

Agroforestry Over Shallow Water Tables

**The Impact of Salinity on
Sustainability**

Edited by Peter Thorburn

A report on a workshop
held by the RIRDC/LWRRDC/FWPRDC
Joint Venture Agroforestry Program

**Water and Salinity Issues
in Agroforestry No. 4**

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Foreword

Agroforestry has been widely seen as an ideal land use in areas with shallow water tables. After all, trees can use water at a high rate while also providing the land manager with an economic return and contributing to landcare objectives. However, scientific research is now showing that salts in the groundwater can build up in the root zone of the trees, limiting the growth of trees and threatening their survival.

This issue was the focus of a workshop held in May 1997, which brought together a wide range of researchers with interest and expertise in this field. This report documents the findings of the workshop, which make it clear that we still don't have a complete understanding of the issue. Nor do we yet fully know the role trees should play in the fight against rising water tables and salinity.

Nevertheless, we have accumulated considerable knowledge that can be used. This report includes a section compiled by two of the workshop participants, Peter Thorburn and Richard George, which distils experience, observations and 15 years of research results in Australia into 'best bet' guidelines for revegetating areas with shallow, saline water tables.

This is the fourth report in a series published by the RIRDC/LWRRDC/FWPRDC Joint Venture Agroforestry Program on water and salinity issues in agroforestry. We still have much to learn. But this series is bringing to light what we do know and highlighting where we need to go next with our research and development efforts.

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Peter Core
Managing Director
Rural Industries Research and Development Corporation

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Executive Summary

Agroforestry has been widely seen as an ideal land use in areas with shallow water tables (ie, groundwater discharge areas) as it is claimed to promote high rates of groundwater discharge while, providing site stability and a reasonable return to the land manager. However, when trees take up water from, or above a water table, groundwater flows towards the roots carrying salts with it. If these salts build up in the root zone, plant growth is limited or threatened. So the questions must be asked to what extent do trees increase groundwater discharge from shallow saline water tables and how sustainable are tree plantings in these areas?

Over the past ten years considerable effort has gone into examining these issues at many sites which supported different plant species in both irrigated and dryland settings. Twenty researchers, who had been active in these studies, came together at a workshop to compare experimental results and examine recent advances made in modelling the processes determining the sustainability of trees planted over shallow water tables. The workshop consisted of technical presentations and group discussions with the aim to better define (1) the extent of our current knowledge and capabilities, and (2) what important information gaps exist.

The workshop brought together a great deal of information on processes of salt accumulation in the root zone. However, it was apparent that less information exists on the removal (by leaching, water table fluctuations or diffusion) of salts from the root zone. A mechanism for salt removal is critical for the long-term survival of plants in these situations.

The workshop also highlighted that there were a variety of sound modelling approaches capable of being used to analyse salt dynamics and plant growth in these environments. However, few were well documented, peer reviewed or widely tested. This situation limits (1) the broader scientific community's confidence in their application and (2) their ability to be used by people outside the development team, so needs to be rectified. The understanding of root water function in saline soils and processes controlling species' salt tolerance, growth and water use was also identified as areas of inadequate knowledge. Ten actions to remedy these limitations were proposed (*see page 4*).

The participants agreed that existing knowledge and experience should be brought together in the form of interim guidelines for establishing tree plots areas in areas of shallow and saline water tables. These interim guidelines are included in the report (*page 12*) and it is envisaged that further research in the field will improve upon them.

The report also contains details of the workshop process and abstracts of all the technical presentations. The full papers have been published in Thorburn P.J. (Editor) (1999). "Interactions between plants and shallow, saline water tables: Implications for the management of salinity in Australian agriculture". *Agricultural Water Management Special Issue*, 39 (2-3), 227 pp.

Section 1. Workshop Report

By Peter J. Thorburn

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1. Introduction

The area of shallow water tables in Australia is increasing, in both irrigated and dryland regions (Figure 1). While altering land use to control recharge of groundwaters is an attractive, sustainable option for managing the problem, it is not always practical to implement. Some reasons for the impracticality include; difficulty defining recharge areas in catchments, high paddock-scale productivity of current land uses in recharge areas, and the long time scales involved in reversing the current trends in water table depths. An alternate management strategy is to adopt a land use in areas with shallow water tables (ie, groundwater discharge areas) that has high rates of groundwater discharge while, ideally, providing site stability and a reasonable return to the land manager.

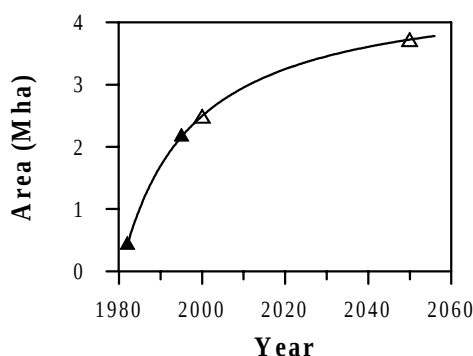


Figure 1. Area affected by shallow water tables in Australia (after Robertson 1996^A). The open symbols are estimates of future areas.

Agroforestry is widely seen as a land use that achieves these objectives. Early studies suggested that rates of transpiration and groundwater uptake by trees underlain by shallow water tables were very high. This, coupled with the growing interest in timber production in Australia, led to the popularity of this management strategy. However, when trees (in fact all plants) take up water from, or above a water table, groundwater flows towards the roots. With it, the groundwater carries salts, most of which are excluded from the root and so accumulate in the root zone. High root zone salinity limits transpiration and growth of plants. This process has not been widely recognised by protagonists of agroforestry in saline areas.

Over the past 10 years considerable effort has gone into examining this issue and enormous progress has been made. Field sites have been established in five states (WA, SA, Vic, NSW and Qld), covering a wide range of plants (crops, pastures, shrubs, and native and planted trees) in both irrigated and dryland settings. The research has been conducted by people from at least six disciplines (agronomists, foresters, ecologists, physiologists, soil physicists and hydrologists). There is also other relevant knowledge, such as data bases on tree performance under saline

^A Robertson G.A. (1996). Saline land in Australia - its extent and predicted trends. *Australian Journal of Soil and Water Conservation* 9: 4-7.

conditions. Thus, there is a wealth of knowledge and experience of the topic and, internationally, Australia is at the forefront of research on this issue.

Despite this knowledge, the issue of salt build up in tree root zones underlain by shallow water tables was identified as a key issue for further research at the recent Agroforestry and Hydrology workshop^B sponsored by the Joint Venture Agroforestry Program. Groundwater uptake, which is intimately involved in the processes of root zone salinisation, was also identified as a substantial gap in modelling. Both these processes are important in determining the impact of agroforestry systems on shallow water tables, and the sustainability of these systems.

Unfortunately, much of the knowledge and experience recently gained is fragmented and dispersed. This situation is expected in a relatively “young” area of research, conducted over such a diverse range of locations and disciplines. Also, there has been no single focus for communicating the results of these studies, especially for process level understanding. Thus, rather than having a broad, coherent view of the problem, the situation more resembles a group of disparate observations of site specific processes. For future research to be conducted efficiently, our current knowledge must be more thoroughly integrated.

Aims

This workshop brought together Australian researchers (Appendix 1) most active in studying these processes, both in the field and via modelling, with the following aims:

- To collate and examine results of different field studies conducted in Australia.
- To describe and examine recent advances made in modelling these processes.
- To identify similarities and differences in processes operating in the different studies.
- To identify areas of inadequate knowledge and limitations of current modelling approaches.
- To provide growers with a consensus scientific opinion on the most likely outcomes for various situations

The outcome of the workshop will be the development of a broader view of the processes operating in these systems than could be gained from the studies independently. This will result in the development of a soundly based research priority in the JVAP.

Workshop process

The workshop was run over two days (Appendix 2) and consisted of three groups of technical presentations (abstracts of which are given in Section 3 of this report) followed by a general discussion period. Presentations were grouped into the subject areas of:

- Irrigated areas,
- Tree growth and physiology, and
- Dryland and natural systems.

^B Stirzaker R., O’Connell D. and Prinsley R. *Agroforestry and Hydrology: What Do We Need to Know?* Report on the Agroforestry and Hydrology Workshop, Kurrajong Hotel, Canberra, 11-12 June, 1996 (RIRDC, Canberra).

Following the presentations in each of these subject areas, discussions were held in small groups to examine the information and issues raised during the presentations.

The technical presentations summarised the current state of knowledge on the workshop subject. From these presentations, two broad statements were made to encapsulate this knowledge. These statements provided a structure for the final discussion period, which was spent identifying gaps in our understanding and recommending further actions that need to be taken to overcome these gaps.

Outcomes and recommended actions

Current state of knowledge

There is a great deal of knowledge about the processes controlling groundwater uptake and salt accumulation in the root zone trees over shallow water tables. The following two statements encapsulate our general knowledge to date about the sustainability of trees planted over shallow saline water tables:

A. Salt accumulates in the root zone in response to groundwater uptake^C -

- *Salt accumulation constrains transpiration and growth and salts need to be removed from the root zone for plant survival.*
- *There are several mechanisms by which salts can be removed from the root zone: leaching by floods, rain, or irrigation; fluctuating water tables; diffusion.*

B. Tools, based on experience and process knowledge, exist to judge the long-term fate of tree plots over shallow water tables^D -

- *Models can be applied where there is detailed information on the site and detailed predictions are wanted.*
- *Guidelines are available which are suitable for more general recommendations.*

Actions to improve knowledge and tools

Despite the clarity of the above statements, they are broad and there are still critical gaps in our knowledge and uncertainty regarding the limits of our experience:

- What are the time scales of salt accumulation/removal and can the process be managed?
- How reliable are the tools and how widely can we apply them beyond the studies/locations on which they were based?

To overcome these deficiencies, 10 actions were proposed to: (1) improve knowledge of groundwater uptake and salt dynamics (accumulation and removal) in the root zone of trees over shallow water tables, and (2) provide more soundly based tools to assess the long-term fate of these systems. These actions, and some immediate benefits leading from them, are (not prioritised):

^C See the following abstracts in Section 3: Connell et al., Heuperman, Mensforth and Walker, Meyer, Meyer and Godwin, Morris, Stirzaker, Thorburn (p 46).

^D See the following abstracts in Section 3: Connell et al., George and Nulsen, Meyer and Godwin, Silberstein, Slavish, Thorburn (p 18), Walker et al..

1. Improve mechanistic understanding of processes controlling water use and salt tolerance of trees *in the field* (eg, minimum soil water potentials for root function and growth, carbon partitioning within plants), to provide:

- Better species selection/tree improvement programs to allow increased growth and water use in saline areas.
- Better process understanding for improving representation of plants in models.
- Data set for validating models.

There are only sparse measurements of tree water use, salt tolerance and water logging tolerance available from which to gain insights into the processes determining the performance of trees in saline areas. Much of the information has come from glasshouse studies. Where studies have been conducted in the field, they generally have been conducted in the short term (eg, over a few years) with the sites being poorly characterised (eg, little soil and groundwater information). Thus, the results are specific to the site and experimental period and difficult to generalise. Differences between species in tree water use and salt tolerance have been well characterised (eg Marcar, Meyer et al.^E) but the reasons behind the differences are not well understood.

2. Refine/further develop rules for describing the depth and temporal distribution of salts in the root zone (initially by a review of current data) and further develop relevant models, leading to:

- Improved site predictions of time to equilibrium, and magnitude of, root zone salt accumulations.

Salt accumulation is well documented (Heuperman, Morris, Mensforth and Walker, Thorburn p 47). However, salts are also removed from the root zone, by mechanisms such as leaching by floods (Mensforth and Walker) or rain (Thorburn p 47), groundwater level fluctuations (Mensforth and Walker), diffusion (Morris), but this process is not as well characterised. The role of diffusion is not well understood in the movement of salts from the root zone (eg the process is often confused with dispersion), but it may be an important process given the time scales involved in salt accumulation in these areas. There is uncertainty about the application of the physics of diffusion and dispersion in the field (as opposed to the laboratory) and argument over appropriate diffusion coefficients. This existing information needs to be collated to better describe and synthesise our current knowledge.

3. Further develop and refine rules for describing root water uptake in saline environments (initially by a review of current data) and further develop relevant models, leading to:

- Improved understanding and model-representation of a process fundamental to short- and long-term performance of trees in saline environments.

Root function is poorly understood. It is very important to differentiate between root distribution (ie presence) which is better known, and root function (ie water uptake). Different mechanisms of root function appear to be operating at different sites (Mensforth and Walker, Dunin), but we are currently unable to predict which mechanism will operate at new sites. Experimental methods have been developed over the past 5-10 years (Mensforth and Walker, Cramer et al.) that allow better

^E The studies referred to in the remainder of these sections are the abstracts in Section 3.

information to be gained on root function, particularly in drier areas. However, a first step in improving our knowledge is to collate existing information and provide databases on which to test new modelling approaches.

4. Monitor root zone salinity at existing field sites and sites used in past studies (selected to represent different environments), to provide:

- Data sets for validating models.

More extensive soil salinity data is required for testing hypotheses about, and models of, salt movement (accumulation and leaching) in soils under tree plots, particularly in eastern Australia. Re-sampling past experimental sites (provided they were originally well characterised) would be an efficient means of collecting long-term data. However, there are general problems with characterising soil salinity profiles. These include the variations in laboratory methods used to measure salinity as well as difficulties in characterising spatial and temporal variations in the field. A more standardised approach is required to allow better inter-site comparisons.

5. Test existing modelling approaches for predicting tree performance and changes in soil salinity and water table depths in areas with shallow, saline water tables:

- at appropriate scales (eg. paddocks to catchments, depending on the model),
- in a variety of hydrologic and hydrogeologic environments,
- where there is an adequate database (in terms of both quantity and quality),
- where there is also good local practical knowledge of dryland salinity processes and management options,

to provide:

- Improved understanding of model performance for providing management oriented predictions of dryland salinity risk and management.
- Increased acceptance by non-modellers of the contribution that can make modelling to practical management problems.

The framework of current models is good. The physical system is generally well understood and all existing models provide some level of understanding and response. Lack of data constrains application of groundwater models, and this will always be a problem. However, the problem needs to be more widely recognised and a basis for decision making in the absence of good quality data needs to evolve. Many different modelling approaches are used in the unsaturated zone in a wide variety of applications. Not all of them may be valid, and certainly not all are appropriate in all situations. However, data (or suitable approximations) are more readily obtainable in the unsaturated zone than for the saturated groundwater case. Similarly, the uncertainty of the approximations may be greater, due to the larger fluxes within the unsaturated zone – there is more happening over shorter time scales. There is a better chance of validating models and their assumptions in the unsaturated zone simply because observations are more easily made.

6. Develop guidelines for planting trees in saline discharge areas, to allow:

- Improved deployment of the substantial human and financial resources already being directed towards this activity.

Currently, many landholders and community groups are investing considerable resources (time and money) establishing trees in saline areas to control and prevent salinity. This activity is being undertaken in the absence of any guidelines. However, there is considerable knowledge about site selection and possible long-term performance of such tree plantings (eg, George and Nulsen) as well as limitations to their benefits (Thorburn, p 18) which could be brought together as interim guidelines. Further research and experience can be used to update these guidelines in the future. **Note**, interim guidelines have been developed after the workshop and these are given in Section 2.

7. Link biophysical models to commercial values to allow economic analyses of management recommendations, to provide:

- A more relevant analysis of the financial implications of management plans identified in modelling exercises.

A significant effort is required to integrate our knowledge into a “whole catchment” picture, and then a regional framework, so that implications of different management scenarios can be evaluated. This needs to include the economic and commercial factors that influence decision making, as well as environmental factors. The biophysical models currently available need to have commercial values added to put “dollar” values on treatments and outcomes. Once models were developed in this way, the economic outcomes of many (eg, thousand’s) of management scenarios should be tested. This path of action leads to a dilemma, however: Do we try to distil our experience and knowledge into a simple broadly applicable model which produces approximate outputs or enhance existing detailed models to attempt to give detailed, more site specific outputs?

8. Improve documentation and peer review of models, to give:

- Greater confidence in the scientific/technical integrity of models.

Too many models are developed and applied “in house” without being properly documented or peer reviewed. The value of results from application of such models can not be properly judged and it is easy (and correct) for potential users of this information to be sceptical of the validity of the information.

9. Standardise and cross check (wherever possible) techniques used in studies and report errors in measurements, to provide:

- Higher quality information from studies and improved ability to judge the significance of the results.

Techniques used in different studies need to be, as far as possible, standardised and the errors associated with results reported. Also, results from a technique need to be cross checked with those from other techniques (eg, comparing transpiration measurements with changes in soil water

profiles). This would provide higher quality results and improve the credibility of the study. These comments apply equally to established methods and new techniques. Limitations of techniques and the assumptions on which they are based are generally forgotten through time.

10. Undertake initial site characterisation (climate, hydrogeology, soil information, etc.) before large trials and treatments are instigated, to provide:

- Improved data for model initialisation, and hence improved model testing and predictions.

More attention should be paid the “down stream” use of information coming from major experimental sites. Information from these sites has great *potential* value in testing, developing and calibrating models. However, models often can not be applied to data from these sites because important information about the site (eg, soil details) have not be determined. Thus, the potential benefit from the community’s investment in the experimental site is limited.

Acknowledgements

I would like to thank Deborah O'Connell for undertaking the arduous task of taking notes during the workshop, while simultaneously taking part in the discussions. Ann Mill’s assistance with organising and running the workshop is also gratefully acknowledged.

Appendix 1. Invited workshop participants.

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* Did not attend.

** Attended part time.

*** Deputised for John Williams

Appendix 2. Workshop program.

Wednesday 28th May

Start	Finish	Title	Speaker
9:30	10:15	Introduction	Peter Thorburn, Ann Mills, Deb O'Connell
10:15	10:25	Tea break	
10:25	10:40	Limits to groundwater uptake from shallow, saline water tables - the big picture ?	Peter Thorburn
		<i>Irrigation areas</i>	<i>Bob Nulsen</i>
10:40	12:30 pm	Sustainable Hardwood Production in Shallow Watertable Areas:	
		• Project overview and methodology	Luke Connell
		• Previous Kyabram work and groundwater results	Alfred Heuperman
		• Tree monitoring and salt diffusion	Jim Morris
		• Modelling	Richard Silberstein
		• Future (scenarios)	Rob Vertessy
		• Discussion	
12:30 pm	1:20 pm	Lunch	
1:20 pm	1:50 pm	Lysimeter measurements of upflow and effects of soils, water table depth, salinity and irrigation practice	Wayne Meyer
1:50 pm	2:20 pm	Trees versus lucerne for water use, water table and salinity management: results from SWAGMAN Destiny	Doug Godwin / Wayne Meyer
2:20 pm	3:10 pm	<i>Discussion - irrigation areas</i>	
		• Do other useful studies exist?	
		• Systems not covered?	
		• Processes not covered?	
3:10 pm	3:30 pm	Tea break	
		<i>Tree growth and physiology</i>	<i>Frank Dunin</i>
3:30 pm	4:00 pm	Effect of salinity on tree growth: species/provenance variation	Nico Marcar
4:00 pm	4:30 pm	Physiological and growth responses of <i>Eucalyptus grandis</i> and <i>Pinus radiata</i> to salinity and vapour pressure deficits under effluent irrigation in dry-land Australia	Richard Benyon
4:30 pm	5:00 pm	Matric and osmotic gradients generated around the roots of transpiring plants in saline soil	Richard Stirzaker
5:00 pm	5:30 pm	<i>Discussion - growth issues</i>	
		• Do other useful studies exist?	
		• Systems not covered?	
		• Processes not covered?	

Thursday 29th May

Start	Finish	Title	Speaker
<i>Dryland and natural systems</i>			
8:15	9:00	Saline farm forest plots in SE Qld:	
		• Tree water use and groundwater uptake	Viki Cramer
		• Root zone salt accumulation	Peter Thorburn
9:00	9:30	What trees do to groundwater and vica versa: Facts and fantasy from WA	Richard George
9:30	10:00	Towards an understanding of the relationship between root distribution and water uptake by perennial communities	Frank Dunin
10:00	10:30	Tea break	
10:30	11:00	Tree water use strategies in naturally saline groundwater discharge areas: Two case studies from SA	Lisa Mensforth
11:00	11:30	"Simple" modelling approaches for analysing groundwater uptake and salt accumulation	Glen Walker
11:30	12:00 pm	Simulating groundwater uptake and salinisation processes using a soil-plant-atmosphere model (WAVES). Implications for defining criteria for sustainability.	Peter Slavich
12:00 pm	1:00 pm	<i>Discussion - dryland and natural systems</i>	
		• Do other useful studies exist?	
		• Systems not covered?	
		• Processes not covered?	
1:00 pm	2:00 pm	Lunch	
2:00 pm	5:00 pm	<i>Discussion :-</i>	
		Can we judge sustainability?	
		• Identify similarities and differences in processes operating at the sites.	
		• What do we know?	
		• What can we currently say about the problem?	
		What are the <i>missing pieces of the puzzle</i>?	
		• What data are missing?	
		• What processes are unclear?	
		• What tools need to be developed?	
		Where to next?	
		• Actions	
		• Future opportunities	

Section 2. Interim guidelines for revegetating areas with shallow, saline water tables

Peter J. Thorburn¹ and Richard J. George²

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Introduction

Shallow water tables occur when there is an imbalance between inputs of water into groundwater within a catchment (*recharge*) and the amount of groundwater leaving the catchment (*discharge*) (Figure 1). This imbalance usually occurs when native vegetation is cleared for agriculture. As a result:

- When more water goes into a catchment than comes out, water tables rise, so
- Shallow water tables will be controlled by *restoring the water balance* in a catchment (Figure 2).

Soil salinity is associated with shallow water tables because salts are carried in water as it moves through soils and the landscape. Salts then accumulate at the soil surface when groundwater evaporates from shallow water tables.

Trees can help restore the balance of groundwater within a catchment in two ways:

- Reducing groundwater recharge - by “using” water in soils and minimising recharge of aquifers. This results in watertable level reductions as the aquifer discharges laterally, underground.
- Increasing groundwater discharge - by roots directly accessing the water table and increasing the rate of groundwater discharge. This can be particularly effective when trees intercept lateral groundwater flow, and reduce the volume of water moving elsewhere in the landscape.

The information presented below attempts to distil experience, observations and results of research studies conducted across Australia over the last 15 years into “*best bet*” guidelines. They concentrate on tree planting in areas of shallow water tables for increasing groundwater discharge, although some reference to recharge control is made. It is intended that these guidelines will be refined as research in this area becomes better developed.

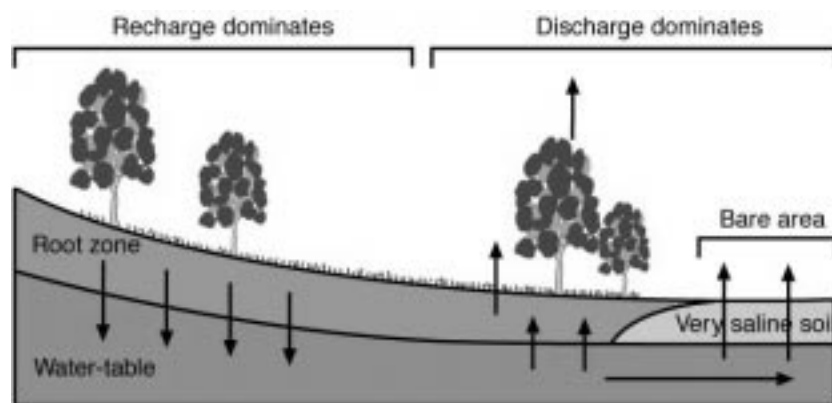


Figure 1: Water movement to (recharge) and from (discharge) the water table in a catchment

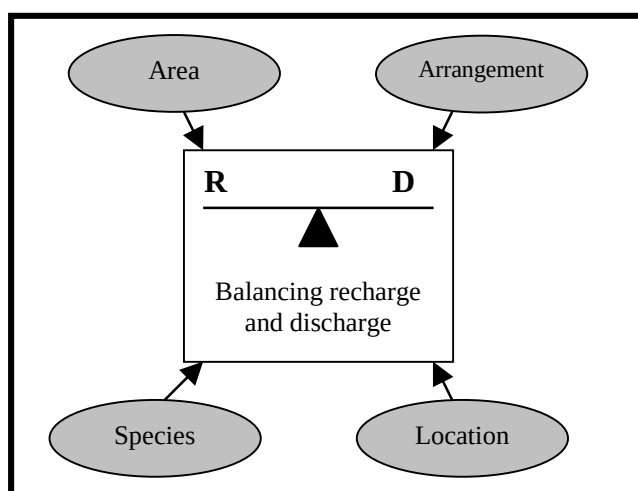


Figure 2: Restoring the balance between groundwater recharge and discharge for dryland salinity control – the four factors that can be managed when planting trees.

Benefits of planting trees for controlling shallow water tables

Experience suggests that, under favourable conditions (described below), trees planted on shallow groundwaters can lower water tables by 1-2 m within 3-5 years.

Trees have other, **very important**, benefits when planted in areas of shallow water tables. They can:

- Reduce the risk of localised salinity spread,
- Reduce the visual impact of salinity (aesthetics),
- Reduce the risk of erosion (provide soil cover),
- Reduce topsoil salinity (by enhancing flushing of salts from the top soil and reducing the amount of evaporation and subsequent salt concentration) allowing other plants to grow on the soils.
- Increase pasture and crop production (if the impact of competition effects - root and shade - are managed)

The impact of trees maybe permanent or seasonal. It may be effected by episodic events that both raise water tables and reduce the effectiveness of the trees, or provide the means of flushing salts from the system, thereby reducing the risk of death from salt accumulation.

Requirements for site definition and species selection

Understanding the hydrogeological system, climate and soils of the area being revegetated is essential to determine the best placement of trees and other perennial vegetation. Useful information can also be gained from vegetation indicators. Some important questions to ask are:

- **Landscape hydrology.**

- ⇒ Spatial and temporal groundwater conditions; what are the watertable depth and salinity, long-term trends and seasonal fluctuations in water table levels, occurrences of flooding and waterlogging?
- ⇒ Aquifer scales; is the aquifer a perched, local, intermediate, or regional aquifer?
- ⇒ Groundwater processes; is the area in a recharge or discharge zone?
- ⇒ Aquifer types; is the aquifer confined or unconfined?

- **Climate.**

- ⇒ Rainfall; what is its amount, timing and variability?
- ⇒ Evaporation; what is its intensity and timing relative to rainfall?

- **Vegetation indicators.**

- ⇒ What was/is the native vegetation - did it tolerate salinity and/or waterlogging?
- ⇒ What is the current vegetation?

- **Soils.**

- ⇒ What is the texture, depth, permeability, salinity, and morphology (eg hardpans)?

Where trees have the greatest potential for lowering water tables

Where water tables are shallow, groundwater is continually discharging from the soil by moving upwards and evaporating from the soil surface. Plants can enhance this process and so contribute to lowering water tables if their roots can take up water closer to the water table, reducing the distance groundwater needs to move through the soil.

Discharge is enhanced by trees **most** where:

- Roots can grow close to the water table (eg, they are not impeded by hard pans in the soil). If roots are active near the water table, groundwater has to move a shorter distance through the soil.
- Water tables are between about 3 and 5 m deep. If water tables are shallower, root zone salting will limit tree water use. Where water tables are deeper, tree roots may not get near the water table.
- Water table salinity is relatively low (ie total dissolved solids – TDS – less than 6,000 mg/l; electrical conductivity less than 10 dS/m). If water tables are saline, salts move into the root zone with the groundwater and accumulate in the root zone. High root zone salinity limits water use and growth of plants.
- Trees are salt tolerant. Salt tolerant trees should be used in areas of shallow water tables even if the soil and water salinities are not very high. They have a greater ability to extract water from saline soil and may prolong the time until salt concentrations become toxic, if this happens.
- Trees are waterlogging tolerant. Waterlogging is common in many saline areas.

- Soils have low permeability at field water contents (ie, either clayey or very sandy textured soils). This reduces the rate of salt accumulation in the root zone. However, in these situations the lateral impact of the trees will be small.
- The impact of trees (ie the amount the water table is lowered) increases upslope from saline areas (subject to the points made above) and as water table salinities reduce.
- Trees may only effect water tables in the dry seasons or dry years. In times when rainfall is high and evaporation low (such as is common in winter in southern Australia), trees may have little impact water levels.
- Trees planted in saline areas may also lower water tables by reducing recharge under the plot or plantation, although greater reductions will occur if groundwater is also used by the trees.

In other conditions, the impact on water tables may be lower, or negligible.

Sustainability of trees growing over shallow water tables

The salts that accumulate in trees' root zone when they grow over saline water tables must somehow be removed from the soil profile for trees to survive in the long term. The rate of salt removal must be significant relative to the rate of salt accumulation for tree survival.

There are several mechanisms of salt removal:

- Leaching by rain, floods or irrigation. As water infiltrates and moves downward through the soil, salts are leached out of the root zone.
- Diffusion of salts from the soil down into the groundwater. Salts will migrate down from the root zone back into the water table when the salt concentration in the root zone is much higher than that in the groundwater. This can be a slow process.
- Fluctuations in water table levels. If water tables move up into the root zone then recede down again, they can 'strip' salt out of the profile. This process will have the greatest impact if there is some lateral movement of groundwater occurring.

Leaching is the only mechanism that can be managed by landholders. Leaching can be promoted by irrigating the area (if irrigation water is available), or by preventing runoff (eg, with small banks) and promoting infiltration. Great care must be taken if leaching is promoted in areas with shallow water tables. The leaching process will recharge water tables and may significantly increase water table levels.

Hydrogeological factors affecting the impact of trees

The hydrogeology of an area exerts a great control over the impact trees will have on water table levels. Experience suggests that:

- Trees planted on thin (< 5-10 m) 'mostly unconfined' aquifers with shallow water tables can significantly reduce groundwater throughflow to seeps and may reduce their extent and severity,
- Trees planted on deep (> 10 m) aquifers with shallow water tables will not significantly reduce groundwater throughflow to seeps,
- Trees planted on 'mostly confined' aquifers will not effect water tables unless they are planted in recharge areas (to prevent inputs to the aquifer) or in discharge areas where the rate of tree water use is greater than the rate of upward flow,

Piezometers and observation wells can be installed to provide information on groundwater depths and salinity, and aquifer conditions. To give a true reading of the salinity of the water table (ie what the trees encounter) piezometers or observation wells need to be screened at the water table (eg < 2 m into the watertable).

Area of trees

Unless a very large area of the catchment is planted, water tables are unlikely to fall significantly (Figure 3). Typically small, localised plantings, selected without knowledge of the catchment hydrology, are unlikely to reclaim existing saline areas or prevent their spread. Experience suggests that:

- Trees need to be broadly distributed (eg planted in alleys or clumps, Figure 4) and extensive (eg > 30-40 % of the catchment) to reclaim most of the existing saline land and prevent new outbreaks.
- In some circumstances, small plantings may lower water tables and reduce salinity if they have been strategically placed, for example interception belts on perched aquifers (break of slope plantings, Figure 5).
- In discharge areas, alley systems with narrow bays (< 30 m wide bays) and belts (1- 3 rows of trees) are able to lower water tables within the bays. However, wide alleys systems (> 50 m) may have little effect on water tables within the bays.
- Both large and small plantings of trees in areas of shallow water tables only affect the area immediately under and adjacent to (< 10-30 m) the area planted.

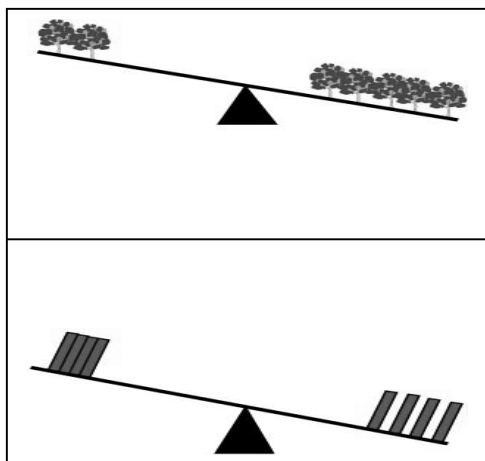


Figure 3: What area of trees should be planted? The greater the area, the greater the impact.

Figure 4: Increase the impact of trees by planting in strips or small groups (note: the total tree area is the same in both arrangements)

Tree performance in areas with shallow water tables

It is important to match the tree species to the site conditions for maximum growth and water use. There is a lot of information on salt and waterlogging tolerant species that grow well in different districts and this should be consulted when selecting tree species. The EM38 meter (a tool used for remotely estimating soil salinity by electromagnetic induction manufactured by Geonics) used in the horizontal mode and **calibrated under local conditions** is a powerful tool for assessing soil salinity (measured as conductivity) for species suitability and performance. Calibration is required as different soils have different inherent conductivities. Thus, a conductivity of 50 mS/m in a sandy soil in Western Australia may be equivalent to 100 mS/m in a clayey soil in eastern Australia. Some broad guidelines for tree performance are:

- Salt sensitive trees do not perform well (tree growth and wood production) on sites with salinities above 50-100 mS/m (ECa, EM38h - see the first point in the following section),
- While some salt tolerant species may survive where salinities are as high as 250-500 mS/m (ECa, EM38h), it is unlikely they will have a significant water use and their hydrologic benefit will be limited,
- Wood production may be reduced by more than 75 % if groundwater salinity is greater than 10,000 mg/l (TDS - EC greater than 15 dS/m) and ECa greater than approximately 150 mS/m.

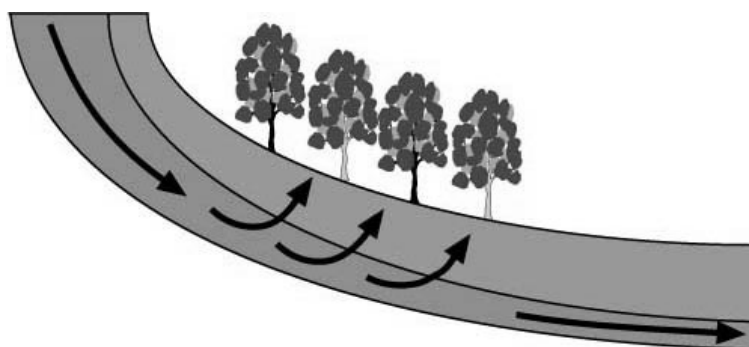


Figure 5: Trees intercept groundwater flowing down a slope. Water used by the trees will reduce recharge of water tables further down the slope

Further reading

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Section 3. Abstracts of technical presentations

The limits to evaporation from shallow, saline water tables – the big picture?

Peter J. Thorburn

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Many people would be aware that rising water tables and associated soil salinisation are an increasing agricultural and environmental threat in Australia. Recently, it has been estimated that nearly 4×10^6 ha will be affected by the year 2050 (Robertson 1996) – that is over 1 % of the country's agricultural land area. While the cause of this problem is generally accepted as increased groundwater recharge associated with agricultural development, it is less certain how best to managing the problem. One strategy is to adopt land uses with high rates of evaporation in areas with shallow water tables (ie, increase diffuse groundwater discharge rates) in an attempt to balance the higher recharge. This raises the question of what are the limits to evaporation from shallow saline water tables?

The situation is well understood in bare soils, with evaporation being a strong function of water table depth and soil hydraulic properties (Figure 1). The limits are transmission through the soil with deeper water tables, and atmospheric demand at shallow water table depths. Salinity is not of primary importance (Thorburn et al. 1992). In vegetated soils it has generally been assumed that the plants, especially trees, will enhance evaporation from shallow water tables because of root activity close to the water table. Certainly early measurements of evaporation from tree plots overlying shallow saline water tables (eg. 1,000-2,000 mm yr⁻¹, Greenwood et al. 1985) supported this belief. However, there have been many studies conducted since that allow a broader examination of the problem.

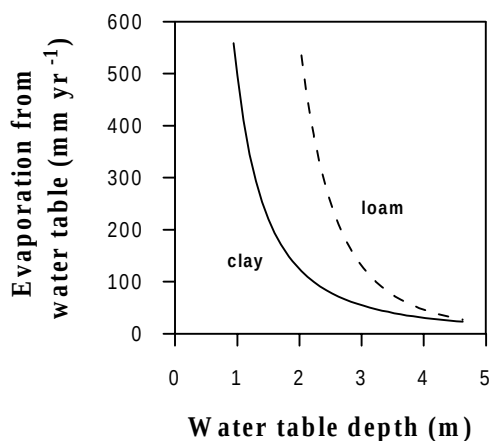


Figure 1 Rates of steady-state groundwater evaporation (estimated from Richards' equation) for bare soils as a function of water table depth.

Measurements of evaporation of groundwater from plants were collated from 20 diverse field experiments where groundwater was at least moderately saline (ie electrical conductivity $> 5 \text{ dS m}^{-1}$). The studies covered trees, crops, shrubs and pastures in rainfed and irrigated areas in Australia (details given by Thorburn 1997). Only studies where the groundwater contribution to evaporation was either measured directly or separated from “total” evaporation were included. Measurements were either made continuously or during different seasons of the year so results could be expressed on an annual basis.

Water table evaporation rates ranged from 10 to 590 mm yr^{-1} , with no particular separation between rainfed and irrigated sites evident in the data (Figure 2). Unlike bare soils, there was little variation in evaporation with water table depth. This result mainly illustrates the range in rooting depths relative to water tables depth at the sites. However, three studies do stand out as having substantially higher evaporation rates than would be expected from bare soils (ie over 300 mm yr^{-1} from water table depths of 3-4 m, Figure 2).

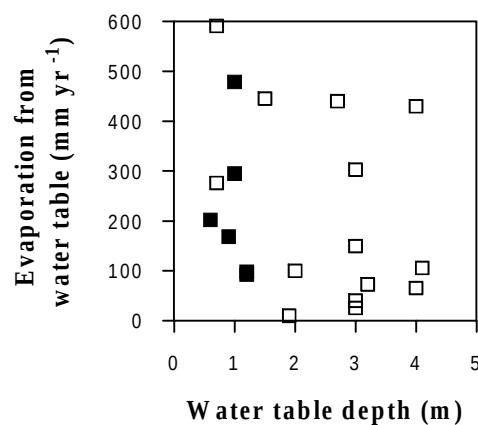


Figure 2 Rates of groundwater evaporation measured from vegetated soils as a function of water table depth (open symbols are rainfed sites, closed are irrigated).

More interesting is the relationship between water table evaporation and water table salinity (Figure 3a). There was only a weak trend of decreasing evaporation with increasing salinity – there was a range of evaporation rates at low salinities, and some high groundwater evaporation rates at high groundwater salinity. Salt tolerance would be one factor that would influence groundwater uptake by plants in saline situations, as salt tolerance allows the plants to extract more water against the low osmotic potentials generated by the groundwater and soil salinities. Notionally, there would be some “threshold” salinity, above which plants can no longer extract water from soil (Passioura et al. 1992, Thorburn et al. 1995). This threshold salinity can be estimated for different species from soil salinity and/or leaf water potential measurements. Such data were available for species at 17 of the 20 sites. When water table salinity is expressed relative to the threshold salinity (Figure 3b) the decrease in evaporation with increasing relative salinity becomes more noticeable. The data close to the origin of Figure 3b (plotted as circles) are studies where leaf area was constrained, by factors such as very low planting density, insect damage, etc. For the remaining points (plotted as diamonds), water table evaporation and relative water table salinity were well correlated ($R^2 = 0.79$). There are sites where evaporation was > 0 even though the relative salinity was apparently $>$

1. This probably arises from the difficulties in measuring (and defining) threshold salinities. Overall, and not surprisingly, salinity appears to limit groundwater evaporation from vegetation but some understanding of plants' salt tolerance can help clarify the situation.

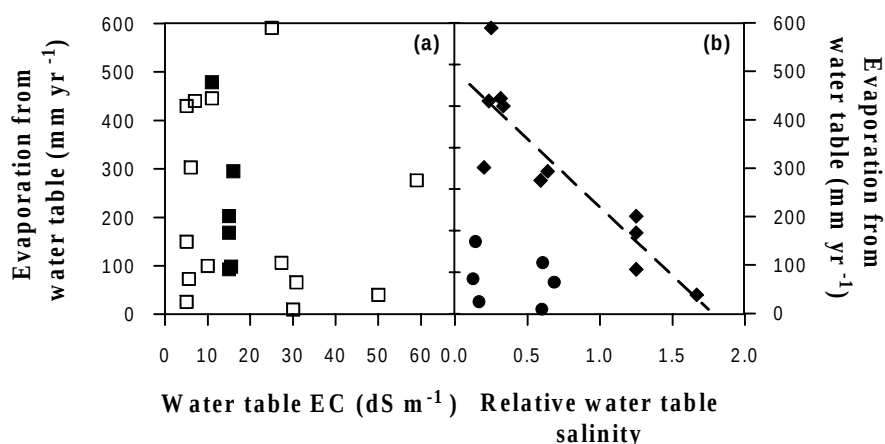


Figure 3 Rates of evaporation of groundwater measured from vegetated soils as a function of (a) actual water table salinity (electrical conductivity, EC) and (b) relative water table salinity.

The results suggest that early conclusions regarding evaporation from tree plots overlying shallow water tables may have been optimistic. However, together with modelling studies (Thorburn 1997) the results indicate that plants have the **potential** to substantially increase evaporation compared with bare soils, provided that (1) water tables are deep (eg., > 3 m), (2) the plant's roots are initially close to the water table, (3) the relative water table salinity is low (ie, < 0.5) and (4) soils are have low permeability at field water contents (ie, either fine or very coarse textured soils). In situations of either permeable soils, high relative water table salinity or shallow water tables, the process of root zone salinisation are rapid and restrict groundwater evaporation rates. If roots cannot penetrate close to the water table, because of either their morphological characteristics of the rooting system or an impediment to root penetration through the soil, groundwater evaporation rates from vegetated soils are also restricted. The challenge now is to disaggregate the data to allow site-based predictions to be made!

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Sustainable hardwood production in shallow watertable areas

Luke Connell¹, Jim Morris³, Alfred Heuperman⁴, Rob Vertessy², Paul Feikema¹, Richard Silberstein², Louise Mann⁴, John Collopy³ and Marek Komarzynski¹

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A potential option for watertable control in shallow watertable areas is the establishment tree plantations. The trees would provide a direct financial return to the grower through wood production, and lead to lower water tables through groundwater being used for transpiration. The feasibility of this concept depends on achievable growth rates (closely related to tree water-use), the extent of the beneficial effect of the trees on surrounding agricultural land (watertable control benefits) and on the sustainability of this system (potential for salt accumulation beneath the trees through concentrated water uptake).

The net benefits, and potential problems, are likely to be site specific. The physical characteristics at a location (such as soil permeabilities, groundwater salinities, and depth to groundwater) combine with climatic conditions to determine how the trees interact with the groundwater system. What is desirable is that the trees use of groundwater be managed to balance salt accumulation, lowering of the groundwater table, and maximising growth rates. One possibility for managing this is in tree planting density; which could be location specific and even altered with time.

This document describes a project funded by the Rural Industries Research and Development Corporation, Land Water Resources Research and Development Corporation, and the Natural Resources Management Strategy. The objective of this project was to develop and validate a model describing salt and water dynamics underneath Eucalypt plantations growing in shallow watertable areas. This model could then be used to answer the following questions:

- Are trees able to control shallow water tables caused by the combination of irrigation and the change from deep rooted native vegetation to shallow rooted pastures and crops;
- If so, what is the spatial extent of this watertable control effect;
- How sustainable is this system, considering the possibility of salt accumulation taking place underneath the trees.

The work conducted in the project was divided into two main activities; field experimentation and model development. The objective of the field work was to improve our understanding of the processes operating at a site felt to be representative, and assemble a database of observations of key flow and transport processes which could be used to test the model developed. The field work was conducted at a 21 year old Eucalypt plantation near Kyabram in central Victoria.

The project was a collaborative venture between three organisations; the Cooperative Research Centre for Catchment Hydrology (through CSIRO, Division of Land and Water and the Department of Civil Engineering at Monash University), the Centre for Forest Tree Technology, and the Institute for Sustainable Irrigated Agriculture.

For a plantation to accumulate salt net tree water use has to exceed the surface water supply (rainfall or irrigation). When this happens the trees create a depression in the watertable, and groundwater flows in from surrounding areas. Salt will accumulate in the parts of the profile where the trees are

using groundwater; the plant root zone near the watertable. Any salt accumulation could be mitigated by leaching events (rainfall or irrigation driven) and possibly diffusion as the concentration gradients increase. The potential exists for salt accumulation to restrict the trees ability to use groundwater, limiting tree water use to what is supplied from the surface.

The field work in the project focused on the processes described above, and was divided into two main activities; monitoring of tree water use, and monitoring of the sub-surface flow and transport processes. Tree water use was intensively monitored at several locations throughout the plantation using the heat pulse method. Groundwater gradients were monitored in several transects using Dataflow loggers. Unsaturated zone water and salt movement was monitored using electrical conductivity sensors and Sentek capacitance instruments. These processes were monitored over approximately two years, a comprehensive database was built up for a range of seasonal inputs. This database allows the model components to be individually tested; and the model representation demonstrated.

In addition to assembling a database of field observations, work was conducted to measure the site specific properties required for model application. Two intensive field studies were conducted to estimate the trees transpiration properties, and a program of work conducted to estimate the sites hydraulic characteristics. A glasshouse study was undertaken to improve the understanding of the interaction between salt concentration and tree water use and growth.

The model must be able to simulate the water, salt and carbon balance of a plantation, established in a high watertable and saline environment which was subject to a variety of management practices. Specific model requirements are that it could:

- be applied to a range of environmental conditions
- account for variability in system properties (such as soil type)
- predict the impact of different types of vegetation (eg. pastures versus trees) on evapotranspiration and groundwater levels
- predict how tree growth would be affected by soil salt content
- predict the impact of different management practices (such as irrigation, fertilisation, groundwater abstraction) on plant growth and the water and salt balance
- be run for at least the length of a plantation rotation

This objective was achieved through the development of a model called Topog_Dynamic. This model simulates water and salt movement over the land surface, into the soil, through the soil and groundwater system, and back to the atmosphere via evaporation and transpiration. At the same time, it also predicts the growth of plants (ie. trees, crops and grasses) and the effect that plants have on mediating water and salt movement. The growth of plants is, in turn, affected by the site water and salt balance, so feedbacks between vegetation growth and hydrology are represented in this model.

Topog_Dynamic has reached operational status, with testing currently focussing on the hydrologic behaviour of the Kyabram plantation. Most of this data is continuous in form, allowing us to robustly test the predictions of these processes by Topog_Dynamic.

Most parts of the model have been tested on other data sets. However, the two areas yet to be scrutinised in detail are:

- the soil water/groundwater linkage scheme
- the groundwater solute transport scheme

These will be evaluated fully in the current testing program, due to be completed by July 1, 1997.

Conclusions from the field program are that:

- water table has been lowered significantly by the trees when compared to surrounding watertable levels;
- the spatial extent of this watertable control is limited to 40 m from the plantation boundary. This is primarily due to low hydraulic conductivities at the site;
- watertable levels under the trees show a seasonal pattern, rising during winter and falling during summer; a trend more marked under the trees than in surrounding irrigated land;
- the watertable is gradually rising underneath the plantation, due to trees using progressively less groundwater and/or from increased irrigation outside the plantation;
- there is an inward lateral and an upward vertical hydraulic gradient around and under the plantation respectively;
- solute accumulation due to concentrated water extraction has occurred in the root zone, leading to salt 'bugles' near the watertable and associated with maximum root density. However, zones of salt accumulation appear to be dynamic, the magnitudes of which increase and decrease on a seasonal basis in response to watertable levels and tree water extraction patterns;
- tree water use is relatively low. Trees are using more water than is provided by rainfall, indicating that they are using groundwater to meet their requirements;
- the trees at Kyabram appear to be moisture limited (with low tree water use and leaf area);
- there is a dry zone within the root zone of the trees that is subject to little or no leaching by infiltrating rain;
- tree growth rates are relatively low for 20 year old trees that may be poor for commercial prospects;
- limitations to growth at the Kyabram site are primarily a result of low soil permeability and high planting density. It is possible that the salt accumulation (while at relatively low concentrations) could be decreasing the 'availability' of groundwater to the trees.

Sustainable hardwood production in shallow watertable areas: Previous Kyabram work and groundwater results

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History of irrigation areas in Northern Victorian

The Northern Victorian irrigation areas have gone through a process of rapid change; water tables have risen dramatically as a result of changed landuse. Management Plans (30 years time span) have been developed for the irrigation areas and are now in the process of implementation. They are based mainly on engineering solutions. Trees are used as a major component in the dryland areas in the catchments for recharge control. With the rise of the watertable, the irrigation areas have now turned from recharge into discharge areas. Crops (including trees), able to access the shallow watertable, will need some form of salinity control to maintain long term rootzone salt balance. It is possible to live with a shallow watertable as long as a small amount of salt is regularly taken out at some depth below the watertable, thus keeping a downward ‘flush’ of salt through the root profile. This is normally provided by sub-surface drainage through groundwater pumping (conjunctive use). Salinity control can also be provided by “over watering”, thus pushing the salt to neighbouring land (or to the drains). This is a popular pastime in the Kerang areas. The ‘neighbours’ in that case are the sacrificial areas, acting as evaporative disposal paddocks.

Sustainability of tree growing

There are 2 reasons why people grow trees in irrigation areas; ‘watertable /salinity’ control and ‘timber production’. To make a profit on the timber component, they have to compete (economically) with other crops (an issue which falls outside the scope of this workshop) plus they have to maintain growth rates uninhibited by rootzone salinity. To provide watertable control, they have to tap into the watertable (or at least the capillary fringe above the watertable). The main competitors of trees in this function are groundwater pumps. Where trees are irrigated, their need to access groundwater will be reduced which in turn has an impact on their watertable drawdown capability. In heavy soils it might be impossible to get enough irrigation water into the profile to satisfy potential evaporative demand. This could result in salt build-up in the top part of the profile (insufficient leaching).

Projects to investigate salt dynamics under trees

Kyabram plantation - non-irrigated tree block in irrigation area, heavy soil; planted in 1975

Impact on watertable local under the tree block. Gradient reversal by trees; trees turn recharge area into ‘sub-surface discharge’ site

EC profiles as measured in wells by EM39. The profiles in the south section seem to slowly increase (peak values) and rise. Some sites in the northern part of the plantation behave different from the south section. Comparison of EM39 with soil samples proved that EM39 gives credible results

There is some evidence of rapid movements of the “bulge” as measured by soil salinity sensors, probably related to watertable fluctuations. Also the possibility of some equilibrium being

established by a diffusive gradient (away from the bulge) balancing the hydraulic gradient (flow towards the bulge) is being floated as a possible long-term salt balance mechanism.

Kyabram irrigated variable spacing trial on heavy soil - E. grandis; planted in 1985

In spite of the trees being irrigated, their roots explore the deeper groundwater. After about 4 years, the high density planting had reversed the hydraulic gradient, setting the scene for salt accumulation to begin.

The tree density had a clear impact on pasture productivity.

Irrigated checkbank plantings on 2 soil types (light and heavy); > 15 years old

The profile underneath the tree line on the heavy soil type showed a clear watertable drawdown in combination with accumulation. Under the light soil type tree line, neither drawdown nor salt accumulation was observed.

Conclusions

Salt accumulation is a 'real' problem for phreatophytes

Irrigation will not avoid salt accumulation, only delay the onset of the problem; there is no scope to *leach* salts out of the rootzone if the drawdown depression is permanent

Diffusion of salts from the bulge acts against the hydraulic gradient created by the tree water uptake, (slightly?) reducing the ultimate peak salinities induced by the trees.

Management systems could be developed based on moving tree plantings around in the landscape; a modern form of 'shifting cultivation'.

Salt accumulation beneath plantations using saline groundwater: Lessons from the Kyabram plantation study

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Salt accumulation has been demonstrated in the root zone of trees using saline groundwater, and invoked as an argument against the sustainability of plantations for control of shallow water tables and salinity in discharge situations. The extrapolation implicit within this argument fails to recognise the existence of three important feedback processes within the rootzone, which limit both the rate and maximum concentration of salt accumulation.

As the watertable falls beneath a plantation using groundwater, roots are required to draw water from greater depth. The deeper root system presents an increasing resistance to water flow, causing transpiration to fall. An equilibrium is created in which the watertable is somewhat lower, and transpiration somewhat less, than before groundwater uptake commenced.

A second feedback results from the formation of a gradient of salt concentration between the zone of active root water uptake and the groundwater below. If the gradient becomes high enough, the rate of downward diffusion may approach the rate of upward salt movement in the transpired groundwater: salinity in the absorbing zone will then be at an equilibrium level.

It has been suggested that the rate of diffusion is normally much slower than the rate of mass flow into the root zone, so that equilibrium is not approached and the rate of salt accumulation in the root zone is not significantly reduced by this mechanism. As a test of this assertion, it is instructive to calculate the expected salinity of the absorption zone for a range of soil conditions and uptake rates.

The molecular diffusion coefficient (D_0) of salts in free water is around $2 \times 10^{-5} \text{ cm}^2 \text{ sec}^{-1}$. For salts in soil solution, diffusivity (D_s) is less as a result of the tortuosity of the diffusion pathway through the film of water surrounding the soil particles, which is a function of volumetric moisture content (θ). Several functions have been proposed by different authors for estimating D_s , with generally similar results; one provided by Campbell (1985) is

$$D_s = D_0 a \theta^3$$

where a is a constant with value approximately 2.8. This leads to D_s of $7 \times 10^{-6} \text{ cm}^2 \text{ sec}^{-1}$ or $6 \times 10^{-5} \text{ m}^2 \text{ day}^{-1}$ at θ of 0.5, typical of moisture conditions close to the watertable in clay soils.

The diffusive flux (J_d) of salts from the root zone to the groundwater is estimated from Fick's law as D_s times the concentration gradient. Hence, for a plantation absorbing groundwater at 0.5 mm day^{-1} with a salinity of 5 dS m^{-1} (salt concentration of 3 kg m^{-3}) equilibrium salinity will occur when $J_d = 1.5 \times 10^{-3} \text{ kg m}^{-2} \text{ day}^{-1}$. The concentration of salt in the soil solution 50 cm above the watertable will then exceed the groundwater concentration by $1.5 \times 10^{-3} \times 0.5 / (6 \times 10^{-5}) = 12.4 \text{ kg m}^{-3}$, leading to a root zone salinity of 26 dS m^{-1} . Lower equilibrium salinity would be obtained if (i) groundwater uptake was less than 0.5 mm day^{-1} ; (ii) maximum uptake occurred within less than 50 cm of the watertable; (iii) moisture content within the absorbing zone was greater than 0.5. Equilibrium salinities at 50 cm for some other values of uptake and moisture content are shown in Figure 1.

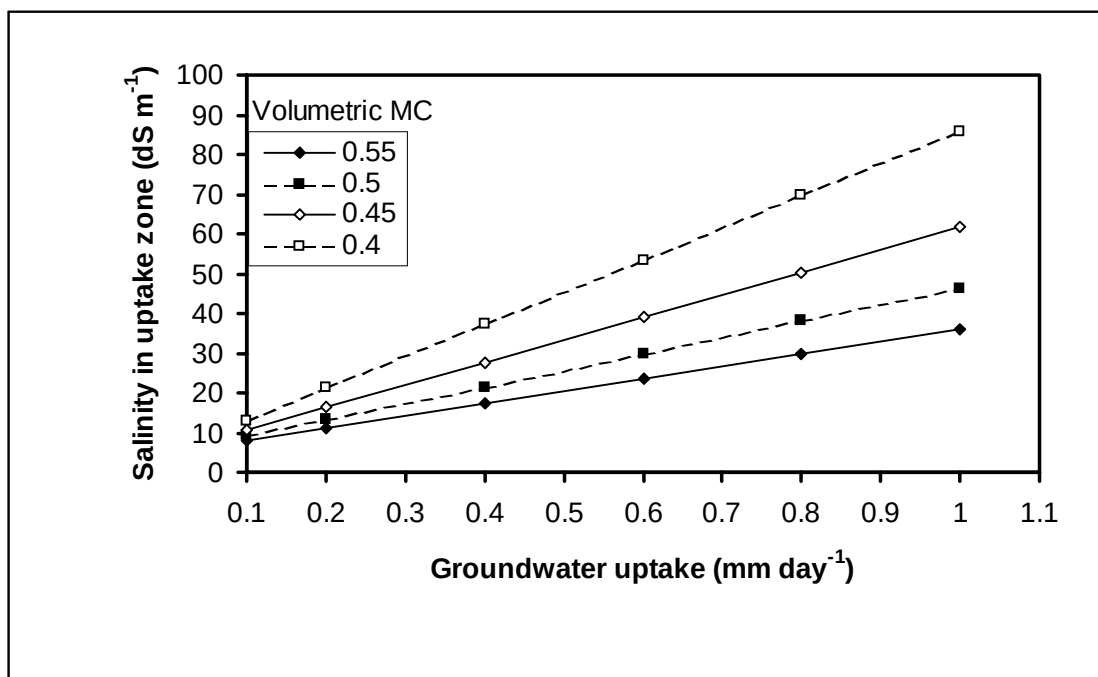


Figure 1. Equilibrium salinity at 50 cm above the water table for groundwater salinity of 5 dS m⁻¹, related to root groundwater uptake and moisture content in the absorption zone.

The first point to be made from these calculations is that predicted equilibrium salinities for plantations using modest amounts of groundwater are within the range of subsoil salinities observed beneath plantations in the field. Beneath a 20 year old plantation at Kyabram, soil solution salinity close to the lowered watertable often approached 20 dS m⁻¹ and sometimes exceeded 25 dS m⁻¹ during 3 years of monitoring. Plantation water use was around 300 mm year⁻¹, and groundwater uptake appears unlikely to have averaged more than 0.5 mm day⁻¹. Salinity of the groundwater was around 5 dS m⁻¹ at 1-2 m below the watertable, but the upper groundwater was more saline so that the salinity gradient actually extended over approximately 1 m rather than 50 cm.

The second point that may be made from the above calculations is that accumulation of salt up to the equilibrium concentration occurs over a period of years. Even ignoring the removal of salt by diffusion, uptake of 5 dS m⁻¹ water at 0.5 mm day⁻¹ adds salt to the root zone at only 1.5 x 10⁻³ kg m⁻² day⁻¹. Assuming the salt is all stored within 1 m of the watertable in a “salt bulge” peaking at 50 cm above the watertable, it would take 2567 days to reach the equilibrium concentration calculated. Allowing for the effects of diffusion, the approach to equilibrium becomes progressively more gradual and the time taken will be rather longer than this.

Evidently salinity equilibrium is not to be expected in young plantations using groundwater; that is, increasing salt storage in the root zone is to be expected for several years but it should not be assumed that this would continue indefinitely. In an older plantation such as at Kyabram (*Eucalyptus* species planted in 1976), however, an equilibrium is more likely to have been reached.

If the accumulation of salt in the lower root zone affects water uptake, it constitutes a third feedback process. The effect of this is to lower the equilibrium salinity and shorten the time taken to reach it. At the same time, an interaction with the first feedback will cause the watertable to rise somewhat as equilibrium is approached. The long-term productivity, water use and effectiveness of plantations

for watertable control will therefore be less than observed in young plantations established on former farmland.

For example, Figure 2 shows the expected changes in salinity of the lower root zone and plantation water use at Kyabram, when daily water uptake is made sensitive to the peak soil water salt concentration (reducing linearly from 1 mm day⁻¹ at zero salinity to zero at 20 kg m⁻³). An equilibrium peak concentration of around 15 kg m⁻³ (25 dS m⁻¹) would be reached by approximately age 20, with continuing groundwater uptake of 0.25 mm day⁻¹. The predicted equilibrium salt store of around 6 kg m⁻³ is also consistent with observations of the “salt bulge” at Kyabram. The prognosis for the plantation is then sustainable, though not vigorous - as is its present condition.

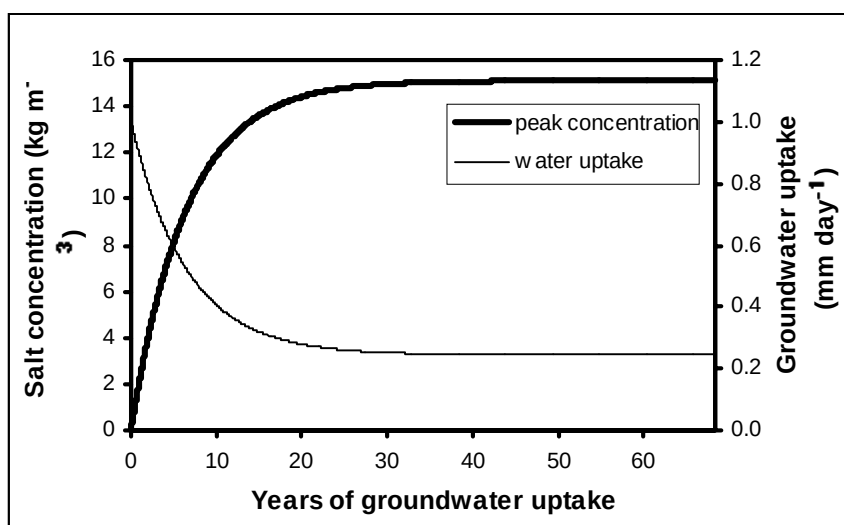


Figure 2. Predicted changes in groundwater uptake and soil water salinity of the lower root zone as a result of salt accumulation at Kyabram (5 dS m⁻¹ groundwater, accumulation in a 2 m wide zone with peak 1 m above the watertable and 50% moisture content; water use reducing with salinity to 0 at 20 dS m⁻¹).

The water relations of the plantation-soil-groundwater system are also subject to a number of other influences, including leaching of accumulated salt by deep infiltration and seasonal or shorter term variations in watertable depth due to climate or irrigation of surrounding farmland. These processes will be important in controlling the long term concentration of salt in the groundwater beneath plantations maintaining equilibrium root zone salinity. Models which seek to predict the long term sustainability of plantations should include these factors as well as the effects of diffusion from the root zone to the groundwater.

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Modelling growth and water use of a *Eucalyptus* plantation with a shallow saline watertable

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The feasibility of plantation establishment on areas of shallow saline water tables depends on the achievable growth rate of the trees (closely related to water use), the extent of the beneficial effect of the trees on the surrounding agricultural land through watertable control, and on the sustainability of this system. The sustainability may be limited by the potential for salt accumulation beneath the trees through concentrated water uptake.

Exhaustive experiments to test the plantation strategy are not possible due the long lead time, and the number and variety of environmental conditions which need assessing. The use of strategically designed experiments together with a model capable of simulating the processes is therefore an essential contribution to our understanding of the system. An ecohydrological model (TOPOG_Dynamic) has been developed to predict the three dimensional water, plant carbon, and conservative solute balances of heterogeneous catchments. The model uses Richards' equation for vertical moisture flow, in multilayered soils, Darcy's Law for lateral saturated flow, the convection-dispersion equation for solute transport, and a surface energy balance based on the Penman/Choudhury and Monteith models driving evapotranspiration. Soil water extraction is through a distributed root system from the multilayered soil, and deep drainage to and recharge from, an underlying aquifer system. A physiologically based plant growth module (IRM) allocates carbon to roots, stems and branches, and leaf compartments, dependent on water, nutrient and light availability, ambient temperature, salinity and atmospheric CO₂ content. Thus plant growth and water use and soil-water solute dynamics are closely linked.

The model is being tested by hindcasting the growth and water use of the plantation at Kyabram, and water table and soil salinity development. The model can then be used to forecast the future of this plantation under current management or modified practices. The impact of rising salinity levels is of particular concern, as the plantation is likely to reduce its water consumption further in response to this stress.

The model can be applied to similar plantations for sites at which we do not have adequate field data. Plantation growth, water use, and soil salt accumulation, can be forecast for sites which have different soil and watertable characteristics. A range of likely plantation and watertable outcomes can also be examined for different sites with different planting and management strategies.

Plantation hydrology in high water table areas - problems and opportunities with complex models

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Introduction

For a decade now, a vigorous debate has been running about the utility of physically-based models in hydrology. Critics have argued that such models (i) cannot be adequately ‘parameterised’, (ii) cannot be ‘validated’, (iii) use inappropriate descriptions of physical processes, and (iv) confer dubious advantages over simpler conceptual models. In this paper we refer to the key problems we faced in applying one such model, Topog, to predict the water, salt and carbon balance of the Kyabram plantation.

We highlight problems in model parameterisation and reality-checking and conclude that uncertainty will always surround predictions obtained using models of this kind. However, we argue that these problems do not necessarily de-base complex models and that they can be used to test a variety of hypotheses of plantation hydrologic function. We stress the need for improved field measurement techniques and continued experimentation, proceeding hand in hand with model application and testing.

Parameterisation

Topog, like other complex models, demands detailed information on the properties of the site it is being applied to. These can be lumped under the general headings of (i) topographic data, (ii) climate data, (iii) vegetation data, (iv) soils data and (v) aquifer data. We had no difficulty obtaining adequate topographic and climatic data for this site, but struggled with the other forms of input.

Most of the vegetation input values we used were taken from the literature, with only a few being measured directly in the field. The most important values (such as plant respiration and growth coefficients, and salt sensitivity) were treated as ‘calibration’ parameters, and were simply ‘tweaked’ until the model produced results which accorded with past observations and/or general wisdom.

A great deal of effort was put into the measurement of site soil properties. These were found to vary enormously throughout the small study area, but not in any systematic manner. Hence, we assumed that the soils were spatially invariant, though we did have sufficient data to discriminate between three different soil layers. Whereas we had several observations of saturated hydraulic conductivity, we had few measurements of the soil moisture characteristic and unsaturated hydraulic conductivity. This meant that we had to rely on ancillary models such as the Broadbridge and White soil hydraulic model to provide a full set of soil property values.

The greatest uncertainty in our parameterisation for the Kyabram site, however, revolved around the aquifer inputs (specific yield and hydraulic conductivity), as we had no direct field measurements of these. These properties are notoriously difficult to measure accurately, so we ended up varying the input values until a satisfactory aquifer response was obtained. Fortunately, we had detailed continuous observations of groundwater level to evaluate model predictions against.

In conclusion, even with a large field experimental effort such as mounted at Kyabram, it is difficult to parameterise physically-based models such as Topog. We conclude that some uncertainty will always surround the application of such models to any given site because many system properties are difficult to measure meaningfully.

Reality-checking

‘Reality-checking’ is an alternative term for what modellers used to call ‘validation’. This is a difficult thing to do because (i) we rarely have simultaneous measurements of all processes being modelled, (ii) those that we do have measurements for are prone to error because of flaws in technique or biased averaging procedures, and (iii) there is often a scale mismatch between observations and predictions.

Accepting that proper ‘validation’ of such models is not possible, an interesting point of modelling philosophy is raised. Is it necessary to test all facets of model operation exhaustively to establish the credibility of model predictions? We think not. In complex models with many degrees of freedom, it is easy to obtain ‘the right answer for the wrong reason’. However, if the internal operation of the model is carefully scrutinised with reference to varied field observations and general wisdom, and the model input values realistically constrained, it is not too difficult to ensure credible model function. For instance, we had good observations of evapotranspiration and groundwater dynamics for the Kyabram site, but our soil moisture measurements were less than satisfactory. Nevertheless, our soil moisture storage predictions could still be evaluated by treating this term as a residual.

In some cases, our ability to evaluate models such as Topog is constrained by our ability to properly measure hydrologic processes, and the onus needs to be placed on the experimentalists. For instance, techniques being used now to measure soil moisture content are either (i) unreliable, (ii) inaccurate, or (iii) subject to the vagaries of spatial variability because of their small sphere of influence. A major instrument development effort is needed in this area if we wish to test models exhaustively.

Parts of the Topog model are too simplistic, and other parts are untested; both problems could be overcome given better understanding of certain hydrologic processes. Aspects of the model which we have most doubt about (because of lack of data) are (i) the root dynamics predictions, (ii) the sensitivity of tree growth to soil salt content, and (iii) plant water uptake from groundwater. It is imperative that future modelling studies are complemented by well targeted field experiments designed to elucidate these hydrologic processes.

In conclusion, we cannot claim that all of our predictions for the Kyabram site are accurate, or that the model is ‘validated’ as such. On the other hand, we are satisfied that Topog yields results which accord with the trend in field observations and general wisdom. To permit more exhaustive testing of models such as Topog, we encourage (i) further development of hydrologic field measurement techniques, and (ii) carefully targeted field experiments to elucidate obscure hydrologic processes.

Hypothesis testing and scenario modelling

Some advocates of physically-based hydrologic models have projected their software as crystal balls, setting up the expectation that they can predict something that we are unable to see in nature. We prefer to think of them as powerful calculators, acknowledging that they can do no more than mimic our formalised perceptions of how hydrologic systems work. Having said this, we have found that they are very useful in highlighting interesting process feedbacks which are not otherwise apparent.

A good example of this is the process of back-diffusion of salts. It has recently been hypothesised that a steep increase in salt concentration near the capillary fringe may result in the diffusion of salt back into the less saline groundwater, thus reducing the rate of salt accumulation in the plantation root zone. Topog could be used to check on the efficacy of this process for sites with varying evapotranspiration rates and soil hydraulic properties. Another hypothesis which could be tested is that site productivity could be significantly enhanced by groundwater re-use, with irrigation volume, timing and salinity being variables of interest. Such ‘computer games’ ought to be complemented by field experiments, and by the same token, field experiments should not be conducted without an appropriate model to extrapolate results.

Similarly, Topog can be used to estimate plantation growth and water balance performance given different site properties. Scenario modelling of this kind can reduce the need for costly and time consuming ‘factorial’ experiments, provided that field observations are made for a strategic mix of field conditions. We have already established a methodology to enable scenario predictions with Topog, including ways of distilling complex model output into a digestible form that can be used to develop plantation design guidelines. This methodology is now being applied in the Joint Venture Agroforestry Program via a project entitled ‘Agroforestry design guidelines to balance catchment health with primary production’. In this instance it is being used to predict the performance of ‘break of slope’ plantations in steep, dryland environments.

For the case of plantations in high water table areas, the site variables which should be considered in a scenario modelling exercise include:

- aquifer type and associated hydraulic properties
- soil hydraulic properties
- aquifer and soil salinity
- rainfall and irrigation regime

If sensible scenarios are to be tested for the Kyabram region, appropriate ranges in these properties need to be established first. In this regard, it makes sense to utilise the broad network of field observations being made by the Trees for Profit group.

In conclusion, physically-based models such as Topog are unlikely to tell us anything we have not observed already experimentally. However, they can help us to explore complex hydrologic feedbacks which are not always apparent in limited field data sets. Such models can also be used to ‘fill the gaps’ in our understanding of plantation performance, which is currently limited by field observations from a small number of sites. Scenario modelling tools to achieve this aim using Topog have already been developed and could be applied to the wider Kyabram region with a modest effort.

Capillary upflow from shallow water-tables - measurement and estimation

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Capillary upflow from saline shallow water-tables is a critical process in salinisation of soil root zones. Lysimeter measurements from a range of crops in two soils show upflow may contribute from 8 to 55% of seasonal total evaporation. Current estimation procedures are limited by their data requirements and sensitivity to variables such as unsaturated hydraulic conductivity and root length density. Alternative procedures using analytical models, modified crop growth and water use models and a functional approximation are useful for particular applications.

The upwards movement of water from a saturated soil layer (a water-table), is termed “capillary upflow” to denote the driving force and flow direction. The rate of this flow is determined by the matrix potential gradient, and the properties (size, continuity and tortuosity) of the soil pores. Downward (mostly saturated) drainage flow and the reverse, upflow, are the key processes which determine the net rate and location of salt deposition within the soil profile. When upflow becomes the dominant flux, increasing salinisation of the soil profile is inevitable. Large areas of Australia are now showing increased rates of salinisation as changed hydrological balances in both dryland and irrigated areas have resulted in water-tables coming close (< 2 m) to the ground surface.

Despite the importance of the upflow process, and its potential to greatly impact on crop growth, its quantification is rudimentary, at best. Direct measurement, even in laboratory conditions is difficult. Generally, most researchers resort to measuring the potential gradient (ψ) between two points at distance Z and interpolating an effective unsaturated conductivity ($K(\psi)$) and estimating a flux rate (q) as

$$q = -K(\psi) (\delta\psi/\delta Z - 1)$$

Application of this approach to a field situation in Australia was comprehensively developed by Talsma (1963). He used steady state analysis to estimate upflow, q . Further, he derived q as a function of Z (in his case the depth from the ground surface to the water-table) for different values of $\delta\psi$. Then, assuming an infinite gradient he defined $Z_{\max}$ as the depth necessary to achieve $q \leq 0.1$ cm/day. This arbitrary threshold defined what is commonly known as the “critical” water-table depth. Talsma’s work provided a milestone but its relevance to the transient conditions of irrigated crops growing above, and interacting with shallow, often saline water-tables, needed to be examined.

To obtain estimates of upflow under near-field conditions, a series of lysimeter experiments has been carried out at Griffith since 1986. The lysimeters, both weighing and drainage types, were equipped to measure the volume of water needed to maintain a static water-table at a pre-set level (Meyer 1987). An abbreviated set of results are shown in Table 1.

Table 1. Seasonal measured upflow as a ratio of measured total evaporation from two soils in weighing lysimeters L1 and L2. F is a fresh water-table (EC = 0.2 dS/m), S is a saline water-table (EC = 15 dS/m).

Season, crop	Lysimeter	Treatment	Depth to water-table (m)	Upflow /Total evaporation
1987 Wheat	L1	F	1.3	0.36
	L2	F	1.3	0.10
1985/86 Soybean	L1	F	1.0	0.25
	L2	F	1.0	0.08
1989/90 Maize	L1	F	0.6 - 1.3	0.29
	L2	F	0.6 - 1.3	0.16
1992/93 Lucerne	L1	S	1.0	0.25
	L2	S	1.0	0.13
1994/95 Pasture	L1	F	1.0	0.14
	L2	F	1.0	0.09

As Prathapar and Meyer (1992) showed, upflow is different between the two soils (Hanwood loam in L1 and Mundiwa clay loam in L2) because of differences in hydraulic properties. Within a soil, upflow was primarily influenced by the depth to the water-table, the water content of the upper soil layers and the root length density in soil layers above the water-table.

Prathapar et al. (1992) and Schwamberger (1995) showed that numerical models based on Richards equation could produce estimates of upflow similar to measured values if soil hydraulic properties and root length density were known. Generally however, calibration adjustment of these factors was needed to achieve a satisfactory fit. Capillary upflow estimates with these models are particularly sensitive to the position of roots relative to the water-table and to parameters used to describe the soil water characteristic (θ_s , the saturated soil water content and ψ_e the air entry potential; Thorburn et al., 1995). Given these problems and the uncertainty associated with the representativeness of a few spot measurements to cover large scale field situations, Prathapar et al. (1992) developed analytical models to estimate capillary upflow. Subsequently the transient state analytical model has been used successfully in the coupled unsaturated, saturated flow model SWAGSIM (Prathapar et al. 1994).

An alternative approach, more associated with agronomic considerations, has been developed within the CERES crop growth, water use, and yield model. The soil water balance subroutine of Ritchie (1984) has been modified to include an upflow. This is a layered soil model, where drainage is simulated as a modified “tipping bucket” responding to differences in water content between layers. Upflow is simulated between layers in response to water content difference and diffusivity, the value of which is determined from a single function related to the difference between the current mean water content and the lower limit of available water for a particular soil. This approach has been incorporated into a water and salt balance program called SWAGMAN[®] Destiny. Comparison of modelled upflow and lysimeter measured values are generally satisfactory; observed treatment differences are always predicted by the model, and absolute amounts are within $\pm 25\%$ of observed values without “corrective calibration”.

Another functional estimation procedure suitable for incorporation into daily irrigation scheduling water balances has been developed. A value of the upflow to daily evaporation ratio is derived from a two-way table

with driving variables of root zone water content (normalised over the available range) and depth to the water-table (as a ratio of $Z_{\max}$). This is a conservative approach with the important components affecting upflow incorporated. It has been tested against measured values for irrigated lucerne and estimated seasonal upflow was within 10% of observed. Further testing with different soil, crop combinations and for weekly or monthly time aggregations is needed.

The evidence is that the steady state estimates of Talsma (1963) overestimate upflow in the transient state conditions of irrigated crops. Further, the concept of a “critical water-table depth” needs to be refined so that the interactions with irrigation intensity, water salinity and groundwaters are considered. Alternative methods of estimating upflow are now available but further testing is needed to define the range of their application.

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Trees versus lucerne for water use, water table and salinity management: Results from SWAGMAN Destiny

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An unfortunate consequence of irrigation development in many cropping areas of the world has been the rise of water tables and the onset of soil salinisation. These problems are often associated with declining productivity and require considerable refinement in management to ensure sustainability. They are not confined to irrigation areas and substantial areas of dryland cropping and pasture land in southern Australian are adversely affected. Identifying crop and land management strategies which minimise watertable rise and salinity development and at the same time are economically viable, is a considerable challenge.

SWAGMAN[®] Destiny is a computer based decision support system centred around a simulation model, a database of crops, soils and weather data and a GUI shell for selection of input options, formulation of runs and interpretation of outputs. It is designed to have broad applicability to cropping and pasture systems wherever these problems may occur. It requires a small set of readily attainable crops, soils, weather and economic data as inputs to the simulation model.

The SWAGMAN[®] Destiny model has the Ritchie (1994) water balance model as its basis. This is a multi-layered daily incrementing model which simulates the infiltration, drainage and upward flux of water associated with evaporation and piezometric fluxes at the lower boundary. It also calculates the potential evapotranspiration and incorporates a root water uptake routine to determine actual transpiration. Within the simulation of water balance are procedures for determining the position and impact of the watertable within or below the root zone. A salt balance with inputs from irrigation water and subsurface sources is maintained as is the simulation of the effect of salt on crop growth. Nitrogen balance and the impacts of nitrogen deficits on crop growth are also simulated.

The crop growth routines of SWAGMAN[®] Destiny comprise simple procedures for estimating daily increments in LAI, aboveground biomass and root biomass and their responses to aeration, nitrogen and water deficit and salt stress. A "generic" growth routine is used for the suite of cropping systems under study. To date, procedures for simulating rice, wheat, maize, sunflower, lucerne, pastures, citrus, vines, eucalypt woodlots and deciduous fruit have been developed.

In this paper SWAGMAN[®] Destiny was used to examine the performance of eucalypt woodlots and lucerne in maintaining/lowering a shallow water table. The consequences of various forms of canopy management and differing salinity scenarios are examined.

Salinity and tree growth: genetic variation and prospects for improvement

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Constraints to growth on saltland

Major constraints to plant growth in the presence of salt are: i) water deficit arising from the low (more negative) soil water potential; ii) ion toxicity associated with excessive uptake mainly of Cl and Na; and iii) nutrient imbalance due to depressed uptake and/or shoot transport and impaired internal distribution of mineral nutrients. In addition waterlogging and salinity restrict root growth and therefore ion and water uptake, primarily by adverse effects on reduced soil oxygen availability and soil physical properties, respectively.

Constraints to growth can be minimised by the judicious choice of genotypes and by the use of appropriate pre- and post-planting techniques. Higher growth rates will generally result in greater water use. Species differences in water use per unit sapwood area (Marcar *et al.* 1996) and leaf area appear to be small, even under moderately saline conditions.

Dealing with salt and waterlogging

Most trees are non-halophytes, ie they do not grow well on salt-affected land. Non-halophytes rely on restricting the entry of salt into the root and transport to the shoot, and retaining most of the salt in old leaves. In order to osmotically adjust, there is a need for non-halophytes to use organic solutes. There are high energy costs associated with this dependence which contributes to slower growth, often seen first in reduced leaf expansion. Adaptations to waterlogging include development of aerenchyma (air-filled) tissues within primary and lower order roots near the soil surface, and extensive lateral root systems, to maximise oxygen uptake and release of potentially toxic gases, such as ethylene.

Evaluation for salt and waterlogging tolerance

Substantial differences in adaptation, growth and quality often exist between trees raised from seed sourced from stands of different geographical areas and environments (these are called provenances). Species or provenances which have evolved in saline habitats often, but not always, have acquired more salt-tolerance.

Glasshouse studies aimed at evaluating salt tolerance of seedlings at the species, provenance and family level have been reported in the literature. These studies usually emphasised survival at high concentrations, but some have concentrated on growth at moderate salt concentrations (eg Marcar *et al.* 1995). Identification of phenotypically-superior variation during glasshouse screening can be an important first step for selecting appropriate seed sources for field evaluation. Evidence to date indicates that some clones developed from plants selected under combined salt and waterlogging treatments perform better than unselected seedlings from the same seed source (Bell *et al.* 1994). Clones of *Eucalyptus camaldulensis* developed from trees selected on saline sites also appear to be performing better than unselected trees when planted on saline land.

Some species evaluation trials include well characterised soil salinities, for example incorporating rapid assessments of salinity under individual trees or plots. Even in these studies, however, the impact of site-specific interacting factors are rarely incorporated. The information generated from such studies is being used to determine threshold salinities for survival and growth for a range of species (Marcar *et al.* 1996). Limited information is available on the ability of species to use groundwater of varying salinity and depth.

Conventional programs for tree selection and breeding provide an opportunity for genetic improvement of salt tolerance. One such program is the open-pollinated seed orchard. Provenance/family trials (for later conversion to seed orchards after thinning poorer trees) have recently been established for *E. occidentalis* (SA) and *E. camaldulensis* (NSW) and, for *E. camaldulensis* and *Acacia ampliceps* in Pakistan. Marked variation for survival, growth and form between seed sources has been found in these trials (N. Marcar, unpublished data).

The success of such activities will depend on the degree of heritability for survival and growth as well as seed production characteristics. Substantial genetic gain can be delivered through conventional approaches, such as the use of seed orchards. Gains beyond the first cycles of tree improvement will depend on accuracy in selecting the best genotypes and management of inbreeding in both the breeding and propagation populations.

Opportunities for ongoing development of salt-tolerant tree genotypes

Although physiological mechanisms have not been extensively used as screening criteria for trees, there are some prospects for including these in selection for salt tolerance. Enhanced ability to exclude Na or Cl from roots or shoots appears to be a most important mechanism operating in salt-tolerant lines of woody species. Recent microcalorimetric studies have shown that decreased growth of eucalypt seedlings under salinity is well correlated with reduced heat loss and CO₂ production of young leaves (N. Marcar *et al.* unpublished data).

Work in progress on combining, through hybridisation, the salt-tolerance of *E. camaldulensis* with the pulping qualities of *E. globulus* may also produce better-adapted and higher yielding trees. Hybrid technology will have to use of clonally propagated material to capture gains.

Conclusions

1. Species can be selected for different salinity conditions with current knowledge.
2. Selection based on growth should also mean selection for increased total tree water use, but not necessarily for increased groundwater use.
3. Genetic variation for salt tolerance at the provenance/family level can be exploited to obtain genetic gain by conventional selection and breeding (eg seedling seed orchards).

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Physiological and growth responses of *Eucalyptus grandis* and *Pinus radiata* to salinity and vapour pressure deficits under effluent irrigation in dry-land Australia

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Introduction

Effluent irrigation of plantations in the dry interior of Australia provides an opportunity to study forests at the limit - to study the effect of replacing one environmental constraint to forest growth with another. In these regions, photosynthetically active radiation (PAR) is not usually a limitation to growth. If water and nutrients are supplied at rates in excess of plantation requirements, as might be the case in a stand irrigated with nutrient-rich municipal effluent, then some other environmental factor will constrain growth and water use. Previously published data from stands of *Eucalyptus grandis* (W. Hill ex Maiden.) and *Pinus radiata* (D. Don), irrigated with effluent at Wagga Wagga in inland New South Wales suggest that in these circumstances, both stomatal response to high VPD and increased soil salinity can limit water use and growth. This paper reports the results of an experiment designed to quantify and isolate the effects of these two environmental constraints.

Stands of *E. grandis* and *P. radiata* were irrigated with secondary-treated municipal sewerage effluent at 3 rates for 5 years in the Wagga Wagga Effluent Plantation Project. The application rates were: the water use rate of the plantation less rainfall (Medium, or M); about 1.7 times the M rate (High, or H); and about half the M rate (Low). Other stands were irrigated with fresh water (low in nitrogen - N and phosphorous - P) at their water-use rate less rainfall.

There was no significant difference in growth rate between the M and the over-irrigated H stands suggesting that water was not limiting growth in the M treatment. In both species, the amount of N added in the effluent, plus N mineralised from the soil, substantially exceeded N uptake by the trees each year. Despite these apparently ideal conditions, the growth rates were lower than has been reported for effluent-irrigated stands in regions of lower vapour pressure deficit (VPD) or those irrigated with fresh water. Periodic measurements of pre-dawn leaf water potential and diurnal stomatal conductance, combined with measurements of electrical conductivity in the root zone (ECe), indicated that physiological function was suppressed each summer when ECe increased to moderate levels (2 dS m⁻¹). Water use estimated by water balance, was similar to, and sometimes less than, water use predicted using the Penman-Monteith model that included a stomatal response to VPD, suggesting stomatal response to high VPD was limiting plantation water use.

Materials and Methods

An experiment was conducted to: (a) quantify the effect of moderate increases in soil salinity on tree water stress, stomatal function, sap flux, substrate carbon conversion efficiency, and leaf and stem growth and, (b) to differentiate the response to salt from stomatal response to high VPD. Treatment plots in both species were irrigated with salt-enhanced effluent at their water-use rates for 14 weeks. Control plots nearby were irrigated with fresh water, also at their water-use rate. Each plot was 180 m² in area, containing 20 - 30 five-year old trees. The risk of nutrient deficiencies developing in the control plots was minimised by locating the plots in stands which had been irrigated with nutrient-rich effluent at the H rate for the previous 5 years.

The salinity of the effluent used to irrigate the salt-treated plots was approximately doubled by adding chlorides of sodium, calcium and magnesium to bring the electrical conductivity (EC) to an average of 2.2 dS m^{-1} . EC of the fresh-water control averaged 0.2 dS m^{-1} . The irrigation strategy aimed to minimise deep drainage and thereby increase the rate of salt accumulation in the root zone while maintaining soil water close to field capacity. Plots were irrigated twice per week with volumes determined by soil water measurements using a neutron probe or water use estimates based on water balance calculations. Rainfall was excluded from salt-treated plots by plastic shelters erected about 2 m above the ground. This was done to prevent heavy rain from leaching salt out of the root zone. After 14 weeks, over-irrigation was applied in salt-treated plots as two 200 mm applications of effluent (salinity 0.5 dS m^{-1}) to rapidly lower root zone salinity, resulting in a leaching fraction equivalent to about 45% of the volume added during the salt accretion period.

The following parameters were monitored throughout the experiment: irrigation volume and EC (two-weekly); soil salinity by Time Domain Reflectometry (TDR) (twice daily) and soil coring (monthly); soil moisture by neutron probe (two-weekly) and TDR (twice daily); sap flux by heat pulse apparatus (every 20 minutes); pre-dawn leaf water potential by pressure chamber (Y_e) (two-weekly); leaf extension rate (two-weekly); stem diameter increment by dendrometer band (two-weekly); and meteorological data (rainfall, air temperature, humidity, solar radiation, pan evaporation, wind speed, wind run and direction) by automatic weather station (hourly). Additionally, at appropriate times, the following parameters were measured: diurnal course of Y ; photosynthesis; substrate carbon conversion efficiency by calorimetry; leaf area by light interception; specific leaf area by destructive sampling; and foliar concentration of Na and Cl.

During the 14 weeks, an average of 9 t ha^{-1} of salt was applied to the salt plots and 1 t ha^{-1} to the controls. An average hydraulic load of 660 and 780 mm was received by the salt and control plots respectively before leaching. This resulted in a maximum soil salinity in the root zone (top 35 cm, which contained 85% of the root mass) at the end of 14 weeks of 5.8 and 6.8 dS m^{-1} in the eucalypt and pine plots respectively. The maximum difference in soil salinity between the salt and control plots was 3.4 and 5.5 dS m^{-1} in the eucalypts and pines respectively. The subsequent heavy leaching in the salt treatments resulted in a return to control-plot levels of soil salinity within one week.

Results

The effect of moderate levels of soil salinity on water stress and growth was much greater in *E. grandis* than in *P. radiata*. Pre-dawn water potential was more than twice as sensitive to increasing soil salinity in the eucalypts than in the pines. Leaf growth rate in the salt-treated eucalypts was depressed by up to 60% relative to the controls, and stem diameter growth by up to 70%. Neither parameter was depressed in the pines. Average area of eucalypt leaves grown under the high salinity was 26% smaller than those on control trees and the specific leaf area was 12% higher, indicating less biomass per unit leaf area. There was no significant difference in these two parameters in the pines.

In the eucalypts, branch water potential throughout the day was consistently lower in salt-treated than in control trees (average 0.16 MPa or 74%). There was no significant difference in photosynthetic rates between salt-treated and control trees. Efficiency of conversion of substrate carbon into biomass, however, was about half in the salt-treated eucalypts compared to the control trees after 14 weeks of irrigation. Three weeks after leaching salt from the root zone there was no significant difference in efficiency between the two treatments. These results suggest that the primary causes of reduced growth rates in the eucalypts in response to increased soil salinity are

water stress and a lowering of the efficiency of conversion of substrate carbon into biomass. Analysis of leaf sodium and potassium concentrations indicated the pines were excluding sodium in preference for potassium. Concentrations of sodium were about ten times higher in the eucalypts than the pines.

During late spring and summer, water use was depressed relative to pan evaporation in both the salt-treated and control plots. Crop factors (transpiration divided by pan evaporation) were as low as 0.4 in the eucalypts and 0.5 in the pines, with a smaller difference between the salt-treated and control plots than between the species. In the pines there was also a significant correlation between soil salinity and tree water use (R^2 0.90). In the salt-treated plot, for each 1 dS m^{-1} increase in soil salinity there was a 0.1 mm d^{-1} reduction in tree water use relative to the control plot. In the eucalypts, however, there was no correlation between soil salinity and tree water use. From the large depression in crop factors in both the control and salt-treated plots, it can be concluded that stomatal response to VPD was more important than soil salinity in controlling water use for soil salinities up to 7 dS m^{-1} ECe.

Conclusions

P. radiata is a more salt tolerant species than *E. grandis*. At soil salinity up to 7 dS m^{-1} ECe, the growth rate of *P. radiata* needles and stems was unaffected by salt. In contrast, leaf and stem growth rates of *E. grandis* were reduced by 60 to 70 % at soil salinity of 6 dS m^{-1} ECe. The reduction in growth rate in the eucalypts appears to be the result of a reduction in respiration efficiency.

In both species, maximum water use rates were controlled mainly by stomatal response to high vapour pressure deficit rather than by soil salinity. In the longer term, however, if moderate soil salinities were maintained, it is likely the reduced foliage growth of *E. grandis* would result in a reduction in the plantation leaf area index, and hence a reduction in plantation water use.

Life on the fringe: trees growing over shallow water tables

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Fluxes of water and salt in saturated soil have been studied for a long time. Similarly, the theory of water movement through unsaturated soil and the uptake of water by plant roots have been well described. With careful measurement of soil hydraulic properties, root length and distribution, the fluxes can be quantified with reasonable precision. Between the saturated zone and the unsaturated soil above lies the capillary fringe, the zone where the soil water matric suction is in equilibrium with the gravitational potential. The thickness of the fringe can be anything from 20 cm for a sand to 150 cm for a clay, with the water content near saturation at the bottom and decreasing sharply with height above the water table.

Towards the bottom of the capillary fringe, conditions are likely to be anaerobic for roots. At the top of the fringe the soil will be dry much of the time. However, there is a section in the fringe where conditions are just right. A tree growing over a water table in a dry climate will extract much of its water from this thin slice of the soil profile. The position of this slice in the fringe will move up and down in the profile in response to changes in transpiration rate and rainfall in the catchment.

If there is salt in the ground water, and if movement of water up from the water table exceeds the downward movement of rain water through the fringe, then salt will accumulate in the capillary fringe. The build up of salt in the fringe has implications for tree growth and survival at two time scales. Over periods of a single day, as the tree transpires water, water and salt are sucked to the roots but the salt is excluded. As a consequence, large osmotic gradients can build up around individual roots and make it much harder for trees to get water out of the soil. Over periods of months or years, salt imported into the fringe will accumulate at the slice where conditions for water uptake are most favourable. Eventually, an equilibrium salt concentration profile will be reached, sometimes fatal to the tree, unless the system is flushed from above.

In this talk I will present laboratory data of high resolution measurement in time and space of water and salt dynamics around individual roots and in the capillary fringe. Knowledge of tree water extraction from the fringe is vital for the prediction of tree growth and survival. If a tree can extract just one extra mm of water from the fringe per day, a local water table could fall at the rate of 1.5 m per year.

Conclusions

1. The tree used in these experiments (*Eucalyptus camaldulensis*) used up to 15 mm of water per day directly from a salty watertable of 5 dS/m (large column experiment - so crown was wider than diameter of the column). In the process salt was accumulated in the capillary fringe, starting near the top of the fringe, and moving down. The threshold osmotic potential was between 450 - 500 kPa, after which the tree exploited water from a lower slice of the fringe. By the time one third to one half of the fringe had reached this osmotic potential, daily transpiration had been reduced to 5 mm/day.

2. Plants growing in slightly saline soil (osmotic pressure < 100 kPa) experience a build up of salt around their roots on a daily basis, as salts are drawn to the roots in the transpiration stream but excluded from entering the root. This build up of salt means that the plants experience an osmotic potential much higher than we measure in the bulk soil (at least five times higher).

Tree water use and root zone salt accumulation in saline farm forest plots in southeast Queensland: I. Tree water use

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The development of saline seepage problems in agricultural regions of southeast Queensland is becoming of increasing management and environmental importance. Tree clearing has led to increased watertable recharge in lower parts of catchment areas, with local factors such as soil type, local geology, topography and land use affecting the extent of the salinity problem. These discharge areas often occur on small farms, where they can have a significant effect on farm productivity, and large environmental consequences in relation to farm size. This project aimed to determine the most effective management strategy to increase saline watertable discharge (salt-tolerant trees, salt-tolerant pastures, or bare soil) and to determine the physiological responses of trees to saline soil conditions and high water tables.

Tree water sources and transpiration rates were determined for *Casuarina glauca* and *Eucalyptus camaldulensis* in plots established at three sites in southeast Queensland (Table 1), using natural abundance stable isotope δD and $\delta^{18}O$ techniques, and sap-flow velocity data-loggers respectively. At this stage, results are only available for the Dalby and Kingaroy sites. Low transpiration rates were recorded in both species (1-3mm day⁻¹), with *E. camaldulensis* transpiration rates at Dalby always lower than the *C. glauca* at Kingaroy. There was only limited response to large rainfall events. *E. camaldulensis* appeared to be better able to respond to rainfall events, showing less reliance on groundwater than *C. glauca*. It appears that both species are able to respond more quickly to summer rainfall events than winter rainfall, which may be linked to both physiological constraints and site conditions. Overall, the trees at Dalby took ~ 50 % of their water from the water table, with the proportion of groundwater used higher at Kingaroy (~ 60 %). This gave annual groundwater uptake of 279 and 431 mm yr⁻¹ at these sites (Table 1).

Table 1 Experimental site details.

Site	Warrill View	Dalby	Kingaroy
Groundwater salinity:			
EC (dS m ⁻¹)	5	6	11
Cl (g l ⁻¹)	1.7	2.0	3.2
Water table depth (m)	1.6-2.9	~ 3.0	~ 1.5
Annual rainfall (mm yr ⁻¹)	605	545	530
Annual evaporation (mm yr ⁻¹)	1730	2430	1770
Pasture species	<i>Chloris gayana</i>	<i>Chloris gayana</i>	<i>Chloris gayana</i>
Trees species	<i>Casuarina glauca</i>	<i>Eucalyptus camaldulensis</i>	<i>Casuarina glauca</i>
Tree density (trees ha ⁻¹)	300	500	1000
Average tree height (m)	3.2	5.7	7.1
Groundwater uptake (mm yr ⁻¹)	not avail.	279	431

Tree water use and root zone salt accumulation in saline farm forest plots in southeast Queensland: II. Root zone salt accumulation

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Root zone salt accumulation was determined in the tree plots to provide an indication of **net** groundwater discharge, ie groundwater uptake minus recharge of the water tables, at the sites. Plots (20 m x 20 m) were also established in nearby areas of pasture and bare, scalded soil (Table 1), to compare groundwater discharge from these land uses with that occurring under the trees. Soils profiles were sampled each 3 months to the depth of the water table or 2 m, whichever was shallowest. Five replicate cores were taken from each plot, divided into 100 mm depth increments to 1 m, and 200 mm depth increments below that. Depth increments were bulked across the 5 cores and chloride, EC and gravimetric moisture were measured on each bulked sample.

For each site-land use combination, the mass of chloride in the soil (kg m^{-2}) to the depth of sampling was regressed against time and the regression slope taken as the rate of chloride accumulation in the plots. The mass accumulation rate was then expressed against the chloride concentration in the soil solution (C_z , Table 2) to indicate the discharge rate (positive upwards).

Table 2 Net groundwater discharge fluxes and results of water balance calculations.

Site	Warrill View	Dalby	Kingaroy
C_z (g l^{-1}) in tree plots	5.3	4.3	5.9
Net discharge - trees	26	155	-43
Net discharge - pastures	-73	170	-16
Net discharge - bare soil	338	116	-14
R_{wbal} (mm yr^{-1})	not avail.	80	233

At Warrill View, there was substantial discharge from the bare soil (commensurate with rates estimated from soil physics theory) but much lower rates from the other two land uses (Table 2), with there being net recharge under the trees. At Dalby, discharge rates were similar under all three land uses. There was net recharge under all land uses at Kingaroy, with recharge under the trees being higher than under the other two land uses.

In the tree plots at both Dalby and Kingaroy, net discharge (Table 2) was considerably lower than groundwater uptake by the trees (Table 1) suggesting that rainfall was draining below the root zone and recharging water tables in these plots. The daily water balance in the tree plots was calculated at these sites from the tree water use measurements and rainfall data to provide an estimate of the recharge rate. The water balance results confirmed that recharge occurred (R_{wbal} , Table 2). These rates of recharge are not high enough to exactly match the difference between the groundwater uptake and net discharge results. However, the water balance approach was simple due to limitations of the site data (eg, there was no information to support a more detailed approach). Within this context, and given the error of the estimates of all the rates of vertical water movement, there is reasonable agreement.

Trees are part of the answer but they are not the solution to dryland salinity in Western Australia

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Summary

In Australia, revegetation of both groundwater recharge and discharge areas is seen as a fundamental element of dryland salinity management. Millions of trees are planted each year with the intention of controlling rising watertables induced by the clearing and the subsequent replacement of native, deep-rooted vegetation with lower water use agricultural systems. These trees are planted in areas with either considerable depths to watertable (recharge areas) or in areas with shallow watertables and high soil salinity levels (discharge areas). To assess how trees established in these areas have altered groundwater conditions, observations from almost 80 sites in south western Australia have been analysed.

Statistical analyses suggest that planting trees in groundwater recharge areas will only lead to significant reductions in water levels if considerable areas of the catchment are planted. In discharge areas, the probability of achieving reduced water levels was lower and the magnitude of the response smaller. Additionally, in discharge areas, the maximum reduction of watertables from revegetation was about 2.5 m and the effect greatest where groundwater salinity was relatively low ($< 5,000 \text{ mg.L}^{-1}$). Best results from revegetation occurred in local-scaled aquifers.

Evidence reviewed from Western Australia suggests that if the hydrogeologic conditions are well defined, tree plantations maybe a useful tool for localised salinity management. However at all but three of the 80 sites reviewed, trees had little or no effect on the watertables more than 10-30 m from the planted area. The exceptions were the Merredin site, where preliminary data suggests that watertables appear to have been lowered by almost a metre, three kilometres from a large plantation, and at the Narrikup and East Belka sites, where the watertable was influenced 75 m upslope (Narrikup) and downslope (East Belka) from the planted area.

If the objective of land managers is to prevent the spread of salinity and reclaim existing areas, then only the adoption of broadacre recharge management systems can be effective in the longer term. Unless specific hydrologic conditions exist, our data suggest that only extensive plantings, perhaps influencing as much as 70-80% of the catchment will lead to significant reductions in watertables and salinity control.

Background

Dryland salinity in Western Australia has occurred as a result of the removal of about 90 percent of the perennial, deep-rooted native forests and woodlands over an area of some 20 M ha and its replacement with predominantly shallow-rooted, annual crops and pastures. By 1996 dryland salinity had affected about 1.8 M ha of previously productive agricultural land in the state (Ferdowsian et al., 1996). At current rates of expansion, salinity threatens at least two to three times this area unless hydrologically appropriate management systems are developed and implemented by farmers and government (George et al., 1997).

The main options available to contain the spread of salinity focus on increasing the water use of annual crops and pastures and planting larger areas of cleared land to trees, shrubs and perennial pasture species to more closely mimic the water balance of natural systems. Additional systems based on artificially managing surface and groundwaters by drainage and groundwater pumping can be used (George et al., 1997). At present, the option receiving most attention, especially in higher rainfall areas ($>500 \text{ mm.yr}^{-1}$), is planting commercial tree species to reduce groundwater recharge, increase groundwater discharge and improve profitability.

Evidence is emerging from research in Western Australia that trees can lower watertables under a wide range of landscape conditions (Schofield et al., 1989; George 1992; Stolte et al., 1997; Raper 1998) and reduce the impact of salinisation. However, a watertable response does not occur at every site where trees are planted and the magnitude of the response is highly variable. Reports of watertable reductions of up to six metres contrast with reports of watertable rise despite revegetation (Schofield et al., 1989; Greenwood *et al.*, 1995). Previous reviews (Schofield *et al.*, 1989; Raper, 1998) indicate that the greater the proportion of the cleared area revegetated and the greater the crown cover achieved, the greater the reduction in watertables.

Evidence of the effect of trees on groundwater salinity is also ambiguous. Schofield et al., (1989) showed that at sites in the higher rainfall ($700\text{-}900 \text{ mm.yr}^{-1}$) Collie catchment with 10-15 year old trees, there was a small decrease in groundwater salinity despite an increase relative to pastured control sites and an increase in catchment water yield. In the lower rainfall agricultural areas ($<500 \text{ mm.yr}^{-1}$), where little data exist on the impact of trees on groundwater salinity, Stolte et al., (1997) show significant increases under similarly aged trees.

Other Australian studies, reviewed by Thorburn (1997), have shown that where watertable reductions have occurred, trees accumulate salts in the root zone which reduces their water uptake and thus lessens their ability to sustain reduced watertables. Therefore, to sustain the hydrological effects of the established trees, a mechanism to allow leaching of salts away from the roots must occur. One such mechanism may be that described by Nulsen et al., (1986) who found that in a recharge area water flowed down an annular soil-root interface of mallee (*Eucalyptus pileata*, *E. eremophila*) to at least 5m depth. They observed no evidence of water flow through the soil matrix of the B horizon which had a hard pan with a bulk density of $2,000 - 2,100 \text{ kg.m}^{-3}$. Their observations confirmed the suggestion by Allison and Hughes (1983) of soil - root interfacial flow. This fresh water flow could leach salts away from the roots and thus create a relatively fresh micro-environment which would not be detected from bulk soil salinity measurements.

In discharge areas, leaching is also possible as a result of lateral saturated and unsaturated flows. Leaching can take place where perched aquifers develop in duplex soils (eg waterlogged areas) and there is an adequate hydraulic gradient for flow or where there are large seasonal watertable fluctuations to mobilise salts from deeper within the sub-soil. Drains may also be installed to enhance the leaching process (George and Conacher, 1993).

Studies of revegetation for salinity management has focused on site adaptation of selected species (Pepper and Craig, 1986), mapping and measuring yield responses (McKenzie et al, 1997) and local site observations of the effect of trees on watertables (Schofield et al, 1989; Smith et al, 1998). Little has been done to place these studies in a regional or catchment hydrology context. In particular, no study to date has surveyed an array of sites to determine response patterns.

A complete account of the results of the statistical analysis and review of five case studies is presented in a special issue of Agriculture Water Management (George et al, 1998)

Conclusions

Analysis of almost 80 sites in Western Australia suggests that trees are best planted in recharge areas for long-term hydrological benefits. In discharge areas, while water levels may be reduced in small-scaled aquifers and local control may be possible in the medium term, it may be more appropriate to plant for reasons other than reclamation of saline land. In these cases, discharge plantings may have benefits such as reduced visual impact of salinity (aesthetics), increased pasture and crop production (species selection, increased biomass, shade and shelter) and reduced risk of erosion (provide cover and protection). If markets exist, salt tolerant vegetation may also have economic value.

Land managers and their advisers should carefully consider the objectives of revegetation before designing systems based primarily on salinity management. For example, our analysis suggests that unless a large proportion of the recharge area is planted, watertables are unlikely to fall significantly under most conditions. In other words, small increases in the proportion of the catchment planted may only lead to a small reduction in watertable levels and little impact on the current area of salinity. Our data suggest that generally only extensive plantings, perhaps influencing as much as 70-80% of the catchment will lead to significant reductions in watertables. Insight gained from case studies indicate that tree plantings will have maximum effect on local watertable levels and the extent of salinity where they are able intercept the full saturated depth of the soil profile, as in the case of perched and local groundwater systems or thin regolith.

Furthermore, the data suggests that the magnitude of watertable reduction in discharge areas is rarely sufficient to allow reclamation of saline areas, and there is evidence that in some hydrological situations such plantings may be unsustainable. To increase the hydrological value of revegetation, land managers should select sites within small-scaled aquifers, plant larger areas and locate trees on groundwaters that are relatively fresh ($< 5,000 \text{ mg.L}^{-1}$).

Small, localised plantings, selected without knowledge of the catchment hydrology, are unlikely to be effective for salinity management. If only small areas of revegetation are to be established, a clear understanding of the type of aquifer system present is required. Unless the catchment water balance is redressed by increased water use on significant areas of the catchment, using a wider range of economically attractive perennial systems than just trees, watertables and hence dryland salinity will not be controlled.

To be more prescriptive in the design of successful planting systems (improve predicability of responses; $r^2 > 0.5$), a longer record and more thorough analysis of existing databases is required. In addition, analysis of the type of planting system (alleys, agroforestry, blocks, plantations) needs to be included. Other factors should also be considered. Some factors may have a complementary effect on watertable response, such as pre-planting depth to watertable and other land management practices undertaken on the cleared portion of the catchment which increase water use (new farming systems). Other factors will have negative effects on the revegetation and water use, such as poor initial species selection, salt toxicity, and drought. Management impacts (harvesting, grazing of forage plants, silviculture) on the trees should also be assessed. We believe that such analysis would be best performed by combining case studies and advanced statistical analysis within a catchment modelling environment.

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Towards an understanding of the relationship between root distribution and water uptake by perennial communities

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Questions abound as to the magnitude and timing of water uptake from the soil profile that has been invaded by roots. Interactions between soil water availability and root function has been the subject of much speculation in part due to a paucity of detailed information on temporal patterns of uptake within the rooting profile. Not surprisingly, our understanding tends to become more limited as we progress from the annual agricultural systems to those dominated by perennial species.

Two case studies each spanning four years are presented to describe the progression of water uptake from different levels in the profile. A forest community in a humid environment (1000 mm, rainfall) with 1.5 m to rock, displayed a steady upward progression in cumulative uptake for each of the four nominated soil layers; the magnitude of uptake declined monotonically with depth. Roots functioned for water uptake throughout the profile and were virtually operative over all seasons. In a cereal rotation incorporating a lucerne phase (550 mm, rainfall), uptake was spasmodic both with soil depth and in time. Factors influencing lucerne root function included soil water availability of a given soil store as an important determinant but the relationship was not complementary as restored availability did not necessarily induce uptake in a given soil layer. Additional complication to coherent description of root function is introduced with seasonal distribution of rainfall having an impact on the magnitude of uptake both seasonally and annually.

We draw on lessons from these one-dimensional systems with year-round activity to seek explanation of the generally low summer uptake from the capillary fringe by woody systems underlain by flowing groundwater. Osmotic limitations imposed by salty groundwater affords an explanation for low level of uptake by *Melaleuca* and *Eucalyptus camaldulensis* at 1 mm/day in S. A. Emerging evidence from W. A. for comparable rates of withdrawal by *Tagasaste* in a sand plain over fresh water suggests excessive stomatal control, presumed to be a response to root signals generating a release of abscissic acid. A similar form of stomatal control seems likely with enduring lucerne on W. A. duplex soil in having only ~30% of the capacity for subsoil water extraction as has been encountered in Eastern Australia.

Tree water use strategies in naturally saline groundwater discharge areas; two case studies

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The water use of trees in saline groundwater discharge areas is of interest in dryland salinity regions. The groundwater use of trees in these areas will depend on a combination of plant characteristics and hydrological site characteristics. In natural systems these two factors will interact to result in a sustainable system of groundwater use.

Processes controlling groundwater use of trees which naturally occur in two contrasting groundwater discharge regions have been investigated in South Australia. The Chowilla floodplain (a *Eucalyptus* forest) is underlain by groundwater with a salinity of 40-60 dS m⁻¹ at 2-4 m depth. In comparison, the discharge areas of the Upper South East (*Melaleuca* shrubland) have groundwater of ~63 dS m⁻¹ salinity, which fluctuates between the soil surface and ~1.3 m depth seasonally. These hydrological characteristics result in different salt and water dynamics in the unsaturated zone. In the Upper South-East salt concentrates in the surface soil first in response to plant water uptake, then proceeds to concentrate in the deeper parts of the profile as the season progresses and plants take up water from deeper in the profile. Conversely on the Chowilla floodplain, salt accumulates from the bottom of the unsaturated zone as groundwater moves upward in response to plant water uptake.

Water use strategies of trees at these sites will be discussed in terms of the hydrology of these systems and the implications for long term sustainability of groundwater use.

Modelling vegetation groundwater use, salt accumulation and vegetation growth in areas of shallow saline groundwater - a review of simple approaches

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Over the last few years, a number of simple models have been developed to simulate:

1. groundwater use by phreatophytic vegetation,
2. impact on groundwater by vegetation transpiration,
3. salt accumulation in soils over shallow water tables,
4. impact of salinity on vegetation growth and health, and
5. critical salinity thresholds.

It is clear that the generic processes underlying these models are well understood and rely on the interaction of roots and salt build-up. Differences in external conditions can lead to a wide, but predictable range of behaviour even though the generic processes are the same. It is also apparent that the processes are the same across a wide range of plants.

Because of the simplicity of these models, they only rely on data that is available at a range of spatial scales. They enable prediction of long term trends in growth, health, water use and groundwater impact. Given the availability of data, it is difficult to do better than this with complex models.

One of the main outstanding problems is to find suitable long-term data with which to calibrate models. Long-term salt accumulation, historical piezometric records and growth rates have been used in current studies. Work on tree ring widths, carbon-14, deuterium and oxygen-18 contents in tree rings all show promise in reconstructing historical tree water relations on a time scale in which we are interested.

The simplicity of the models make them suitable as a basis for developing guidelines. However, since many of the papers and reports are written for specific sites, there is a need for a synthesis across sites and vegetation types before developing guidelines. The range of behaviour in saline areas is in part caused by differences in the type of groundwater system and catchment and this linkage needs to be better understood to develop guidelines and to link management of saline lands to overall catchment management. Some minor modelling needs to be done to cover the range of conditions that are likely to be found in practice.

Recommendations:

1. There is little need to further understand generic processes before starting the development of guidelines for the management of vegetation in areas of shallow water tables
2. There is a need to develop techniques that provide data and information on processes over the longer time scale.
3. There is a need for a synthesis of the current studies in order to provide a basis for developing guidelines and this may entail some minor modelling

Simulating groundwater uptake and salinisation processes using a soil-plant-atmosphere model (WAVES). Implications for defining criteria for sustainability

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Management options to maintain the health of Black Box (*Eucalyptus largiflorens*) on the Chowilla floodplain were evaluated using both a dynamic soil-vegetation-atmosphere model (WAVES) and a simpler steady state lumped parameter model. The aim of this paper is show how some of the major long term features of the predictions made using a complex model like WAVES can also be simulated with much simpler models. Some simple criteria, which are important for sustained vegetation, are also presented.

In this work WAVES uses a new 'big leaf' canopy conductance model to link canopy carbon and water vapour transfers.. The carbon assimilation and transpiration are linked to a carbon allocation model for growth in leaf area, stems and roots, a carbon loss model through respiration and mortality, and to a soil water and non-reactive solute (chloride) transport model. The allocation model assumes the proportion of daily assimilate allocated for leaf growth decreases as the soil water availability (X_w) decreases. The behaviour of the conductance model is consistent with the notion that canopies reduce their leaf area in water limited environments, and increase their leaf area in wet environments, so as to increase the carbon assimilated per unit of water transpired. Soil water and solute movement is modelled using a finite difference solution to the Richard's and convective dispersion equations, respectively. Daily transpiration, estimated from the Penman-Monteith equation is distributed between soil layers according to the relative density of roots and the water availability of the layer, and hence determines the plant water extraction from each layer. The model simulates the daily carbon and water balance components, ie transpiration, soil water evaporation, net flow to or from a watertable; the profile distribution of soil water content and chloride concentration; production of leaf, stem and root biomass and changes in root distribution. Growth stress indices for light, temperature, leaf evaporation rate and soil water availability used in the canopy conductance model are calculated daily from climatic data and the modelled changes in movement soil water and chloride.

Soil salinisation from deep water tables can also be described using steady state groundwater discharge theory by a simple moving salt front model. Simulations were run using both WAVES and the moving front model for the 1970-1994 period using daily climate records and estimates of daily watertable level and flood depth. The long term features of the WAVES simulations could be described by the moving front model when the watertable was relatively deep (1-4 m) and the groundwater discharge rate was limited by soil hydraulic properties rather than transpiration capacity of the canopy.

The WAVES model and the simulations for the Chowilla study were used to develop simple models which predict average annual transpiration rates and leaf area growth rates from estimates of average annual soil water availability. These relationships were extended to estimate the long term soil water availability required to maintain a given equilibrium leaf area. These relationships were used to define a series of criterion which may be used to assess the sustainability of vegetation in areas with shallow saline water tables.

Models for integrating the economic effects of tree growing for salinity control

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Background

A computer model called SALTREC (Salt-Trees-Economics) was developed for the Department of Agriculture with the aid of a RIRDC grant in 1991. It was designed to help evaluate the economics of tree planting for salinity control, by estimating the costs of planting and management, the water use and effect on groundwater levels, agricultural productivity, water yield and stream salinity, and value of timber returns, in different layouts and different land types.

The model brought together basic scientific data and relationships with costs and price data. It incorporated simple water use and groundwater routines: For dryland situations, there was an underlying 'bath-tub' model in the discharge area, separate from the recharge areas. For irrigation areas, watertable results from MODFLOW were fed into the agricultural productivity routine. The programs were written in QuickBasic, occupied about 600 kB of disk space, and took less than 1 second to run for a single stand and scenario.

The methodology and results were reported in the final Report for State Salinity Program and Rural Industries Research & Development Corporation, *Tree-Salinity-Economic Model*, September 1992 and in a more summary form in the following:

Linking Science and Economics for Policy Advice - Case-Study of Trees for Salinity Control, Review of Marketing & Agricultural Economics, 60(2), August 1992.

An economic model for evaluation of trees and other plants for salinity control, *Saltforce News*, DCNR, Melbourne, April 1994.

Further proposals for economic model

A plan to build on the above SALTREC model was included in a RIRDC-funded project "Trees For Profit - Integrated Economic Model - Farm-Level & Regional Study" which began in 1993. The first stage - a regional input-output study of farm forestry - was completed, but the second stage was deferred and will be reconsidered following the RIRDC workshop on trees in high watertable areas.

The plan is to develop an Integrated Economic Model to assist evaluation of tree growing in areas of high water tables (irrigation or rainfed) for multiple benefits - particularly wood production & salinity control on land and water. The computer model would link the various components of the Trees for Profit system - trees, land, water and salt - in an economic framework. It would focus on management decisions so that the input parameters will include factors such as tree species and spacing and irrigation regime, while the final outputs will be expressed in a common monetary unit where practicable.

Models based on purely physical variables are unable to fully compare the trade-offs between different strategies. Certain strategies may improve the output of one component but at the expense of increased cost or reduction in output of another. For example, use of more saline water would improve the medium-term salinity benefits but could prejudice longer-term tree growth and timber returns. Or closer tree spacings involve higher initial cost but may provide higher timber volumes and earlier salinity benefits. A comparison of the overall benefit of different strategies can be made by

economic cost-benefit analysis. There will be certain other benefits and costs that cannot be realistically valued in monetary terms; and these still have to be taken account of, but it is preferable to aggregate those effects that do have a common economic base.

The main component modules are as follows:

Costs - cost of establishing trees at different spacings, and cost of groundwater pumps and irrigation infrastructure (as complements or as alternative solutions)

Tree growth - tree survival, growth and volume

Harvesting and transport costs

Wood products - wood quality and value; eg density & fibre length for pulp at different salinities & growth rates

Water balance, Groundwater, Salt movement - volume and salinity of water applied, water use, groundwater levels, soil salinity (salt accumulation), stream flows and salinity level

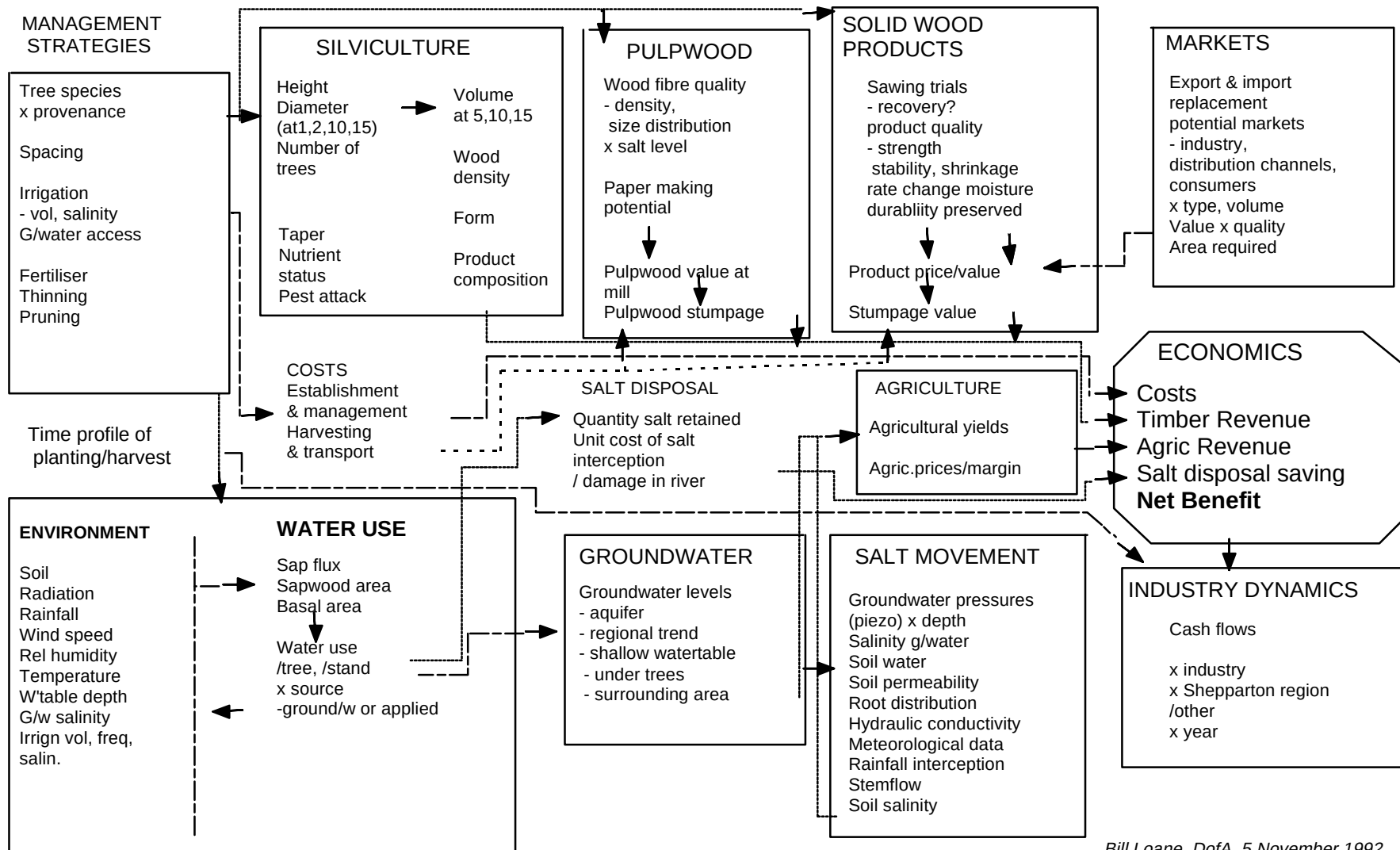
Economics - Cost-benefit analysis over long-term of different management strategies, placing monetary values on components fed from the modules - forest products, agricultural yield, salt export, and costs.

Figure 1 is a flow-chart showing the main variables and linkages envisaged.

The data and relationships for these modules can generally be supplied by other contributors to the TFP program (eg. CRC for Catchment Hydrology, DNRE, CFTT, CSIRO Forestry & Forest Products). The major new task will be the pulling together of data and relationships from disparate sources and formats, and programming them in an integrated model. The work will require some input from specialist groundwater modellers and programmers, as well forestry and economic expertise.

The new model needs to incorporate modules for water use and groundwater model that are more sophisticated than SALTREC and should cover both the single tree effects and farm-level and possibly regional effects. However, it still needs to operate at a broad level and with a relatively small number of parameters such that the model can be run rapidly and allows a large number of options and scenarios to be compared in a reasonable time. It is not clear at this stage whether an existing model can be found that is suitable or whether a new module, amalgamating appropriate parts from others, should be developed.

TREES FOR PROFIT RESEARCH - FLOWCHART FOR ECONOMIC



Bill Loane, DofA, 5 November 1992