation LAI traces start to separate around year 15 (1990), but growth does continue for the low salinity waters. However, for the high salinity water (5000 mg/L), the plantation heads in to decline over the next few years, and never recovers from the low rainfall period in 1994. It would seem from the figure, that the plantation would die around age 35 years.

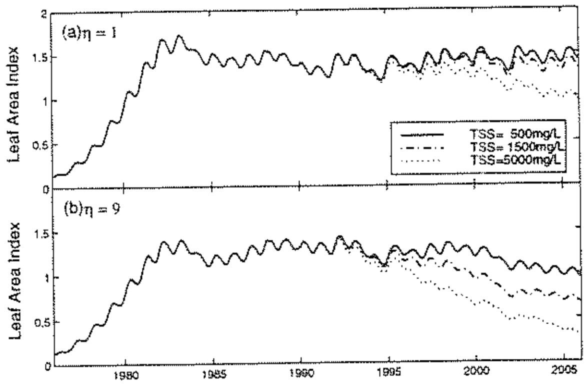

Figure 5: The effect on plantation leaf area of groundwater salinity and salt sensitivity.

The impact on root growth of groundwater salinity and salt sensitivity is shown in Figure 6. For η=1, there is less difference in root development than shown above for LAI. This is due to the fact that when the trees are under stress, a greater proportion of fixed carbon is assigned to roots. Over time, however, the drop in LAI will eventually impact through lower total carbon assimilation. With a high η, the roots show a much more significant response to the high salinity water and show a similar trend to that of leaf area. The impact on water use is shown in Figure 7, and it is less dramatic than that on LAI or root growth, due to the higher moisture content under these conditions. However, there is a gradual decline in water uptake becoming significant over age 20 (1997).

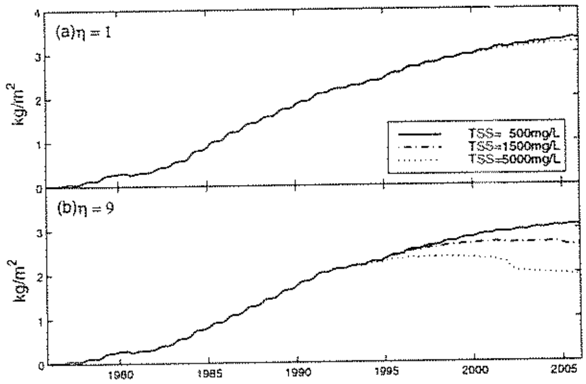

Figure 6: The effect on root development of groundwater salinity and salt sensitivity.

4.3 Variation in Salt Sensitivity

Figures 5 and 6 show clearly that the higher the salinity the more significant is the plants' sensitivity to salt and its impact on growth, as might be expected. The consequence of this on salt accumulation and the soil moisture regime is shown in Figures 8 and 9. Figure 9 shows that the rate of salt accumulation is definitely higher for plants that are less sensitive to salt. This is a consequence of the higher rate of water uptake by these plants under salty conditions, and therefore the greater influx of saline groundwater.

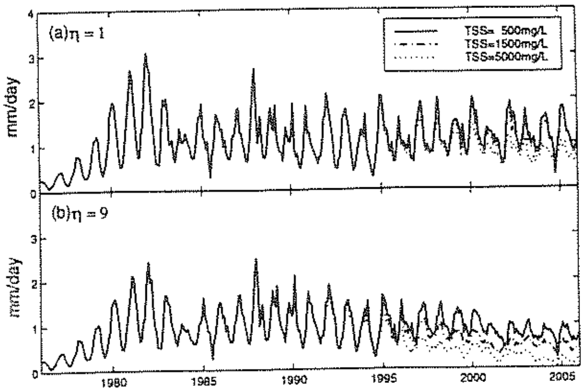

Figure 7: Plantation monthly mean transpiration for different groundwater salinities and salt sensitivities.

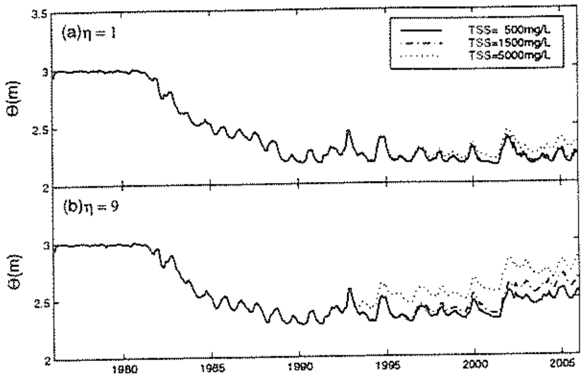

Figure 8: Soil moisture storage under plantations over groundwaters of different salinities, and with different sensitivities to salt.

Figure 8 shows the substantial influence of η on soil moisture storage. When η=9 the water storage rises over 500 mm relative to the low sensitivity (η=1) run. This equates to a watertable being over 2 m higher.

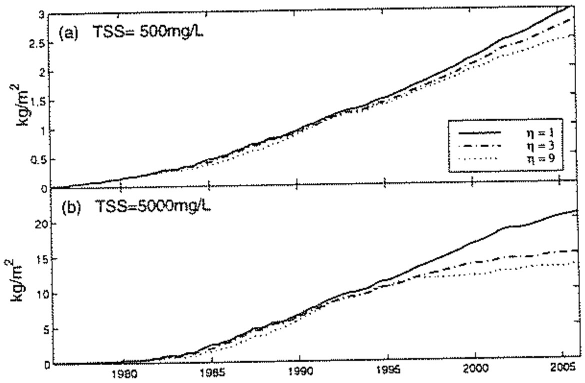

Figure 9: Salt accumulation under the plantation with water of different salinities and different sensitivities to salt.

5 DISCUSSION

These modelling experiments have illustrated how ground-water depth and salinity can impact on tree growth. The effect on transpiration is more subtle, however. As LAI falls, conductance per unit leaf actually increases slightly to compensate, as a result of the higher water storage in the soil. However, over time the response is eventually a decline in transpiration. The time scale for significant influence of the salinity of groundwater at this site seems to be about 20 years. This coincides with the present age for the plantation at Kyabram. The simulations suggest that the plantation is just starting to decline in response to salt accumulation and a lack of water due to the reduction in soil moisture, although these simulations were initialised with no salt in the soil column which was not the case at Kyabram. Initialising the simulations with higher salt content would result in the decline in growth occurring proportionately earlier. Unfortunately, this means we require monitoring at Kyabram for a further few years to test how well the model is representing the situation, and how rapidly the decline will take effect, if indeed it is real. The lack of soil moisture tends to cloud the effect of the salt accumulation, as the two work in concert. However, the separation of LAI traces around year 20 for the different salinities suggests that until this time, the effect of salt in the soil is not of great consequence, and it is the lack of water which is the governing influence on the trees' water use and growth. The site is not truly low in water with the watertable at 4m, but due to the low conductivity of the soil, once the trees have withdrawn available moisture, replenishment is a slow process. At a site with a higher hydraulic conductivity, this may not be such an issue, as soil moisture may more readily be supplied to the roots and into the plantation from surrounding irrigated fields.

The simulations suggest that plantations grown over waters with lower salinities may continue almost indefinitely, and certainly beyond 30 years, which is probably sufficient for a single plantation rotation. The impact of higher salinity waters can be seen, partly, as a loss in resilience of the plantation with a reduction in the ability to recover after a drought period. This is illustrated by the response after the drought in 1994-1995.

6 CONCLUSIONS

Over shallow watertables of low salinity (around 500 mg/L) the plantation appears to be able to continue at its current rate of slow growth. However, simulations suggest that 20 years is about the time scale for serious limitations to set in, if the site is relatively fresh to begin with. If there is significant salt storage in the profile at planting, then it is likely that the plantation will reach its point of decline earlier. For trees which are more sensitive to salt, the decline is likely to be swifter, and sooner. The concentration of salinity in the groundwater seems to have a kind of threshold effect in its limitation to growth. The system appears to be able to continue at reasonable rate with low to medium levels of salt (500-1500 mg/L), however, when salinity reaches 5000 mg/L, the plantation reaches a point where it goes into what appears to be fairly rapid decline.

Further work is required to identify the nature and severity of trees' sensitivity to salt and how this combines with soil water shortage to have an enhanced effect. Further work is also required to better understand the range of behaviours that might be expected at a variety of field conditions. These simulations are to be extended to investigate the effects of different soil properties on the trees' response, and on the drawdown and any beneficial effect on the surrounding pasture. We also intend to test management scenarios, which include rotating the site of plantations every 30 years (after harvest), to move the salt concentration zone.

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