

Sustainable Hardwood Production in Shallow Watertable Areas

Edited by

Rob Vertessy, Luke Connell,
Jim Morris, Richard Silberstein,
Alfred Heuperman, Paul Feikema,
Louise Mann, Marek Komarzynski,
John Collopy and Des Stackpole.

A report for the
RIRDC/ LWRRDC/ FWPRDC
Joint Venture Agroforestry Program

**Water and Salinity Issues in
Agroforestry No. 6**

RIRDC Publication No. 00/163
RIRDC Project No. CSI- 3A

© 2000 Rural Industries Research and Development Corporation
All rights reserved

ISBN 0 642 58193 2
ISSN 1440-6845

Sustainable Hardwood Production in Shallow Watertable Areas
Publication No. 00/163
Project No. CSI-3A

The views expressed and the conclusions reached in this publication are those of the author and not necessarily those of persons consulted. RIRDC shall not be responsible in any way whatsoever to any person who relies in whole or in part on the contents of this report.

This publication is copyright. However, RIRDC encourages wide dissemination of its research, providing the Corporation is clearly acknowledged. For any other inquiries concerning reproduction, contact the Communications Manager on phone 02 6272 3186.

Researcher Contact Details

Name	Dr Rob Vertessy
Address	CSIRO Land and Water GPO Box 1666 Canberra, ACT 2601
Phone:	02 6246 5790
Fax:	02 6246 5845
Email:	rob.vertessy@cbr.clw.csiro.au
Website:	http://www.catchment.crc.org.au/staffpages/vertessy.htm

RIRDC Contact Details

Rural Industries Research and Development Corporation
Level 1, AMA House
42 Macquarie Street
BARTON, ACT 2600
P.O. Box 4776
KINGSTON, ACT 2604

Phone:	02 6272 4539
Fax:	02 6272 5877
Email:	rirdc@rirdc.gov.au
Website:	http://www.rirdc.gov.au

Published November 2000
Printed on environmentally friendly paper by Union Offset

Foreword

It is now well accepted that the widespread clearing of forests in Australia has left a long-term legacy of salinisation. The prime cause of this is that trees use more water than pasture so that their removal results in higher rates of recharge to groundwater. Over long periods, the rising watertables eventually reach the surface zone, bringing with them salt which (formerly) had been locked up deep in the sub-layers. In certain areas, this process has been accelerated by irrigation. For instance, around Shepparton, Victoria, irrigation has led to about 200 000 ha of land being affected by shallow, saline groundwater.

This report describes an investigation into the water and salt balance dynamics taking place beneath a eucalypt plantation established over a shallow, saline groundwater system. With an understanding of the processes, a computer model was developed to simulate plantation behaviour under different site conditions and management regimes. The modelling capability developed in this project will help land and catchment managers of the future to better design agroforestry systems for salinity control.

This project was funded by three R&D Corporations — RIRDC, LWRRDC and FWPRDC which are funded principally by the Federal Government.

This report, a new addition to RIRDC's diverse range of over 600 research publications, forms part of our Agroforestry and Farm Forestry R&D program, which aims to integrate sustainable and productive agroforestry within Australian farming systems. It is the sixth report in the '*Water and Salinity Issues in Agroforestry*' series.

Most of our publications are available for viewing, downloading or purchasing online through our website:

- downloads at www.rirdc.gov.au/reports/Index.htm
- purchases at www.rirdc.gov.au/eshop

Peter Core

Managing Director

Rural Industries Research and Development Corporation

Acknowledgments

The authors gratefully acknowledge the financial support of the Joint Venture Agroforestry Program and the administrative support given by Dr Sharon Davis and Dr Roslyn Prinsley at RIRDC. Additional financial support for this project was provided by CSIRO Land and Water and the Cooperative Research Centre for Catchment Hydrology.

For project guidance and peer review of our work, we thank Dr Rory Nathan, Dr Tom Hatton, Dr Glen Walker, and Mr Arnis Heislars. For their contributions to field data collection, we thank Mike Hansford, Andrew Hamlet, Robert Turnour, Peter Ryan, David Cornwall, and Graeme Phyland. The Kyabram Dairy Centre (Institute of Sustainable Irrigated Agriculture) kindly provided access to the field site and maintained the experiment over the years.

Finally, we thank Dan Figucio for drafting the diagrams, and Tanya Jacobson for formatting and proofing this report.

Contents

FOREWORD.....	III
ACKNOWLEDGMENTS	IV
CONTENTS.....	V
EXECUTIVE SUMMARY.....	VII
1 INTRODUCTION	1
1.1 Background to the study problem.....	1
1.2 Study objectives – modelling.....	3
1.3 Study objectives – field experimentation	3
1.4 Site description	4
1.5 The study team.....	8
2 WATER MOVEMENT BENEATH THE PLANTATION.....	9
2.1 Soil and aquifer hydraulic property measurement.....	9
2.1.1 Unsaturated-zone properties.....	9
2.1.2 Saturated-zone properties.....	14
2.2 Unsaturated-zone moisture content monitoring.....	15
2.3 Unsaturated-zone salinity monitoring.....	17
2.3.1 Methods.....	17
2.3.2 Results	17
2.4 Groundwater elevation monitoring.....	20
2.4.1 Watertable levels and salinities	21
2.4.2 Piezometric levels and salinities	21
3 TREE–WATER RELATIONS.....	25
3.1 Leaf area index	25
3.2 Tree water use.....	29
3.3 Canopy conductance and water potential	35
3.4 Throughfall, interception, and stemflow	42
4 ROOT RESPONSE TO SALINITY	46
4.1 Glasshouse study	46
4.1.1 Introduction.....	46
4.1.2 Methods.....	46
4.1.3 Results	47
4.2 Root distribution field measurements.....	52
5 MODELLING OF PLANTATION SUSTAINABILITY	55
5.1 Introduction to the model.....	55
5.2 What does Topog_Dynamic predict?	56
5.3 Model description	57
5.3.1 Structure of the model.....	57
5.3.2 The flow net	58

5.3.3	The evapotranspiration module.....	58
5.3.3.1	The radiation balance.....	58
5.3.3.2	Computing evapotranspiration.....	59
5.3.3.3	Calculating canopy conductance	60
5.3.3.4	Soil moisture extraction by roots	60
5.3.4	Soil evaporation	61
5.3.5	The vegetation growth module.....	61
5.3.6	The soil water and solute transport module	63
5.3.6.1	Vertical unsaturated flow	63
5.3.6.2	Lateral saturated flow	63
5.3.6.3	Solute transport.....	64
5.3.7	The groundwater flow module.....	64
5.3.7.1	Two-dimensional flow equation	64
5.3.7.2	Groundwater solute transport.....	65
5.3.7.3	Linkage between the groundwater system and surface water column.....	65
5.4	Key model inputs.....	65
5.5	Testing the model	67
5.5.1	Field data sets for model input and testing.....	67
5.5.2	Model setup.....	68
5.5.3	Comparison of model results and field observations	70
5.5.4	Discussion of model performance.....	73
5.6	Set up of modelling experiments	75
5.6.1	Plantation sensitivity to environmental conditions	75
5.6.2	Harvesting, rotation, and irrigation impacts.....	75
5.7	Results of modelling experiments	76
5.7.1	Effect of initial watertable depth.....	76
5.7.2	Effect of groundwater salinity and salt sensitivity.....	79
5.7.3	Harvesting, rotation, and irrigation impacts.....	89
5.8	Discussion of modelling experiments.....	94
5.8.1	Effect of initial watertable depth.....	94
5.8.2	Effect of groundwater salinity and salt sensitivity.....	94
5.8.3	Harvesting, rotation, and irrigation impacts.....	96
5.8.4	Conclusions from the modelling experiments.....	97
5.9	Current status of the model and future work	98
6	CONCLUSIONS.....	99
6.1	Groundwater impact	99
6.2	Solute accumulation in the unsaturated zone.....	99
6.3	Tree water use and tree growth.....	100
6.4	Modelling.....	100
7	REFERENCES	101

Executive Summary

A canvassed option for watertable control in shallow watertable areas is the establishment of tree plantations. Proponents expect that the trees will provide a direct financial return to the grower through wood production, and lead to lowered watertables through groundwater uptake by trees. 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 of plantation establishment over high watertables, and its potential problems, are likely to be site-specific. Site characteristics such as soil permeability, groundwater salinity, and depth to groundwater will combine with climatic conditions and tree species factors to determine how the plantation interacts with the groundwater system. These factors will affect potential growth and evapotranspiration rates, and patterns of groundwater uptake by trees. They will also affect salt accumulation beneath the trees and thus the long-term performance and sustainability of the plantation.

The prime objective of this project was to develop and validate a computer model describing salt and water dynamics underneath eucalypt plantations growing in shallow watertable areas. This model was called on to answer the following questions:

- Are trees able to lower shallow watertables 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 lowering?
- How sustainable is such a system, taking into account the possibility of salt accumulating beneath the plantation?

This project entailed both field experimentation and model development. The objective of the field work was to improve our understanding of the processes operating at a representative site, 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.

Field Observations

The field work in the project focused on the processes described above, and was divided into two main activities: monitoring tree water use, and monitoring 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 logging water-level sensors. Unsaturated-zone water and salt movements were monitored using electrical conductivity sensors and capacitance probes. These processes were monitored over approximately 2 years, producing a comprehensive picture of the site water and salt balance. These data were used to elucidate site processes and to test model predictions of them.

In addition to assembling a database of field observations, work was undertaken to measure the site-specific properties required for model application. Two intensive field studies were

conducted to (i) better understand the transpiration behaviour of the trees, and (ii) estimate the hydraulic properties of the study site soils. In addition, a glasshouse study was undertaken to improve our understanding of the interaction between salt concentration and tree water use and growth.

Model Development

The model developed, called Topog_Dynamic, 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 (i.e., 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.

Specifically, the model can:

- account for variability in system properties (such as climate, soil type, and profile);
- predict the impact of different types of vegetation (e.g., pastures versus trees) on evapotranspiration, groundwater levels, and salt movement;
- 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;
- run for at least the length of a plantation rotation.

In this study, we demonstrated that Topog_Dynamic could successfully simulate the relationships between plant growth and water and salt movement at the Kyabram field site. Having tested the model, we then used it to simulate water and salt balance dynamics for a range of land management scenarios under varying site conditions.

Conclusions

The main conclusions from the project are listed below.

Groundwater impact

Our field observations of groundwater dynamics at the Kyabram site revealed that:

- the watertable has been lowered significantly beneath the plantation, relative to the level beneath the adjacent irrigated pastures;
- the spatial extent of this watertable lowering is limited to 40 m from the plantation boundary, primarily due to low soil hydraulic conductivities at the site;
- seasonal fluctuations in watertable levels beneath the plantation are greater than beneath the adjacent irrigated pastures;
- the watertable is gradually rising beneath the plantation, due to trees using progressively less groundwater and/or from increased irrigation outside the plantation;
- the hydraulic gradient beneath the plantation is moving vertically upwards and the hydraulic gradient around the plantation is moving laterally inwards.

- plantations can effectively cancel groundwater recharge.

Salt accumulation in the unsaturated zone

Our field observations of salt storage dynamics at the Kyabram site revealed that:

- salt accumulation due to concentrated water extraction has occurred in the root zone, leading to salt ‘bulges’ near the watertable associated with maximum root density;
- these salt bulges are dynamic, shrinking and expanding on a seasonal basis in response to watertable levels and tree water extraction patterns;
- there is a dry zone within the root zone of the trees that is subject to little or no leaching by infiltrating rain.

Tree water use and tree growth

Our field observations of transpiration and tree growth at the Kyabram site revealed that:

- tree water use is relatively low, averaging about 300 mm/yr;
- the trees are using more water than is provided by rainfall, indicating that they are taking up groundwater;
- the trees appear to be moisture limited, indicated by low tree water use and leaf area;
- tree growth rates are relatively low* for 20-year-old trees;
- low soil permeability and high planting density appear to be the main limitations to tree growth;
- salt accumulation is reducing the ability of the trees to use the groundwater.

Modelling

The main conclusions of our modelling work with Topog_Dynamic are that:

- the model can differentiate between plantation water use and that of surrounding irrigated pasture;
- the model can predict the effect of plantation water use on the water balance of the area and particularly on the watertable;
- plantation leaf and stem growth and root dynamics are simulated realistically;
- a site with conditions like those at Kyabram appears to have a time-scale of about 20 years (the current age of the plantation) before the effects of salt accumulation and water limitation caused by the low permeability become apparent;
- our predictions are strongly influenced by our assumptions of tree sensitivity to salt in soil moisture, and how this sensitivity varies with declining available soil moisture;

* Subsequent to the completion of this work, yield has been estimated as a mean annual increment of about 15 m³/ha/yr; with the best plots of *E. grandis* showing 22 m³/ha/yr).

- the model output can (and should) be used to generate input for economic scenarios and analysis of management and plantation options;
- shorter plantation rotations may alleviate the impact of salt accumulation;
- irrigation of the plantation throughout its rotation would lessen salt accumulation within the root zone and improve growth rates, but at the environmental cost of a higher watertable compared to that under a rain-fed plantation, and such an elevation would not provide the local sub-surface sink for salt draining from the surrounding irrigated pasture.

A general conclusion from the modelling work is that when a plantation's density is sufficiently high, evaporative demand exceeds infiltration and trees will extract water from a shallow watertable underneath. Under such conditions, salt accumulation will occur at a rate dictated by the net groundwater discharge (difference between transpiration and infiltration) and the groundwater salt concentration. The plantation groundwater usage will decline as the watertable falls and as salt accumulation increases, resulting in a corresponding decline in the magnitude of the depression in the watertable. This process will also mean that plantation growth will slow down. If salt accumulates to the point where the trees can no longer use groundwater, growth will be limited by rainfall availability. However, mitigation of these effects may come from periodic leaching events caused by rainfall, irrigation, or seasonal watertable fluctuations. Diffusion of salts back towards the watertable, and away from the high concentrations in the root zone, may also help to lessen the impact on the trees. The work described in this report does consider the impact that irrigation of the plantation can have on growth, but does not address the back-diffusion question directly.

Recommendations for Further Work

Further research on the sensitivity of trees to salt in the soil under field conditions is required. Such work should be complemented by an assessment of the importance of diffusion against the groundwater flow as a mechanism that can alleviate the accumulation of salt as concentration gradients build up.

This study has provided a biophysical assessment of plantation performance in an irrigated area, but has not included any economic analysis. Such an additional analysis is needed so that environmental consequences can be balanced against economic factors. If such an analysis were to be done, the Topog_Dynamic model should be modified so that its growth output is given in terms more amenable to economic analysis. Specifically, tree growth should be represented as mean annual increment (MAI) and total wood volume, rather than as 'live stem carbon'.

1 Introduction

In this section we introduce the background to the study problem and describe our research objectives. Next, we introduce the modelling methodology we used, the field properties we measured, and the environmental processes that we monitored in the field. We conclude this section with a brief field site description and an overview of the project team involved in the study.

1.1 *Background to the study problem*

Large areas throughout the Murray–Darling Basin and Western Australia are threatened by waterlogging and salinity, problems caused by injudicious tree clearing and excessive irrigation. These problems are leading to loss of production and habitat, the degradation of water quality, and increases in flood risk. There is growing awareness that salinity problems are also leading to rapid deterioration of infrastructure such as roads, pipes, bridges, and buildings.

There is significant interest in tree planting as a way of countering the salinity problem. However, most plantings have been advocated in recharge areas, where the watertable may lie at some depth. More recently, it has been suggested that trees should also be established in lowland areas affected by shallow watertables. This report investigates the feasibility of such plantings.

The Shepparton Irrigation Region Land and Water Salinity Management Plan covers an area of 500 000 ha in the Northern Victorian irrigation areas. Over 200 000 ha of land in this area is affected by shallow watertables. In order to maintain productivity of these shallow watertable areas, a number of control practices have been identified. One option involves the establishment of tree plantations over large areas. The trees would provide a direct financial return to the grower through wood production, and could lead to lowered watertables through transpiration of groundwater. The feasibility of this concept depends on achievable growth rates (closely related to water use by trees), the extent of the beneficial effect of the trees on surrounding agricultural land (watertable control benefits), and the sustainability of this system (potential for salt accumulation beneath the trees through concentrated water uptake).

The net benefits of plantation establishment over high watertables, and its potential problems, are likely to be site-specific. Site characteristics such as soil permeability, groundwater salinity, and depth to groundwater will combine with climatic conditions and tree species factors to control how the plantation interacts with the groundwater system. These factors will affect potential growth and evapotranspiration rates, and patterns of groundwater uptake by trees. They will also affect salt accumulation beneath the trees and thus the long-term performance and sustainability of the plantation.

The possibility of salt accumulating beneath a plantation is probably the greatest concern and is poorly understood. Heuperman (1995) found that salt was accumulating beneath an 18-year-old plantation at a site where the soil permeability was low and the watertable shallow. 1 shows the change in the electrical conductivity through the soil profile over a 9-year period for the plantation considered by Heuperman (1995), indicating that significant salt accumulation has occurred within the zone of watertable fluctuation. Salt accumulation

in the plantation root-zone will certainly occur if the trees are net users of groundwater and create a sustained depression in the watertable. However, the concentrations reached will be determined by the rate of accumulation (a function of the amount of groundwater used and its salinity) and the processes which might act to mitigate this accumulation (such as leaching and back-diffusion).

The prime objective of this project was to develop and validate a computer model describing salt and water dynamics beneath eucalypt plantations growing in shallow watertable areas. This model was required to answer the following questions:

- Are trees able to lower shallow watertables 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 lowering?
- How sustainable is such a system, taking into account the possibility of salt accumulating beneath the plantation?

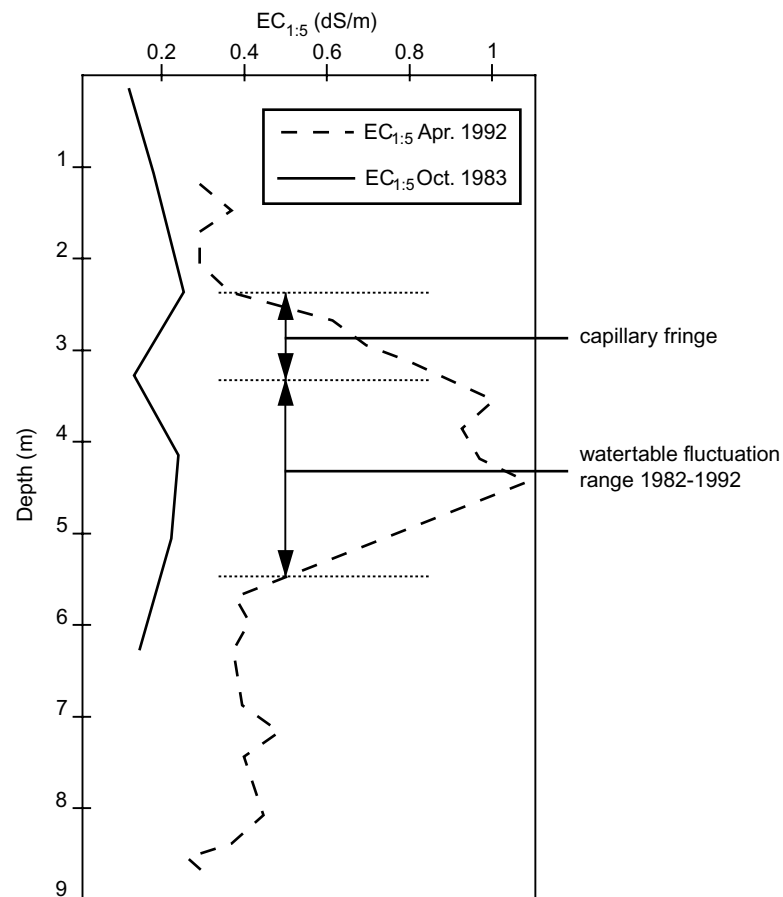


Figure 1. Change in the electrical conductivity of the soil profile as the Kyabram plantation grew, from Heuperman (1995).

1.2 Study objectives – modelling

The primary objective of this study was the development and testing of a model capable of simulating the water, salt, and carbon balance of a plantation established over a shallow, saline watertable, and subject to a variety of possible management practices. The model had to explain the following sub-surface water movement processes:

- unsaturated flow (capillary rise of groundwater to the plantation root-zone, infiltration of rain, and downward water movement);
- groundwater flow (primarily lateral movement of water).

These water movement processes had to be solved in a coupled fashion, along with salt transport. Plant transpiration and growth and the response of this to salt accumulation within the plantation root-zone were critical processes that the model had to be capable of evaluating.

In relation to the above physical processes, the model had to be sensitive to the following site properties and management factors:

- differing tree species, densities, and harvesting regimes;
- climate, including rainfall amount and timing;
- soil type, including depth and permeability;
- initial groundwater depth and salinity;
- irrigation, fertilisation, and groundwater abstraction.

The model chosen to underpin this study was the CSIRO package Topog_Dynamic (Vertessy *et al.* 1996b, Silberstein *et al.* 1999, Vertessy and Elsenbeer 1999). 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. In this project Topog_Dynamic was modified so that it could also predict the growth of plants (i.e., trees, crops, and grasses) and the effect that they have on mediating water and salt movement. Because plant growth is affected by site water and salt balance, feedbacks between vegetation growth and hydrology are represented in this model.

Topog_Dynamic is a physically based model, meaning that it is based on mathematical representations of environmental processes that are well established in the scientific literature. It is also a distributed-parameter model, meaning that it can accommodate spatial variation in input parameters such as topography, climate, soil, and land cover. In principle, such models have powerful predictive capacity, but their utility depends strongly on the availability of quality data to parameterise and test them.

Model testing was conducted by applying the model to a field site that was considered representative of plantations in shallow, saline watertable areas.

1.3 Study objectives – field experimentation

Another important objective of this study was to conduct field experiments to improve our understanding of the processes operating at a typical saline, shallow watertable plantation site. We undertook these experiments at a 21-year-old eucalypt plantation near Kyabram in central Victoria, where the watertable was observed to be within 2 m of the soil surface and

where salt accumulation had been observed. Field data were also needed to parameterise and test the computer model that we developed.

Our field experiments included the monitoring of tree physiology and water use, and sub-surface flow and salt transport processes. Tree water use was intensively monitored at several locations throughout the plantation using the sap-flow method. Groundwater gradients were monitored along several transects using logging water-pulse sensors. Unsaturated-zone water and salt movement was monitored using electrical conductivity sensors and capacitance probes. These processes were monitored over approximately 2 years, producing a comprehensive picture of the site water and salt balance. These data were used to elucidate site processes and to test model predictions of them.

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 (i) better understand the transpiration behaviour of the trees, and (ii) estimate the hydraulic properties of the study site soils. In addition, a glasshouse study was undertaken to improve our understanding of the interaction between salt concentration and tree water use and growth.

Table 1 presents a summary of the properties measured and processes monitored in the project.

Table 1. Processes monitored and properties measured at the Kyabram field experiment

Model properties measured	Processes monitored
Groundwater hydraulic conductivities	Groundwater elevations (spatially)
Unsaturated-zone hydraulic conductivities	Unsaturated-zone water content profiles
Leaf Area Index	Unsaturated-zone electrical conductivity
Stomatal conductance	Transpiration rates
Root distribution	Stemflow
	Canopy interception

1.4 Site description

The Shepparton Irrigation Region in North Central Victoria has a relatively flat topography (average slope about 0.2 m/km). The original vegetation of deep-rooted trees and native grasses was cleared some 150 years ago and replaced by shallow-rooted ‘improved’ pasture species, with irrigation introduced about 100 years ago. As a result of these land use changes, watertables rose from about 20 m below the surface early this century to about 2 m below the surface across much of the irrigated part of the region today. Current land use in the region is dominated by irrigated dairy pastures.

In August 1976, a 2.4-ha site just south of Kyabram (lat. 36°20’S, long. 145°05’E) was planted to a range of eucalypt species by the (then) Forest Commission of Victoria, to assess their growth potential under irrigated conditions. The species planted were southern mahogany (*Eucalyptus botryoides*), flooded gum (*E. grandis*), river red-gum (*E. camaldulensis*), southern blue-gum (*E. globulus*) and Sydney blue-gum (*E. saligna*). The planting layout is shown in Figure 2, with the groundwater monitoring transects and piezometer nests (labelled alphabetically) presented in Figure 3.

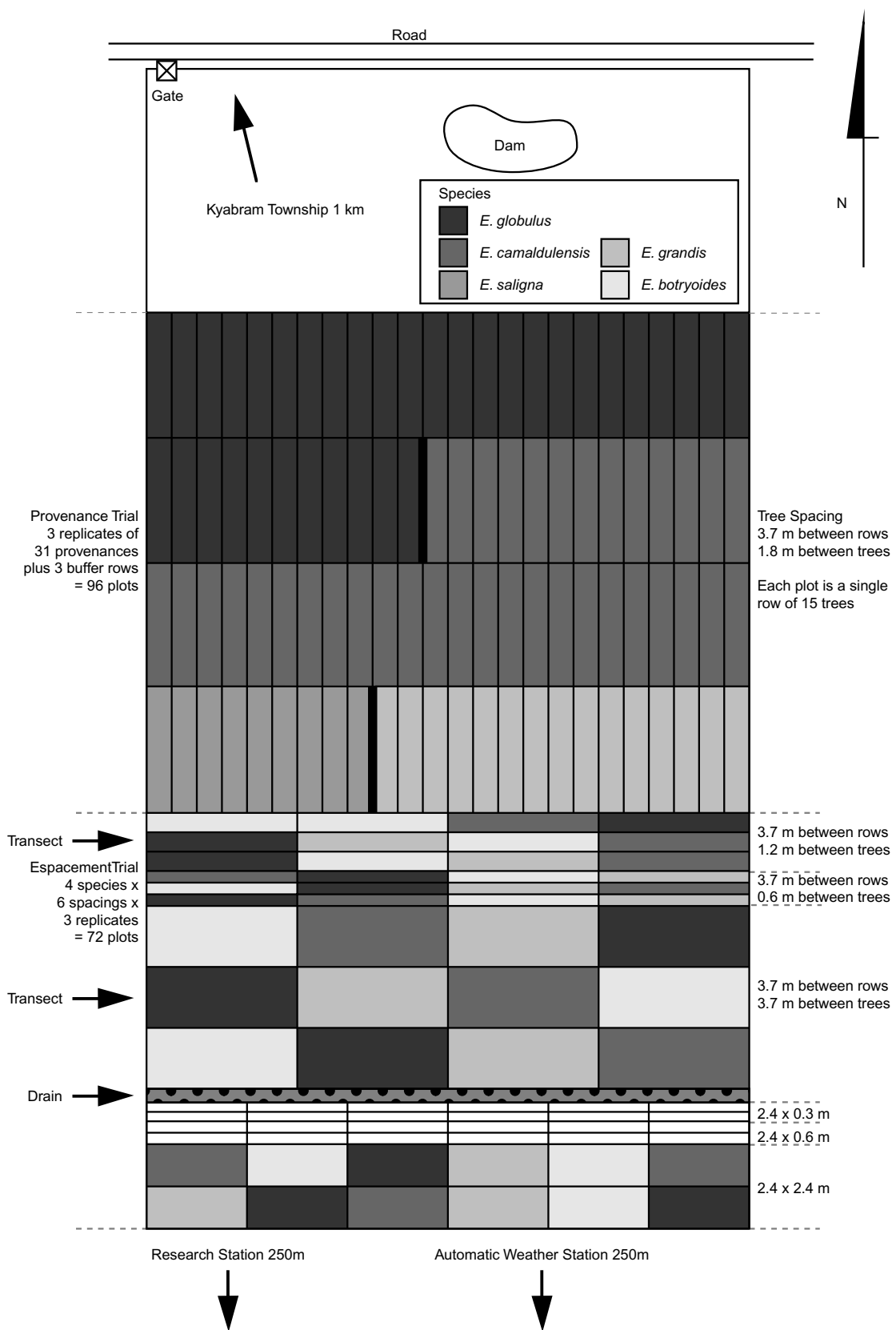


Figure 2. Species planting layout for the Kyabram plantation site (not to scale).

November–April and 44.5 mm (maximum average 46.5 mm, minimum 41.3 mm) during the period May–October. Of the annual evaporation, 1272 mm or 78% occurs during the October–March period. These climatic conditions are not considered suitable for commercial tree growing, so irrigation is deemed necessary unless there is access to shallow groundwater reserves.

During the course of this project, climate data was collected using an automatic weather station situated in the Bureau of Meteorology compound at the Kyabram Dairy Research Institute, approximately 250 m south of the plantation site. This information is compared with the long-term (1942–97) averages from Tatura (some 15 km away) in Figure 4.

Soil at the Kyabram study site is classified as Lemnos loam (Skene and Poutsma 1962), a red-brown duplex soil common across the Shepparton Irrigation Region.

The Kyabram plantation was irrigated between 1976 and 1982, and height increments of up to 2.5 m/yr were measured during that period for most of the planted species (Heuperman *et al.* 1984). Irrigation ceased during the 1982 drought due to water shortages. Since then, no irrigation has been applied, with the exception of some occasional unscheduled events caused by channel overflow before 1990.

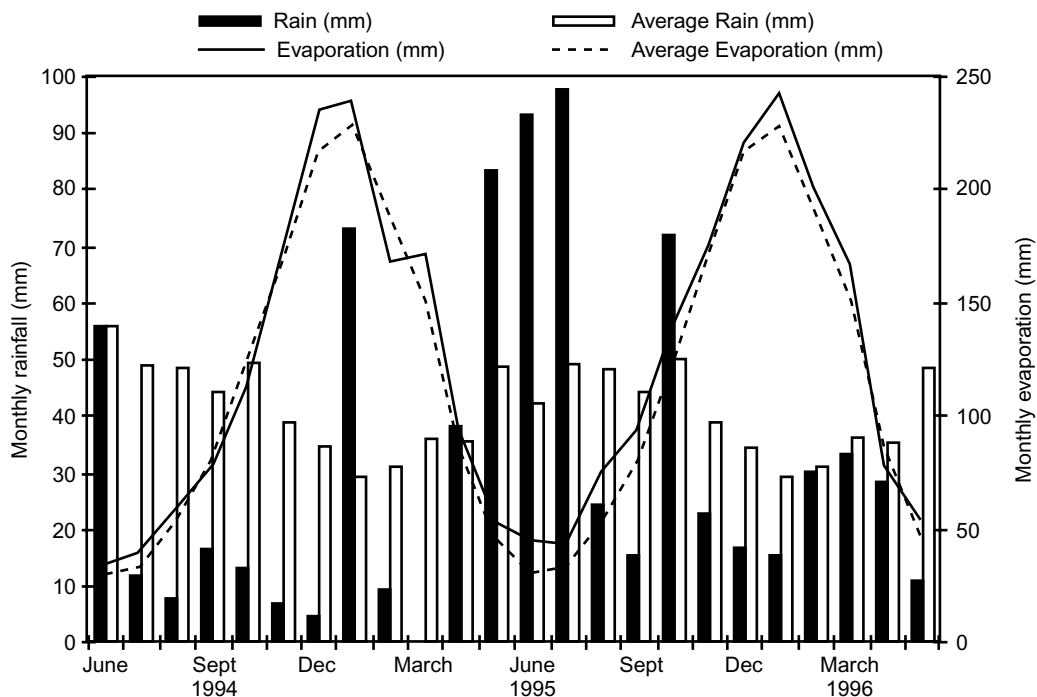


Figure 4. Rainfall and evaporation monitored during the experimental program at Kyabram compared with long term averages (1942–97 Tatura).

1.5 The study team

Several scientists, technicians and students from a variety of organisations were involved in this study. Their names, affiliations, and roles are listed in Table 2.

Table 2. Study team members, their roles and affiliations

Organisation	Team members	Responsibility
Centre for Forest Tree Technology, CRC for Catchment Hydrology	Jim Morris (Task Leader) John Collopy	• Tree physiology studies and sap flow measurement • Unsaturated-zone salinity monitoring • Glasshouse study of salt effects
Department of Civil Engineering, Monash University, CRC for Catchment Hydrology	Luke Connell (Project Manager) Paul Feikema Marek Komarzynski	• Project management • Site hydraulic characterisation • Leaf Area Index measurement
CSIRO Land & Water, CRC for Catchment Hydrology	Rob Vertessy (Principal Investigator) Richard Silberstein (Task Leader)	• Hydrologic modelling
Institute of Sustainable Irrigated Agriculture	Alfred Heuperman (Task Leader) Louise Mann	• Groundwater and unsaturated-zone monitoring • Climate monitoring • Sap flow measurements
Department of Natural Resources & Environment	Des Stackpole	• Field data collation and site maintenance

2 Water Movement Beneath the Plantation

In this section we report on the hydraulic properties of the soil and aquifer beneath the plantation. These data were necessary to parameterise the sub-surface hydrology components of the Topog_Dynamic model. We also report on the soil moisture and salinity dynamics beneath the plantation. These data were needed for model testing. We conclude this section with an analysis of watertable fluctuations beneath and outside the plantation. These data provide important insights into the hydrologic impact of the plantation, and were used during model testing.

2.1 Soil and aquifer hydraulic property measurement

Key inputs to the modelling of sub-surface water movement are the soil hydraulic properties, which determine the rates of water movement and the storage and release of water from the soil matrix. This section presents the measurement of soil hydraulic properties for the unsaturated zone and the saturated zone at the Kyabram site.

2.1.1 Unsaturated-zone properties

The unsaturated-zone hydraulic properties were measured using *in situ* methods, as these preserve soil structure and permit sampling of larger (and thus more representative) soil volumes. We used disc infiltrometers and constant-head well permeameters. Disc infiltrometers were used to measure the surface and near-surface properties, and well permeameters were used between 50 and 350 cm. The well permeameters were constant-head devices, and were deployed using the procedures of Talsma and Hallam (1980) and Amoozegar (1989) to determine sub-surface K_s profiles for the unsaturated zone. The disc infiltrometer was used to determine surface saturated and unsaturated vertical hydraulic conductivities at discrete values of supply potentials, following procedures outlined by Perroux and White (1987) and White and Sully (1988).

The surface hydraulic conductivity results, measured at five sites using disc infiltrometers at supply potentials of +1, -1, and -4 cm at three sites, are presented in Figure 5. All measurements were made twice at each measurement site and averaged. The variability between measurements was low, and all measurements at each supply potential were of the same order of magnitude. The value of K_s outside the plantation was lower than any measured beneath the trees, suggesting that tree-root activity near the surface may lead to increased macro-porosity of the soil. The significant increase in hydraulic conductivity at site B when the supply potential moves from being a suction to positive head suggests the presence of macropores. Larger macropores will become active under positive head conditions.

Sub-surface measurements of K_s in the unsaturated zone were made using a constant-head well permeameter near existing monitoring sites within the plantation. Holes were drilled with a 5-cm diameter hand auger, and the inside of the holes lightly brushed to reduce the effects of smearing. Measurements were taken in close proximity to piezometers C, 5, B, and 10, located along the southern well transect, and piezometers 24, 21, and 19 in the northern well transect. Additional measurements were taken in the northern part of the plantation, near piezometer nests D, E, F. Measurements were taken at four depths at each site (at 50, 150, 250, and 350 cm), using a wetted-depth of 30 cm.

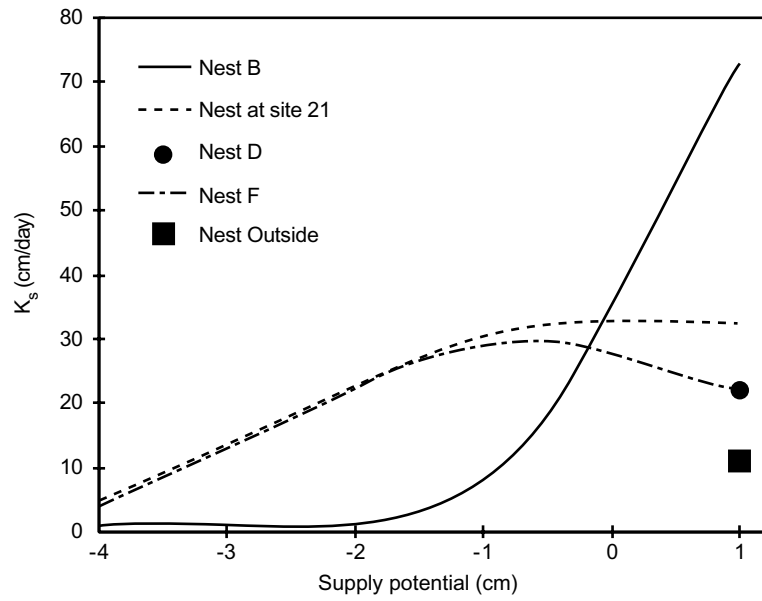


Figure 5. Surface hydraulic conductivities at different supply potentials measured using disc infiltrometers.

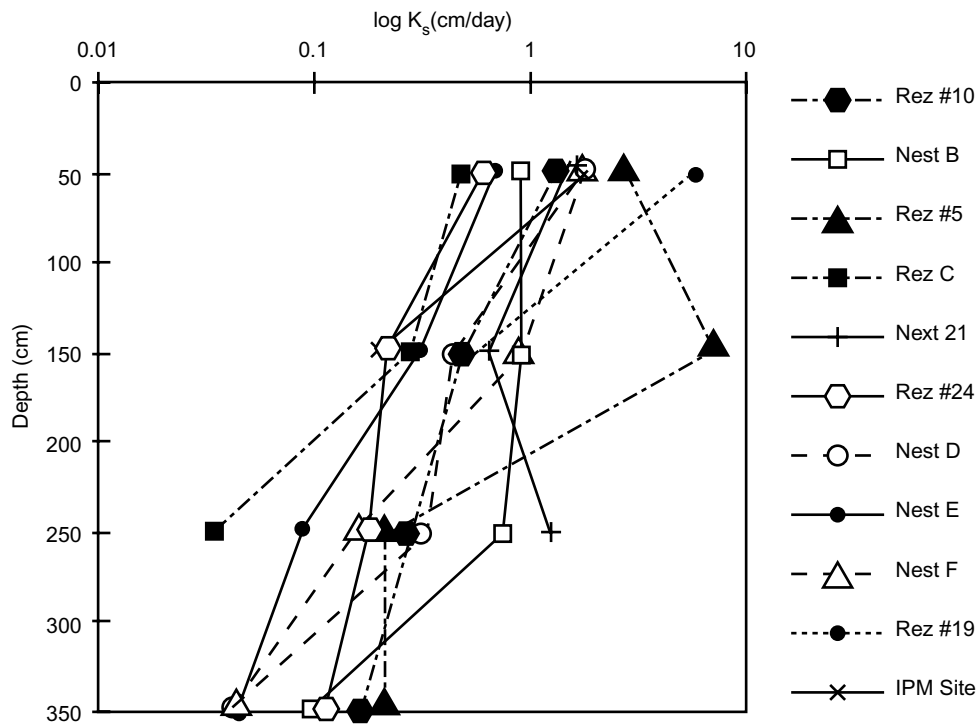


Figure 6. Values of measured K_s versus depth of measurement for 11 sites.

In total, 40 K_s measurements were made at 11 sites. Figure 6 presents the $\log K_s$ values with depth of measurement. Values of K_s tend to decrease and become less variable with depth, and the variability of K_s between sites is generally contained within one order of magnitude.

At depths of 50 and 150 cm, the values are spread over a wider range than at 250 and 350 cm depth. The wider range of K_s values at shallower depths can be explained by much

greater biological activity and higher root density. Indeed, augering revealed an abundance of tree roots in shallow soil layers beneath the plantation.

Values of K_s in the unsaturated zone give a measure of the macro-porosity of the soil matrix. Those values measured beneath the plantation were high when compared to those measured at the piezometer nest outside the plantation (approximately 0.3 cm/day). This difference may be explained by the presence of macropores arising from tree-root activity at these depths. Extreme values of K_s were observed close to piezometers 5 and 19 (Figure 6). Both of these piezometers are located at the plantation boundary, adjacent to irrigated pasture where root activity could be expected to be relatively high, given higher water availability.

Descriptive statistics for K_s measurements are provided in . Results indicate that the highest variability in values of hydraulic conductivity occurs at a depth of 150 cm and is reflected by a coefficient of variance (C.V.) of 186.9. This high value is strongly influenced by one extreme measurement at a site located close to piezometer 5. By removing two extreme measurements (trimming the data by 10%) the C.V. value was reduced to 51.4. Trimming the data by 10% for the measurements at depths of 50, 150, and 250 cm significantly reduced the coefficient of variation in all three cases. Relatively small variations of K_s between measurement sites supports the adoption of the mean or median value to characterise the whole plantation for a given depth.

Table 3. Descriptive statistics of K_s

Depth (cm)	K_s (cm/day)			
	50	150	250	350
Min	0.47	0.21	0.04	0.04
Max	5.62	7.55	1.22	0.21
Mean	1.77	1.14	0.36	0.10
Median	1.61	0.52	0.22	0.10
Variance	1.77	4.58	0.15	0.004
Std Dev.	1.45	2.14	0.39	0.07
Observations	11	11	9	7
C.V.*	82.0	186.9	106.3	66.3
Mean_(tr10%)	1.48	0.54	0.29	
Variance_(tr10%)	0.47	0.07	0.05	
Std Dev._(tr10%)	0.69	0.27	0.23	
C.V.*_(tr10%)	46.3	51.4	78.5	

$$* C.V. = \frac{Std\ Dev.}{Mean} \times 100$$

Depth variations in mean values of K_s are presented in Figure 7, indicating a strong exponential relationship between K_s and depth of measurement ($y = -114.12 \ln(x) + 92.60$; $r^2 = 0.99$). This behaviour is typical of monolithic soils where hydraulic conductivity decreases with depth due to decreases in biological activity and increases in soil bulk density. Both of these factors influence the presence of voids and preferential flow paths, and thus the magnitude of K_s . When the surface K_s is included, a power function ($y = 20.073x^{-1.927}$; $r^2 = 0.91$, where y is depth and x is hydraulic conductivity) best explains the trend with depth (Figure 8).

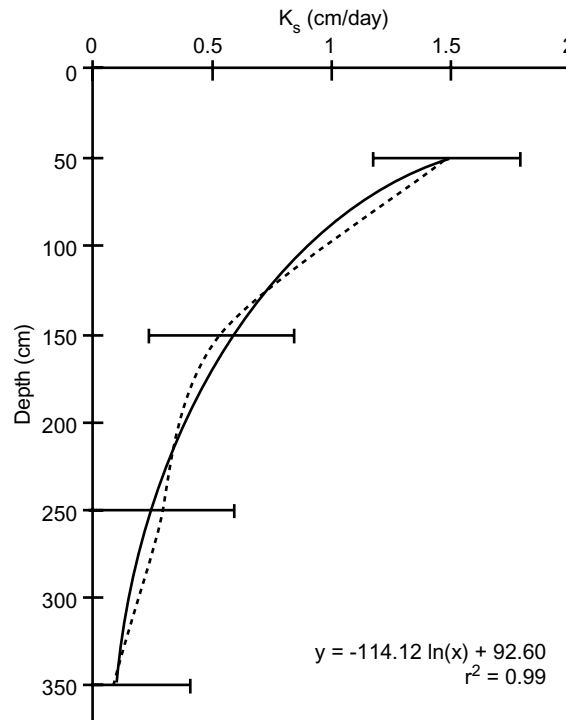


Figure 7. Actual values and regression of mean sub-surface hydraulic conductivity (trimmed 10%) versus mean depth of measurement. Standard error for each depth measurement is included.

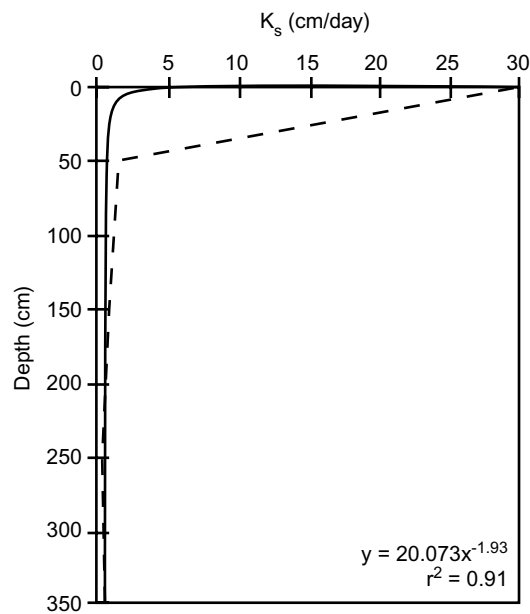


Figure 8. Actual values and regression of mean hydraulic conductivity (trimmed 10%) including surface measurements.

Well logs and particle-size distribution analysis indicate that the soil beneath the plantation can be classed as silty clay. Some sites located in the northern part of the plantation exhibited an increase in silt content with depth, but the change in texture was gradual and

was the change in K_s values. Variations in K_s for the same depth at different sites are most likely attributable to plant biological activity induced by different planting densities and associated changes in macro-porosity.

The lowest values of hydraulic conductivity were recorded at site C, located approximately 100 m outside the western plantation boundary. This site is in irrigated perennial pasture where there is little or no plant-root activity taking place at depths greater than about 50 cm. In contrast, the highest values of K_s were observed at site 5, which is located on the plantation boundary, adjacent to a regularly used irrigation channel. With an abundance of water and nutrients, tree-root activity could be expected to be very high. Abundant roots were observed down to about 2 m during drilling at this site.

Using easily measured soil properties to estimate K_s

The values of sub-surface K_s ranged between 10^{-2} and 10 cm/day, which is the expected range for the variety of soil textures observed at the Kyabram site (Table 4). The values given in the table compare well to those given for the same soil textures in Domenico and Schwartz (1990).

Table 4. Typical values of K_s for differing soil textures at Kyabram

Soil Texture	K_s range (cm/day)
silty clay	0.1–0.2
fine sandy clay	0.2–0.7
fine sandy silt	0.2–0.5
silty clay/very fine sand	2–9
silty fine sand	5–9
fine sand	20–50
fine-medium sand	10–140

There are a range of pedotransfer functions which can be used to estimate K_s from soil texture data. For instance, Campbell and Campbell (1982) developed the following function to estimate K_s :

$$K_s = 0.004 \exp[-6.9m_c + 3.7 m_s] \quad (1)$$

where K_s is the saturated hydraulic conductivity, m_c is the clay mass fraction, and m_s is the silt mass fraction.

We applied Equation (1) to the soils of the Kyabram site, using the clay (m_c) and silt (m_s) mass fractions reported by Skene and Poutsma (1962) for Lemnos Loam. The estimated values of K_s were of a similar order of magnitude to our measured values (Figure 9), though the estimates were significantly higher than the measured values between depths of 50 and 200 cm.

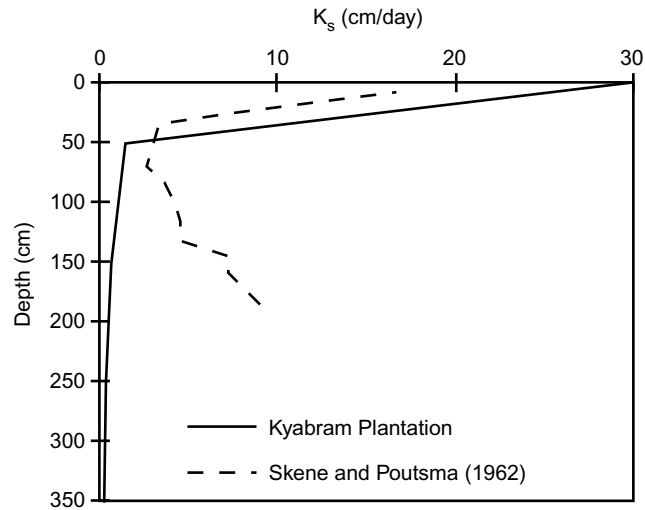


Figure 9. Measured and predicted values of K_s with depth.

2.1.2 Saturated-zone properties

The well permeameter method described above is not suitable for determination of hydraulic conductivities in the saturated zone. Hence, the slug-withdrawal method of Bouwer and Rice (1976) and Bouwer (1989) and an auger-hole method described in Kessler and Oosterbaan (1974) were used in the piezometers across the site to measure saturated hydraulic conductivity (K_s) of the semi-confined aquifer below the plantation. Measurements were repeated once, in a number of wells, to identify whether there were differences in subsequent measurements in the same well. No significant differences were noted between the first and repeat measurements.

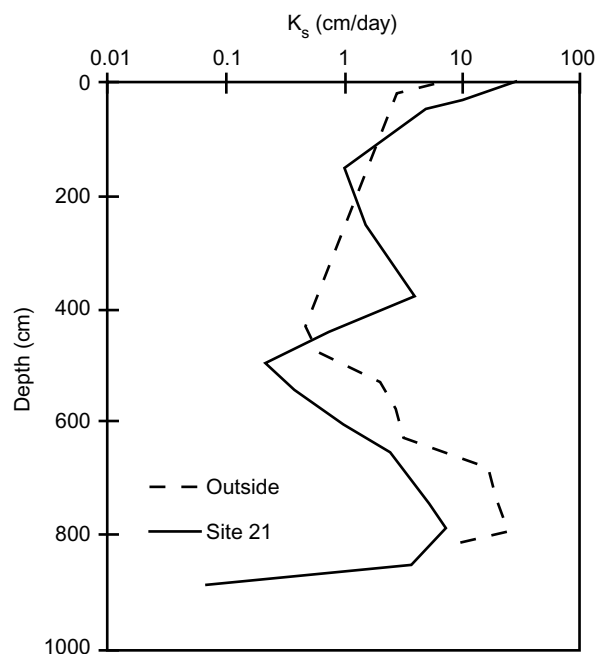


Figure 10. Profile of K_s for the nests at site 21 and outside the plantation.

Profiles of K_s in two piezometer nests (at site 21 and the 1992 installation outside the plantation) revealed an underlying aquifer with a K_s of 10–20 cm/day, positioned between about 6 and 9 m below the surface (Figure 10). Above the aquifer there is a 4.5–5 m thick clay unit of lower permeability (~ 1 cm/day) which acts as a semi-confining layer.

Our K_s profiles for the remaining (newer) piezometer nests (installed in 1994) give no indication of the aquifer system described above (Figure 11). This suggests that time may be required for piezometers to clear before they give representative test results.

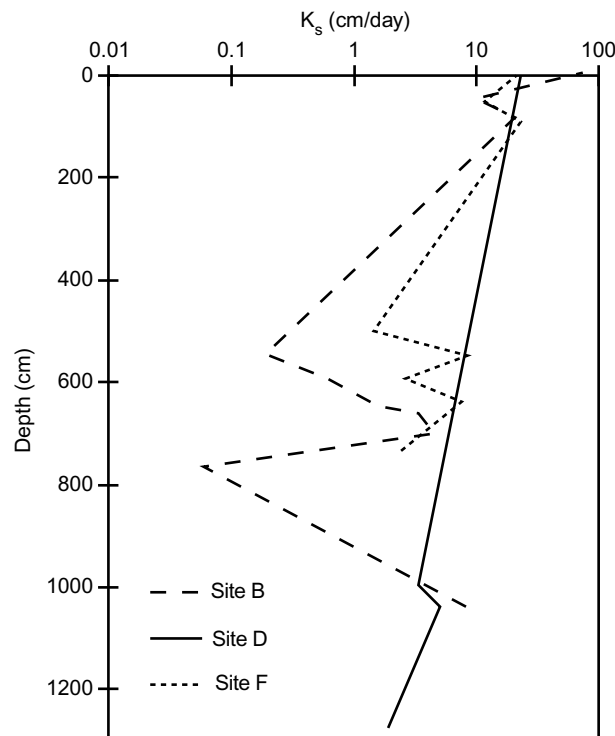


Figure 11. Profile of K_s at sites B, D, and F.

2.2 Unsaturated-zone moisture content monitoring

Four Sentek Enviroscan soil moisture probes were installed at sites B and D (under *E. grandis*) and sites E and F (under *E. camaldulensis*). At each site, soil moisture was logged at 6-hour intervals at eight depths down to 3.8 m (sites B, D, and E) and 2.0 m (site F). As the sensors were not calibrated, the measured values can only be considered as indicative of the actual soil moisture. Despite this, the measured patterns of soil moisture content clearly show the movement of wetting fronts induced by infiltration of rainfall.

Changes in soil moisture at various depths through 1995 are plotted in Figure 12. Breaks in this data series indicate missing data caused by sensor malfunction. Figure 12 shows that most rainfall events induced soil moisture changes in the upper 50 cm of the soil profile. Some periods of very high rainfall (e.g., May/June 1995) resulted in soil moisture changes at 1.6 m depth, but no change was noticeable at 3.8 m depth (Figure 12). The significant rise in soil moisture at 380 cm depth at site B was caused by a watertable rise commencing in July 1995.

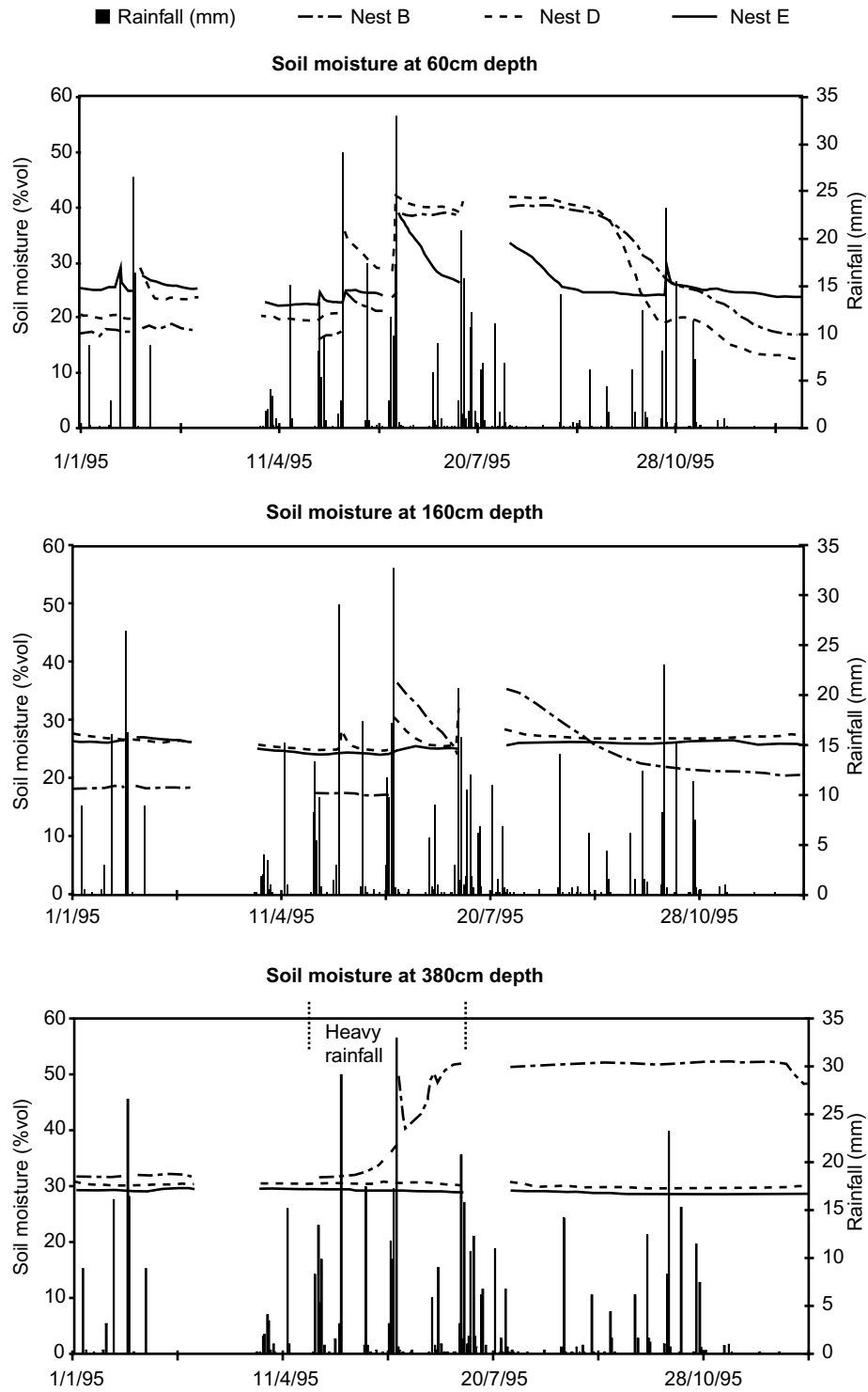


Figure 12. Soil moisture levels in 1995 underneath the Kyabram plantation and rainfall events.

2.3 *Unsaturated-zone salinity monitoring*

2.3.1 Methods

Changes in the salinity of the upper 4 m of the soil profile were intensively monitored over 30 months using buried salinity sensors from Soil Moisture Corporation (USA). In May 1994, eight sensors were installed at each of sites B, D, E, and F as two sets of 4 in augered holes spaced 4 m apart. In each set, sensors were buried at 40, 150, 300, and 400 cm depth. The soil was carefully tamped into place during refilling of the auger holes to ensure firm contact between the sensors and the soil and prompt reestablishment of equilibrium with the undisturbed surrounding soil. The sensors at each location were connected to a Tain Electronics (Box Hill, Victoria) data logger, programmed to record 2-hourly observations of soil temperature and soil solution EC from each depth. Daily means were calculated for comparison of seasonal and longer term changes in these variables.

The sensors were individually calibrated, prior to installation, in sodium chloride solutions of a range of salinities and temperatures. As a check on their field performance, after 2 years soil samples were collected in May 1996 from two auger holes within 40 cm of each set of sensors at sites B and F. The chloride concentration, EC of 1:5 and saturation extracts, and saturation moisture content of these profiles were determined at 30-cm intervals from 10 to 100 cm, then at 50-cm intervals to 400 cm. The EC_{sat} measurements were compared with the salinity sensor data from the corresponding depths using regression analysis.

2.3.2 Results

Salinity variations at each site for the period May 1994 to November 1996 are shown in Figure 13. Salinity of the upper 4 m of the profile at sites D and E remained low throughout this period, although the deeper profiles described in section 4.2 of this report showed higher salinity below this depth. At sites B and F, the chloride ‘bulge’ resulting from root uptake of groundwater occurred at a shallower depth and the dynamics of this accumulation zone could be studied by means of the salinity sensors. In most cases the two sets of sensors at each site showed similar behaviour, although the level of salinity at site F sometimes differed by more than 10 dS/m over the 4 m horizontal distance between them.

During winter 1994, the salinity at 400 cm at site B increased strongly to over 10 dS/m, while at 300 cm and above it remained below 5 dS/m. In spring and summer, the salinity at 400 cm fell to around 6 dS/m, although the soil moisture data of section 2.2 show no evidence of leaching during this period of low rainfall. In winter 1995, the salinity at 400 cm rose again to around 18 dS/m, but fell dramatically during July and August then continued to decline to around 1 dS/m by early 1996. The sharp decline in late winter 1995 was followed by a rise in salinity at 300 cm, implying that the zone of chloride accumulation had by then moved upward. Soil moisture data for this period confirm that during winter 1995 the profile at 320 cm depth at site B became saturated and remained so until at least March 1996. These observations are consistent with a shift in the depth of maximum root water uptake from below 4 m in 1994–95 to around 3 m from spring 1995 onwards, in response to a rise in the watertable during winter 1995. The increase in salinity watertable movements and at 300 cm during spring 1995 illustrates how rapidly salinity

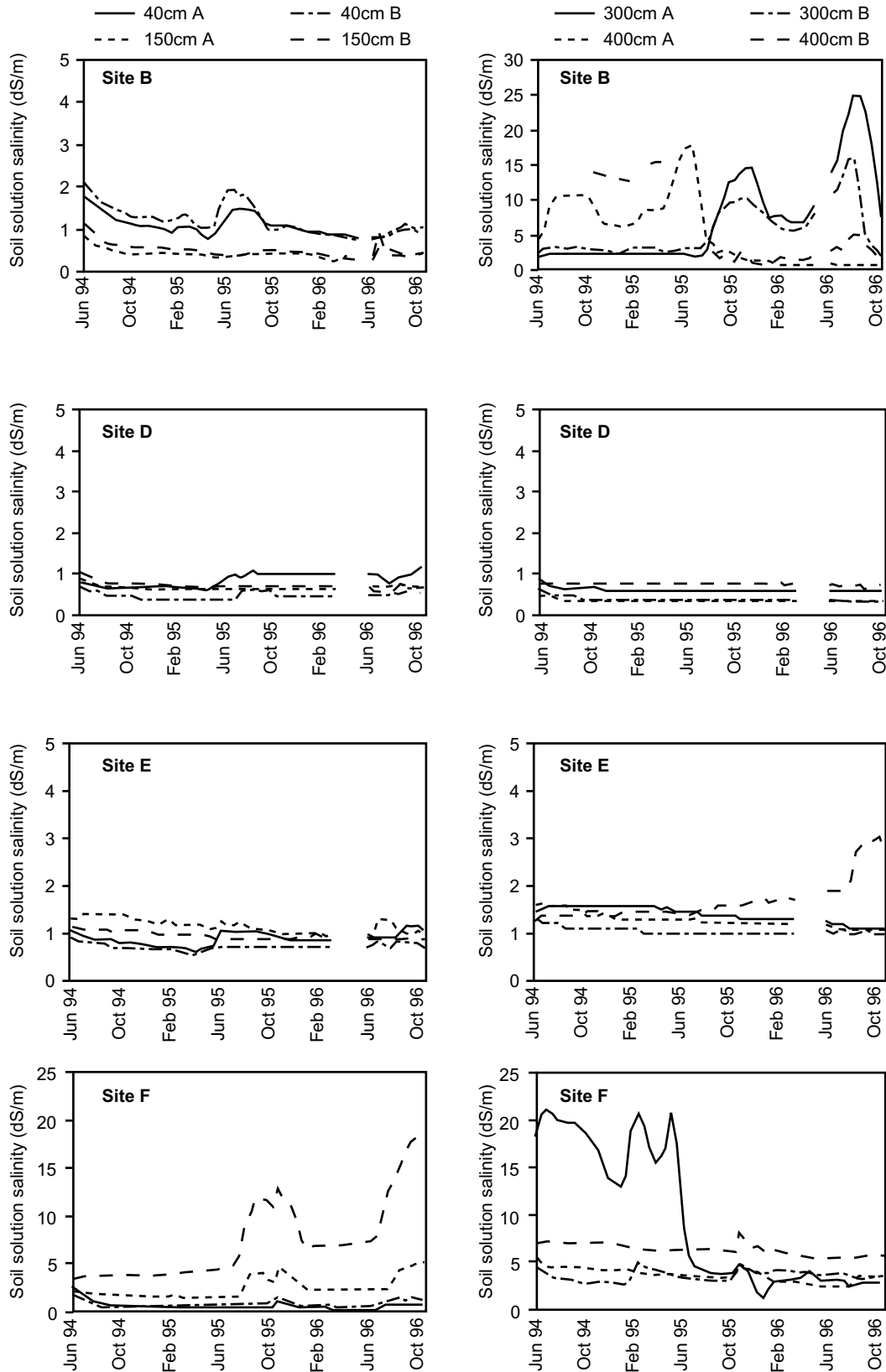


Figure 13. Soil solution salinity at 40, 150, 300, and 400 cm depth at four sites within the Kyabram plantation between June 1994 and October 1996 (fortnightly means of half-hour observations).

may change as a result of active groundwater uptake by roots. An important conclusion from these results is the recognition that zones of salt accumulation are closely linked to zones of maximum current water absorption, and may dissipate over weeks to months when uptake at that depth is diminished, independently of any leaching by deep infiltration.

At site F, the pattern of change in soil salinity with time was strikingly similar to that of site B, except that the initial and final zones of maximum salinity were shallower, namely at 300 and 150 cm depth. This reflects the presence of a shallower watertable at this site, close to the western edge of the plantation.

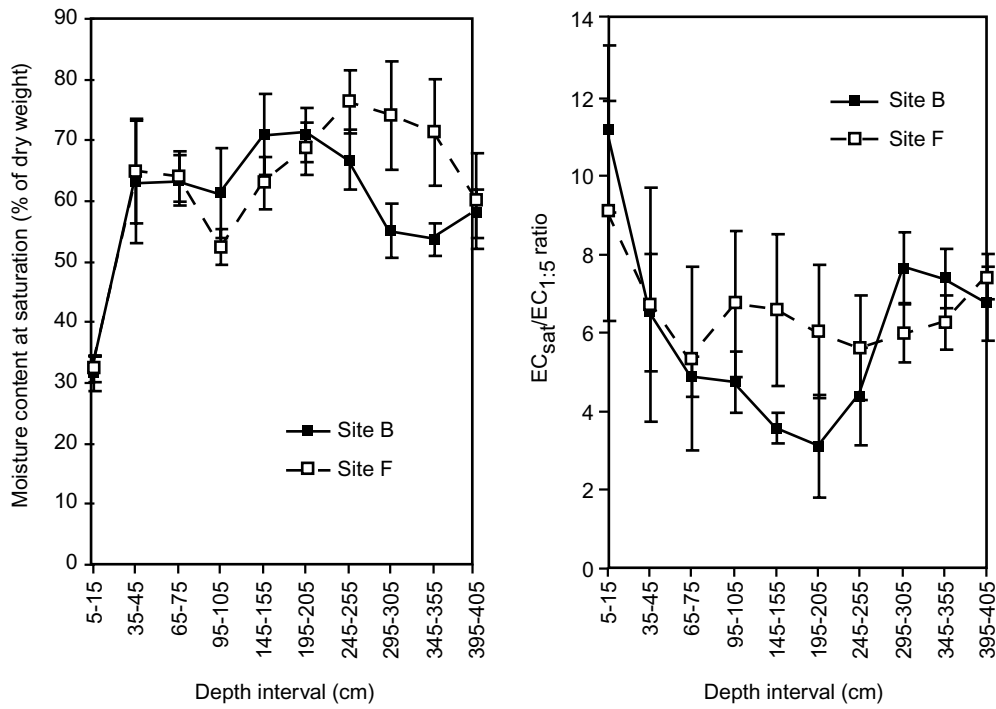


Figure 14. Moisture content at saturation, and the ratio of EC_{sat} to EC_{1:5}, for soil in the upper 4 m of the profile at sites B and F. Values shown are the mean of 4 samples from each site; bars indicate one standard error of the mean.

The comparison of soil solution EC data from the salinity sensors with EC_{sat} measured on samples of soil from corresponding depths in June 1996 showed a significant ($P < 0.01$) linear regression, with $r^2 = 0.45$ for 16 observations. Some scatter is to be expected in these results, in view of the observed spatial variation in EC over short distances at a given depth. The satisfactory regression fit confirms that the calibration of the sensors had not degraded during the observation period, and the data should be a valid assessment of soil solution salinity. The slope of a regression line through the origin was close to unity, indicating that the profile was in fact close to saturation at all the depths sampled by June 1996. Saturation moisture content and the ratio of EC_{sat} to EC_{1:5} were found by linear regression to be related by

$$f = 1.19 + \frac{2.96}{\theta_{sat}} \quad r^2 = 0.52 \text{ for 78 observations} \quad (2)$$

where f is the ratio of EC_{sat} to $EC_{1:5}$ and θ_{sat} is moisture content at saturation. This is close to the relationship reported by Slavich and Petterson (1993). The variation of these parameters with depth, shown in Figure 14, indicates the presence of significant texture variation only near the surface at sites B and F. Accurate modelling of moisture and salinity in the plantation root zone is limited to some extent by the lack of knowledge of spatial texture variation. Figure 15 shows seasonal variation in soil temperature in the upper 400 cm of the profile, typical of all four sites monitored. Although current models of root zone salinity do not directly take soil temperature into account, the gradient of up to 9°C between 40 and 400 cm, reversing twice each year, may be a significant influence on root growth and the distribution of moisture and solutes.

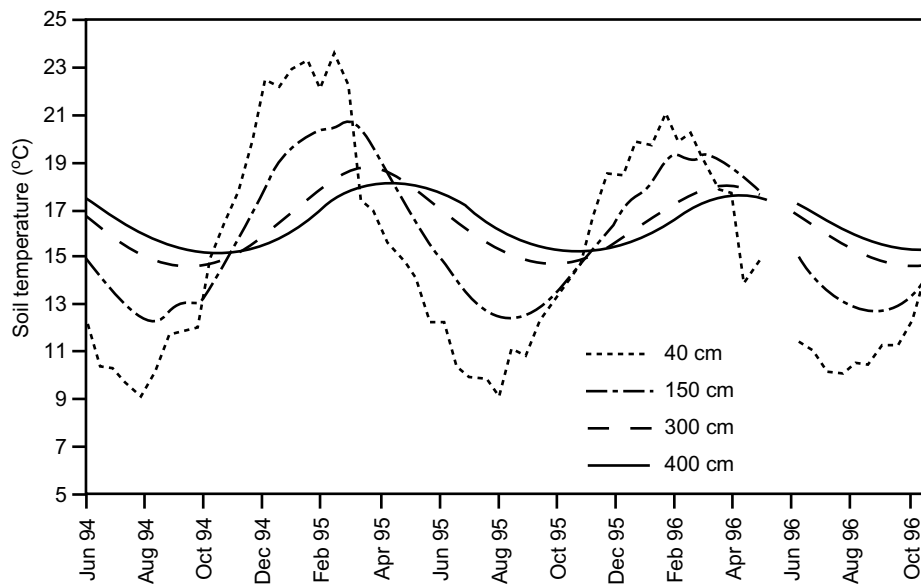


Figure 15. Variation in soil temperature at four depths beneath the Kyabram plantation between June 1994 and October 1996 (fortnightly means of half-hour observations).

2.4 Groundwater elevation monitoring

A monitoring network of observation wells was installed in November 1982. Observation bores (4–5 m deep and slotted from about 1 m below surface) and piezometers (9–10 m deep with a slotted bottom section ranging from 0.5 to 1.5 m) were installed in two transects through the plantation (Figure 3; section 1 south, section 2 north). The transects were spaced 58 m apart. In May 1984, additional observation bores (6 m deep) were installed in Section 2 inside the plantation, at sites where the previously installed shallower bores were found to be permanently dry.

In May 1991, the bore transects were extended eastwards into the irrigated pasture paddock, up to 170 m away from the edge of the plantation. Monthly watertable measurements were taken until February 1988 and resumed in February 1991. Watertable salinity measurements were made at 6-monthly intervals during 1982–88, and monthly from 1991.

Two nests of piezometers with screen lengths of 20 cm were installed in July 1992. Screens were positioned at 0.5 m depth intervals from 4.5 to 9 m below surface. One nest was

installed in the centre of the plantation near site 21, whereas the other was located in the irrigated pasture, 40 m east of the plantation boundary (see Figure 3). To improve monitoring of the watertable rise that occurred during the wet summer of 1993, two extra, shallower piezometers were installed at site 21 in February 1993. These were screened at 4 and 3.5 m below the surface, respectively.

Soon after the start of the current study, the monitoring network was expanded yet again to include additional piezometer and observation wells (sites A, C, H, I, and G) and piezometer nests (sites B, D, E, and F; see Figure 3)

2.4.1 Watertable levels and salinities

Figure 16 shows that the plantation had a strong effect on watertable levels and salinities. Watertable salinities were higher beneath the plantation than under the adjacent irrigated pasture. Rising watertable levels inside the plantation were observed over the 1982–93 pre-project monitoring period (Heuperman 1995), suggesting that the trees had reduced their drawdown impact over that period (although increased irrigation of the surrounding farmland during this period may also have contributed to rises).

There was a progressive increase in watertable salinity during the pre-project monitoring period of 1982–93. Salinities measured in the observation bores were clearly higher inside and immediately adjacent to the plantation than in the surrounding irrigated area by 5–15 dS/m.

2.4.2 Piezometric levels and salinities

Logging pressure sensors (DataFlow, Melbourne) were installed in piezometer wells both inside and outside the plantation at well sites 14D, AD, CD, GD, ID; nest site 21(21-10, 21-6, 21-7, 21-8, 21-9); nest site B (B10, B3, B9); nest site D (D11, D6); nest site E (E10, E9); and nest site F (F1, F4, F7). At each of these sites, the loggers recorded piezometric pressures four times a day.

The lowering of the watertable beneath the plantation resulted in a reversal of the hydraulic gradient at the site. Outside the plantation, a recharge scenario became established with piezometric pressure levels lower than the watertable. Inside the plantation, the watertable drawdown resulted in an upward gradient with piezometric pressure levels higher than the watertable. Figure 17 shows piezometric pressure levels and salinities measured in the different piezometer nests for summer and winter observations.

At site 21, site B, and to a lesser extent site F, the data show a drawdown in the shallow piezometers with a concomitant high EC of the groundwater at the shallow piezometer screen depths. The level measured in the shallowest piezometer represents the actual watertable. This suggests that the trees ‘skim off’ the watertable and thus concentrate salts in the upper part of the zone of watertable fluctuation. The deeper layers in the profile show lower salinities and higher piezometric pressure levels.

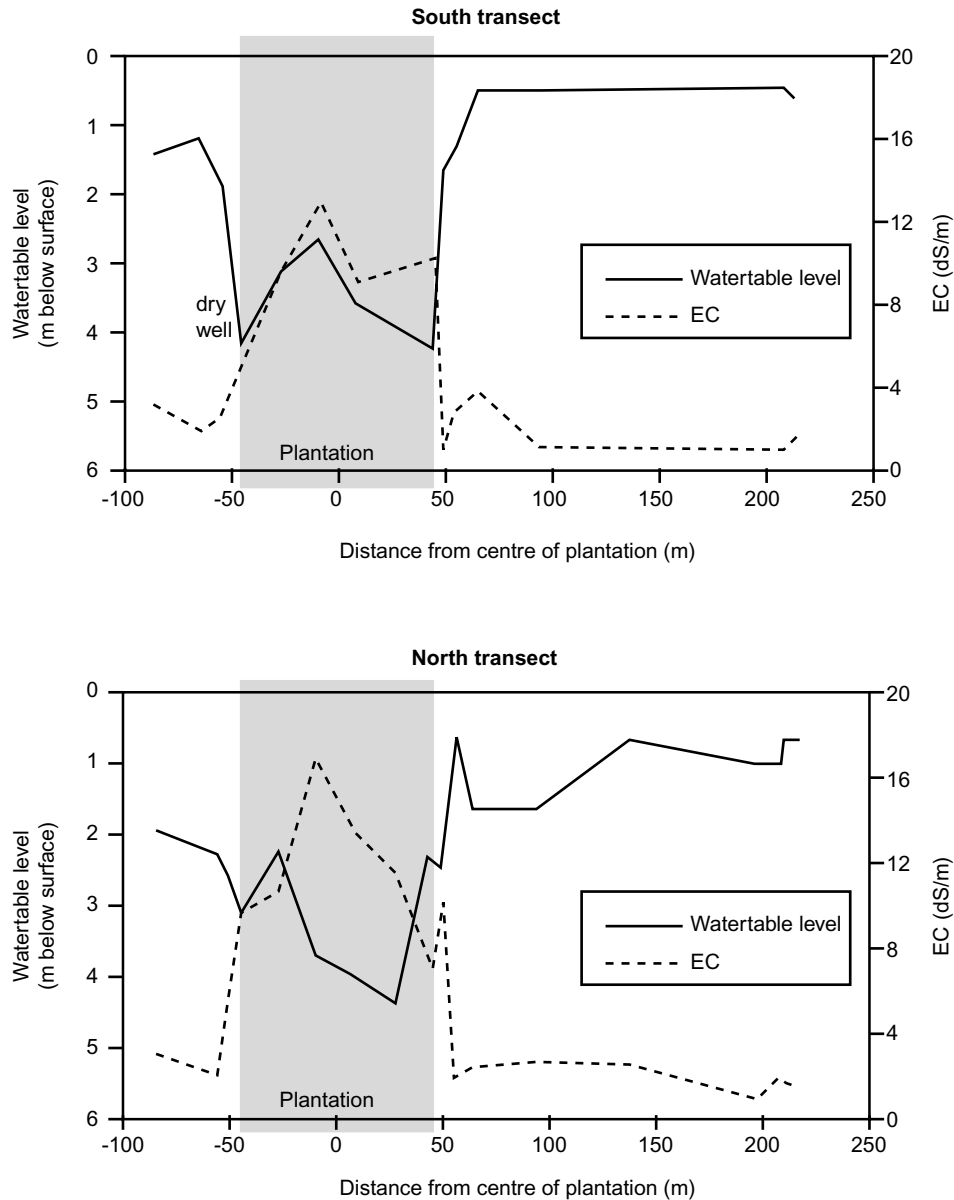


Figure 16. February 1995 watertable level and salinity cross-sections under the Kyabram plantation.

The scenario in the ‘outside’ nest is reversed with flat to slightly downward hydraulic gradients, and the EC of the groundwater increases with depth. However, these EC levels are all substantially lower than those measured beneath the plantation.

The scenarios at sites D and E are harder to explain. At site D the two piezometers at 11 and 11.5 m depth showed very low pressure levels, suggesting either very low hydraulic conductivities or very high extraction rates by the roots at those depths. Salinities in the shallowest piezometers also did not show the high levels found at sites 21, B, and F. At site E, the scenario was even more extreme. In this case all piezometers shallower than 6.5 m in July 1995 (winter) and shallower than 9 m in January 1996 (summer) were dry, but the salinity in the only piezometer intercepting the saturated profile was relatively low (January 1996).

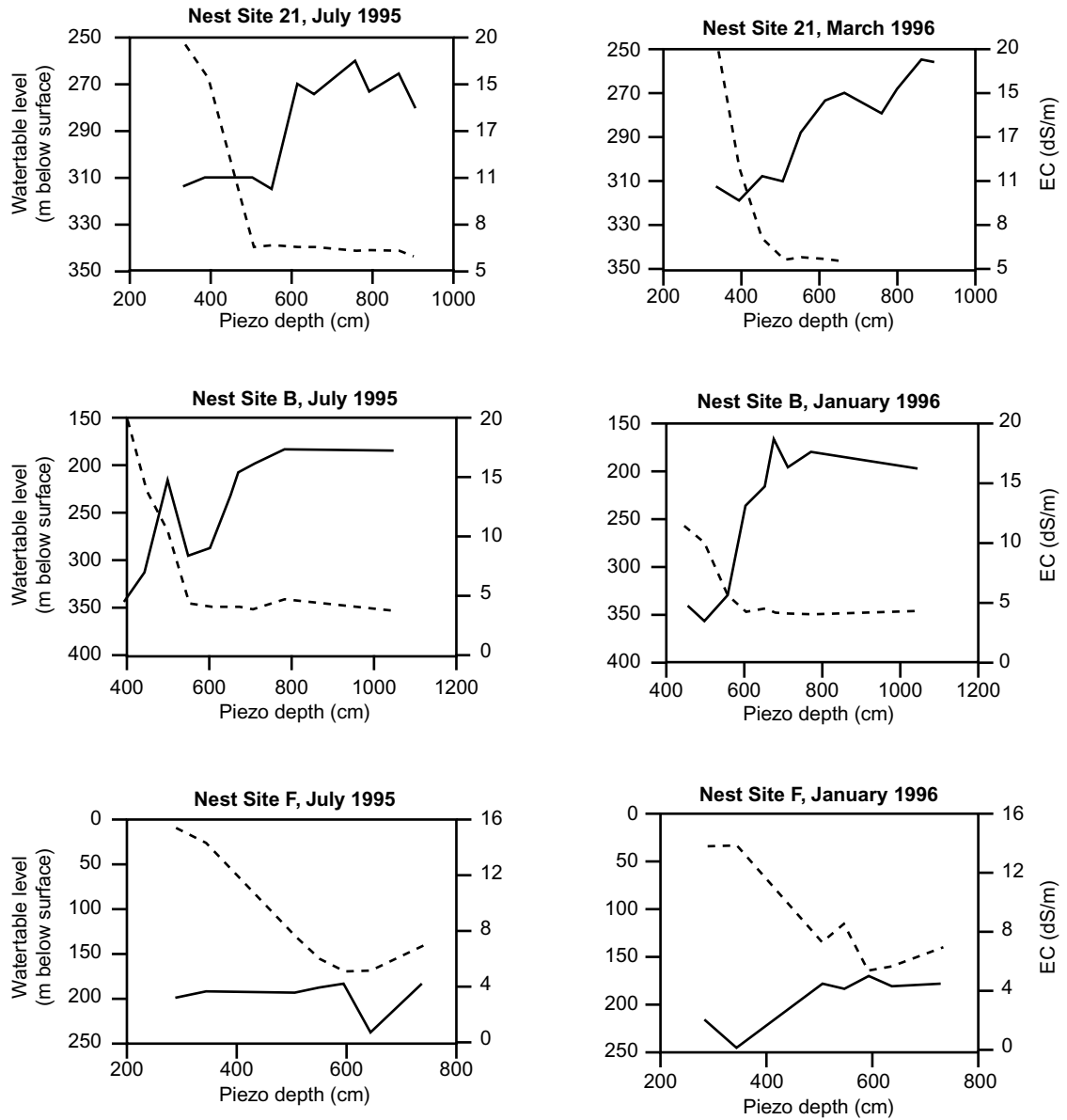


Figure 17. Piezometric pressure levels and salinities in piezometer nests; summer and winter observations. Solid line shows watertable level, dashed line shows EC.

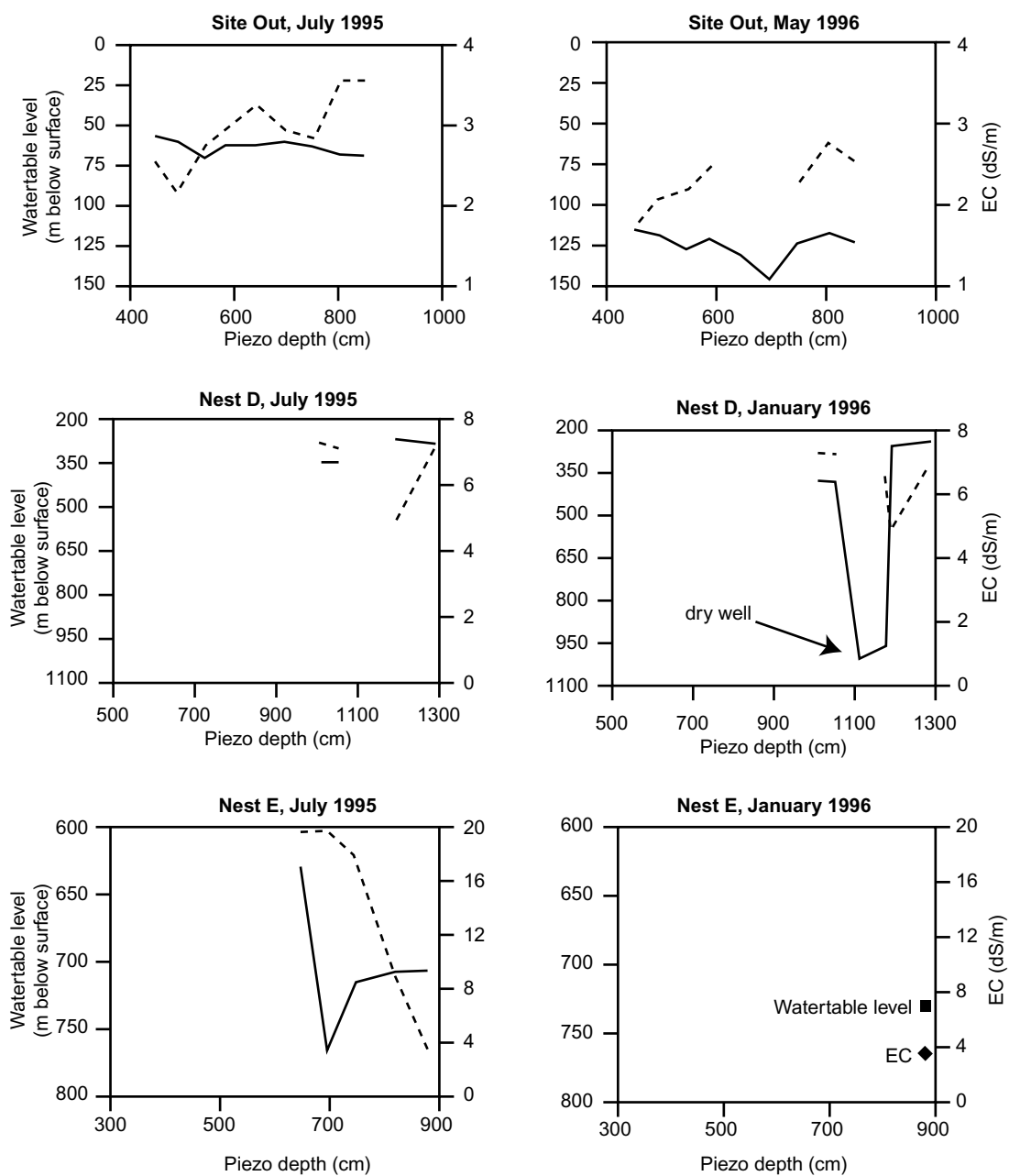


Figure 17 (continued). Piezometric pressure levels and salinities in piezometer nests; summer and winter observations.

3 Tree–Water Relations

In this section we report on various aspects of tree physiology and water relations at the Kyabram plantation. The field data gathered were used to elucidate poorly understood processes, and to parameterise and test the Topog_Dynamic model.

We begin this section by describing our measurements of leaf area index (LAI), which is a prime determinant of rainfall interception and transpiration rates. Next we describe our measurements of tree water use, conducted on a number of trees throughout the year. These tree water use measurements were complemented by canopy conductance and xylem pressure potential measurements. These were made under varying climate conditions to elucidate the environmental controls on transpiration. We conclude this section by reporting on plantation rainfall interception rates, deduced from field measurements of gross rainfall, throughfall, and stemflow.

Most of the tree physiology findings reported in this section have been published recently in the international journal literature by Morris *et al.* (1998).

3.1 Leaf area index

Plant canopies exert a profound influence on plant–environment interactions. The structure and density of the plant canopy influences radiation penetration, rainfall interception, and evapotranspiration. In hydrologic terms, the most important attribute of the plant canopy is the leaf area index (LAI), defined as the area of leaf per unit area of ground (m^2/m^2). In temperate zones, LAI will vary depending on a variety of factors, including age and site conditions, particularly water availability and soil fertility. Typically though, LAI values for plantations in south-eastern Australia vary between 0.3 and 6.0.

Measurements of LAI were taken using a Li-Cor LAI 2000 Plant Canopy Analyser (PCA). This device indirectly estimates LAI from measured relative light interception using a gap-fraction formula defined by Miller (1967). Indirect methods incorporate radiation transmission through the canopy that is closely associated with radiative transfer and canopy structure, and use statistical tools and/or mathematical assumptions to calculate leaf area. Although indirect methods are associated with low costs and virtually instantaneous estimates, they have undergone little testing and may produce erroneous estimates of LAI where species composition differs or within single species when the canopy structure varies (Gower and Norman 1991). The canopy at Kyabram is fairly uniform. Vertessy *et al.* (1995) found the PCA gave comparable results to destructive sampling and hemispherical photography for 15-year-old Mountain Ash (*E. regnans*) forests. Battaglia *et al.* (1998) obtained good results with the device in *E. globulus* plantations in Tasmania, but for estimates to match observed values, a correction factor had to be applied. They found that the PCA tended to exaggerate LAI by a factor of roughly 1.6. This experience was also reported by McJannet and Vertessy (2000) for *E. globulus* plantations in Victoria.

LAI measurements were made at the Kyabram site between September 1995 and December 1996 at five sites along two parallel transects within the plantation. Sites were chosen to be representative of *E. camaldulensis* or *E. grandis*, the two species focused on in this study. Measurements were taken at intervals of 1–2 months and repeated once or twice at each site at each sampling time.

The technique assumes that foliage is black and therefore should not be applied if foliage is lit by direct sunlight. Hence, our measurements were made primarily under cloudy conditions (diffuse-radiation dominated) or at dawn or dusk when the canopy was not sunlit. Only readings from the four inner rings of the sensor were used, and together with the 90° view cap, confined the field of view to an arc with a radius of less than 35 m (0.38 ha or 3848 m²).

Two plant canopy analysers (PCAs) were used. One of these was set up in the open about 100 m from the plantation to automatically record light conditions every 15 sec, while the other was used manually inside the plantation. Canopy transmittance was derived from the difference between simultaneous measurements of light intensity inside and outside the plantation.

Seasonal variation in LAI of *E. camaldulensis* and *E. grandis*, together with total monthly rainfall and weekly averaged vapour pressure deficit (VPD), are shown in Figure 18 and Figure 19. The LAI of *E. grandis* was greater than that of *E. camaldulensis* at all times throughout the sampling period. LAI peaked in late December to early January for *E. camaldulensis* and later (early February 1996) for *E. grandis*. The error associated with our LAI measurements is $\pm 10\%$. Given this, the majority of differences in LAI presented are not statistically significant. This may be related to the lack of seasonal trends in tree transpiration rates (see next section). Nonetheless, the observed trends in LAI for each site correlate well with environmental conditions, as discussed below.

E. camaldulensis was subjected to severe herbivore damage during the summer of 1995–96. Trees were affected throughout the region and not just at the study site. The LAI of *E. camaldulensis* was reduced by over 20% from just under 1.2 in January to 0.95 in April 1996. Both species had a minimum LAI in early April. *E. grandis* underwent a flush of leaf growth in autumn, presumably concurrent with increased moisture availability, whereas *E. camaldulensis* did not undergo a flush of new shoot growth at this time. This may have been a result of subsequent heavy fall of older insect-damaged leaves (Aston 1979). In addition, partially damaged laminas of young leaves and apices of young shoots may not be significant in terms of immediate loss of biomass, but may influence shoot development and the potential for rapid leaf area recovery.

The study site is characterised by a winter rainfall maximum with relatively dry summers (Figure 18). February–March is usually the driest time of year and September tends to be the wettest. The monitoring period was characterised by a wetter than usual summer. LAI seemed to more closely follow the seasonal variation in VPD than rainfall (Figure 19). However, LAI appears to be suppressed due to a limited moisture supply leading into the summer of 1996–97, and coincides with tree water use being limited by water availability during periods of low rainfall and high VPD (see next section).

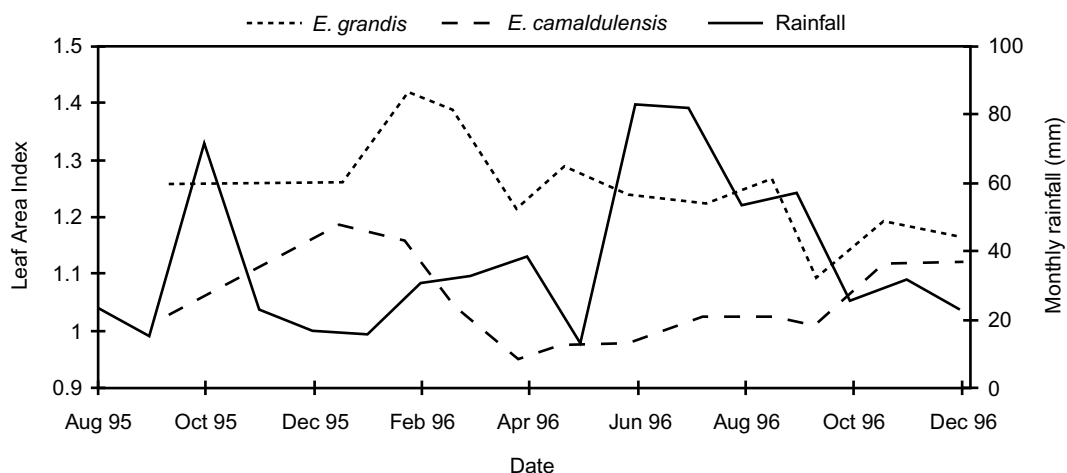


Figure 18. Leaf area index and monthly rainfall at Kyabram.

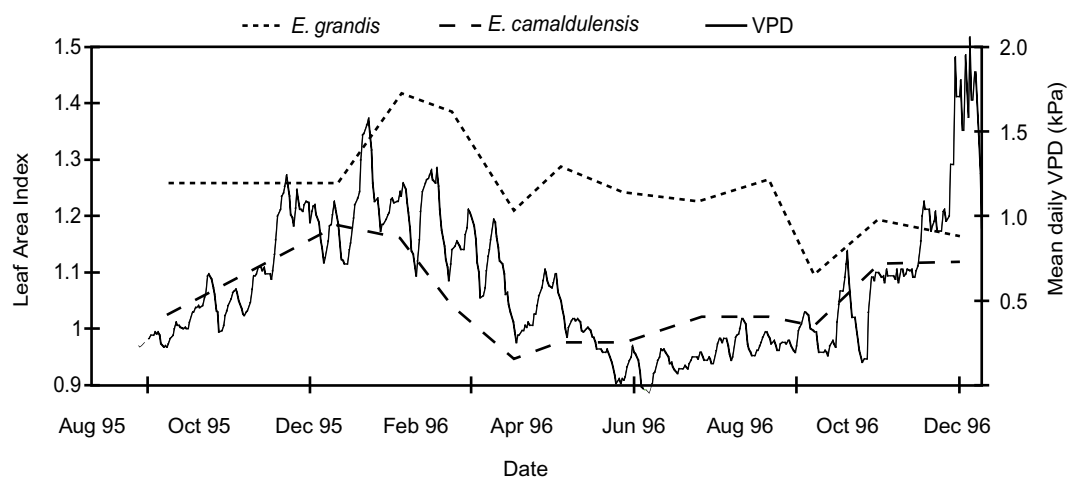


Figure 19. Leaf area index and VPD at Kyabram.

According to Stone and Bacon (1994), moisture stress may influence leaf size and shape, leaf area, and the percentage of leaf area lost to insect herbivory. The average life of leaves on naturally occurring eucalypts is about 18 months (Jacobs 1955). However, leaves may be retained on trees for up to 2–3 years and shed not only in relation to new foliage production but also during drought or stress periods (Pook 1984a).

Figure 20 and Figure 21 show the pattern of net leaf gain (defined as the difference between LAI at one measurement and the preceding measurement, i.e., $LAI_t - LAI_{t-1}$) with moisture status, $R-E$ (rainfall minus pan evaporation, mm), and average weekly temperature. Although the values of net leaf gain carry an error similar to that for LAI measurements ($\pm 10\%$), some general observations can be made. Maximum values of LAI were attained at the peak of growth seasons when rates of leaf production were high relative to leaf loss. In general, there was a low net leaf gain or net leaf loss associated with periods of high $E-R$ (low moisture status). Periods of higher net leaf gain were associated with periods of low $E-R$. Shoot growth appears to occur whenever environmental conditions are favourable.

Under ‘normal’ growth conditions, moderate variation in forest LAI may result from the lag in peak rates of leaf fall behind leaf production (Pook 1984b). Leaf production and leaf fall may be out of phase by up to 2 months and production usually occurs prior to leaf loss (Pook 1984b). The observed seasonal fluctuations in LAI of up to 0.4 are relatively small compared with changes that occur in pastures, crops, and deciduous forests. Although relatively small, these variations may have important consequences for seasonal patterns of evapotranspiration and hence water balance for the site.

By reducing canopy storage capacity, leaf shedding may significantly decrease direct evaporative losses during rainfall and enhance the ability of rainfall to recharge soil water, thereby increasing moisture availability to trees (even if litter storage increases, because this will decrease soil evaporation).

E. camaldulensis started losing its leaves before *E. grandis* due to insect herbivory in the summer of 1995–96. Both species increased leaf production in autumn, which correlated with increased moisture availability. *E. grandis* underwent a relatively considerable phase of net leaf loss in the spring of 1996 for no obvious reason. However, it is possible that the root-zone salinity fluctuations shown in Figure 13 may be related to these leaf area changes.

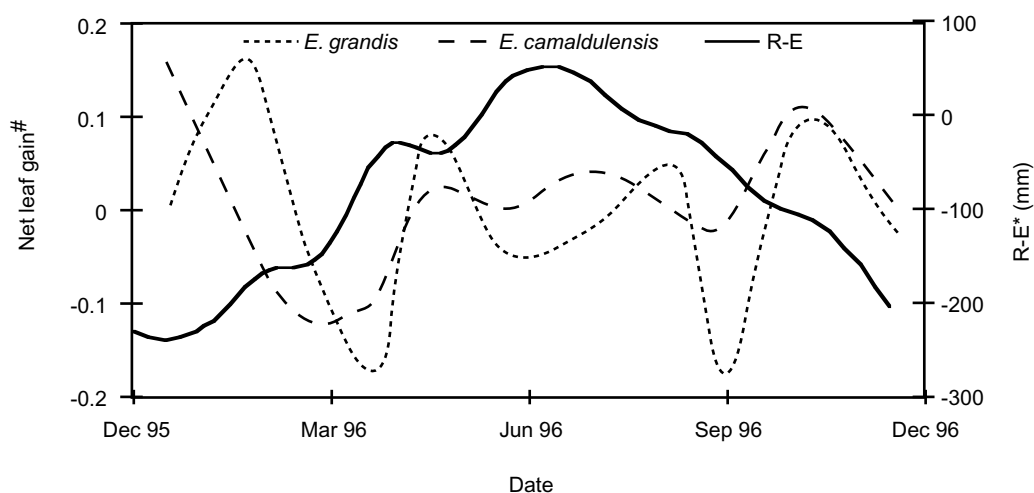


Figure 20. Net leaf gain and R-E for Kyabram.

Specht *et al.* (1981) suggested that for dominant species in Australian sclerophyllous vegetation, 25°C is the upper limit of the temperature range for shoot growth. At Kyabram, leaf production was not stopped due to weekly average temperatures up to 24°C, nor due to low winter temperatures down to 6°C (Figure 21). *E. camaldulensis* appeared to be better suited to colder temperatures as it was able to maintain a net leaf gain throughout winter. *E. grandis*, on the other hand, underwent net leaf loss when average weekly temperatures reached 10°C. This species is generally found in warm, humid areas of New South Wales and Queensland, with mean annual rainfall of between 1000 and 3500 mm. It may be that leaf production of *E. camaldulensis* was also suppressed to a lesser degree by lower temperatures in the colder months. This is reflected in its wide distribution under a wide range of climatic conditions, with a mean annual rainfall range between 250 and 600 mm.

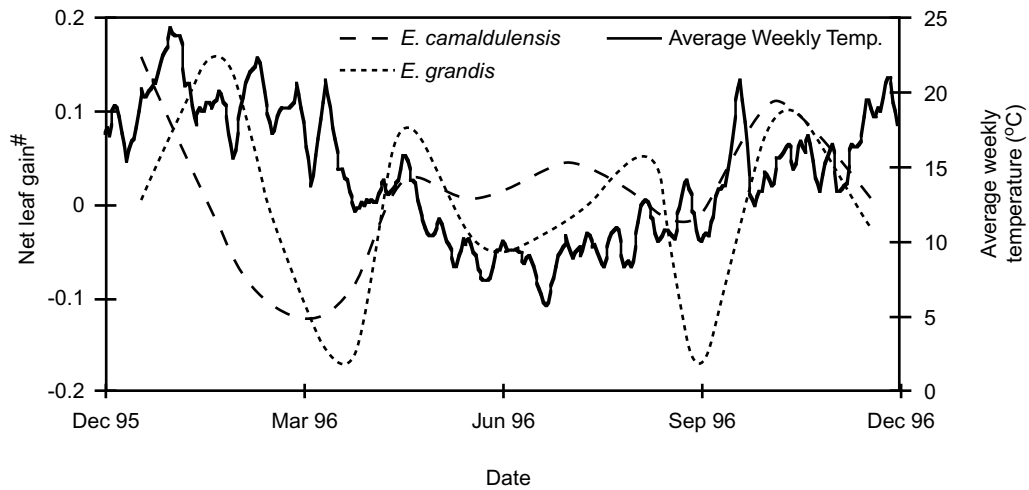


Figure 21. Net leaf gain and average weekly temperature at Kyabram.

3.2 Tree water use

Water use by *E. camaldulensis* and *E. grandis* was monitored from February 1994 to March 1996 in two sections of the plantation. One section was situated at the southern end, comprising a group of three plots of each species, planted at 4×4 m spacing. The other section was situated toward the northern end of the plantation, comprising three plots of each species, planted at a 4×2 m spacing, but later thinned to approximately half this density. Plot areas and tree sizes are listed in Table 5.

Table 5. Area of and tree density within four strata defined for assessment of plantation water use at Kyabram

	<i>E. grandis</i>		<i>E. camaldulensis</i>	
	4×4 m	4×2 m	4×4 m	4×2 m
Initial Spacing				
Stocking in 1994 (stems/ha)	492	483	532	639
Mean diameter (cm)	27.0	25.2	19.6	20.9
Basal Area (m^2/ha)	28.89	25.48	19.50	24.30
Sapwood area (m^2/ha)	7.96	7.00	5.95	7.22
Plot area (m^2)	1728	1800	1728	4680

Sap-flow loggers (Greenspan Technologies, Warwick, Qld) were used to measure water use by selected trees in each section. A total of 6 loggers were used; one for each species in the 'wide spaced' section and two for each species in the 'close spaced' section. Trees for monitoring during the first year were chosen by listing the trees in each section in order of diameter at breast height, and selecting every n -th tree from the list, n having been chosen to provide approximately 25 trees per sap-flow logger. The set of trees selected in this way closely matched the diameter distribution of the whole stand, and allowed approximately 2 weeks of continuous monitoring of each tree. In the second year this selection process was repeated, as far as possible selecting trees that had not been monitored in the previous year. In total, 114 *E. grandis* trees and 115 *E. camaldulensis* trees were sampled over 2 years.

The sap-flow loggers recorded apparent heat-pulse velocity at four points in the sapwood of each tree at 30-minute intervals throughout each day. Supplementary measurements of the probe separation, volume fractions of water and woody matrix in the sapwood, and wound diameter from probe insertion were used to correct and convert the heat-pulse velocities to estimates of sap flux density (SFD) using the method of Edwards and Warwick (1984) as revised by Olbrich (1991). Integration of the four point SFD values to a whole-tree estimate was performed using the weighted-mean method of Hatton *et al.* (1990), followed by calculation of instantaneous water use using a sapwood area estimate derived from under-bark diameter and sapwood width at four points around the stem. Daily water use was determined by integrating the half-hourly values over each day. Dividing this figure by the sapwood area yielded a mean daily SFD.

The minimum SFD measurable with the Greenspan loggers was found to be between 3.5 and 5 cm/hr. This value corresponds to a maximum valid heat-pulse time of around 250–300 seconds, in varying conditions of interprobe spacing, wound size, and sapwood moisture content. The manufacturer's documentation also specifies a maximum heat-pulse time of this order for the Greenspan logger. As the rate of sap flow slowed to below this value soon after sundown on most days, water use during the night was estimated as a declining percentage of the apparent measured value between 2000 h and midnight, zero from midnight to 0600 h, and an increasing percentage of the apparent value from 0600 to 0800 h. This approach was validated by comparison of the Greenspan data logger with a Custom heat-pulse logger (HortResearch, Palmerston North, N.Z.), capable of measuring SFD down to approximately 1 cm/hr (i.e., maximum valid heat-pulse time of over 750 seconds, resulting from a larger heater current in this logger). Six trees were simultaneously monitored with both systems over 3 months in summer 1994/95. Comparison of the daily water use measurements from the Custom with Greenspan data, filtered as described above, showed a difference of approximately 10%, which is within the limits of accuracy usually recognised for the heat-pulse method (see Olbrich 1991, Hatton *et al.* 1995).

Scaling of individual tree observations to stand water use was based on sapwood area, following the approach of Khanzada *et al.* (1998). The mean daily SFD values recorded for individual trees were assumed to be unbiased estimates of the mean SFD of the whole stand. This assumption is supported by the observation that differences in SFD between trees measured sequentially were usually small compared to daily SFD variation within each tree. Furthermore, an examination of SFD in relation to sapwood area of individual trees showed no evidence of a consistent relationship with tree size for either species. An estimate of stand water use for each section of the plantation may therefore be obtained by multiplying the mean SFD of the monitored trees in that section by the total sapwood area of all the trees it contains. To determine total sapwood area for the plantation, an exponential regression was fitted to relate the measured sapwood areas of the monitored trees to their overbark diameters. Data from both species were found to fit the single regression line

$$SA = 23.933 \times 10^{(0.0302 \text{ DBH})} \quad \text{---} \quad \text{Figure 3: A scatter plot showing the relationship between sapwood area (SA) and diameter at breast height (DBH). The x-axis is labeled 'DBH (cm)' and ranges from 0 to 10. The y-axis is labeled 'SA (cm²)' and ranges from 0 to 100. Data points are plotted for two species, and a single exponential regression line is fitted to the combined data. The equation for the line is shown as SA = 23.933 × 10^(0.0302 DBH). The line shows a positive, non-linear relationship, with SA increasing rapidly as DBH increases.$$
 (3)

where SA is sapwood area in cm^2 and DBH is diameter at breast height in cm. The r^2 value for this relationship exceeded those of alternative linear or second-degree polynomial functions. Equation (3) was applied to the diameters measured for all trees in February 1994 and October 1995 to determine the total sapwood area for each section and hence derive daily stand water use in mm/day.

The mean daily SFD and stand water use for each species are shown in Figure 22. Variation between the wide-spaced and close-spaced plots of each species was found to be less than the variation between individual trees. This result was not unexpected, since the differences in basal area between the sections were small (Table 5). The SFD data in Figure 22 are therefore averaged over both wide- and close-spaced trees. It is also evident from this data that species differences in mean SFD are transient or non-existent, so that differences in water use between species are largely or wholly attributable to differences in their sapwood area per hectare.

Although the daily SFD data displayed a large degree of short-term (daily to weekly) variation in response to fluctuating weather conditions, Figure 22 shows that seasonal variation was not great, with only weak peaks in spring and summer of each year. Highest daily water use was recorded in the first 2 months of monitoring, during late summer of 1994. Below-average rainfall during 1994 may account for the lower stand water use in the following summer, but water use in summer 1995/96 was only marginally greater, despite wetter conditions in winter–spring 1995. Monthly water use is compared with rainfall in Figure 23, and annual values summarised in Table 6. The weak relationship between rainfall and water use probably reflects a strong dependence on groundwater for the plantation’s water requirements, which is consistent with the observed depression in watertable depth beneath the plantation compared to surrounding pasture. The absence of a pronounced peak in water use during summer, when both radiation and vapour pressure deficit (VPD) are relatively high, suggests that water use is most likely limited by the availability of water during this period.

Table 6. Annual water use by species and stratum (mm/yr) for two years of sapflow monitoring at Kyabram

	Mar 94–Feb 95	Mar 95–Feb 96
<i>E. grandis</i>		
Wide-spaced	352	362
Close-spaced	280	309
<i>Overall</i>	<i>315</i>	<i>335</i>
<i>E. camaldulensis</i>		
Wide-spaced	254	221
Close-spaced	314	341
<i>Overall</i>	<i>298</i>	<i>308</i>
Whole plantation	304	318
Rainfall	215	506

The wide-spaced *E. camaldulensis* plots differed from the others studied in that their water use declined in the second year while that of all other plots increased by 3–10%. This may be a result of a poorly suited provenance of *E. camaldulensis* planted in the wide-spaced plots, which were originally part of a spacing trial. The wide-spaced *E. camaldulensis* also had the lowest basal area and sapwood area per hectare. Canopy damage by leaf-eating insects during summer 1995–96 may also have contributed to this result, though this probably would have affected all trees. The close-spaced *E. camaldulensis* plots, originally

a provenance trial, contained a mixture of twelve provenances, mostly from northern and western Victoria.

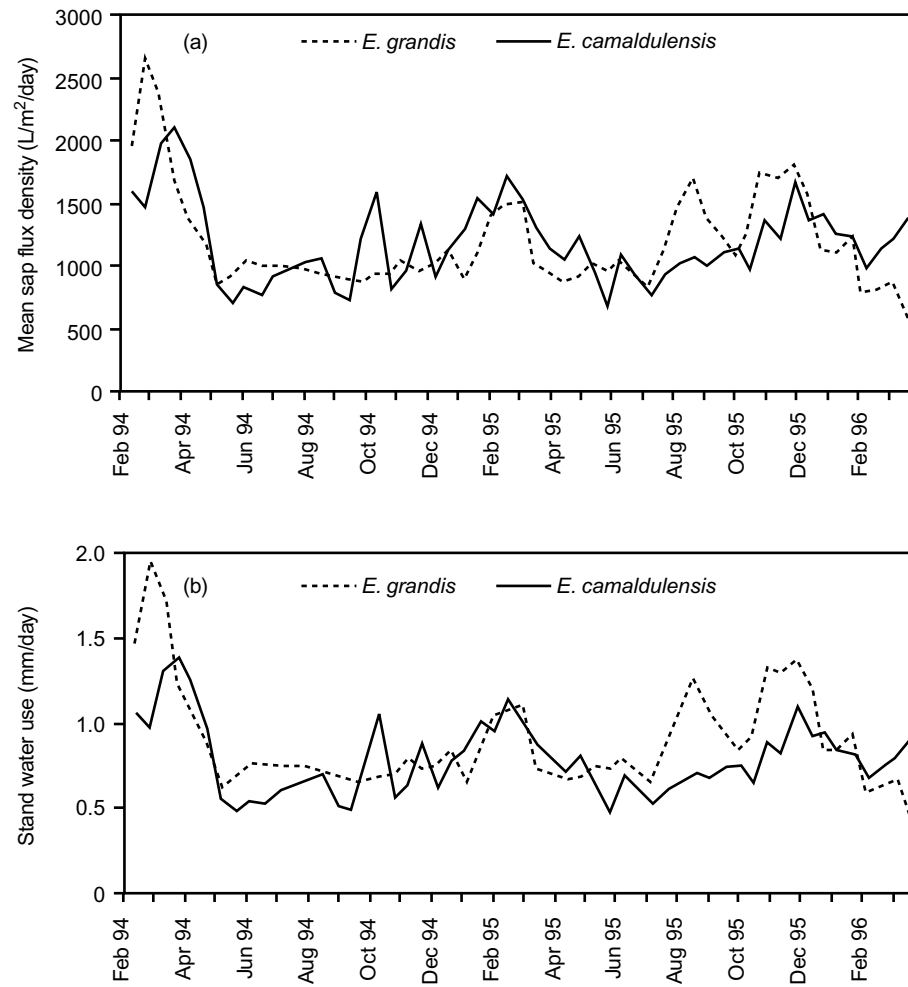


Figure 22. Fortnightly means of (a) daily sap-flux density and (b) stand water use for *E. grandis* and *E. camaldulensis* at Kyabram between February 1994 and March 1996.

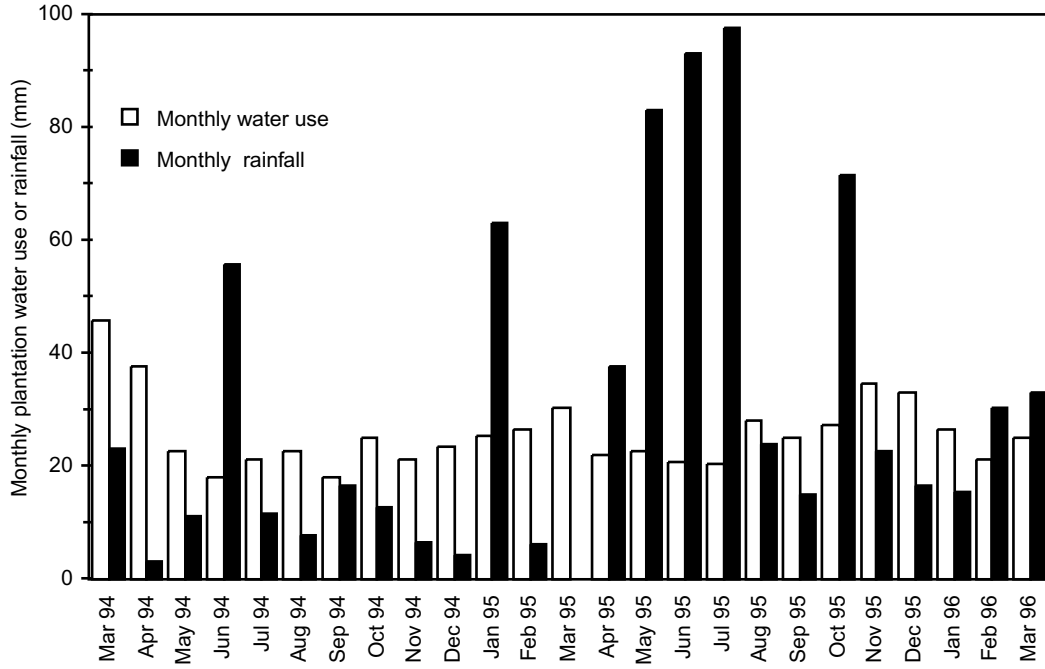


Figure 23. Monthly rainfall and stand water use for the Kyabram plantation between March 1994 and March 1996.

Since the water use of trees is driven by the gradient of water potential from soil to air, a measure of the ‘stand conductance’ may be derived by dividing daily water use (E) by the daily mean vapour pressure deficit (VPD) as an estimate of this gradient. The conductance obtained in this way relates the conducting pathway to the bulk air from a notional point within the soil–plant system, where it is assumed that the water potential is equivalent to vapour saturation at air temperature. The location of this point is not clearly defined because it is subject to the effects of differences in temperature and gravitational potential between the source and sink of water flow, as well as the gradient of matric and/or osmotic potential. Nevertheless, it reflects the integrated effects of seasonal differences in plant and environmental conditions on transpiration. Figure 24a shows temporal variations in stand conductance between August 1994 and March 1996, calculated as

$$g_c = \frac{\gamma \lambda E}{\rho C_p D} \quad (4)$$

where g_c is canopy conductance in cm/sec, E is the time-averaged stand water use (mm/sec), D is the mean vapour pressure deficit (Pa), ρ is the atmospheric density (kg/m³), C_p is the specific heat of dry air at constant pressure (J/kg/K), γ is the psychrometric constant (Pa/K), and λ is the latent heat of evaporation of water (J/m³).

Daily stand conductance remained below 0.3 cm/sec during both summers of monitoring, but rose as high as 2–3 cm/sec between April and September. Some apparently higher values obtained for a few days during winter 1995 were rejected as artefacts arising from the overestimation of E by the sap flow loggers on days when SFD fell below their limit of resolution. Plotting daily stand conductance against VPD (Figure 24b) reveals a strong hyperbolic relationship. This should not be seen as evidence that stomatal conductance varies inversely with atmospheric VPD, since the calculated stand conductance embodies a

more complex sum of conductances in series. The established relationship is however potentially useful in modelling the response of plantation water use to climatic conditions.

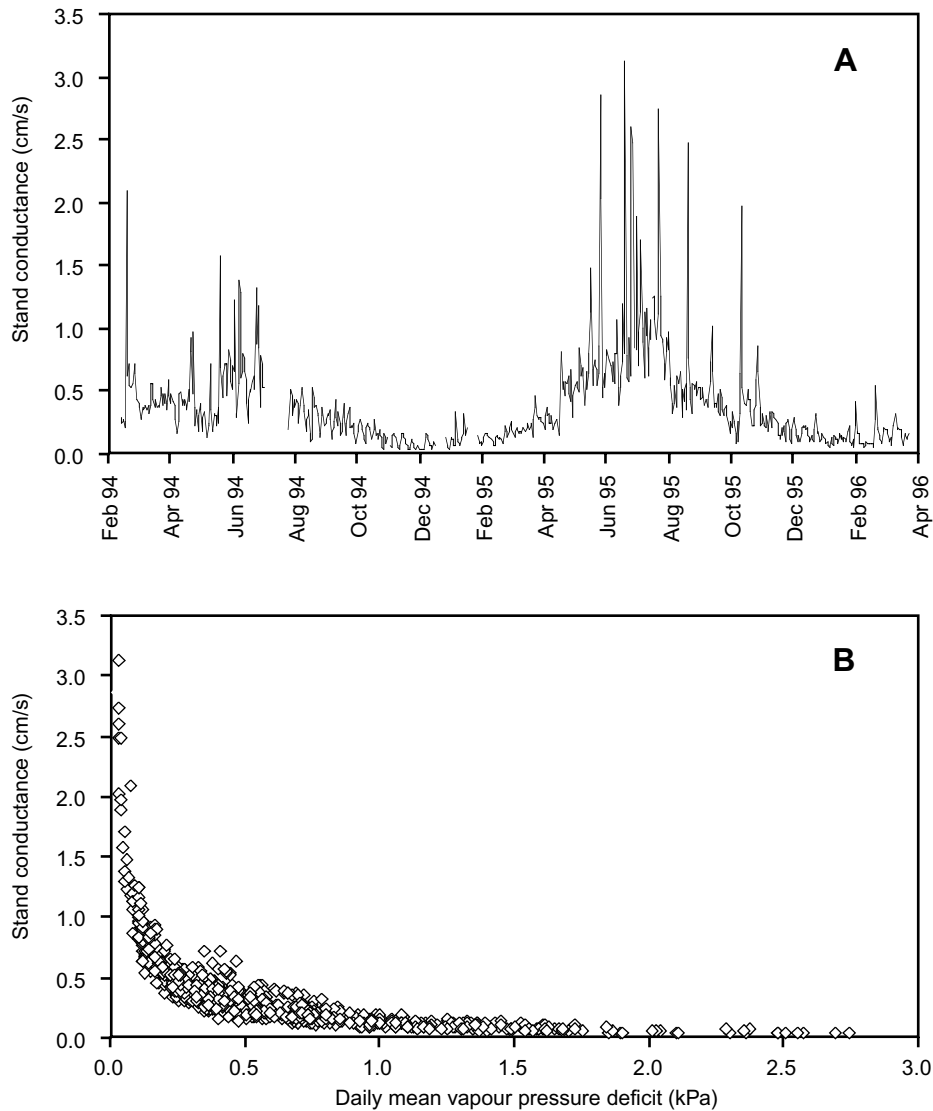


Figure 24. (a) Variation in daily stand conductance for the Kyabram plantation between February 1994 and March 1996. (b) Plot of stand conductance against daily mean vapour pressure deficit.

Similar values of conductance were obtained by a more sophisticated method, based on an inverse application of the Penman–Monteith equation to the observed daily water use data and values of net radiation, VPD, and aerodynamic conductance estimated from the climate station data using the methods of Allen *et al.* (1989). Jarvis (1981), Landsberg (1986), and other authors have demonstrated the validity of

$$E \propto g_c D \quad (5)$$

as a good approximation for evaporation from rough canopies, indicating that radiation is usually less important than VPD as a driving factor for canopy transpiration. It is usually assumed that g_c is a function only of stomatal conductance and leaf area index. Similarly, the surface conductance term of the Penman–Monteith equation is usually assumed to relate

to the conductance from a saturated mesophyll surface to the outside of the leaf (Monteith 1965). While this assumption is usually valid for well-watered plants in humid conditions, in the conditions of the Kyabram plantation it cannot be assumed that resistance from soil to roots to leaves is negligible in comparison to stomatal resistance. The daily stand conductance data may more usefully be conceptualised as incorporating the whole pathway of moisture flow from soil to air.

3.3 Canopy conductance and water potential

Observations over 2 years at Kyabram have shown that annual water use by both species monitored is relatively low and appears to be limited by moisture availability during summer. To ascertain the importance of stomatal regulation of water loss and the response of stomates to environmental factors, intensive studies of canopy characteristics were conducted on two days in February, 1995 and four days in October, 1995. During both experiments, a 24-m elevated work platform was used to gain access to the canopy of one tree of *E. camaldulensis* and one of *E. grandis* from the close-spaced section of the plantation, near sites E and D respectively (3).

Stomatal conductance of a set of 20 leaves distributed through the mid to upper, outer part of the tree canopy was repeatedly recorded, up to 12 times between sunrise and sunset, using a Licor LI-1600 null-balance diffusion porometer. Leaf water potential was also assessed repeatedly through each day, using a pressure bomb and Wescor (Logan, Utah) psychrometers to measure groups of up to 16 leaves sampled from the mid to upper canopy at 6–12 times between sunrise and sunset.

Sap flow in the study trees was monitored at 30-minute intervals using Greenspan loggers. The leaf area of each tree was assessed by visually estimating the number of leaves on each branch, and applying a correction factor derived from a count of the actual number of leaves on a sample of branches selected using a probability proportional to prediction (3P) sampling approach (Grosenbaugh, 1979). The corrected total leaf number for each tree was multiplied by the average single leaf area, determined by scanning a sample of at least 100 leaves with a Delta-T (Cambridge, UK) image analysis system. The leaf areas determined for the trees monitored in February were 17.29 m² for *E. grandis* and 12.46 m² for *E. camaldulensis*; in October the corresponding areas were 60.22 m² and 25.23 m². The species differ in that *E. camaldulensis* leaves are amphistomatous while those of *E. grandis* are substantially hypostomatous, confirmed by a comparison of upper and lower surface conductance measurements on a set of 20 leaves. The single-sided leaf area of *E. camaldulensis* was therefore doubled for calculation of transpiration per unit leaf area and estimation of boundary-layer conductance within the canopy. All four trees were assumed to occupy a ground area of 16 m² for purposes of estimating leaf area index to relate the single-tree data to whole-canopy conductance estimates.

A climate monitoring station was mounted in the crown of an *E. grandis* tree near the centre of the plantation, to monitor solar radiation, temperature, humidity, and wind-speed at canopy level and 1 m above at 30-minute intervals. Leaf temperatures of the study trees were recorded every 5 minutes by means of eight fine-wire thermocouples glued to the underside of leaves distributed through the mid to upper canopy. An additional four thermocouples recorded the temperature of the air within the canopy. A reference-junction temperature for the thermocouples was provided by a semiconductor temperature transducer

mounted in a well insulated, thermally stable, aluminium block installed in the upper canopy and connected with the thermocouples to a DT100 data logger from Data Electronics (Bayswater, Victoria).

The weather during the February study was warm, dry, and uniform, with daily temperature maxima of 27, 28, and 25°C for 7, 8, and 9 February, respectively. A prolonged drought, with only 59 mm of rain in July through December 1995, had been relieved by 63 mm rainfall in January, with the most recent shower on 28 January. Though the trees appeared less stressed in February than a month earlier, the crowns were still sparse following leaf shedding during spring and early summer.

By the second study period in October 1995, soil moisture availability had increased considerably. Within the week preceding the study, 7.8 mm of rain was recorded, and a further 15.2 mm fell during the study period. Daily maximum temperatures were 23, 21, 30, and 17°C for the four days from 10 to 13 October. Weather during this period was variable, with intermittent cloudy conditions on 10 and 11 October, heavy rain in the afternoon and evening of 11 October, a clear, warm day on 12 October, and cool, cloudy conditions with a strong wind and some rain showers on 13 October. *E. grandis* was monitored on 7 February, 11 and 13 October, and *E. camaldulensis* was monitored on 9 February, 10 and 12 October. Temporal variations in solar radiation and vapour pressure deficit above the canopy during the two studies are shown in Figure 25.

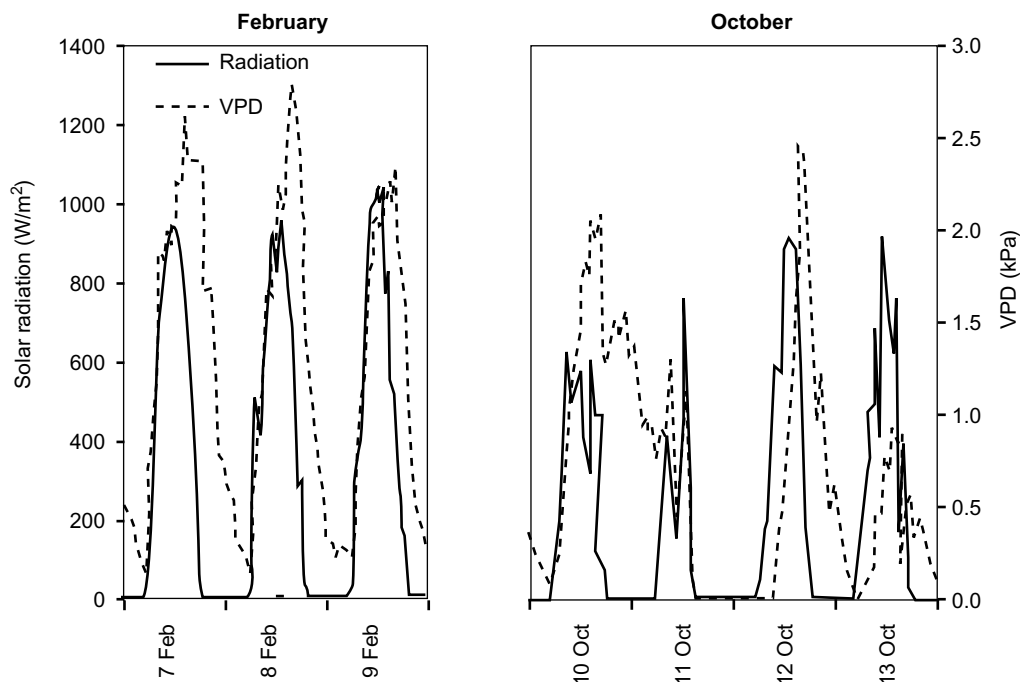


Figure 25. Half-hourly observations of solar radiation and vapour pressure deficit above the Kyabram plantation during the two canopy process studies in February and October 1995.

Analysis of the large amount of data assembled during the 6 days of intensive monitoring was focused on three objectives. The first was to relate the stand conductance derived from sap flow and VPD to directly measured stomatal conductance. The second objective was to

estimate the responsiveness of tree water use to changes in stomatal conductance by derivation of the decoupling coefficient Ω , defined by Jarvis and McNaughton (1986) using the relationship

$$\frac{\partial E}{E} = (1 - \Omega) \frac{\partial g_s}{g_s} \quad (6)$$

where g_s is stomatal conductance and E is transpiration. The third objective was to examine the relationships between transpiration, conductance, and leaf water potential, and the implications for resistance to flow within the soil–plant hydraulic pathway.

Temporal variations in stomatal conductance (g_s) values for the two periods are plotted in Figure 26, with corresponding values of transpiration per unit leaf area and leaf-to-air vapour pressure difference. The conductance values shown are means of 3–15 single-leaf measurements, recorded within a 15-minute period. This approach has been chosen in preference to using a single average of all 20 leaves measured in each set, because variation between canopy sectors was found to be small compared to variation within each sector and 15-minute values provide more data points for comparison with environmental variables. The most obvious features of Figure 26 are the high g_s values in October, and the climate-related variation in transpiration and g_s between days of measurement. Apart from this effect, the differences between species are minor. Although all three variables plotted tend to follow a similar diurnal course, a plot of g_s versus VPD shows no evidence of a relationship, in contrast to the inverse relationship observed for daily stand conductance data (Figure 26). Leaf temperatures were usually close to air temperature (difference of less than 1°C and mostly less than 0.5°C), so the use of VPD outside the canopy as an index of leaf-to-air vapour pressure difference has little effect on the form of relationships with g_s .

A tree conductance g_t , analogous to the stand conductance calculated from daily water use data, was derived from the ratio of transpiration to VPD, with units converted to m/sec as described previously for Equation (4). Plotting this against VPD again showed a hyperbolic relationship, and a linear regression of tree resistance r_t (the inverse of g_t) against VPD showed a good fit to the straight line

$$r_t = 99 + 995V \quad r^2 = 0.82 \quad (7)$$

where r_t is the resistance in sec/m and V is the VPD in kPa. Equation (7) was used to normalise the g_t data (multiplying each value by $99 + 995V$), and the resulting values were compared with solar radiation values by linear regression. The regression was significant with $P < 3.7 \times 10^{-7}$ and $r^2 = 0.22$ for 105 observations. The slope of the regression relationship indicated that conductance increases by 5.7% for each 100 W/m of radiation intensity. The relatively low r^2 value reflects the influence of factors other than radiation and VPD on resistance, but does not invalidate the relationship.

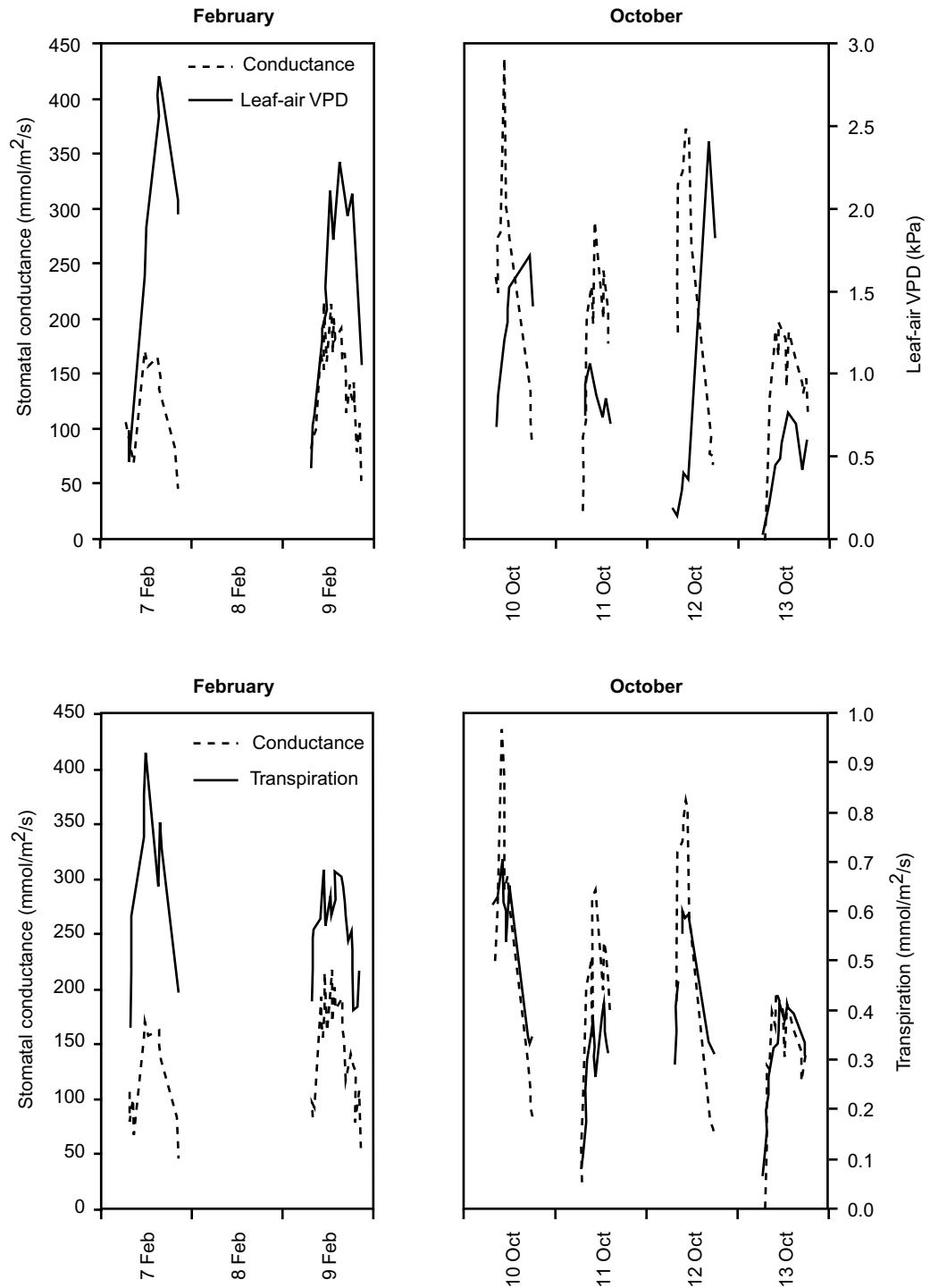


Figure 26. Stomatal conductance (g_s) compared with transpiration and leaf-to-air vapour pressure gradient at Kyabram in February and October 1995. Data for 7 Feb, 11 Oct, and 13 Oct are from *E. grandis*; those for 9 Feb, 10 Oct, and 12 Oct are from *E. camaldulensis*.

Plotting the g_s and g_t observations together in the same units (Figure 27) shows that tree conductance is usually much smaller than stomatal conductance. In other words, the combined resistances to water movement from the soil to the leaf and from the leaf surface to the open air are usually somewhat greater than the stomatal resistance. This is not the case in the early morning, when g_t peaks and is comparable to g_s . On some days, g_t actually

exceeds g_s (notably the morning of 13 October), but these are most likely times when the radiation, VPD, and wind conditions are such that approximation of g_t as the ratio of transpiration to VPD is invalid. The value of g_t usually declines through the day, which may be seen as an effect of drying of the root zone as the trees extract water more rapidly than it can be replaced from groundwater. An exception to this rule occurs on 11 October, when g_t was already low in the early morning following a night of relatively high VPD. Under such conditions at Kyabram, it is common for sap flow to continue through the night.

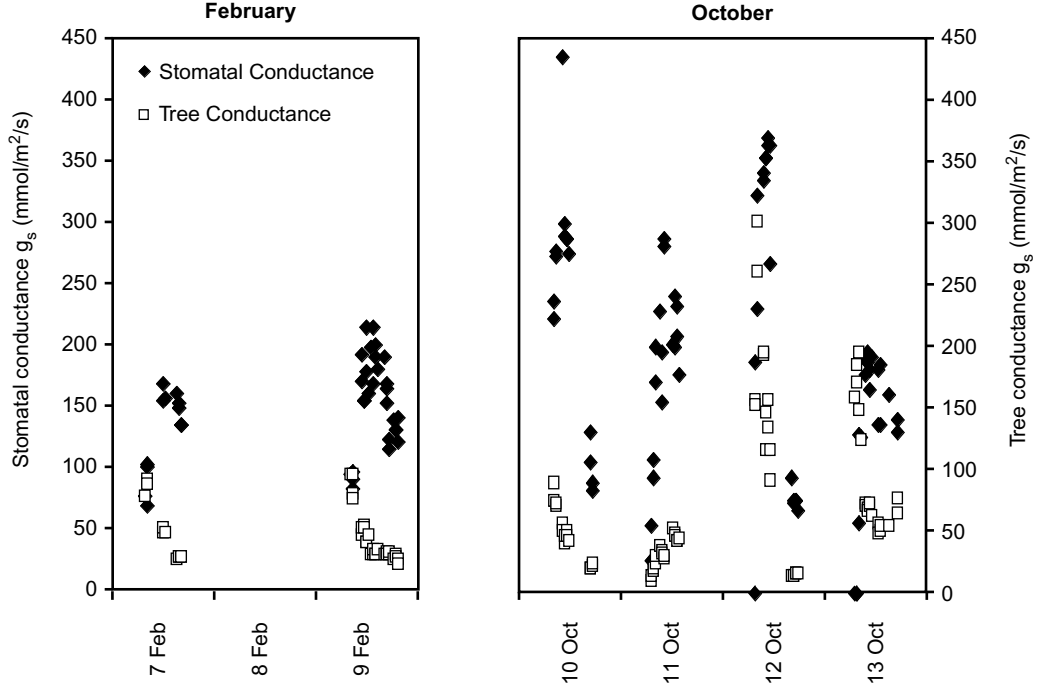


Figure 27. Comparison of stomatal conductance (g_s) and whole-tree conductance derived from sap-flow and VPD observations in February and October 1995.

Our field data permit us to use a variety of methods to derive a decoupling coefficient. The approach taken by Meinzer *et al.* (1993) was to partition g_t into stomatal (g_s) and boundary layer (g_{bl}) components, and then calculate Ω from these two conductances using the method of Martin (1989). The decoupling coefficient for the symmetrical amphistomatous leaves of *E. camaldulensis* is

$$\Omega = \frac{1 + \xi + \frac{g_r}{g_{bl}}}{1 + \xi + \frac{g_r}{g_{bl}} + \frac{(g_r + g_{bl})}{g_s}} \quad (8)$$

where $\xi = \frac{\Delta}{\gamma}$ and g_r is a radiative conductance given by

$$g_r = \frac{4\varepsilon\sigma T^3}{\rho C_p} \quad (9)$$

where Δ is the slope of the saturated vapour pressure – temperature curve (Pa/K), T is the leaf temperature (K), ϵ is the emissivity of the canopy estimated as 0.97, and σ is the Stefan–Boltzmann constant ($56.697 \times 10^{-9} \text{ W m}^{-2} \text{ K}^{-4}$). For the hypostomatous leaves of *E. grandis*, the derivation of Ω is similar, except that the constants in the numerator and denominator of Equation (8) are both set to 2, rather than 1.

Application of this approach to our field data yielded the results shown in Figure 28 (open symbols), with Ω usually ranging between 0.7 and 0.9, except at the beginning and end of the day, when the data may be affected by the time lag between sap flow and canopy transpiration. These high values of Ω for both species in both spring and summer indicate a heavily damped response of transpiration to changes in stomatal conductance. This is supported by a comparison of the transpiration and g_s data from February and October in Figure 26. However, the implicit assumption that g_t contains only stomatal and boundary-layer components leads to a low estimate of g_{bl} , which cannot be reconciled with estimates derived from wind-speed observations. If it is accepted that significant resistance to water flow occurs in the soil–plant pathway, then this may either be partitioned from g_t before deriving g_{bl} (to allow a true comparison of stomatal and boundary layer components) or included with g_s to form a ‘soil–plant’ conductance g_x which is then compared with g_{bl} .

The latter approach was adopted to calculate the second set of Ω values shown in Figure 28 (closed symbols), using a Penman–Monteith function to derive surface conductance from transpiration, aerodynamic conductance, VPD, and available energy estimated from the climate observations. The resulting values of Ω are lower, typically 0.2–0.3 for both species, suggesting that water use is relatively responsive to vegetation control in both spring and summer. However, since the calculations are based on a combined ‘soil–plant’ conductance rather than g_s , the low Ω should be interpreted as a responsiveness of transpiration to this combined conductance. In other words, it is responsiveness to the effects of root-zone soil moisture availability in series with stomatal and other plant conductances, rather than a responsiveness to stomatal conductance alone.

The alternative approach, using measured values of g_s and estimates of g_{bl} from climate data, led to a third set of Ω estimates which generally fell between the other two. These ranged between 0.6 and 0.8 in February, and between 0.3 and 0.7 in October. However, the significance of these results is obscure, since they measure how transpiration would respond to stomatal conductance if there were no other significant resistances in the soil-to-air flow pathway. The data presented show that this is not the case in the Kyabram plantation.

The magnitude of g_x , the conductance from soil to leaf, may be determined from either of the first two Ω calculations by partitioning either g_{bl} (from climate data) or g_s (from porometer measurements) from the respective combined conductances. The results obtained are practically identical for either approach. The form of daily variation in g_x shown in Figure 29, is similar to that of g_t in Figure 27, reflecting the fact that this conductance is usually small compared to g_s , the other component of g_t . It is notably higher in October than in February, declines rapidly during the morning and recovers in the evening, typically falls to around $50 \text{ mmol/m}^2/\text{sec}$ during the day, and is generally similar for both species. Again, these characteristics are consistent with a resistance to water movement to the roots, increasing as the soil around the active roots dries during water uptake during the day. This

component of the pathway is presumably much less conductive than the ‘within plant’ component comprising the xylem of roots, stem, and branches.

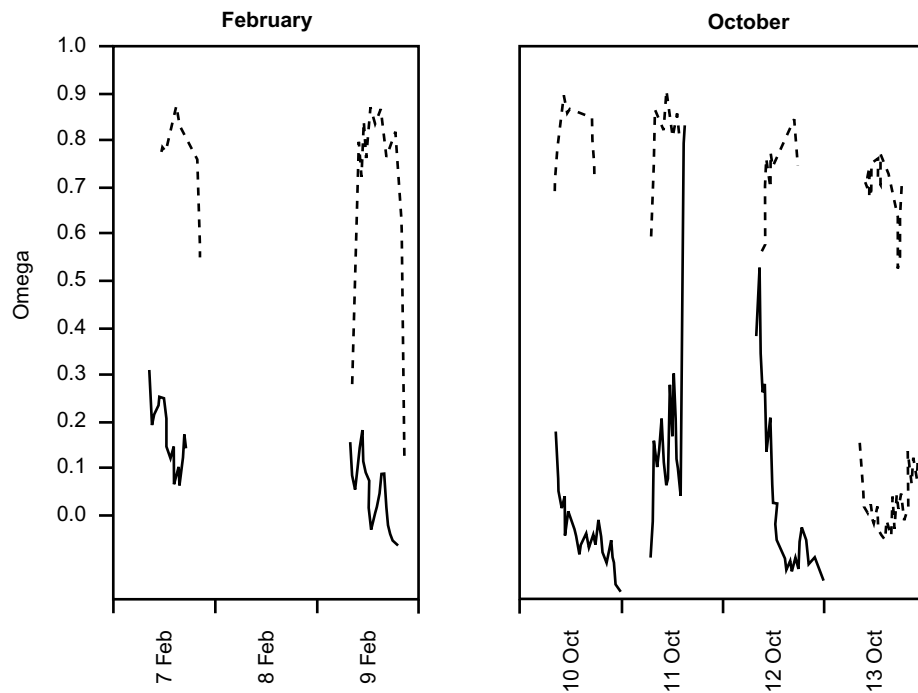


Figure 28. Values of the decoupling coefficient Ω for the Kyabram plantation canopy in February and October 1995. Dashed line is Ω derived by assuming tree conductance is a combination of stomatal conductance and boundary layer conductance only; solid line is Ω derived from Penman–Monteith surface conductance and boundary layer conductance estimated from wind-speed observations.

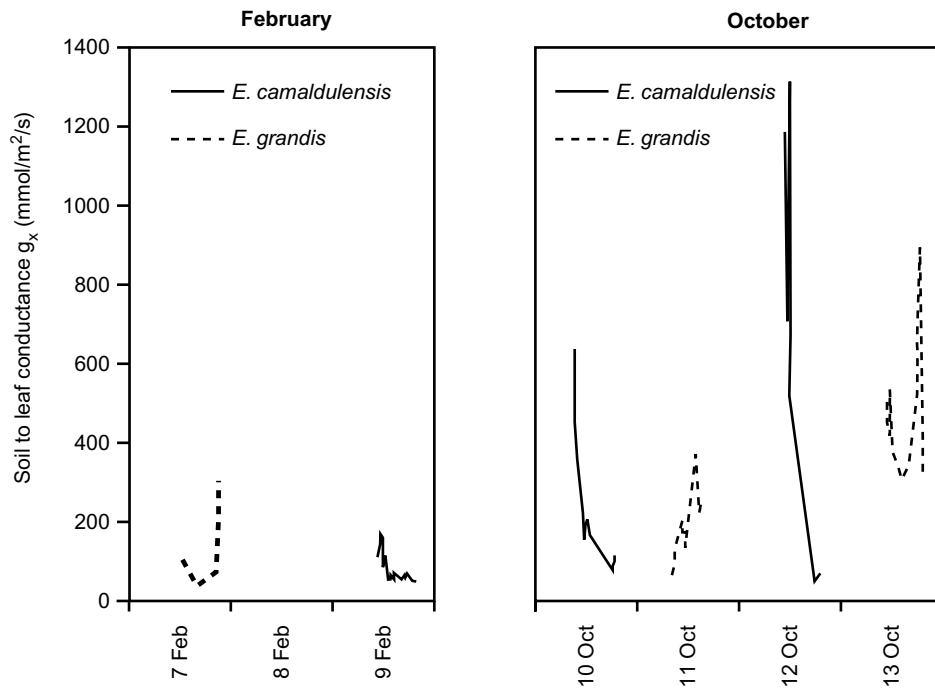


Figure 29. Soil-to-leaf conductance g_x derived from stomatal conductance and Penman–Monteith surface conductance for *E. grandis* and *E. camaldulensis* at Kyabram in February and October 1995.

If g_x estimates the conductance of the pathway from saturated soil to leaves, then dividing the observed transpiration rate by this conductance should yield an estimate of the potential gradient to the leaves, i.e., the leaf water potential. The results of such a calculation are shown in Figure 30, with the gradients in non-dimensional (mole fraction) form compared to the observed water potentials in bars. As far as can be judged from the limited data, the form of variation of the calculated potentials matches that of the observed values reasonably well. However, the potentials calculated for October are relatively low compared to those for February; that is, the observed water potentials in October are higher (actually more negative) than predicted from g_x and transpiration. The data collected do not permit further elucidation of the cause of this difference.

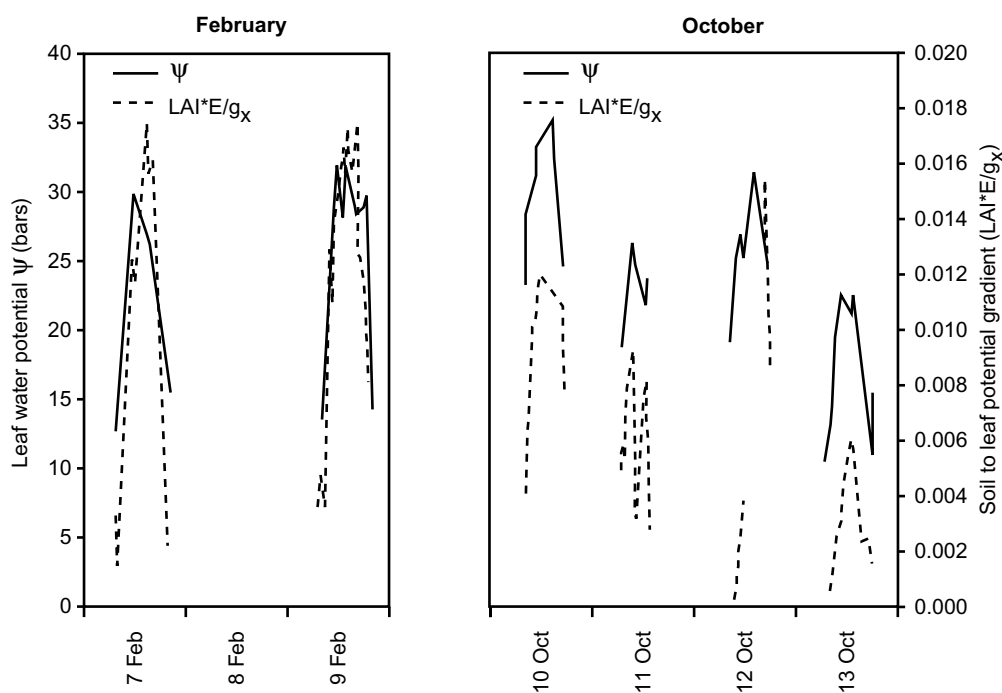


Figure 30. Comparison of observed leaf water potential with a soil-to-leaf potential gradient calculated from g_x and observed transpiration by *E. grandis* and *E. camaldulensis* in February and October 1995.

3.4 Throughfall, interception, and stemflow

Two sets of galvanised-steel throughfall collector troughs were installed in the plantation in early 1994. One set was located beneath the *E. camaldulensis* canopy near site F, and the other beneath *E. grandis* near site B (). Each set consisted of six 240-cm long $\times$ 30-cm wide V-section troughs, radiating from a central collecting drum. Rainfall collected by the troughs ran into the drum, where capacitance water-pulse sensors recorded the depth of water at half-hourly intervals. The volume of water added during each day was divided by the total trough area to derive throughfall depth in mm/day.

Regression analysis of the data from 173 rain days between June 1994 and March 1996 showed a strong linear relationship between throughfall and rainfall for *E. grandis* (equation 10) and for *E. camaldulensis* (equation 11):

$$E. grandis \quad T = 0.65R - 0.32 \quad r^2 = 0.87 \quad (10)$$

$$E. camaldulensis \quad T = 0.68R - 0.37 \quad r^2 = 0.89 \quad (11)$$

where T is the daily throughfall and R is the daily rainfall, both in mm. For both species, these relationships predict zero throughfall for rainfall less than 0.5 mm/day. This is generally in accordance with observations, with the exception of a small number of days when less than 0.5 mm of rain presumably fell in a brief, relatively intense shower. We note that 0.5 mm is a typical value of instantaneous canopy storage for eucalypt forest with an LAI of around 1.0.

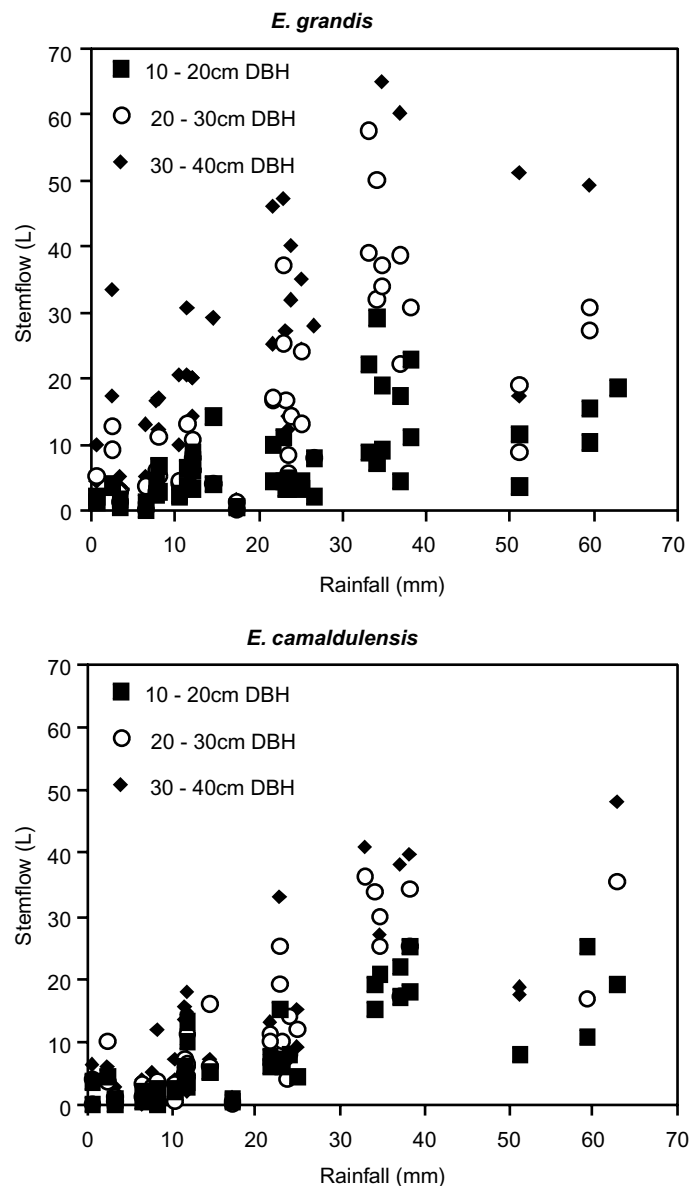


Figure 31. Observed stemflow in relation to rainfall for single trees from three diameter classes of *E. grandis* and *E. camaldulensis*.

Forcing the regressions through the origin allows a simple expression of canopy interception as a fraction of incident rainfall, with only marginal reductions in r^2 . For *E. grandis*, interception averaged 37% of rainfall, while the corresponding figure for *E. camaldulensis* is 34%. These values are higher than might be expected in light of the low leaf area index of the plantation. However, they reflect the fact that most rainfall at Kyabram fell as low-intensity showers dispersed through the day, so that the interception storage capacity of the canopy was repeatedly replenished. On a few days of high intensity rain, daily throughfall actually exceeded 90% of rainfall in both species.

Stemflow was measured on six trees of each species, selected to represent the range of diameters present. A representative distribution within the plantation was also ensured by selecting one tree within each of the twelve plots recognised for monitoring of tree water use. The bark of each selected tree was smoothed with a rasp at 1–1.5 m above ground, and a 5 × 5 cm folded aluminium collector trough was fitted to the stem. The troughs were sealed to the tree stems with bituminous paint and silicone sealant, spiralling around the circumference to intercept any water flowing down the stems. Water from each trough flowed into a 50-L drum at the base of the tree. The drums were emptied and the volume of their contents recorded after significant rain events, roughly every 3 weeks between June 1994 and March 1996.

Stemflow for each tree was compared with the total rainfall during the collection period (Figure 31), revealing a scattered but generally increasing trend with increases in both rainfall and tree diameter. Multiple linear regression was used to fit a log–log model to the data for *E. grandis* and *E. camaldulensis*:

$$\begin{aligned} E. \textit{grandis} \quad \ln S &= 0.54 \ln R + 2.37 \ln D - 6.81 & (12) \\ (132 \text{ observations, } r^2 &= 0.47; \text{ significant at } P = 2.7 \times 10^{-18}) \end{aligned}$$

$$\begin{aligned} E. \textit{camaldulensis} \quad \ln S &= 0.69 \ln R + 0.75 \ln D - 2.27 & (13) \\ (115 \text{ observations, } r^2 &= 0.33; \text{ significant at } P = 1.6 \times 10^{-10}) \end{aligned}$$

where S is stemflow (litres), R is rainfall (mm), and D is diameter at breast height (cm). The low r^2 values of these regressions reflect a high degree of scatter in the data, arising in part from variations in the average intensity of rainfall during each collection period. The large species difference in the coefficient of $\ln D$ suggests that stemflow tends to be proportional to basal area rather than diameter in *E. grandis*, though not in *E. camaldulensis*.

The regressions were applied to predict stemflow for each tree in the four species × planting density strata represented in the study area, for values of rainfall of 1–50 mm and tree diameters measured in November 1995. Stand stemflow in mm was derived by summing the values for all trees in each stratum and dividing by the total plot area for that stratum. Linear regression of the resulting stemflow against rainfall yielded an estimate of the fraction of incident rainfall reaching the ground as stemflow in each stratum (Equations 14–17).

$$E. grandis \quad 4 \times 4 \text{ m spacing:} \quad \text{stemflow} = 2.59\% \text{ of rainfall} \quad (r^2 = 0.79) \quad (14)$$

$$4 \times 2 \text{ m spacing:} \quad \text{stemflow} = 2.23\% \text{ of rainfall} \quad (r^2 = 0.79) \quad (15)$$

$$E. camaldulensis \quad 4 \times 4 \text{ m spacing:} \quad \text{stemflow} = 1.78\% \text{ of rainfall} \quad (r^2 = 0.94) \quad (16)$$

$$4 \times 2 \text{ m spacing:} \quad \text{stemflow} = 2.11\% \text{ of rainfall} \quad (r^2 = 0.94) \quad (17)$$

The value of approximately 2% of rainfall appearing as stemflow is consistent with results obtained in other studies of plantation hydrology. The minor differences observed between species and planting densities are associated with differences in both canopy architecture and plot basal area.

4 Root Response to Salinity

In this section we describe a glasshouse study conducted to elucidate plant sensitivity to soil salt content. We also describe field investigations into rooting profiles beneath the Kyabram plantation and we relate these to soil salt concentrations measured within the same profiles.

4.1 Glasshouse study

4.1.1 Introduction

One of the information requirements for modelling of root system growth and water absorption at Kyabram is an estimate of the sensitivity of these factors to salinity and moisture stress. A glasshouse study was therefore designed to derive a first estimate of these sensitivities for the roots of *E. camaldulensis* seedlings. The study also presented an opportunity to record some detailed responses of growth and water uptake by young *E. camaldulensis* plants to salinity and moisture stress. Further research is required to refine these estimates for varying field conditions and to determine the extent to which they are affected by factors such as soil texture, bulk density, and temperature.

4.1.2 Methods

E. camaldulensis seedlings of a single clone (CFTT clone C23, selected from a population in north-western Victoria) were transferred to 60-cm deep, 10-cm diameter, black-plastic tubes containing sieved topsoil from the vicinity of the Kyabram plantation. The soil surface in the tubes was covered with 2 cm of white plastic (Alkathene[®]) beads to limit evaporative moisture loss. Mean height at the time of transplanting was 35 mm (standard error 2 mm with $n = 100$ plants).

All tubes were thoroughly flushed with a dilute nutrient solution before and after transplanting. The plants were irrigated twice weekly with one of five irrigation treatments. These were Control (18 mL nutrient), moderate moisture stress (M1: 6 mL nutrient), severe moisture stress (M2: 2 mL nutrient), moderate salt stress (S1: 18 mL nutrient containing 2 g/L NaCl), and severe salt stress (S2: 18 mL nutrient containing 4 g/L NaCl).

The heights of all plants were measured fortnightly. Half the plants were harvested after 6 weeks (H1) and the rest after 12 weeks (H2). Measurements on the harvested plants included fresh and dry weights and moisture contents of shoots, and root length and dry weight in each 15-cm depth layer. The total fresh weight of soil in each layer was recorded, and a 100-g sample removed for determination of moisture content (percent of dry weight) and salinity ($EC_{1:5}$).

Water use between harvests was estimated from the difference between total soil water volume at the beginning and end of each inter-harvest period, plus the volume of irrigant solution applied in that time. Water use efficiency was estimated as dry weight gain divided by water use for each period. At the time of transplanting, $EC_{1:5}$ was assumed to be 0.2 dS/m throughout the root zone and soil moisture content was gravimetrically estimated as 32% of dry weight (close to saturation), from measurements in a pilot trial using the same soil. Root length and dry weight of the H1 plants were assumed to be negligible at the time

of transplanting, and estimated for each H2 plant at 6 weeks after transplanting from regressions against plant height for the ten H1 plants in each treatment group. 'Midpoint' estimates of soil moisture and $EC_{1.5}$ in each layer were calculated as the means of their values at the beginning and end of each inter-harvest period.

4.1.3 Results

The mean soil moisture content and salinity in each 15-cm depth layer for the five treatments at each harvest are shown in Figure 32. Water extraction during the first 6 weeks was predominantly from the upper soil layers, although roots penetrated to the bottom of the tubes in all treatments within this time. A gradient of increasing moisture content with depth was apparent at H1. Moisture contents in the M1 and M2 (limited irrigation) treatments were significantly below the Control, and in the S1 and S2 (saline irrigation) treatments were significantly above Control as a result of reduced growth and water uptake.

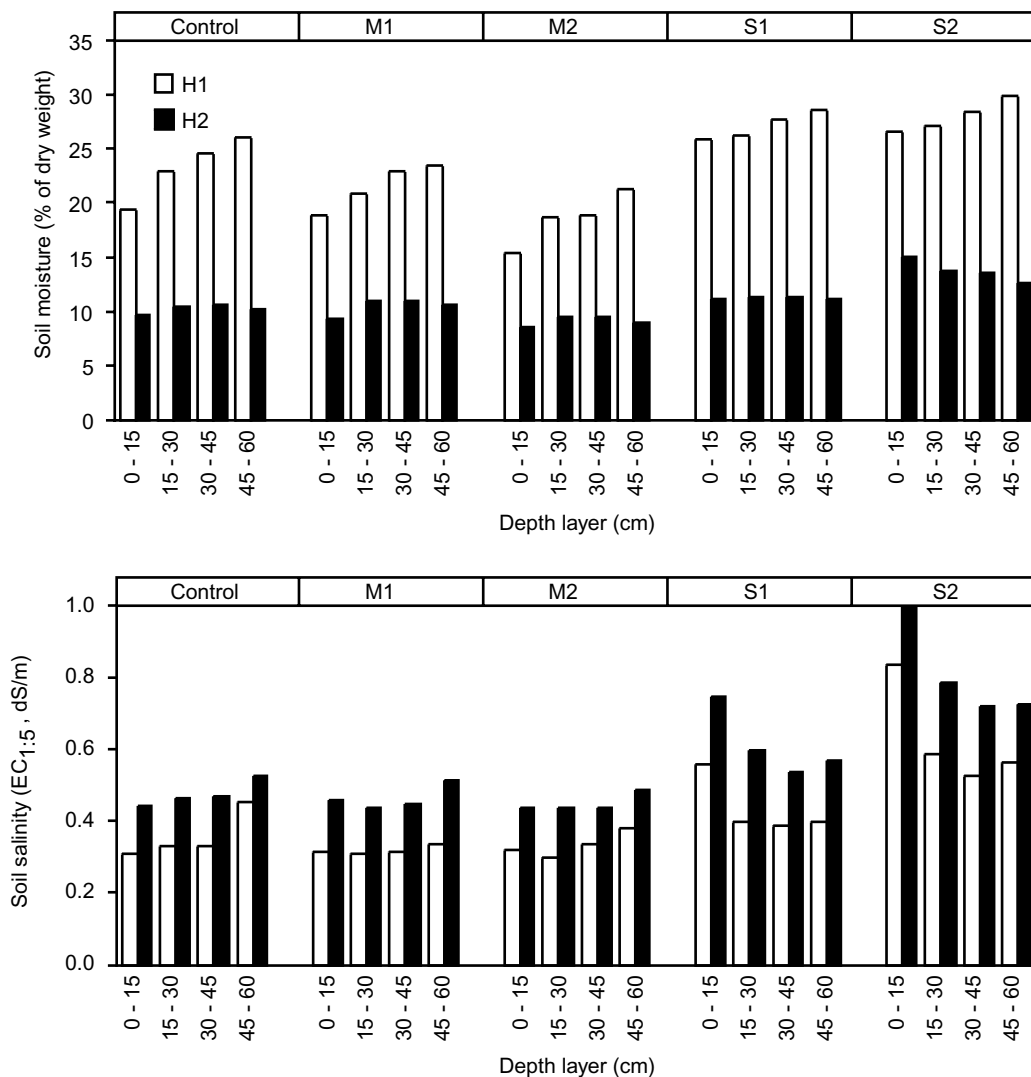


Figure 32. Mean soil moisture content and salinity ($EC_{1.5}$) in four depth layers of tubes containing *E. camaldulensis* plants at 6 weeks (H1) and 12 weeks (H2) from the application of moisture and salinity stress treatments. Values shown are the means of 10 plants per treatment.

During the second 6 weeks, water uptake in all treatments exceeded the rate of application, so that moisture contents were considerably reduced at all depths, and by H2 the differences

between treatments were less marked. The M2 plants remained significantly drier, and the S2 plants significantly moister than Controls. In addition, there was a significant gradient of decreasing moisture content with depth in the S2 treatment, a reversal of the H1 condition.

The saline irrigation treatments significantly increased salinity in the upper 15 cm of the S1 tubes and at all levels in S2 tubes by H1. Salinity continued to increase during the second 6 weeks so that both treatments were more saline than controls at all levels by H2. Accumulation of salt in the upper layers created a strong gradient of decreasing salinity with depth. The low concentration of dissolved salts in the nutrient solution applied to the M1, M2, and Control plants caused a small increase in salinity over the 12 weeks of the trial, with a slight tendency for greatest accumulation in the lowest soil layer.

The effects of these treatments on plant growth and water uptake are shown in Table 7. The saline-irrigated plants grew more slowly than the other treatments at first, and by H1 were significantly smaller in terms of height, shoot fresh weight, and total dry weight. However, their growth rate increased relative to the Control plants during the second 6 weeks while that of the moisture-limited plants decreased, so that by H2 height differences were eliminated and only the M1 and M2 treatments had significantly smaller fresh weights than controls. Shoot moisture content differed little among treatments at H1, but by H2 the moisture content of M2 plants was significantly below control, while that of S2 plants was significantly greater, and whole plant dry weight was less than Control in all treatments.

Table 7. Growth and water uptake by *E. camaldulensis* plants at 6 weeks (H1) and 12 weeks (H2) from commencement of moisture and salt stress treatments.

Treatment	Height (cm)	Shoot Fresh Weight (g)	Shoot Moisture Content (percent of FW)	Total Dry Weight (g)	Root:Shoot DW Ratio	Water Use (mL/wk)	Water Use Efficiency (g/L)	Root water uptake (mL/m/wk)
H1 Control	38.3	4.36	76.7	1.30	0.26	108	1.94	11.2
M1	37.3	4.11	77.9	1.17	0.28	99	1.86	10.8
M2	37.5	4.76	75.8	1.61	0.40	118	2.21	9.1
S1	29.0	2.58	78.3	0.75	0.32	74	1.49	11.0
S2	31.5	2.87	77.5	0.84	0.30	65	2.00	8.4
LSD ($P<0.01$)	7.5	1.24	2.1	0.42	0.08	29	0.43	2.7
H2 Control	49.2	6.20	61.3	3.57	0.49	155	2.96	7.5
M1	46.6	4.81	59.3	2.77	0.42	114	2.64	6.9
M2	45.0	4.86	56.8	2.92	0.39	90	2.38	4.6
S1	51.9	5.83	62.2	3.13	0.42	182	2.16	10.4
S2	49.9	5.75	65.7	2.72	0.36	165	2.19	11.3
LSD ($P<0.01$)	8.6	0.92	3.8	0.62	0.07	25	0.65	2.6

The root:shoot dry weight ratio of M2 plants was significantly greater than control at H1, suggesting a stimulation of root development by limited moisture availability to the young plants. By H2 the proportion of dry weight represented by the root system had increased in all treatments, and declined significantly with both moisture and salinity stress.

The rate of water uptake by the M1 and M2 plants was similar to controls in the first 6 weeks, but the S1 and S2 plants used significantly less. In the second 6 weeks, water

uptake by the controls increased by about 40% and that of the saline treated plants by about 150%, while the rate of uptake by M1 and M2 plants was unchanged. At H1 there was some evidence of a reduction in the effectiveness of S2 roots, compared to the other treatments. However, by H2, the saline treatments both showed significantly greater water uptake than control per unit of root length, whereas the M2 plants showed significantly less water uptake. Neither moisture nor salinity stress induced a measurable improvement in water use efficiency during the 12 weeks of the experiment. By H2, water use efficiency actually tended to decrease with increasing moisture stress and was significantly less than Control in both salt stress treatments.

Variation in root growth with depth is depicted in Figure 33 for each of the five treatments. Initially, growth of root length was greatest in the upper 15 cm of the tubes, but by H1 there was evidence of increasing root growth in the deepest (and moistest) layers of the Control, M1, and M2 plants. During the second 6 weeks there was little further extension growth of roots in the upper 15 cm, but considerable growth in the lower layers, so that by H2 the bottom 15 cm of the tubes had the greatest root length for all treatments.

Root length growth generally decreased with increasing salinity, but the distinction between treatments was not so clear among the moisture stressed plants. Root length of M2 plants was greater than Controls at H1, and remained greater than M1 plants at H2.

Dry weight growth of the root systems differed from length growth, most obviously in the upper 15 cm of soil where increasing lignification and radial growth of the roots led to large increases in dry weight in the absence of any increase in root length. By H2 there was a clear gradient of decreasing dry weight per unit root length down the tube in all treatments. The extent of this secondary growth in the upper 15 cm of soil decreased significantly in response to both moisture stress and salinity.

The data set for analysis of root growth in relation to salinity and moisture stress potentially consisted of 400 six-week growth measurements, with corresponding estimates of midpoint salinity and moisture content. However, the saline-irrigated plants were subjected to some degree of moisture stress in the second 6 weeks of the experiment, and the deeper layers of some Control, M1, and M2 plants may have experienced some salinity stress in the same period (Figure 32). To obtain a data set for which growth was predominantly influenced by salinity, it was necessary to eliminate observations from soil layers or time intervals when moisture was limiting, and vice versa. Inspection of graphic plots of the complete data set suggested that reduction of root growth by salinity was negligible in soil layers with salinity less than 0.4 dS/m, and reduction by moisture stress was negligible when soil moisture content was greater than 18% of dry weight.

Within the data sets defined by these cut-off values, some further tailoring was required to isolate subsets of soil layers in which root growth was not strongly affected by other factors. Figure 34 shows the scatter of data points obtained for root length growth in relation to moisture content, with salinity less than 0.4 dS/m.

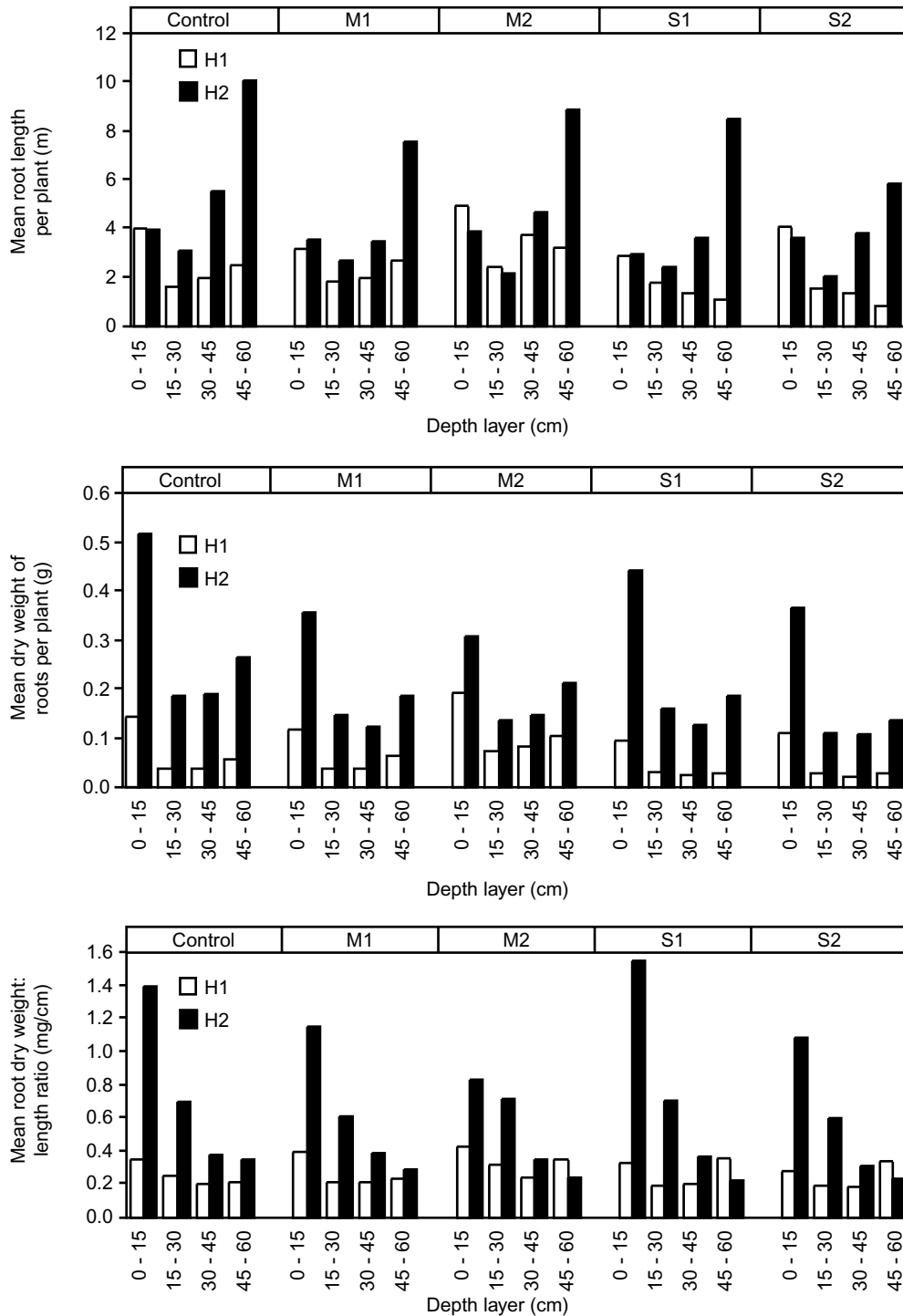


Figure 33. Root length, dry weight, and weight:length ratio for *E. camaldulensis* plants subjected to moisture and salinity stress for 6 weeks (H1) and 12 weeks (H2). Values shown are the means of 10 plants per treatment.

The apparent decline in growth rate with increasing moisture content above approximately 23% is due to the presence of data (mostly from the first 6 weeks) from layers in which roots had only partially colonised the soil. In this range, the data exhibits a response of moisture content to root growth rather than the opposite. The analysis of root length growth

in relation to moisture content was therefore confined to soil layers in which moisture content was less than 23% and salinity less than 0.4 dS/m.

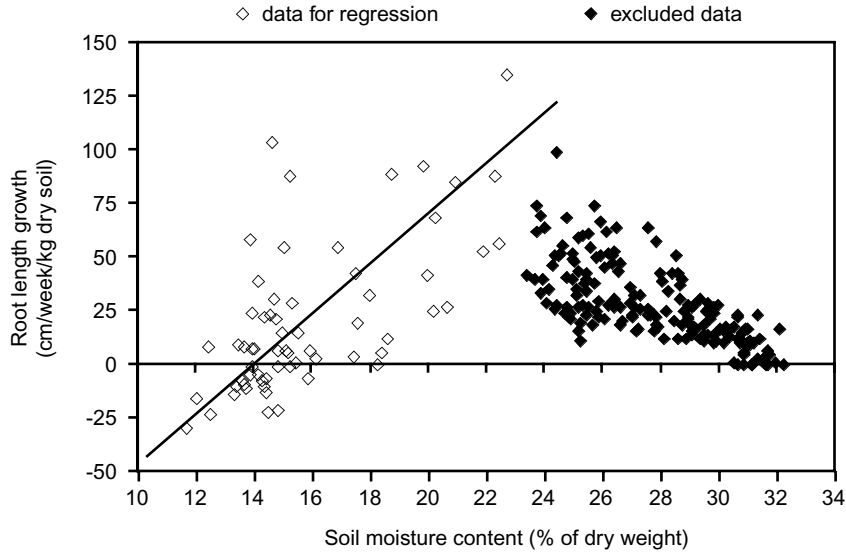


Figure 34. Observed rates of root length growth in relation to soil moisture content for *E. camaldulensis* plants in soil layers with $EC_{1:5}$ of less than 0.4 dS/m, and a regression line ($L = 8.6 M - 116$) derived from points with moisture content less than 23% of dry weight.

For the analysis of root dry weight growth, it was also necessary to exclude data from the upper 15 cm of soil, to avoid the effects of secondary thickening. Similarly, the analysis of root length growth in relation to salinity was confined to soil layers with moisture content above 18% and excluded the lower three layers of the H1 tubes, in which root colonisation was incomplete.

The resulting least-squares linear regression equations relating root length and dry weight growth to salinity and moisture in the root zone are as follows (Equations 18–21):

$L =$	$66 - 59.4 S$	$r^2 = 0.14$	significant at $P < 4.4 \times 10^{-6}$	(18)
$L =$	$8.6 M - 116$	$r^2 = 0.43$	significant at $P < 4.3 \times 10^{-9}$	(19)
$W =$	$2.7 - 2.25 S$	$r^2 = 0.18$	significant at $P < 1.3 \times 10^{-4}$	(20)
$W =$	$0.09 M - 0.2$	$r^2 = 0.09$	significant at $P < 4.9 \times 10^{-2}$	(21)

where L is the root length density growth in cm/kg/week, W is the root dry weight density growth in g/kg/week, S is the salinity as $EC_{1:5}$ in dS/m, and M is the soil moisture content as percent of dry weight. The slopes of these regressions are all significant and may be expected to provide a reasonable estimate of the response of root growth to moisture and salinity in the root zone. However the low r^2 values of equations 18–21 reflect a high degree of scatter in the data. This results largely from the use of midpoint moisture and salinity values for 6-week inter-harvest intervals during which both varied considerably. Ideally soil moisture would have been maintained at a constant level within each salinity treatment, and vice versa. This approach would have necessitated a greater degree of control over root zone conditions than was feasible for the large number of plants utilised in this study. In any case, the maintenance of constant moisture and salinity throughout the depth of the root zone in the presence of root activity presents major practical difficulties.

As an alternative approach, multiple linear regression may be used to simultaneously relate root growth to both moisture content and salinity. This approach was applied to a data set comprising all soil layers with moisture content less than 23%, leading to the relation given by equation (22):

$$L = 5.4 M - 62.7 S - 34 \quad r^2 = 0.12 \text{ significant at } P < 4.3 \times 10^{-6} \quad (22)$$

The coefficients of this equation are generally similar to those derived from the single factor regressions on more limited data sets, suggesting that there is little or no interaction between the reduction of root growth by salinity and by moisture stress. Shalhevet and Hsiao (1986) also found evidence that water stress and salt stress may have an additive, non-interactive effect in depressing growth.

The slopes of the regression lines provide a first approximation to the response of young, actively growing roots in the Kyabram plantation to changes in the moisture content and salinity of the profile as a result of plant water extraction, infiltration, and discharge from the saline watertable. It is not intended that these regressions should be used to predict root growth rates directly, since these will be subject to bulk density, soil structure, and a number of other soil and plant factors under field conditions. Rather, they should provide a rational means of estimating modifiers (to account for the effects of moisture stress and salinity) for the allocation of carbon to sections of the root system in modelling vegetation growth.

If the limiting values of soil moisture and salinity for root growth in the glasshouse approximate those in field conditions, then the roots in the actively growing zones of the profile at Kyabram would be expected to bring the soil there to a moisture content of 14% and $EC_{1.5}$ of 1 to 1.2 dS/m (in the absence of replacement by infiltration or capillary rise). This level of salinity corresponds to approximately 3000–3600 mg total dissolved salts per kg of dry soil, consistent with the observed peak Cl concentrations of 1200–1800 mg/kg beneath the plantation (Figure 35). *E. grandis* and other species in the Kyabram plantation are generally considered less salt-tolerant than *E. camaldulensis* (see Marcar *et al.* 1995) and are therefore unlikely to concentrate salt to a greater extent than this. It is appropriate to question whether the sensitivity of root growth to salinity and moisture in the glasshouse really can provide a valid approximation to field performance, given possibly substantial differences in bulk density, aeration, and soil temperature. More intensive study of roots in the field environment would be required to reach a definitive answer. For the time being, the similarity between peak Cl levels observed in the field and glasshouse is simply presented as preliminary evidence that the sensitivity of root growth may be approximately the same in both. On this basis the peak concentration in the ‘salt bulge’ at Kyabram would not be expected to increase substantially beyond the current level as a result of root water uptake.

4.2 Root distribution field measurements

Depth variations in root density and soil salinity were assessed by analysis of soil cores collected in February 1994 and February 1995. A soil corer mounted on a drilling rig was used to extract 47-mm diameter cores to a depth of approximately 10 m. On each occasion, one set of cores was collected from sites B, D, E, and F. Roots were extracted from each 30-cm depth interval of the cores by washing, sieving, and manual sorting. Root length was

measured using a rotating scanner. A 100-g sample of soil from each interval was reserved for determination of Cl concentration and electrical conductivity of a 1 : 5 water extract.

The results of root length density and Cl determinations are shown in Figure 35. Root density was greatest near the surface, reaching 20 to 50 m/dm³ between 0 and 30 cm depth. This fell to less than 5 m/dm³ at 1–2 m depth, but in most cases rose again to display one or more secondary peaks of root density in the lower profile, between 2 and 7 m. Live roots were clearly evident below this depth, to at least 10 m, at densities of less than 1 m/dm³. Although these roots were growing well below the watertable, the soil around them was evidently not hypoxic.

Cl concentrations of the profiles generally showed a ‘bulge’ of high concentration somewhere between 2 and 8 m depth. The secondary peak of root length density was usually associated with this bulge, occurring either within, slightly above, or slightly below the interval with greatest Cl concentration. Site D in February 1994 was exceptional, displaying very low Cl concentration throughout the profile, although there was a peak of root density between 5 and 8 m. The depth of maximum Cl concentration and root density varied among the four locations sampled, being shallowest at site F (around 2–3 m), then site B (4–5 m), followed by D and E (6–7 m).

By February 1995, following the drought year of 1994, Cl concentrations had increased at all four sites. The depth of the Cl bulge at E and F was shallower than in early 1994, and a strong Cl peak was apparent at D. At site B however, the peak had fallen by about 1 m. Changes in root density generally appeared to follow these movements in the depth of maximum Cl concentration. Because sampling was limited to a single profile from each site on each occasion, spatial variation within sites may confound the interpretation of root growth and salt movement over time. The continuously monitored soil salinity data discussed in section 2.3.2 provide a more detailed record of changes in salt accumulation with time in the upper part of the profile. The more spatially intensive data obtained from these profiles helps to confirm the changes in salt distribution inferred from the salinity sensor data, and at the same time demonstrates that in most cases there was a single distinct zone of Cl accumulation within each profile.

Our data show that Cl concentration and root density may vary considerably over short distances. They also suggest a strongly dynamic nature for the distribution of both root density and salt accumulation within the profile. Large changes, both positive and negative, are observable at a given depth over a year, as the depth of maximum root growth and peak Cl concentration moves up or down in response to changes in soil moisture and watertable depth. These results, together with those reported in section 2.3.2, suggest that salt accumulated in the profile by groundwater uptake by trees is mobile in response to changing root zone conditions. The Cl bulge appears to identify the zone of current maximum water uptake, and to be capable of relatively rapid dissipation and re-formation in response to fluctuations in root activity linked to changes in watertable depth. This interpretation contrasts with a commonly held perception that, in the absence of leaching, accumulated salt is permanently stored in the root zone and that a salt bulge indicates the part of the profile salinised by previous (rather than current) root activity.

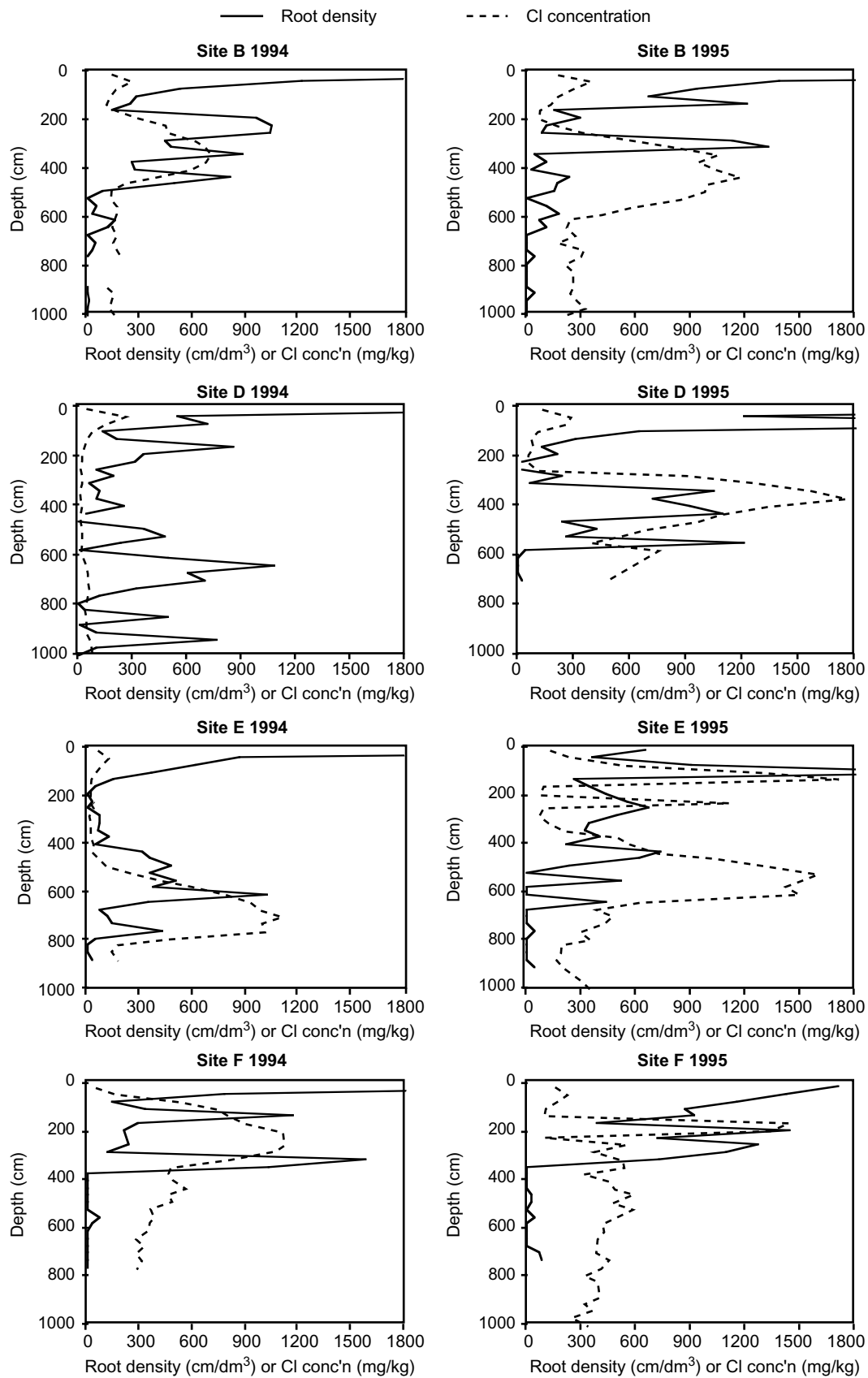


Figure 35. Variation in root length density and chloride concentration with depth at four sites in the Kyabram plantation in February 1994 and February 1995. Solid line is root density, dashed line is chloride concentration.

5 Modelling of Plantation Sustainability

In this section we describe the model developed to simulate water, salt, and carbon balance of the Kyabram plantation and adjacent irrigated pastures. Details of the main model algorithms are presented and we describe the required data inputs to the model. The model is then tested by applying it to the Kyabram site, using field data gathered prior to and during this study. We conclude this section by describing a variety of modelling experiments, performed to illustrate the hydrologic function of the Kyabram plantation. These were conducted to (i) predict the future behaviour of the plantation, and (ii) elucidate plantation response to varying boundary conditions, such as initial groundwater level and salinity and various plantation management regimes. In most of these modelling experiments we explore the impact of assuming different levels of plant sensitivity to salt.

Most of the modelling results reported in this section have been published recently in the international journal literature by Silberstein *et al.* (1999).

5.1 Introduction to the model

Our objective was to build a model that could simulate the water, salt, and carbon balances of a plantation, established in an environment with a high and saline watertable, and subject to a variety of management practices. Specific requirements were that the model should:

- account for variability in system properties (such as climate, soil type, and profile);
- predict the impact of different types of vegetation (e.g., pastures versus trees) on evapotranspiration, groundwater levels, and salt movement;
- 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;
- capable of being run for at least the length of a plantation rotation.

These requirements were met 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 (i.e., 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.

A number of other models exist which fulfil some of these requirements of this project, but none include all the required components or are as flexible as Topog_Dynamic. The SHE model (Abbott *et al.* 1986a,b) and its derivatives (for example, MIKE-SHE, see Refsgaard and Storm 1995) do model flow and solute transport in the unsaturated and saturated zones, but do not include vegetation growth. While MODFLOW (McDonald and Harbaugh 1988) does provide a good representation of saturated groundwater flow, it is restricted to a rectangular flow net, and it does not have a representation of the unsaturated zone. It requires recharge inputs to each cell to be defined for each time-step and has no representation of vegetation interactions. Specifically, these models have no way of modelling the interaction and feedbacks that occur between vegetation (as it grows and develops roots) and the soil water and solute profile.

Topog_Dynamic is referred to as a ‘deterministic’, ‘distributed parameter’ model. The term ‘deterministic’ means that it is based on biophysical principles, which are applicable to a diverse set of environmental conditions. The term ‘distributed parameter’ means that the model accounts for heterogeneity in site properties. Thus, spatial variability in soil and aquifer properties, or surface cover and climate, can be accommodated. However, it is important to note that the model can be run assuming that there is no spatial variability in catchment properties.

Most parts of the model employ state-of-the-art mathematical descriptions of the key hydrologic and plant physiological processes. It is specifically set up as a research tool to ask ‘what if’ questions about how plantations will behave and perform if established in degraded environments. Some research models treat the key processes in even greater detail, but no other model treats as broad a range of processes as Topog_Dynamic.

Although Topog_Dynamic offers the potential to address quite complex questions, its sophistication also poses some problems. First, it is complicated to run and requires considerable training to use properly. Second, it has quite onerous data input requirements. Often, appropriate input data is not available so this must either be (i) gathered at considerable cost, or (ii) estimated from secondary sources, leading to uncertainty. Third, the model is computationally intensive, necessitating the use of a high-performance workstation, rather than a desktop PC. Fourth, the model is difficult to validate. Critics of this type of model argue that because there are so many parameters to adjust, you can obtain any answer you want. Doubts about the validity of model predictions can only be addressed if detailed field observations are available to test several components of the model.

5.2 *What does Topog_Dynamic predict?*

Prior to the commencement of this project, the model was able to simulate:

- interception of rainfall by plants;
- evaporation from the canopy surface and soil surface;
- overland flow;
- infiltration and vertical redistribution of water in the unsaturated zone;
- 1-dimensional lateral movement of perched groundwater;
- plant transpiration from a single vegetation layer; and
- recharge losses to deep groundwater.

During this project, the model was further developed to also simulate:

- plant growth for two vegetation layers, including effects of salinity and fertility;
- plant transpiration from a second vegetation layer;
- conservative solute transport in the soil and groundwater systems;
- hydrologic linkages between the shallow and deep hydrologic zones;
- 2-dimensional lateral movement of deep groundwater, including the effects of groundwater abstraction by pumping; and
- discharge from deep groundwater.

Each of the above processes is modelled using a daily time-step, and solved for each element in the flow net being simulated.

5.3 Model description

Topog_Dynamic simulates the 3-dimensional water and solute dynamics within a catchment (as a set of coupled 1-dimensional and 2-dimensional equations) on a daily time-step, and couples these to plant growth and carbon allocation. This model is a development of an earlier version entitled Topog_IRM (Dawes and Hatton 1993, Hatton and Dawes 1993, Dawes *et al.* 1997, Vertessy *et al.* 1996b). Catchments can have spatially distributed soil profiles, vegetation types and combinations, and climate. The processes represented in each model catchment element are illustrated in Figure 36.

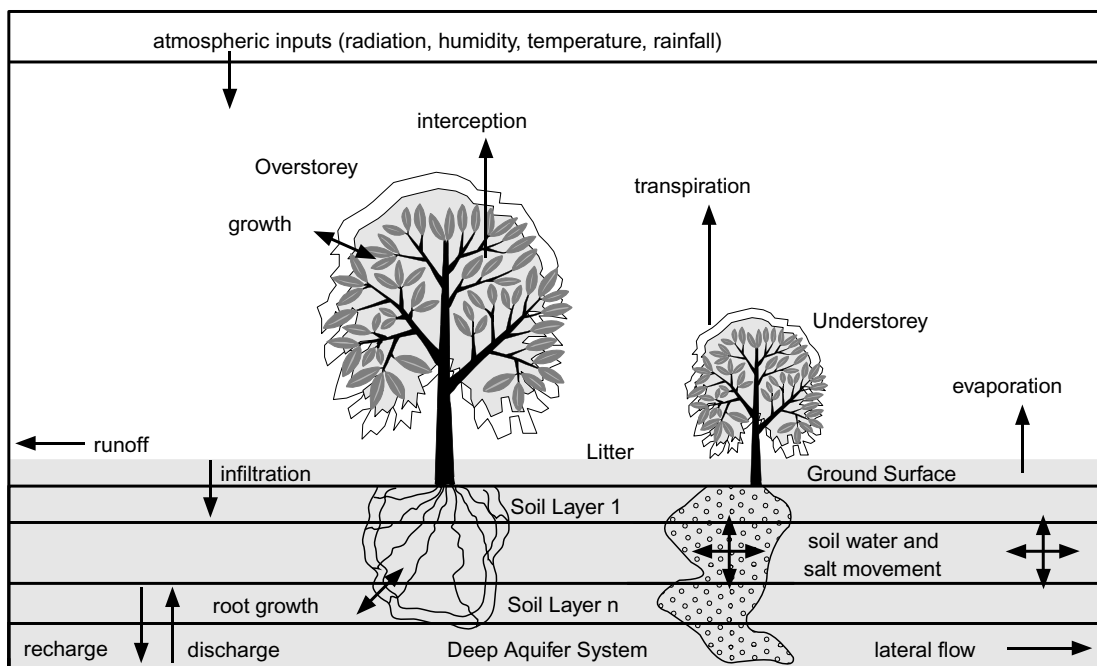


Figure 36. Processes modelled by Topog_Dynamic for each catchment element.

5.3.1 Structure of the model

The processes modelled by Topog_Dynamic are solved by a number of different computational modules, including:

- a flow net module;
- an evapotranspiration module;
- a plant growth module;
- a soil water and solute transport module; and
- a groundwater flow module.

These various modules are described in detail below. It is important to note that not all components of the model have to be run in any given simulation. For instance, the model can be run without invoking the groundwater flow or solute transport. Similarly, the groundwater module can be run on its own.

5.3.2 The flow net

All catchment models require a ‘flow net’ of some kind, which defines the direction of water flow through the area of interest. For surface and shallow sub-surface flows, Topog_Dynamic uses a flow net defined by elevation contours and lines of steepest descent (O’Loughlin 1986, Dawes and Short 1994). For deep groundwater flow, a triangular finite-element mesh is used. It is possible to ascribe varying system properties (such as soil type, rainfall rate, or vegetation cover) across both flow nets.

5.3.3 The evapotranspiration module

The evapotranspiration module computes the following processes:

- rainfall interception by overstorey and understorey vegetation, and by the litter layer;
- evaporation of intercepted rainfall from vegetation surfaces, and from the soil;
- transpiration by overstorey and understorey vegetation; and
- extraction of water (by plant roots) from the soil profile and groundwater system.

5.3.3.1 The radiation balance

For each layer, the surface radiation balance consists of four components, including incoming short-wave radiation (a model input), reflected short-wave radiation from the surface, incoming long-wave radiation from the atmosphere, and emitted long-wave radiation from the surface. Ignoring advection, for each catchment element, the radiation balance can be written as:

$$R_n = R_{sd} - R_{su} + R_{ld} - R_{lu} \quad (23)$$

where R_n is the net radiation, R_{sd} is the short-wave downward radiation, R_{su} is the short-wave upward radiation, R_{ld} is the long-wave downward radiation, and R_{lu} is the long-wave upward radiation. The short-wave downward radiation on a horizontal surface is modified according to the slope and aspect of the element (Klein 1977).

An approach similar to that of Monteith and Unsworth (1990) is adopted in Topog_Dynamic for modelling the radiation balance of each layer. By assuming all leaves are randomly distributed with horizontal inclination, the radiation balance for the overstorey is written as follows:

$$R_{sv1} \downarrow = R_{sd} [1 - \exp(-K_e LAI_1)] \quad (24)$$

$$R_{sv1} \uparrow = R_{sd} \alpha_1 [1 - \exp(-K_e LAI_1)] \quad (25)$$

$$R_{lv1} \downarrow = R_{ld} [1 - \exp(-K_e LAI_1)] \quad (26)$$

$$R_{lv1} \uparrow = R_{lu} [1 - \exp(-K_e LAI_1)] \quad (27)$$

where the subscripts $sv1$ and $lv1$ indicate short-wave and long-wave radiation, respectively for vegetation layer 1 (overstorey). The arrows indicate the flux directions, K_e is the radiation extinction coefficient for the overstorey, LAI_1 is the cumulative leaf area index of the overstorey, and α_1 is the albedo of the overstorey.

Following Brutsaert (1982), the long-wave radiation is estimated as:

$$R_{ld} = \varepsilon_a \sigma T_a^4 \quad (28)$$

$$R_{lu} = \varepsilon_s \sigma T_a^4 \quad (29)$$

with

$$\varepsilon_a = 1.24 \left(\frac{e_a}{T_a} \right)^{1/7} \quad (30)$$

where ε_a is the atmospheric emissivity, T_a is the air temperature in K, e_a is the vapour pressure in hPa, ε_s is the surface emissivity (assumed to be 0.97) and σ is the Stefan–Boltzman constant. The radiation balance of the understorey canopy and the soil surface are treated in a similar fashion.

The energy balance for the canopy and soil layers is thus:

$$R_{nv1} = R_{sv1} \downarrow - R_{sv1} \uparrow + R_{lv1} \downarrow - R_{lv1} \uparrow \quad (31)$$

$$R_{nv2} = R_{sv2} \downarrow - R_{sv2} \uparrow + R_{lv2} \downarrow - R_{lv2} \uparrow \quad (32)$$

$$R_{ng} = R_{sg} \downarrow - R_{sg} \uparrow + R_{lg} \downarrow - R_{lg} \uparrow \quad (33)$$

where R_{nv1} , R_{nv2} , and R_{ng} are the net radiation for overstorey, understorey, and ground surface, respectively.

5.3.3.2 Computing evapotranspiration

Evapotranspiration is calculated using the Penman–Monteith equation:

$$\lambda E = \frac{sR_n + \rho c_p \frac{D_a}{r_a}}{s + \gamma \left(\frac{1+r_c}{r_a} \right)} \quad (34)$$

where s is the slope of the saturation vapour pressure curve, R_n is net radiation, ρ is the air density, c_p is the specific heat of air, D_a is the vapour pressure deficit of the air above the canopy, γ is the psychrometric constant, r_a is the aerodynamic resistance, and r_c is the canopy (surface) resistance. As in Running and Coughlan (1988), Hatton *et al.* (1992), and Leuning *et al.* (1991) we assumed r_a to be constant for a given canopy and is an input parameter. On a daily time-step, soil heat flux is assumed to be negligible.

5.3.3.3 Calculating canopy conductance

For transpiration, the canopy conductance is calculated using the empirical model of Ball *et al.* (1987) as modified by Leuning (1995):

$$r_c = \left\{ g_o LAI(k) + \frac{g_1 A}{(C_a - \Gamma) \left(1 + \frac{D_c}{D_{co}} \right)} \right\}^{-1} \quad (35)$$

where g_o is the residual stomatal conductance, g_1 is an empirical coefficient scaling assimilation to vapour pressure deficit, A is the assimilation rate, C_a is the CO₂ mol fraction at the leaf surface, Γ is the CO₂ compensation point, LAI is the leaf area index, k is the light-extinction coefficient within the canopy, D_c is the vapour pressure deficit at the canopy surface, and D_{co} is an empirical coefficient.

The vapour pressure deficit (VPD) at the overstorey canopy (D_c) is modified to reflect the effective deficit at the understorey canopy surface (*sensu* Grantz and Meinzer 1990). This modified deficit (D_{mod}) is calculated using the omega coefficient (Ω) proposed by Jarvis and McNaughton (1986):

$$D_{mod} = \Omega D_{eq} + (1 - \Omega) D_c \quad (36)$$

with

$$D_{eq} = \gamma R_n \left(\frac{r_c}{\rho c_p} \right) \left(\frac{\varepsilon}{(\varepsilon + 1)} \right) \quad (37)$$

$$\Omega_c = \frac{\varepsilon + 1}{\varepsilon + 1 + \frac{r_c}{r_a}} \quad (38)$$

where Ω_c is the decoupling coefficient, D_{eq} is the equilibrium saturation deficit, and ε is s/γ . A similar approach is used to reduce the vapour pressure deficit below the understorey for the soil surface, except instead of using D_c in Equation (36), the understorey canopy value of D_{mod} is used.

5.3.3.4 Soil moisture extraction by roots

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

$$x_w = \frac{1}{\psi_{lmax} z_r} \sum \rho_i \Delta z_i \min(\psi_{lmax} - \psi_i + \eta \pi_i, 0) \quad (39)$$

where the parameter x_w represents the combination soil moisture and salinity stress, ψ_{lmax} is the maximum leaf water potential (i.e., most negative) of the plants, z_r is the maximum rooting depth of the plants, ψ_i is the soil moisture potential, and π_i is the osmotic potential due to salt in the soil moisture, within each depth interval i , of thickness z_i , and ρ_i is the

proportion of roots within the depth interval, and η is the salt-sensitivity factor. The salt-sensitivity factor is used in the model to scale the osmotic potential of the groundwater relative to soil moisture potential. Generally, η is set at 1, though evidence is mounting through laboratory experiments that indicate that as soil dries, even slightly below field capacity, it could be much higher (Stirzaker and Passioura 1996). Later in this section we show how the use of different η -values affect model results.

5.3.4 Soil evaporation

Soil evaporation is calculated using the Penman–Monteith equation with the surface resistance set to zero if the soil surface is not air-dry, or determined by the method of Choudhury and Monteith (1988) when in second-phase drying:

$$r_s = \frac{\tau}{\eta} \frac{l}{D_m} \quad (40)$$

where η is the porosity of the soil, D_m is the molecular diffusion coefficient for water vapour, τ is the tortuosity factor, and l is the depth of the air-dry soil layer, determined dynamically by the Richards equation solution for water content.

5.3.5 The vegetation growth module

The vegetation growth module computes the following processes related to leaf, stem, and root growth for both understorey and overstorey vegetation:

- photosynthesis by leaves;
- carbon allocation to leaf, stem, and root compartments;
- distribution and density of roots through the soil profile;
- leaf, stem, and root respiration and leaf mortality; and
- litter accumulation and decay.

Detailed descriptions of the plant growth model in Topog_Dynamic can be found in Hatton *et al.* (1992), Dawes and Hatton (1993), Vertessy *et al.* (1996b), and Wu *et al.* (1994). We use the underlying principle of the Integrated Rate Method (IRM) of growth determination, that actual growth rate can be represented by a potential growth rate modified by a dimensionless parameter between 0 and 1.

Leaf, stem, and root growth and senescence are modelled for each vegetation type given within the domain. The model assumes that the actual CO₂ assimilation rate depends on a maximum rate and the relative availability of light, water, and nutrients. It computes the assimilation index (r_g) of (Wu *et al.* 1994):

$$r_g = \frac{1 + w_h + w_n}{\left(\frac{1}{x_l x_T}\right) + \left(\frac{w_h}{x_n x_w}\right) + \frac{w_n}{x_n}} \quad (41)$$

where w_h is the weighting of water relative to light, w_n is the weighting of nutrients relative to light, x_w , x_n , and x_l are the relative resource availabilities for water, nutrition, and light,

respectively, and x_T is the modifier of light availability due to temperature. The latter modifier is based on a Gaussian distribution of temperature effects parameterised by the optimal temperature and the temperature at the half-saturation response. Finally, carbon assimilation (A_g) is calculated as:

$$A_g = r_g A_{max} \quad (42)$$

where A_{max} is the maximum mean daily assimilation rate of CO_2 .

Five carbon pools are defined, these being litter, leaf, root, live stem, and a soluble pool expressed as a fraction of leaf carbon. Maintenance respiration is calculated as a function of temperature as in Running and Coughlan (1988) and net photosynthesis is calculated as assimilation less total respiration. When daily respiration exceeds assimilation, carbon is taken from the soluble pool (if present), then from the leaf and root pools. Growth respiration is assumed to be a constant fraction of allocated carbon (Rauscher *et al.* 1990).

On days when assimilation exceeds respiration, a soluble carbohydrate pool is filled. When it reaches its maximum, the excess is assigned dynamically to leaves, roots, and stems. Leaf carbon may not exceed a level where 95% of incoming light is intercepted, nor exceed stem carbon. These conditions recognise that once canopies capture all available light, there is little point adding more leaves, and that leaves require some minimum mechanical and hydraulic support. Carbon allocation to leaves, roots, and stems is dynamic and follows the approach of Running and Gower (1991) in that the leaf : root ratio is based on the relative availabilities of above- and below-ground resources (*sensu* Chapin *et al.* 1987, Wilson 1988), in this case as calculated by the equation for r_g .

The partitioning of fixed carbon between above-ground and below-ground ‘pools’ is determined by the moisture stress, x_w , (defined above) of the vegetation. The proportion of carbon allocated above ground (to leaves and woody stems) is given by:

$$a_{above} = a_{min} + x_w (a_{max} - a_{min}) \quad (43)$$

where a_{max} and a_{min} are the maximum and minimum above-ground fractions, respectively.

Increments to root carbon are distributed by dynamic allocation of carbon through the root zone. We assume that root carbon is continuous from the surface downwards, that roots are added to the wettest (most favourable) region of soil, and that roots grow downwards in search of water, if necessary. The favourability of a soil region is a function of its moisture potential and osmotic potential as represented by x_w above.

Irrespective of daily assimilation, each of the three living carbon pools suffers daily decrements, representing the turnover of leaves, bark, and roots. Shedding from the two above-ground carbon pools, as well as any carbon from net negative assimilation, contributes to the litter pool. This litter pool decays as a function of temperature and moisture (Hatton *et al.* 1992).

5.3.6 The soil water and solute transport module

The soil water and solute transport module computes the following processes:

- infiltration of rainfall into the soil;
- vertical percolation of moisture through the soil profile;
- development of perched watertables;
- lateral sub-surface flow (saturated flow only);
- recharge to a deep groundwater store; and
- the effect of line sources and sinks on soil water redistribution.

5.3.6.1 Vertical unsaturated flow

The soil water module is driven by a numerical (finite-difference) solution of the Richards equation (Beverly 1992, Short and Dawes 1995), in Fokker–Planck form:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left(K - \frac{\partial U}{\partial z} \right) \quad (44)$$

where U is the Kirchoff transform:

$$U = \int_{-\infty}^{\psi} K d\psi \equiv \int_0^{\theta} D d\theta \quad (45)$$

where K is the hydraulic conductivity for a given soil moisture potential (ψ) and D is the soil water diffusivity for a given soil moisture content (θ). Unsaturated flow is handled in the vertical dimension only, and hysteresis effects are ignored. Multiple layer and variable soil depths are accommodated, as are spatially variable soil profiles. Allowance has been made for the specification of line sources (e.g., sub-surface infiltration trenches) and sinks (e.g., drains).

5.3.6.2 Lateral saturated flow

Lateral flow is permitted to occur downslope only after a watertable develops. Hence, no allowance is made for unsaturated lateral flow, though this is not a common occurrence in nature (usually taking place only in highly anisotropic media, and even then only as small fluxes). Lateral sub-surface flow is modelled using Darcy's law, with topographic slope (rather than piezometric levels) being the primary driving gradient:

$$q_i = K_i z_i \frac{dh}{dx} \quad (46)$$

with q the lateral flux, K the lateral hydraulic conductivity, z the saturated depth of the soil column and dh/dx the local slope of the catchment element i . For flat terrain (such as at the Kyabram site), it is necessary to activate the groundwater flow module to ensure that lateral sub-surface flows are modelled properly.

5.3.6.3 Solute transport

We model salt movement in the soil column using a transient, conservative-solute transport equation, based on the traditional 1-dimensional convection–dispersion equation, which neglects reactive and sorptive processes:

$$\frac{\partial(\theta c)}{\partial t} = \frac{\partial}{\partial z} \left(D_{zz} \frac{\partial c}{\partial z} - q_w c \right) \quad (47)$$

where q is the solute flux, c is the solute concentration, D_{zz} is the vertical component of the hydrodynamic dispersion tensor, q_w is the vertical water flux, and the other terms are as previously defined. Salt is assumed to move in solution with soil water. The extraction of moisture by roots, which develop in response to soil conditions, and by periodical influx events from the surface or deeper groundwater, results in movement and redistribution of the salts within the soil profile. Further details of the solute transport are provided in Dawes and Short (1993).

5.3.7 The groundwater flow module

The finite-element groundwater flow module computes the following processes:

- groundwater level for each element in the aquifer flow domain;
- flux of groundwater flow between neighbouring aquifer elements;
- groundwater discharge into the soil water system;
- conservative solute transport through the aquifer flow domain; and
- effects of groundwater abstraction on groundwater flow.

5.3.7.1 Two-dimensional flow equation

Flow in the deep groundwater system is modelled using a two-dimensional saturated flow equation, with flow rates specified on the boundary of the domain to represent sources and sinks:

$$\frac{\partial}{\partial x} \left(K_x \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_y \frac{\partial h}{\partial y} \right) + q = S_s \frac{\partial h}{\partial t} \quad (48)$$

where q is the specified flow rate (positive into the mesh), S_s is the specific storage, K_x and K_y are the soil hydraulic conductivities in the x - and y - directions, respectively, and $h(x,y,t)$ is the groundwater piezometric level through the mesh in time.

Equation (48) is solved across a finite-element mesh that is co-registered beneath the surface-element mesh used by the other Topog_Dynamic modules. Automatic mesh-generation software has been provided to enable simple creation of the finite-element mesh, and includes graphically based routines to simply customise mesh attributes on the computer screen.

Boundary conditions for the groundwater flow module can be set to constant or time-varying head or flux, and imposed conditions can be set at any node within the groundwater flow domain. Provision has been made for groundwater abstraction by pumping at any point

within the domain. Simulations can be set up assuming confined or unconfined conditions, and the model is able to handle spatial (but not vertical) variability in aquifer properties, such as conductivity and storage.

Once an element in the groundwater system is saturated, discharge into the soil water system is allowed to occur using the linkage scheme described below in section 5.3.7.3.

5.3.7.2 Groundwater solute transport

Within any finite element, the concentration of a conservative solute can be described by the convective–dispersion equation as:

$$\frac{\partial C}{\partial t} = D\nabla^2 C - v\nabla C \quad (49)$$

where C is the element mean concentration (assumed uniform within an aquifer mesh element), D is the two-dimensional dispersivity tensor, and v is the two-dimensional velocity vector, and ∇ is the two-dimensional differential operator.

5.3.7.3 Linkage between the groundwater system and surface water column

A simple linkage scheme (based on a potential transfer flux) is used to transmit water between the soil water and deep groundwater systems. The watertable within the soil profile is considered to overlie the deeper aquifer. When the underlying aquifer intersects the base of the soil column, a comparison between the intrusion height and the current day's watertable depth is made to determine the potential transfer flux required to equilibrate the two heads. When the head of the underlying aquifer differs from that of the soil watertable, there is a flux, $q^\dagger$, between them. This is calculated as the harmonic mean of the soil moisture deficit ($\theta_{sat} - \theta$) and aquifer specific storage, S , divided by the time-step length, t , and the soil profile conductivity, K_s , and the saturated hydraulic conductivity of the aquifer, K_{aq} . The term $q^\dagger$ is more easily represented by its reciprocal:

$$\frac{1}{q^\dagger} = \frac{1}{4} \left(\frac{t}{\theta_{sat} - \theta} + \frac{t}{S} + \frac{1}{K_s} + \frac{1}{K_{aq}} \right) \quad (50)$$

This method is chosen because it gives a smooth transition between aquifer recharge and discharge regimes (since it is always less than the minimum value of the four parameters which limit the flux), thus ensuring a well-behaved numerical condition.

5.4 Key model inputs

The model input requirements for Topog_Dynamic can be lumped into five categories, these being: topographic, climatic, vegetation, soils, and aquifer data (Table 8). Typical parameter values for most of these inputs can be found at the Topog Online web site at <http://www.clw.csiro.au/topog>.

Table 8. Data inputs and and data sources for Topog_Dynamic

Data Type	Data Source
<i>Climatic inputs</i>	
• daily rainfall	local meteorological station
• daily max. and min. temperature	local meteorological station
• total daily solar radiation	local meteorological station
• mean daily humidity	local meteorological station
• irrigation daily rate (if applicable)	local irrigation records
<i>Vegetation inputs (for each vegetation type specified within the catchment)</i>	
• initial leaf, stem, and root biomass	measurement or calibration
• initial root distribution through the soil profile	measurement, or assumed from a set of choices from literature
• respiration coefficients for leaf, stem, and root compartments	calibration, measurement if available
• maximum above-ground carbon partition	literature or calibration
• mortality coefficients for leaf, stem, and root compartments	literature
• maximum carbon assimilation rate	literature or calibration
• albedo of canopy and soil surface	measurement or literature
• aerodynamic roughness of canopy and soil surface	measurement or literature
<i>Soil inputs (for each soil type specified within the catchment)</i>	
• depth	field survey
• $K-\theta-\psi$ relationship	measurement or literature based on texture
• groundwater recharge/discharge coefficients	set to <i>on</i> or <i>off</i>
• initial moisture content	measurement or calibration
• initial salt concentration	measurement or calibration
• <u>flow sources or sinks (if applicable)</u>	field survey
<i>Aquifer inputs</i>	
• aquifer thickness	field survey
• initial groundwater level	measurement
• boundary flow conditions (e.g., constant head or flux)	chosen according to field conditions or simulation choice
• saturated hydraulic conductivity	measurement, literature or calibration
• storage coefficient (for unconfined aquifer case)	measurement, literature or calibration
• porosity (for confined aquifer case)	measurement, literature or calibration
• groundwater abstraction rate (if applicable)	measurement, literature or calibration
• initial salt concentration	measurement, literature or calibration
• salt concentration boundary conditions (e.g., constant or time varying)	measurement, literature or calibration
• longitudinal salt dispersivity (i.e., in direction of flow)	measurement, literature or calibration
• transverse salt dispersivity (i.e., tangential to flow)	measurement, literature or calibration

5.5 Testing the model

5.5.1 Field data sets for model input and testing

Testing a model such as Topog_Dynamic is problematic. To begin with, because of spatial variability it is very difficult to characterise the physical properties of a catchment. Soil and rainfall variability, in particular, are common sources of input error in any modelling analysis (Davis *et al.* 1999, Vertessy and Elsenbeer 1999). Then there is the problem of determining a suitable data set with which to compare the model. Most data sets usually include observations on one or two phenomena such as runoff and/or groundwater level. To properly evaluate a model such as Topog_Dynamic, it is necessary to have simultaneous observations of several phenomena. Fortunately, these requirements have largely been met by the excellent data set compiled for the Kyabram site.

As noted earlier in this report, the Kyabram field site was monitored intensively between February 1994 and March 1996 to acquire sufficient data to parameterise and test Topog_Dynamic. Below we provide a brief overview of these data sets.

The saturated hydraulic conductivity of the unsaturated-zone study site soils was measured at five depths in the unsaturated zone, using the disk permeameter and constant-head well permeameter techniques (see section 2.1.1). Similar measurements were made for the saturated zone using the slug well withdrawal method on four piezometers permanently penetrating the watertable (see section 2.1.2). Moisture retention characteristics for the soils were derived by fitting the model of Broadbridge and White (1988) to measurements made on samples of soil from the site and from the Lemnos Loam profiles found elsewhere in the study area (K.A. Olsson, ISIA, Tatura, unpublished data).

Several soil moisture and salinity monitoring instruments were installed throughout the plantation to build up a picture of how water and salt move (see sections 2.2 and 2.3). A dense network of piezometers yielded data to provide a spatio-temporal pattern of groundwater levels beneath and outside the plantation (see section 2.4). The leaf area index (LAI) of the plantation was estimated on 23 occasions from 1995 to 1997, giving an indication of how the trees reacted to soil moisture and salinity stress during the study period (see section 3.1). Water use data were collected from a total of 229 trees, with a diameter distribution closely matching that of the whole stand (see section 3.2). The physiological behaviour of the plantation canopy was investigated, providing useful parameterisation and validation data for the vegetation growth and evapotranspiration modules in Topog_Dynamic (see section 3.3). The dynamics of rainfall interception (a major component of the Kyabram water balance) were measured throughout the study (see section 3.4). Finally, we examined rooting patterns beneath the plantation and their relation to soil salinity levels (see section 4.2).

In addition to the above measurements, which have been reported earlier in the report, we compiled data on stem growth rates. Annual stem growth through the life of the plantation was estimated from the mean value of tree-ring radius measurements on four *E. grandis* trees, chosen as representatives of the plantation. Two estimates of live stem mass were made by taking the annulus area of the current and three previous years' rings and calculating volumes from the estimated mean plantation height by assuming pyramidal and conic sections. The use of a total of four growth rings as our estimate of live stem wood was

made on the basis of the sapwood observations. The value for mass of wood was converted to stem carbon for comparison with the value computed by the model by assuming that carbon was half the total mass, and that the wood had a density of 500 kg/m^3 . The estimates of live stem carbon are affected by several sources of errors. These include difficulties in ring discrimination, asymmetry of rings, variability in the trees sampled and in the rest of the plot, and the error introduced by using the conic and pyramidal volume for total wood volume. The measurement standard errors are plotted later with the results.

5.5.2 Model setup

Our field observations were sufficient to calibrate the model, though some simplifying assumptions were necessary, particularly some regarding the vegetation growth module parameters. We assumed that all species in the plantation could be adequately represented by a single set of vegetation parameters. This assumption was necessary because there were insufficient data to distinguish the model parameters between the species planted at Kyabram. Plant respiration coefficients were treated as calibration parameters to ensure LAI fell within the measured bounds, and that modelled transpiration over the measurement period was similar to that measured. The maximum carbon assimilation rate (A_{max}), required for the canopy conductance model, was taken from Slavich (1997), and the optimum temperature was estimated to be the mean temperature for the site. Tree leaf turnover time was estimated to be about 2 years, which equates to a model leaf mortality of 0.0014. Stem mortality was set at 0.0007, equating to a 4-year turnover as discussed above, and root mortality was assumed to be the same as for leaves. All vegetation parameter values adopted are given in Table 9.

Since the Kyabram site had no vertical relief, the catchment network had no topographic gradient driving lateral flow. The only lateral flow that occurs is sub-surface, driven by the piezometric gradient of the groundwater. Hence, the surface element network was derived by setting up a flat, square grid, and co-registering this on a finite-element mesh that had its base 20 m below the surface. The soil column was assumed to contain five different soils within the top 8 m (see Table 10), grading from a loam ($K_{sat} = 0.33 \text{ m/day}$) at the surface through a clay-loam, to a clay ($K_{sat} = 0.1 \text{ m/day}$). We assumed a more conductive silty-loam ($K_{sat} = 2.0 \text{ m/day}$) to occur between 6 and 8 m depth. Our field observations indicate that this is actually only 1-m thick, but we doubled it as it spanned the junction between the soil profile and the deep aquifer system. The model watertable depth was initialised at 3.7 m in the plantation and at 2.0 m in the adjacent irrigated pasture, these being the average levels observed in the field.

Figure 37 shows the model layout for the Kyabram plantation, illustrating the proportions of the domain ascribed to trees and irrigated pasture.

Table 9. Vegetation and soil surface parameter values used for simulations described

Vegetation name	Irrigated pasture	Plantation
rain interception coefficient	0.0001	0.0015
light-extinction coefficient	-0.65	-0.4
canopy albedo	0.1	0.15
soil albedo	0.15	0.15
maximum assimilation rate (kg/C/m ²)	0.02	0.025
slope of Ball & Berry (g1)	1	1
maximum leaf water potential (m)	-100	-150
ratio mesophyll to gas phase conductance (wh)	0.2	0.2
IRM weighting for nutrients	0	0
optimum temperature for growth (°C)	15	15
year-day of germination (-1 = N/A)	-1	-1
degree-day-hours for growing season (-1 = N/A)	-1	-1
saturated light value (μmoles m ⁻² s ⁻¹)	1200	1200
specific leaf area (m ² /kg/C)	24	12
leaf respiration coefficient	0.0025	0.0013
stem respiration coefficient	-1	0.00001
root respiration coefficient	0.0002	0.00025
leaf mortality rate	0.0055	0.0014
stem mortality rate	0	0.0007
root mortality rate	0.00002	0.0015
above-ground carbon partitioning	0.4	0.6
salt factor, η	1	1
maximum rooting depth (m)	0.5	8
canopy aerodynamic resistance (s m ⁻¹)	30	15
soil aerodynamic resistance (s m ⁻¹)	60	60

Table 10. Soil parameter values used for the Broadbridge and White (1988) model of the soil moisture characteristics

	Loam	Clay-loam	Clay	Clay	Silty-loam
Depth Interval	0–0.2 m	0.2–0.6 m	0.6–1.4 m	1.4–6.0 m	6.0–8.0 m
K _{sat} (m/day)	0.33	0.30	0.20	0.10	2.00
θ _{residual}	0.22	0.28	0.28	0.20	0.23
θ _{sat}	0.41	0.40	0.40	0.40	0.40
λ _c	0.20	0.50	1.00	1.00	0.25
C	1.50	1.30	2.00	2.00	1.05

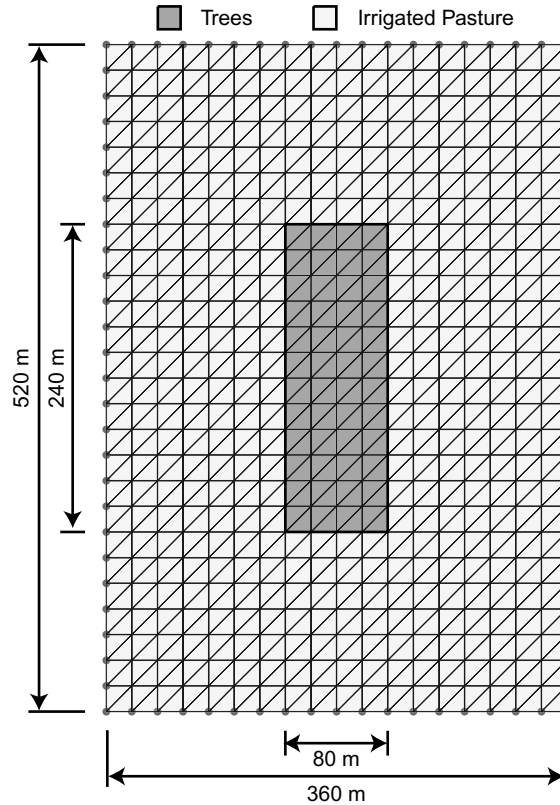


Figure 37. The model layout for the Kyabram plantation surrounded by irrigated pasture. The square soil column mesh is shown co-registered with the underlying triangular finite-element aquifer mesh, and boundary nodes are indicated. The node interval is 20 m.

5.5.3 Comparison of model results and field observations

Figure 38 shows the comparison of measured and modelled daily transpiration, leaf area index (LAI), and watertable elevation for the plantation site at Kyabram. In each case the dotted lines indicate standard error bounds of the measurement. In Figure 38b, values are given for both the estimates of LAI as measured by the Li-Cor instrument (the lower squares) and for these values corrected following Battaglia *et al.* (1998) (the upper squares). The correction given by Battaglia *et al.* (1998) applies for *E. globulus* plantations, whereas the Kyabram plantation is of mixed species, so we present the uncorrected values as a lower estimate and we expect the true value to lie somewhere in between them. The dotted lines indicate the measurement standard errors outside these ranges. In Figure 38c, the error bounds shown for the watertable measurements are estimated from the variability of watertable levels in the deep piezometers within the plantation. However, variation between some piezometers was greater than that shown.

Figure 39 shows the modelled daily transpiration rate, plotted against the measured rate for (a) the entire 4-year measurement period, and (b) the first 150 days of measurement only. The dotted lines are the 1:1 lines. The comparison over the full period suffers as a result of the very low range of daily transpiration values, though over the first 150 days the model does reasonably well. Linear regression analyses yielded the following relationships and r^2 values:

For the entire 4-year period:

$$\text{Modelled } T = \text{Measured } T * 0.908 + 0.149 \quad (r^2=0.36, N = 111).$$

For the first 150 days of measurement:

$$\text{Modelled } T = \text{Measured } T * 0.950 + 0.148 \quad (r^2=0.72, N = 22).$$

The results of a 20-year simulation are shown in Figure 40, where watertable depths, salt storage within the top 8 m of soil, plantation live stem carbon, and LAI are plotted with the measured data. The watertable depth was estimated from all piezometers that penetrated permanently to the watertable, and the two salt storage measurements were estimated from data presented by Heuperman (1995). The live stem carbon measurements were estimated from the annual ring measurements, with the two traces representing the different masses resulting from the pyramidal (the upper trace) and conic section (the lower trace) volume calculations. The error bounds indicate the measurement standard errors in each case, except for the salt storage calculations where the error was estimated to be 20% on the basis of known variability at the site currently. The only LAI data available are those over the 4 years presented in Figure 38, and these are reproduced in Figure 40 for illustration.

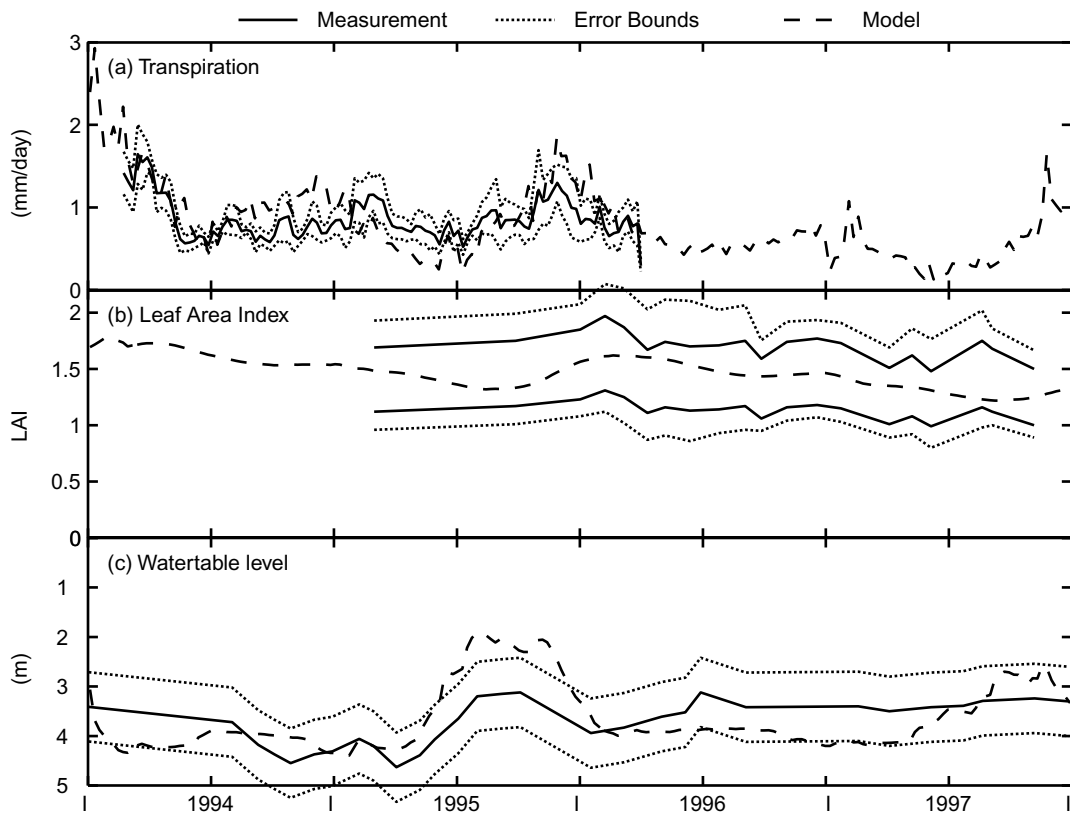


Figure 38. Comparison between field observations and model simulations of (a) transpiration, (b) leaf area index, and (c) watertable depth under the plantation during the intensive monitoring period. The watertable depth plotted is the average level in all piezometers penetrating permanently to the watertable. Dotted lines indicated estimated standard error bounds.

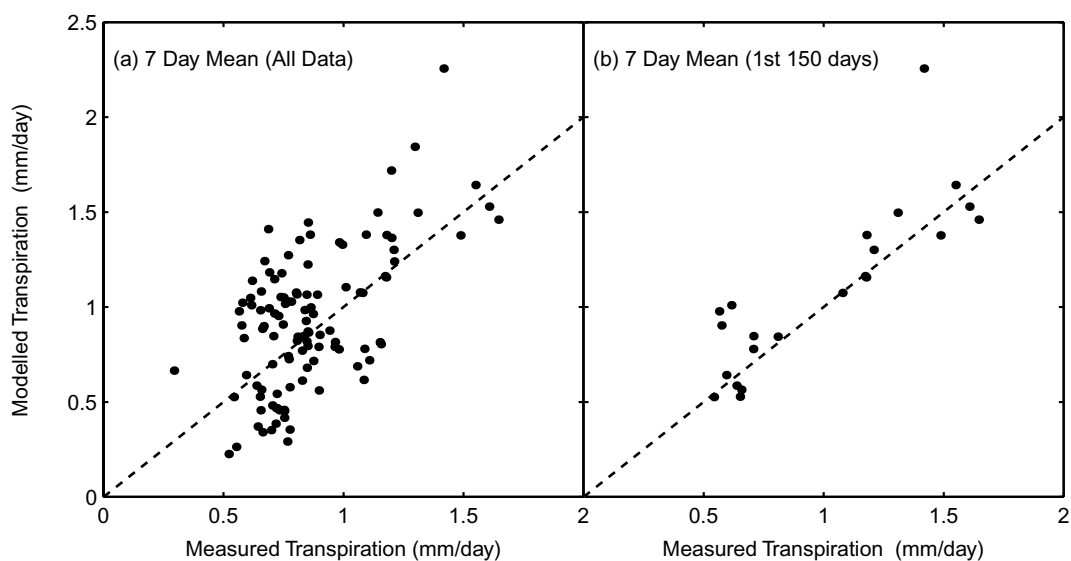


Figure 39. Modelled transpiration (as 7-day mean) plotted against measured values for (a) the entire 4-year measurement period, and b) the first 150 days. The dotted line is the 1:1 line.

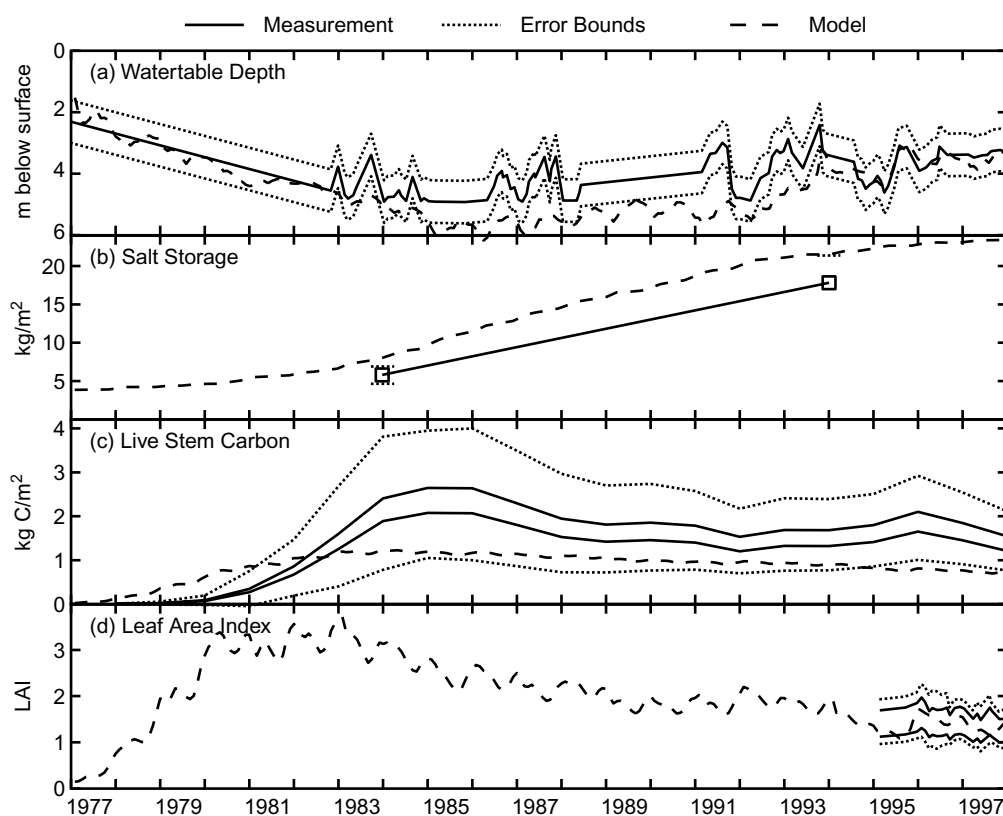


Figure 40. Modelled and measured trends in (a) watertable depth, (b) salt storage within the top 8 m of soil, (c) live stem carbon, and (d) LAI through the 21-year life of the plantation at Kyabram. The dotted lines indicate the estimated standard error bounds.

Figure 41 compares measured and modelled profiles of root carbon, averaged for the period March 1994 to March 1995. Also shown in Figure 41 are model predictions of the salt

profiles in 1983 and 1992, alongside measured profiles reported by Heuperman (1995), recalculated as storage of salt per unit volume of soil. The model profiles presented are those predicted to exist on the day of the measurements in 1983 and 1992. The simulation commenced at the time of planting (January 1977) and was initialised with a constant vertical salt profile totalling 3.9 kg/m^2 . The root profile was initialised to an exponential distribution to 30 cm as an estimate of seedling roots.

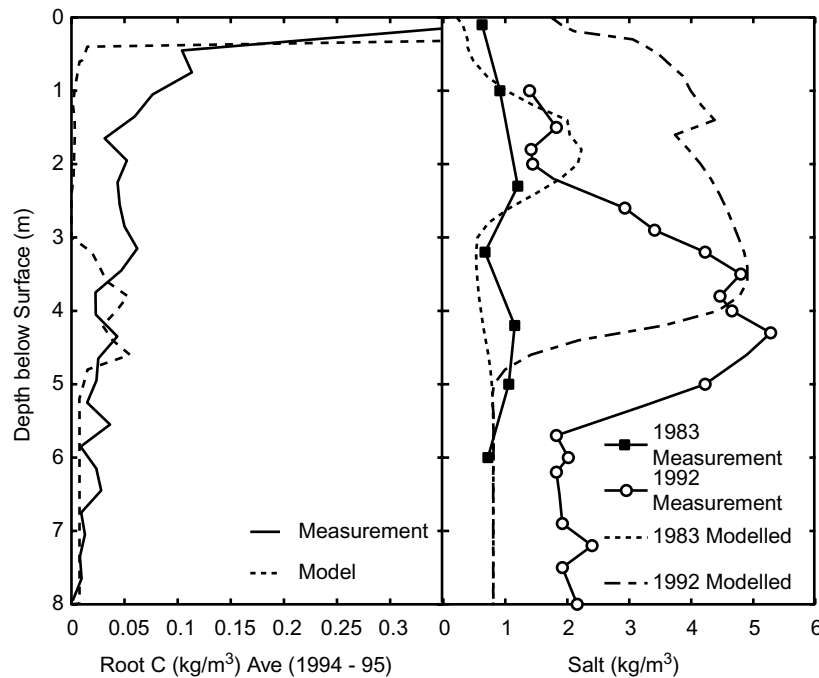


Figure 41. Soil profiles of (a) root density and (b) salt storage as measured at Kyabram, shown with those developed through the 21-year simulation of Topog_Dynamic.

5.5.4 Discussion of model performance

Thus far, we have shown that the model credibly reproduces most of the field measurements of water, salt, and carbon balance made at the Kyabram site. Leaf respiration was used as a calibration parameter to restrict the range of LAI to within the measured bounds, but we did not have control over the general declining trend during the 4-year measurement period which occurred within the model and which fits the measured trend reasonably well. The differences in the seasonality between the modelled LAI and the field measurements were partly due to attacks by defoliating insects which occurred during this time, and which were not represented by the model. For the 21-year simulation (Figure 40d), the model was initialised with an estimate of seedling leaf area, yet still produced a good comparison with the measured LAI in the final 3 years. This result was attained with the same respiration coefficients as the short-term simulation, indicating that the model is reasonably stable and has represented growth processes in a credible manner.

The mean transpiration rate through the 2-year measurement period was only 1 mm/day and leads to a relative error of around 30% at times. This makes it very difficult to examine the modelled differences and hence to determine how the model could be improved. Only through the first 150 days of measurement was there much variation, and this was

reproduced by the model quite well, as evidenced by a coefficient of determination of 0.72. This corroborates earlier studies which validated the same transpiration model at different sites with different climatic conditions (Vertessy *et al.* 1996, Dawes *et al.* 1997, Zhang *et al.* 1996, Zhang *et al.* 1999).

The watertable dynamics simulated by the model show good agreement with the measured watertable behaviour, particularly over the 4-year intensive field programme. Over the 21-year life of the plantation, the simulated watertable also follows that of the measured one, although the model suggests that it would have been drawn down to deeper levels during the period 1984–91 when growth was at its best (Figure 40a). The determination of the ‘true’ watertable depth is problematic. In the field, the groundwater system exhibits significant heterogeneity, with watertable measurements in neighbouring piezometers within the plantation varying by several metres at any one time. Part of the problem appears to be the low permeability and heterogeneity of the soil, with the consequence that the profile is not really in the steady state required for a piezometer to give a reliable measurement. In the model, we cannot realistically represent the myriad of different soil structures and textures, even if we could determine them. The model does not have the same heterogeneity and does not strictly represent confining structures, so the representation of the watertable depends on the particular choice of soil moisture retention function used. In the model, the watertable is defined as the soil moisture potential at the base of the 8 m soil column, although it can also simulate the development of shallower saturated (perched) layers.

As far as we can tell, the model reproduces salt accumulation at about the right rate (Figure 41b). This is particularly encouraging, for it means that the model simulates the right balance of tree water uptake from rainfall and groundwater. If this balance were incorrect, the observed and predicted salt accumulation rates would differ. The shape of the salt accumulation ‘bulge’ over the 21 years of the plantation is reproduced very well by the model (Figure 41b), and the sharp ‘kink’ in salt concentration at around 2 m depth in the measured profile also appears in the modelled profile. The main body of salt concentration is a little higher in the profile than it should be. This is likely to be caused by root activity being focused too much in the shallower soil, and not enough at depth. As noted earlier, active roots were found at 10 m below the surface, well into the apparent watertable. The measured watertable is seldom more than 5 m from the surface, and roots do not flourish under waterlogged conditions. It is therefore difficult to see how this could be modelled. In the simulations, the comparable root activity occurred at around 4–5 m, in the region of watertable fluctuation.

Finally, our simulation of live stem carbon may be regarded as satisfactory. However, while the trend is reasonable, with a peak at about the right time and a slow fall off, the model has not reached the size of the peak it should have, and has too flat a response. This is likely to be because the partitioning of carbon between leaves and stems is too simplistic (it is assumed to be 50% each). There is no allowance for varying this as plantations age, nor as site conditions and stresses vary. It is our intention to remedy this by incorporating recent developments in modelling forest growth, as presented by Landsberg and Waring (1997). It is likely that root activity also has to be examined, as there was too little root growth between the surface and the active region around the watertable. This also suggested by the location of the salt bulge being too near the surface, as discussed above.

5.6 Set up of modelling experiments

5.6.1 Plantation sensitivity to environmental conditions

To examine how a plantation like that at Kyabram might perform through a whole rotation and to consider how site characteristics might affect such a plantation, the model was used to simulate tree growth from planting to age 30 years. To do this a longer climate series had to be assembled. This was done by copying the first 10 years of climate data and adding it to the 20-year sequence used in earlier simulations.

The unsaturated soil column was initialised with a salt content of 3.9 kg/m^2 , determined by extrapolating back to 1976 from the 1983 data presented by Heuperman (1995). The effects of three variables were examined in detail. First, the simulation was performed with groundwater initially at 1 m, 2 m, 4 m, and 6 m below the surface. Then, for each watertable depth, the groundwater was ascribed three different levels of salinity: 700, 2000, and 6000 mg/L. Finally, the simulations were repeated for varied salt sensitivity factors, η , of 0.5, 1, and 3.

5.6.2 Harvesting, rotation, and irrigation impacts

Additional simulations were conducted to explore the effects on growth and salt and watertable dynamics of a plantation grown for 21 years and then replaced with irrigated pasture, at which time a second plantation was established in a neighbouring paddock. This was accomplished in the model by terminating a simulation after a 21-year run, and replacing the vegetation parameters in the plantation elements with those for pasture. At this point in time the elements that had been ascribed pasture parameters were changed to plantation. The period of 21 years was chosen because that is the current age of the plantation and so we could simulate the effect of harvesting now. The area under irrigation was modified by changing the climate distribution within the domain, and the climate used for both 21-year rotations was the same. The second plantation was established at a different site from the first because the salt accumulation within the root zone of the first plantation would certainly have a severe impact on the second rotation. Simulations were then conducted, maintaining irrigation to the plantations throughout their life cycle. These simulations were initialised with conditions, estimated from measurements, to be the same as at the time of planting at Kyabram. The salt sensitivity factor, η , was set to 1, the watertable was set at 2 m below the surface, and a constant-head boundary condition was assumed for the groundwater system.

Figure 42 shows the model domain for these simulations. Firstly, plantation was ascribed to the elements labelled as 'I', and after 21 years this was replaced with irrigated pasture and a new plantation was ascribed to the area labelled 'II'. For these simulations, both of the plantations were irrigated for the first 6 years, as was the case for the actual plantation at Kyabram.

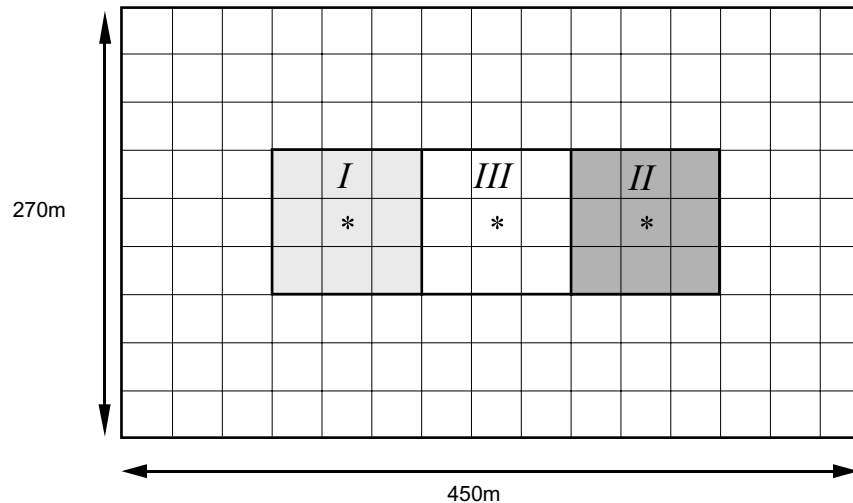


Figure 42. Model domain for the simulation of two plantation rotations (labelled I and II). The permanent irrigated pasture is labelled III. The * indicates elements traced for figures discussed in later sections.

5.7 Results of modelling experiments

5.7.1 Effect of initial watertable depth

When simulating the effects of different watertable depths at the time of planting, a zero flux boundary condition was used for the aquifer finite-element mesh. Figure 43 shows the predicted leaf area index (LAI) for four different initial watertable depths and three different values of groundwater salinity. There was rapid growth in the early years while the plantation was irrigated, and about 4 years of peak growth in the period 1980–83, even under conditions of high salinity groundwater. There was a decline in LAI over the subsequent 2 years, even under the freshest groundwater conditions. This decline coincided with the onset of a severe drought and the cessation of irrigation for the plantation. The trace in Figure 43b, corresponding to an initial watertable depth of 2 m, is based on conditions experienced at the Kyabram plantation.

Figure 44 shows model predictions of live stem carbon dynamics, indicating a similar trend to LAI dynamics, but with a smoother trace resulting from the 4-year life span of sapwood.

Figure 45 shows the LAI for the neighbouring pasture assuming various initial watertable depths. The pasture was assumed to have an LAI of 3.0 at the time of plantation establishment. The LAI values are plotted as moving 12-month averages for clarity. The effect of initial groundwater depth is evident, with the best growth occurring when the watertable was deepest, and especially when the groundwater TSS was 6000 mg/L.

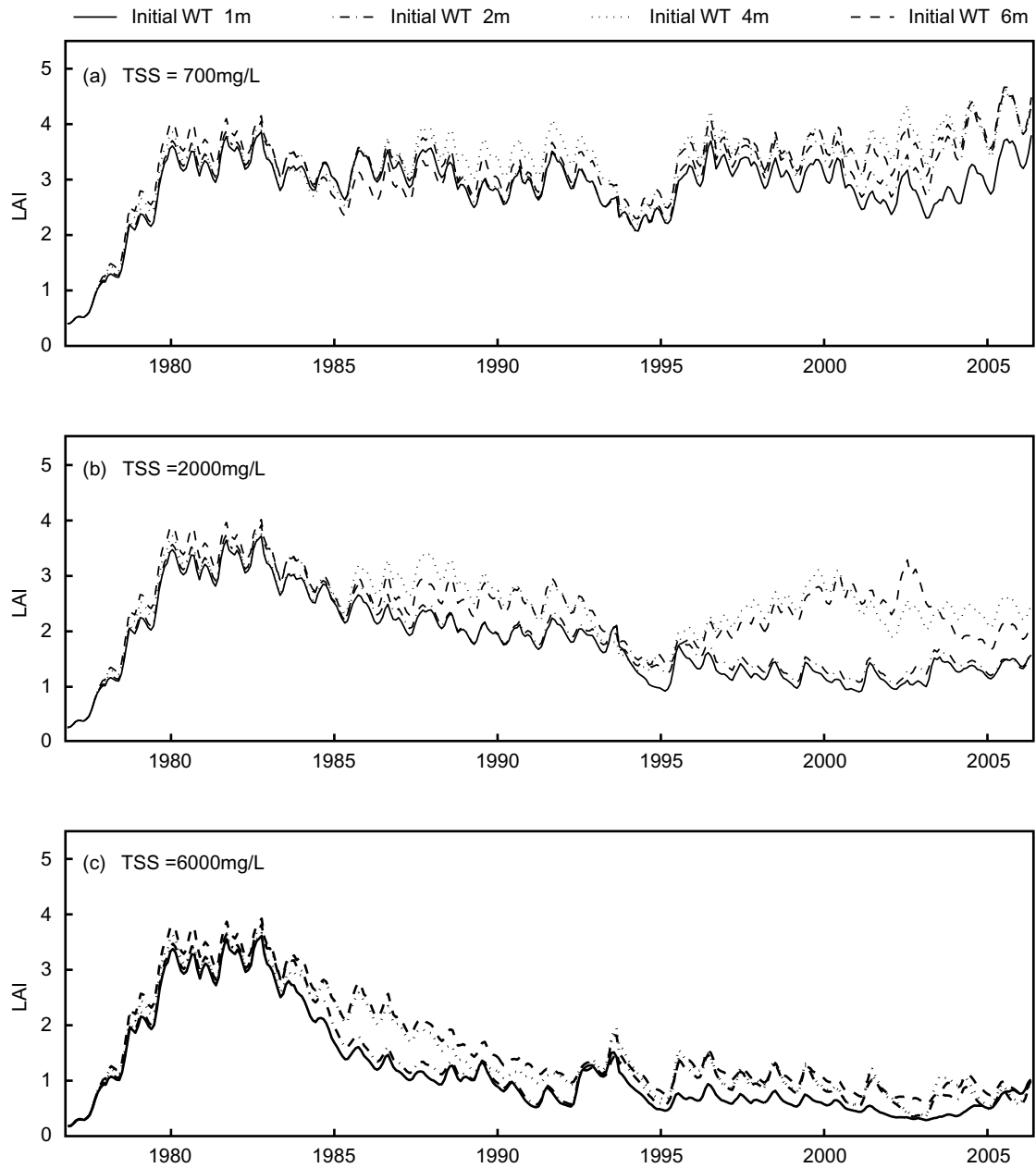


Figure 43. The effect on plantation leaf area of watertable (WT) depth at time of planting, for (a) low-salinity groundwater, (b) medium-salinity groundwater, and (c) high-salinity groundwater.

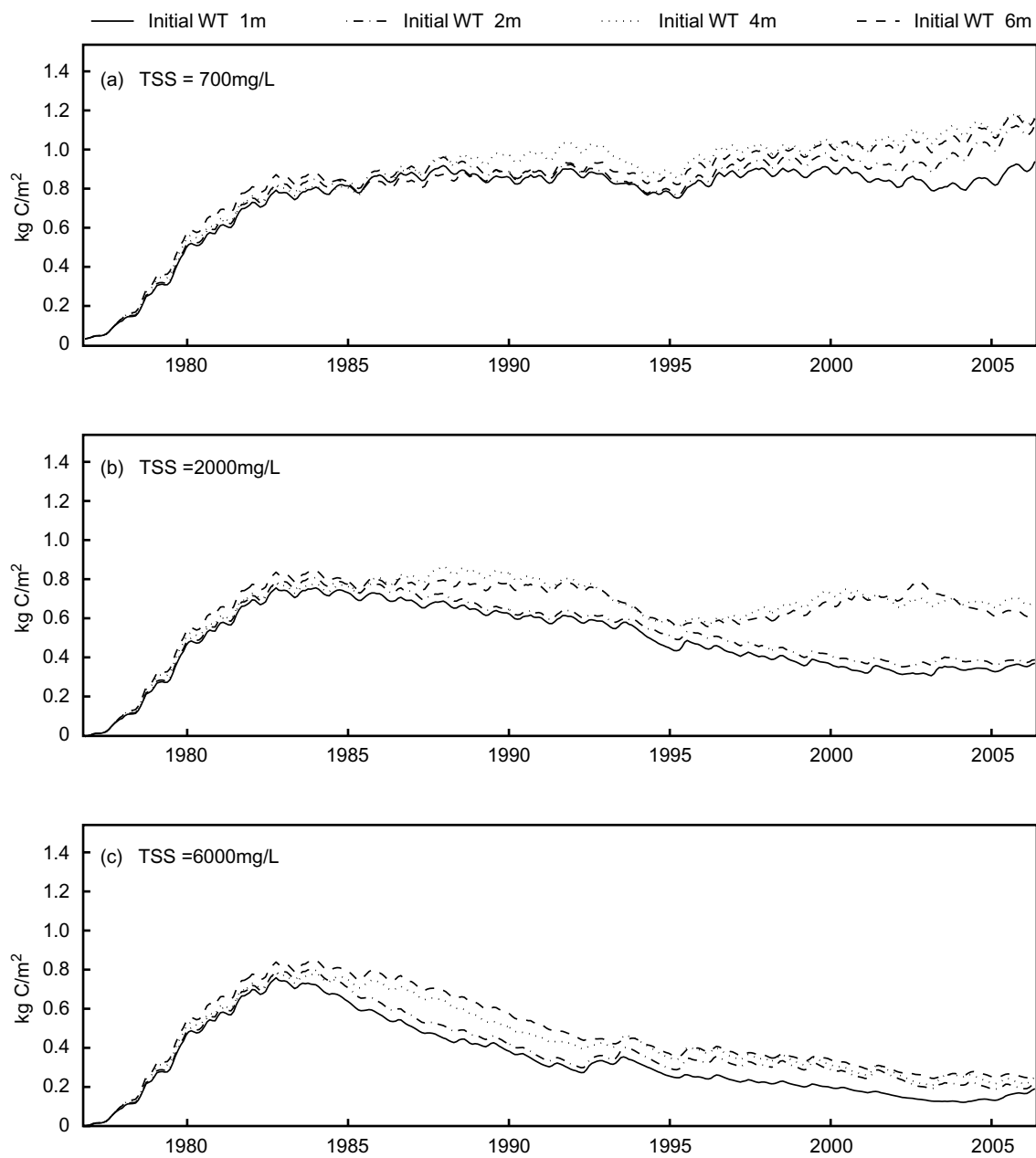


Figure 44. The effect on plantation live stem carbon of watertable (WT) depth at time of planting, for (a) low-salinity groundwater, (b) medium-salinity groundwater, and (c) high-salinity groundwater.

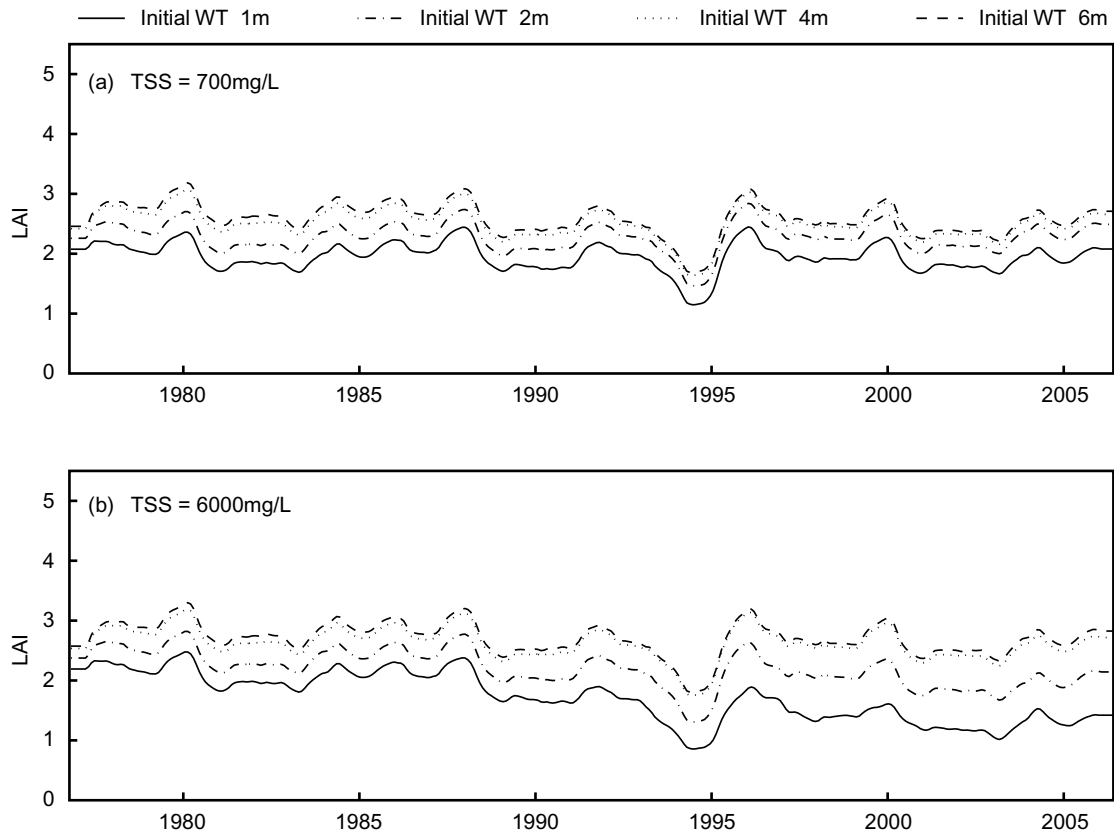


Figure 45. The effect on pasture leaf area of watertable (WT) depth at time of planting for (a) low-salinity and (b) high-salinity groundwater.

Figure 46 shows the long-term watertable dynamics beneath the plantation assuming various initial watertable depths. The initial rise in watertable elevation from deeper starting conditions is caused by irrigation, before the subsequent drawdown when the plantation was at its growth peak. When the groundwater was fresher, the watertable remained deeper for longer than when it was more saline as a result of the higher LAI and consequent greater water use by the plantation.

5.7.2 Effect of groundwater salinity and salt sensitivity

For the remainder of the simulations discussed below, the initial watertable was set at 2 m (this being the field situation at the time of tree planting), and a constant-head boundary condition was imposed on the aquifer finite-element mesh.

The impact of groundwater salinity on LAI is shown in Figure 47 for three values of the salt sensitivity factor, η . The effect of groundwater salinity was not evident until about 1984 (2 years after irrigation of the plantation ceased) when, for all values of η , LAI reduced as salinity increased.

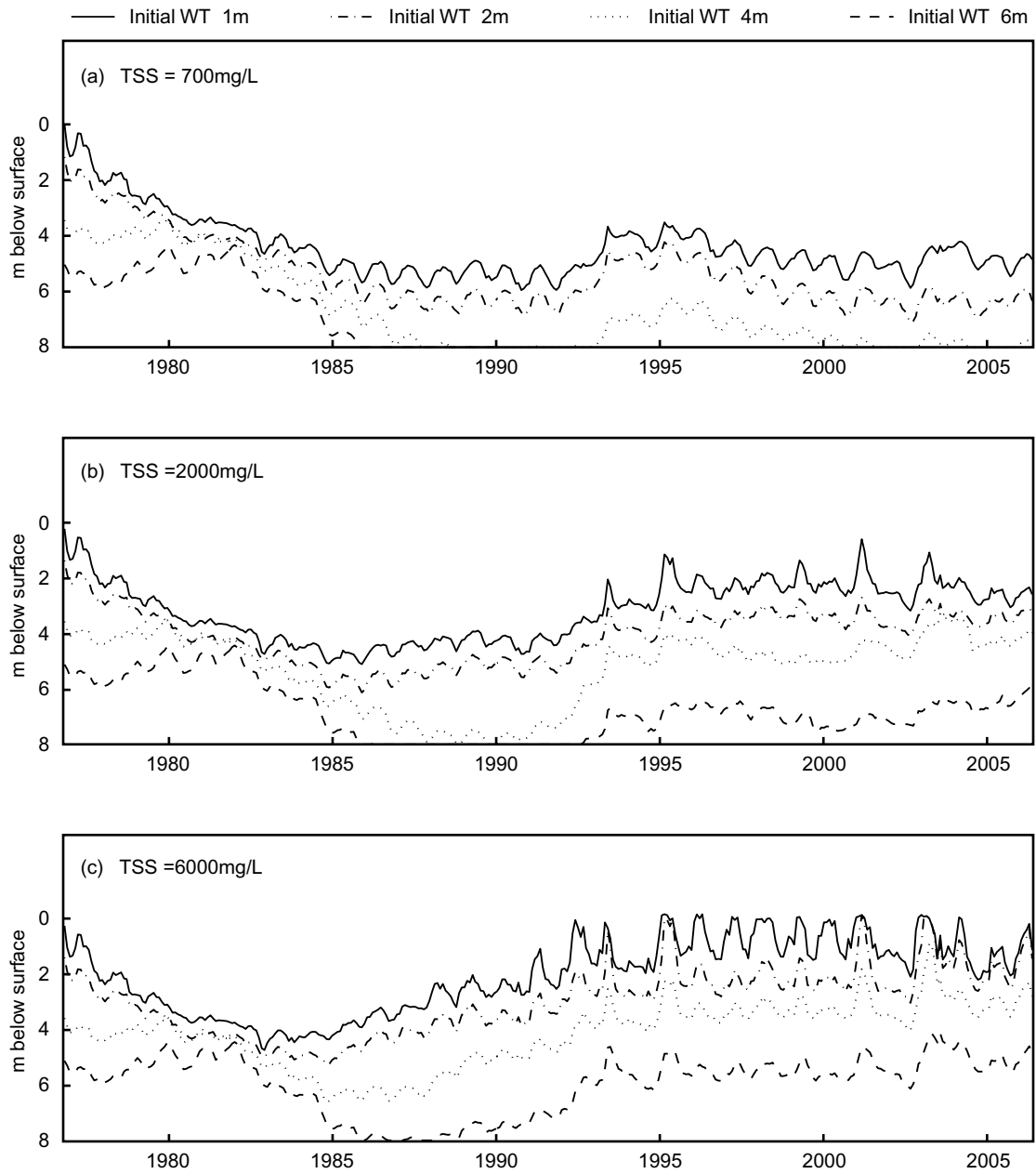


Figure 46. Watertable under the plantation over time for different initial watertable (WT) depths for (a) low-salinity, (b) medium-salinity and (c) high-salinity groundwater.

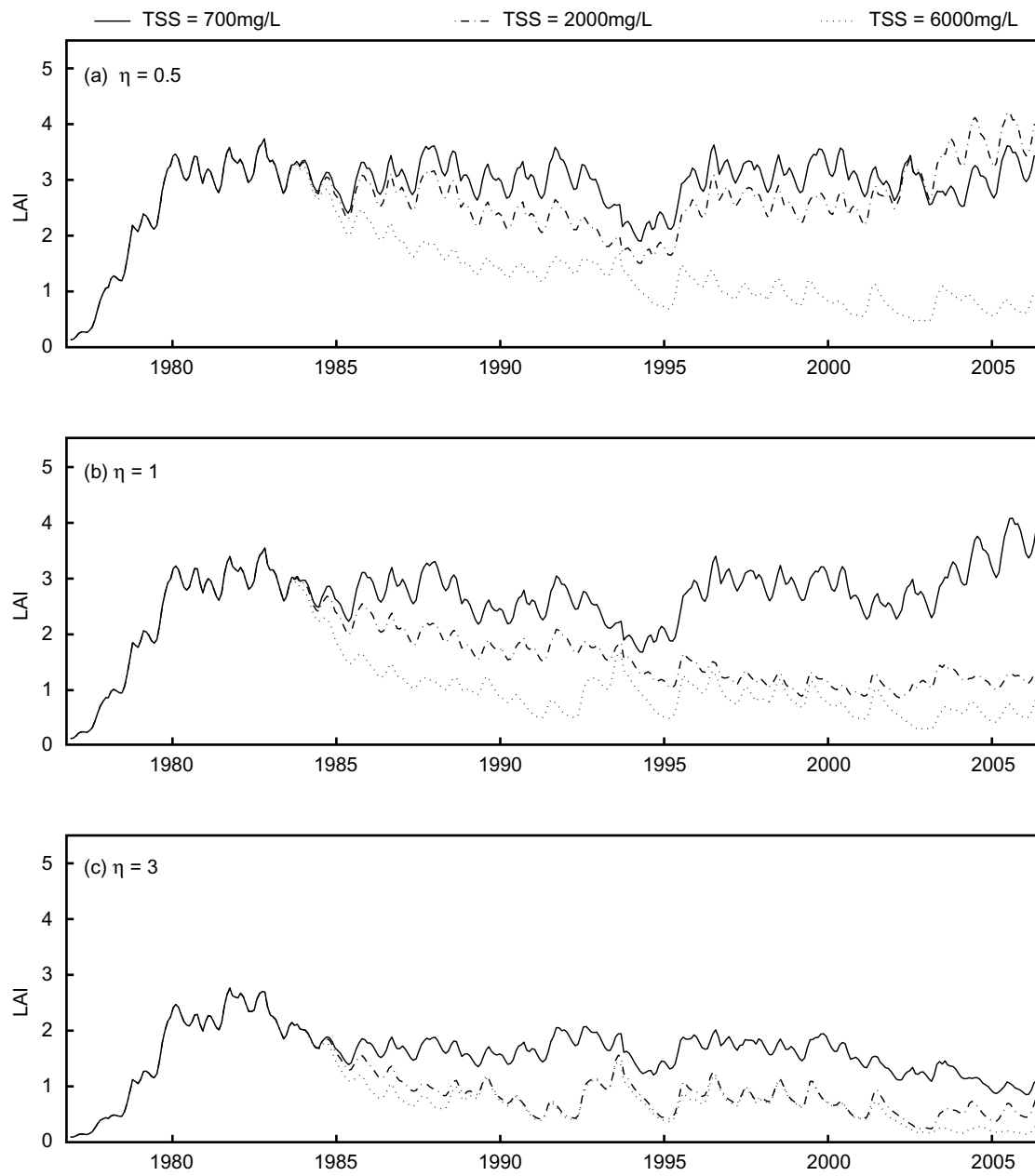


Figure 47. The effect on plantation leaf area of groundwater salinity (TSS) for three values of salt sensitivity (η).

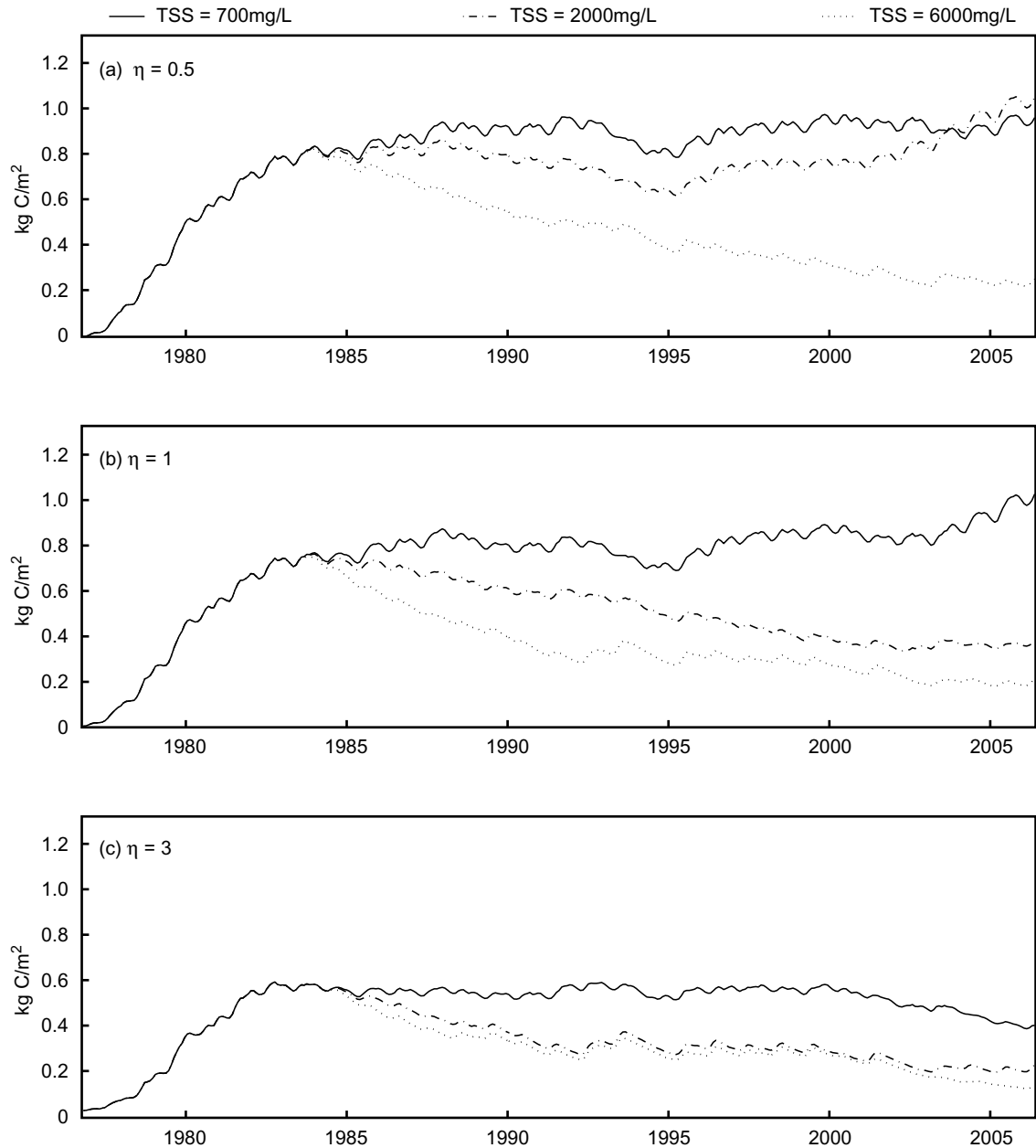


Figure 48. Live stem carbon mass shown for three values of groundwater salinity (TSS) and salt sensitivity (η).

Figure 48 shows the effect of groundwater salinity on stem growth, represented as live stem carbon, for three different values of η . For higher levels of TSS and η , growth slowed once irrigation ceased, and this tendency was amplified as η increased.

Figure 49 shows the root development over time for different assumptions of groundwater salinity and salt sensitivity. All simulations, with the exception of the 700 mg/L salinity case for $\eta = 0.5$, indicate that root growth is maintained at a reasonably steady level, until some kind of threshold appears to drive growth down to a new, lower level. The timing of this drop becomes earlier as η increases and as TSS increases, indicating the importance of salt accumulation within the root zone.

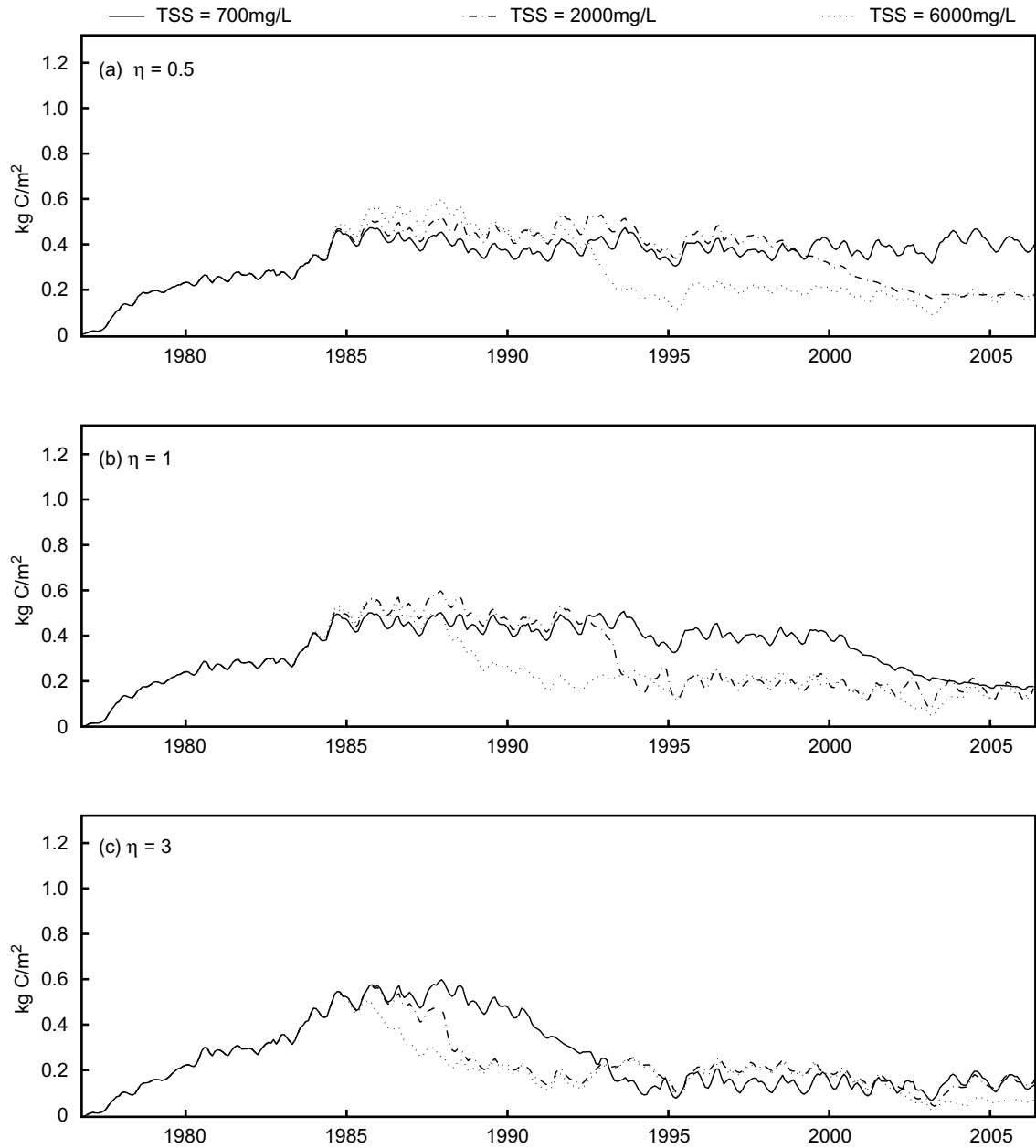


Figure 49. Live root carbon mass development for three values of groundwater salinity (TSS) and salt sensitivity (η).

The salt accumulation in the top 8 m of soil is plotted in Figure 50, for $\eta = 0.5, 1$, and 3 . The rate of salt accumulation was highest when salt sensitivity was lowest, due to higher rates of water uptake and a greater influx of saline groundwater.

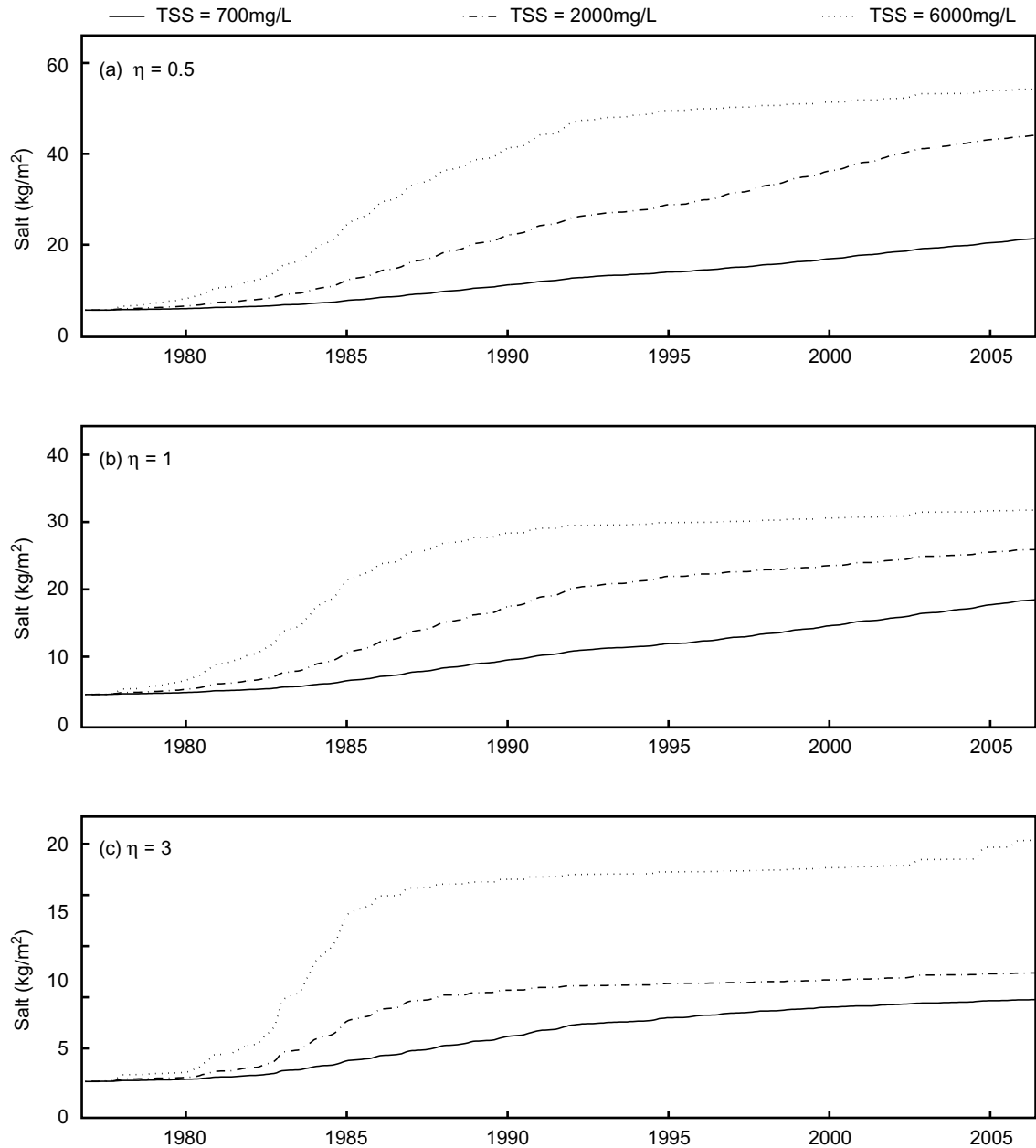


Figure 50. Salt storage in the top 8 m of soil under the plantation for different groundwater salinities (TSS) and salt sensitivities (η). (Note different scale for each value of η .)

The impact of salinity and salt sensitivity on water use is shown in Figure 51 as a moving 12-month average daily value. The effect of the 1994 drought was evidenced by a drop in transpiration, particularly for the low-salinity groundwater. Under these conditions the watertable was proportionally deeper and so the lack of moisture in the surface soil had a proportionally greater effect. For the higher η value and more saline groundwater conditions, there was a rise in transpiration during the drought, possibly due to the lower watertable providing space for the dilution of salt by infiltrating rainfall.

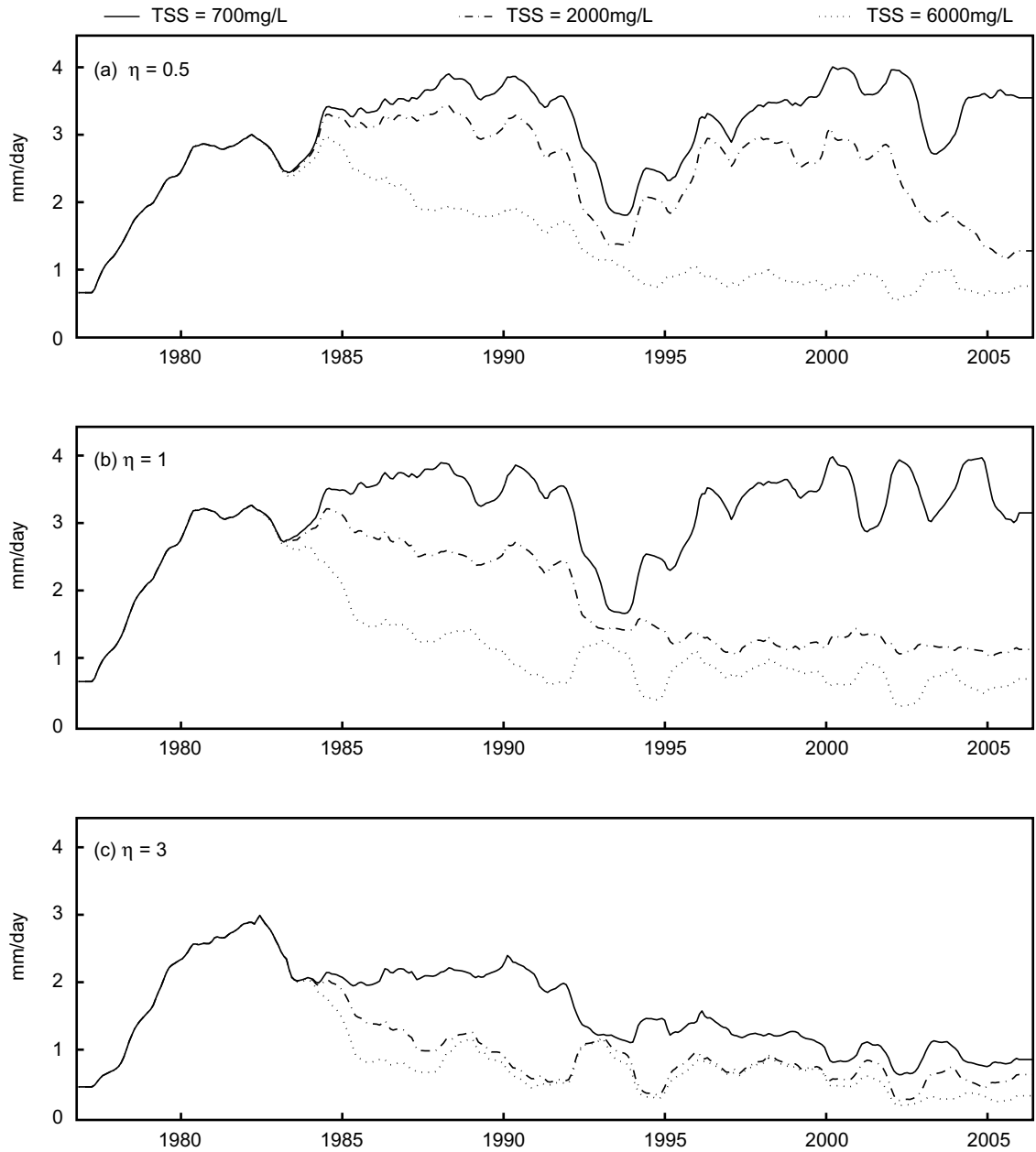


Figure 51. Plantation moving annual mean daily transpiration for different groundwater salinities (TSS) and salt sensitivities (η).

The effect of the salt sensitivity factor η on LAI and stem growth is shown more clearly in Figure 52 and Figure 53, respectively. These show that for $\eta = 0.5$ and 1 with TSS = 700 mg/L, both LAI and stem carbon maintained a good level. However, for $\eta = 3$ and TSS = 700 mg/L, or $\eta = 1$ and TSS = 2000 mg/L, both LAI and stem carbon reduced over time from their peak around the time irrigation ceased in 1982. For $\eta = 3$ or TSS = 6000 mg/L, the decline in LAI and stem carbon was sharper and started sooner.

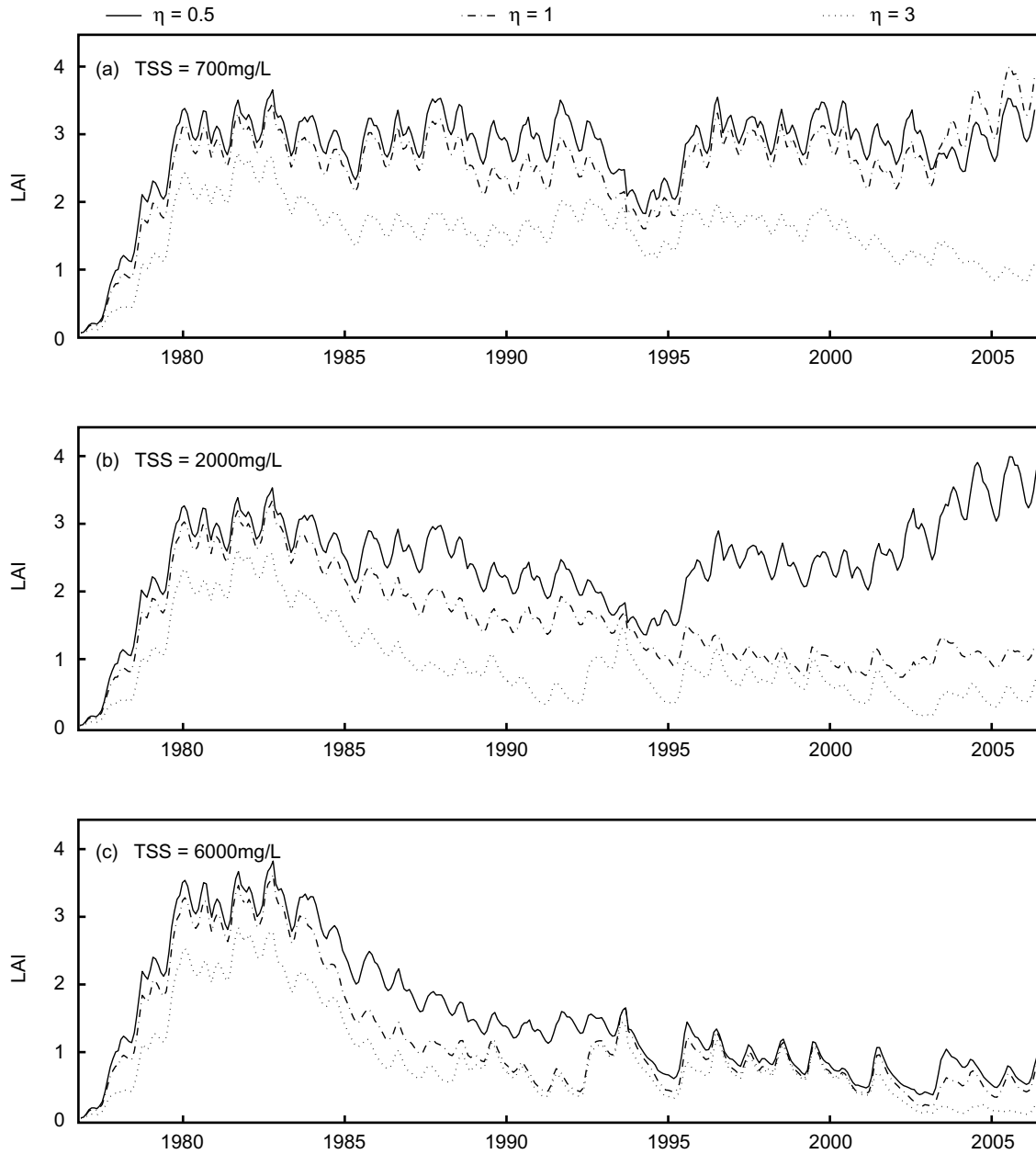


Figure 52. Plantation leaf area index for varying groundwater salinity (TSS) and illustrating the effect of the salt sensitivity factor (η).

The effect of the salt sensitivity factor on salt accumulation is illustrated in Figure 54. When η was low, salt accumulated much more rapidly than when it was high. This occurred because the relatively high tolerance to salt in the profile (low η) led to a higher rate of transpiration, and therefore increased salt movement from the groundwater.

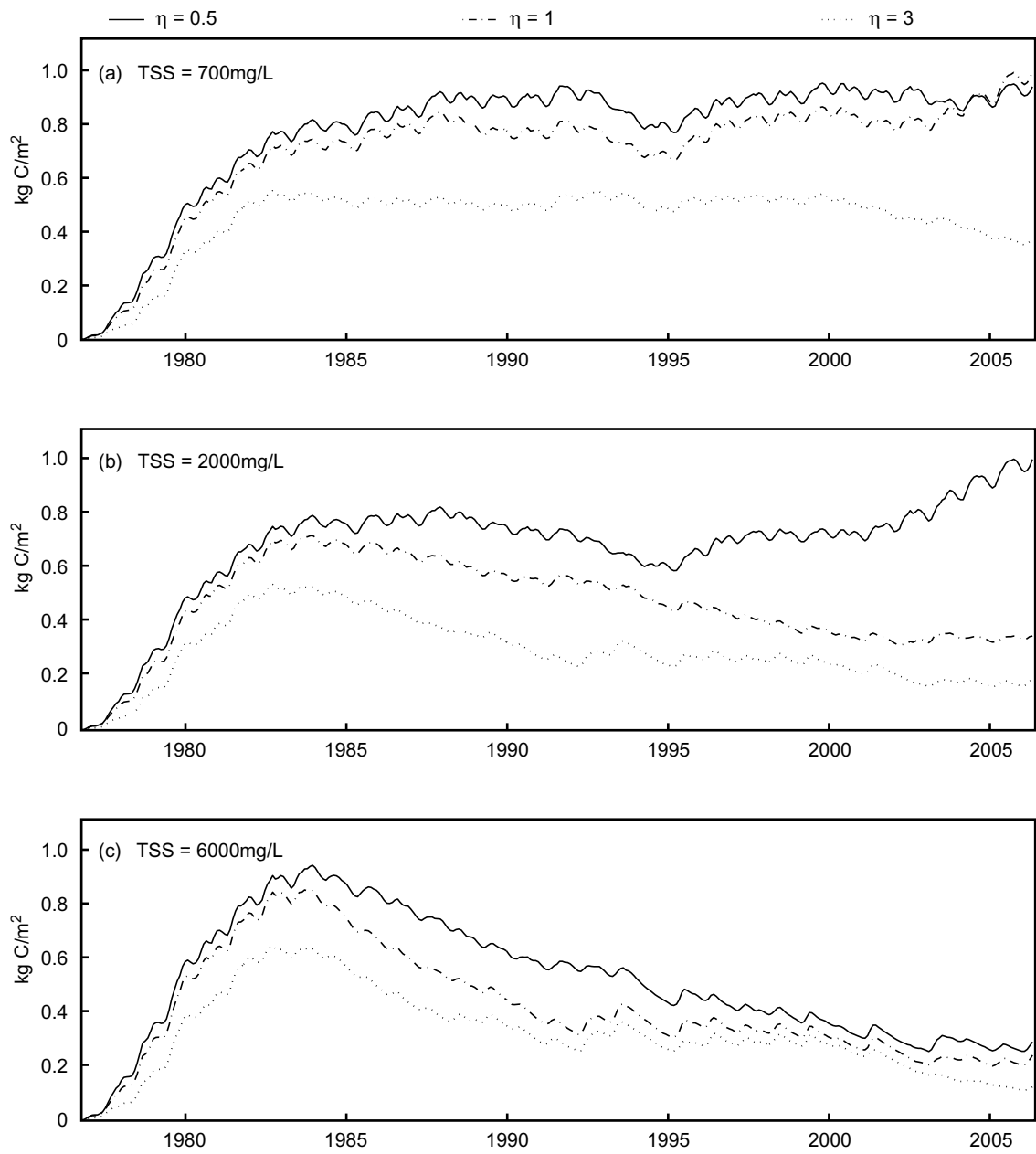


Figure 53. Plantation live stem carbon for varying groundwater salinity (TSS) and illustrating the effect of the salt sensitivity factor (η).

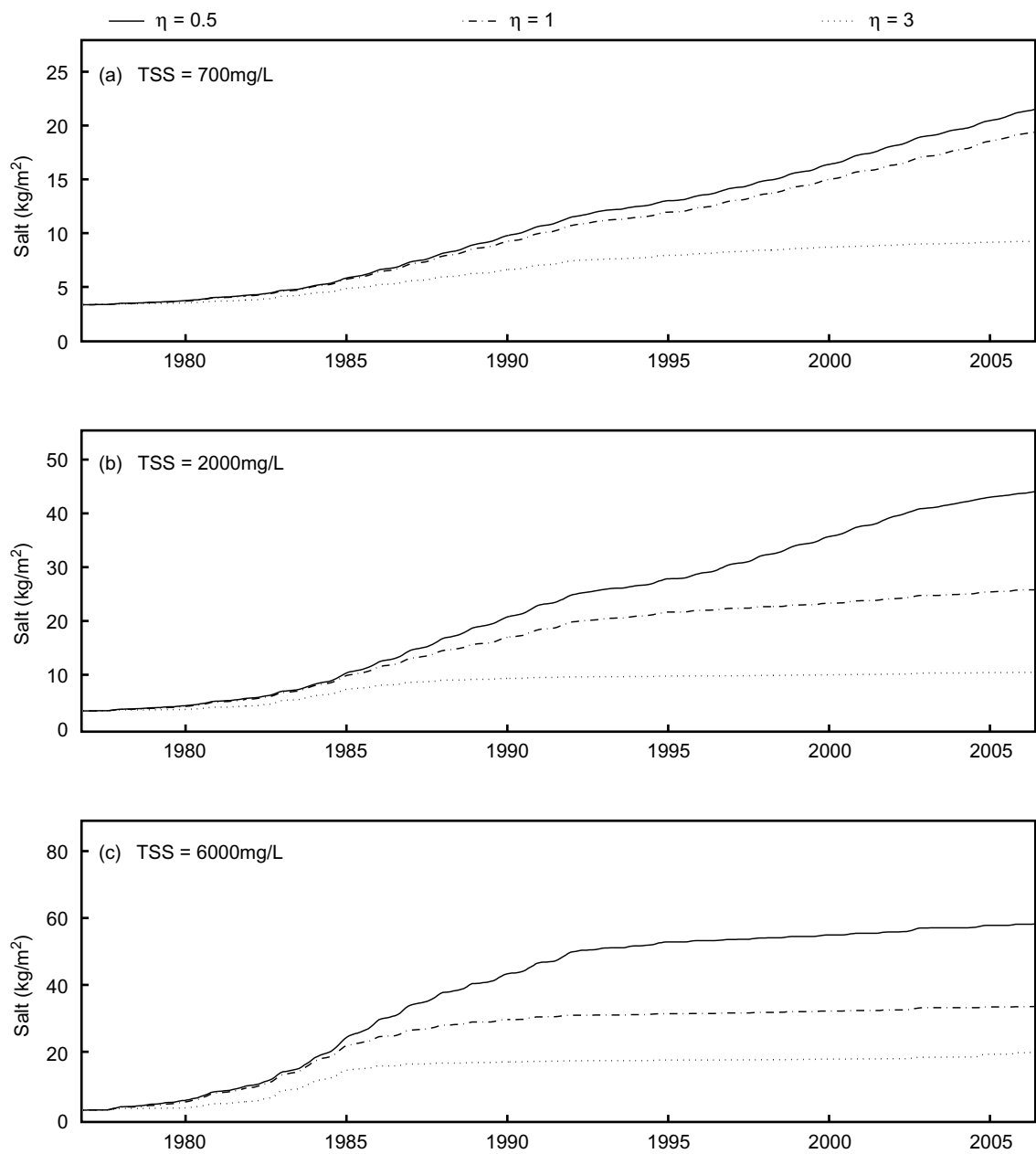


Figure 54. Salt accumulation beneath the plantation for varying groundwater salinity (TSS) and salt sensitivity factor (η). (Note the different scales for each value of η .)

5.7.3 Harvesting, rotation, and irrigation impacts

Figure 55 summarises the effect of removing a plantation after 21 years, replacing it with irrigated pasture, and planting a new plantation in a neighbouring paddock. The results shown are LAI, stem carbon, salt storage, and watertable depth for the three elements indicated in Figure 42. In all simulations conducted, the trees were irrigated for the first 6 years, as was the case at Kyabram. It should be noted here that the domain used in these simulations differed slightly from that used previously, so traces presented here are not strictly applicable to the Kyabram plantation. However, they are conceptually similar.

Figure 56 shows the salt accumulation within the top 8 m of soil under the first and second plantation rotation, in relation to the surrounding areas under irrigated pasture. Figure 57 shows the watertable depth. The lateral extent of the watertable depression is predicted to be quite limited in this case. This is observed at Kyabram where, although a measured effect can be discerned as far as 100 m from the plantation boundary, it is only significant out to less than 30 m (Heuperman 1995).

The results presented in Figure 58 are for a simulation similar to that in Figure 55, but with irrigation maintained throughout the 21-year lifetime of the plantation. In Figure 59, the first plantation was harvested after only 10 years. Initial conditions for all three simulations were the same.

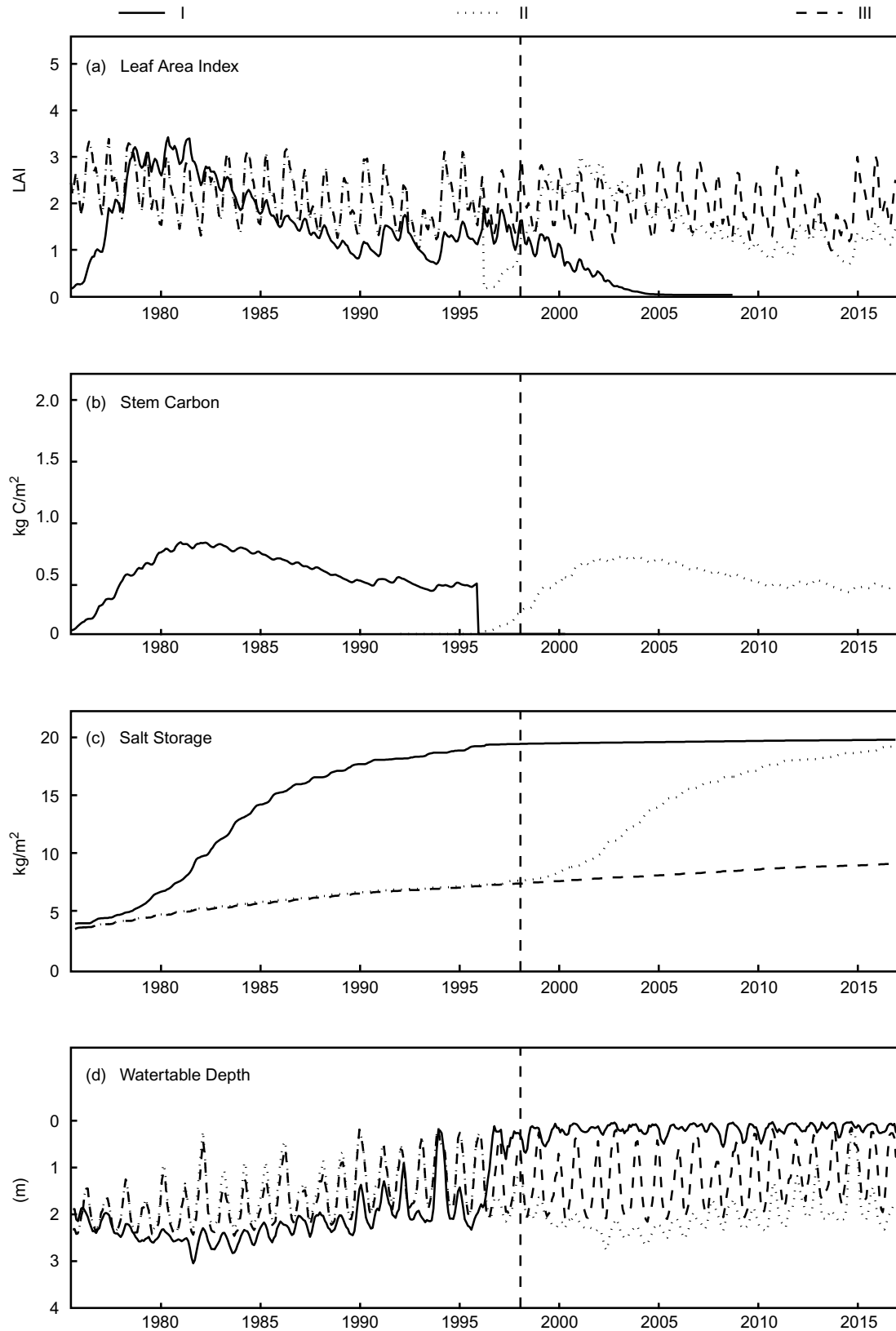


Figure 55. Environmental conditions for first and second rotation plantations at Kyabram. The data are plotted for three domain elements indicated in Figure 42, with I indicating the first plantation, II the site with the second plantation, and III indicating permanent irrigated pasture. The vertical dashed line indicates the timing of the harvest and second planting.

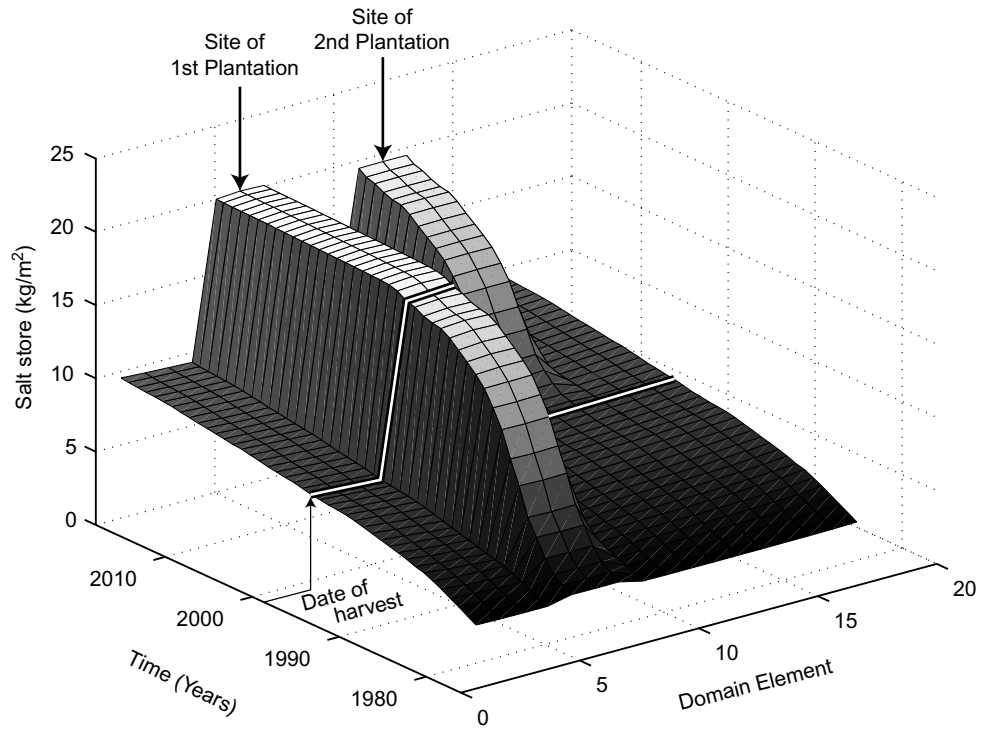


Figure 56. Salt accumulation under the first and second plantations and surrounding pasture through two rotation cycles. The harvest of the first plantation was the planting date of the second.

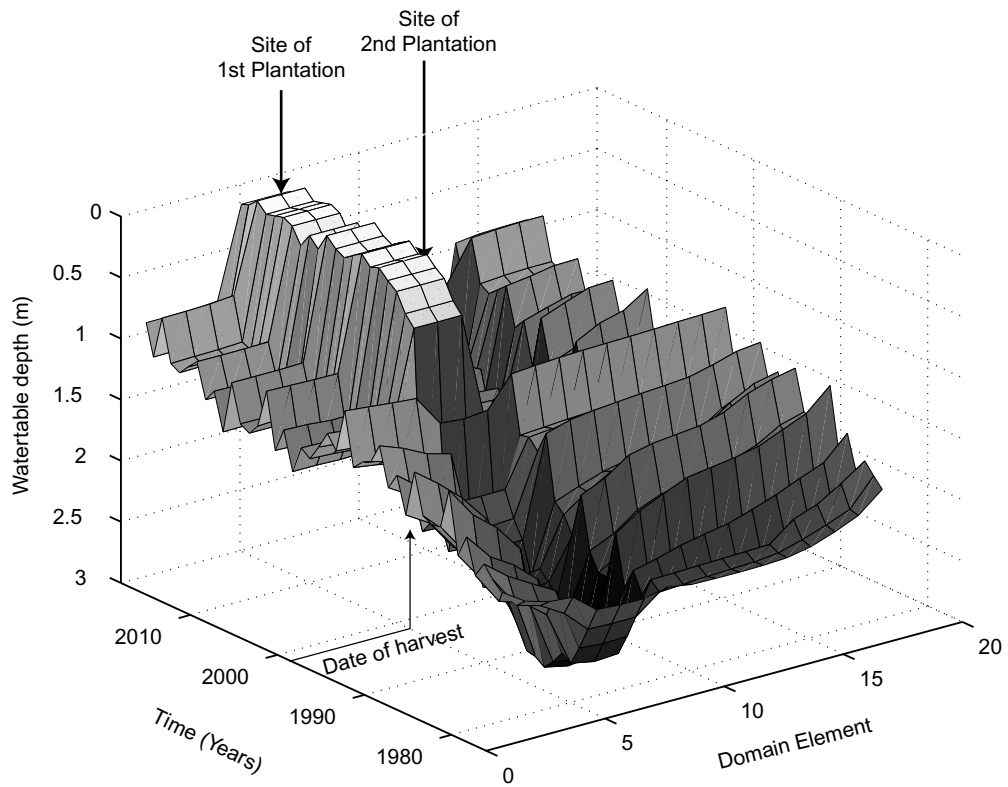


Figure 57. The watertable under the first and second plantations and surrounding pasture through two rotation cycles. The harvest of the first plantation was the planting date of the second.

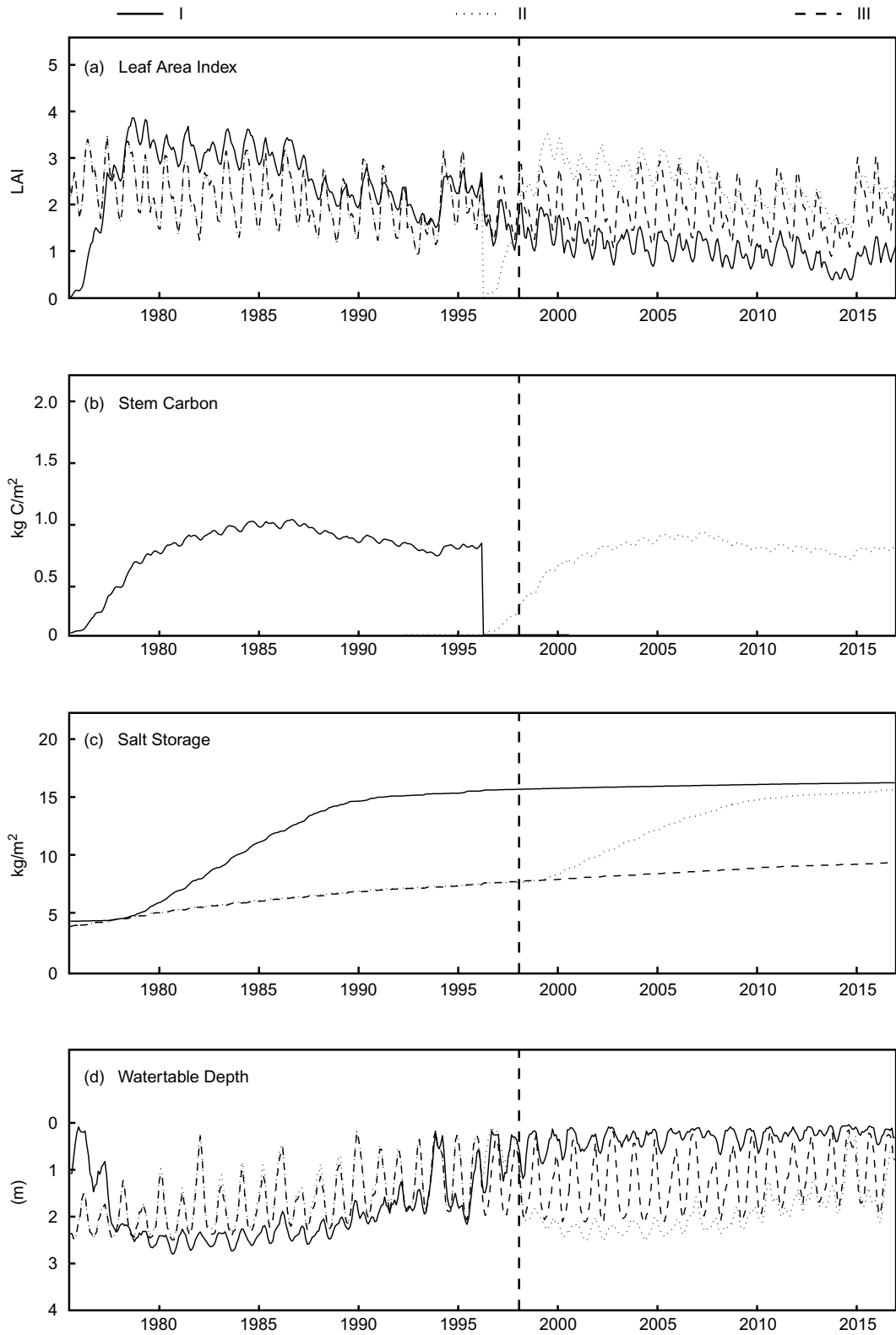


Figure 58. Environmental conditions for the first and second rotation plantations at Kyabram, with irrigation applied for the whole rotation. The data are plotted for three domain elements indicated in Figure 42, with I indicating the first plantation, II the site with the second plantation, and III indicating permanent irrigated pasture. The vertical dashed line indicates the timing of the harvest and second planting.

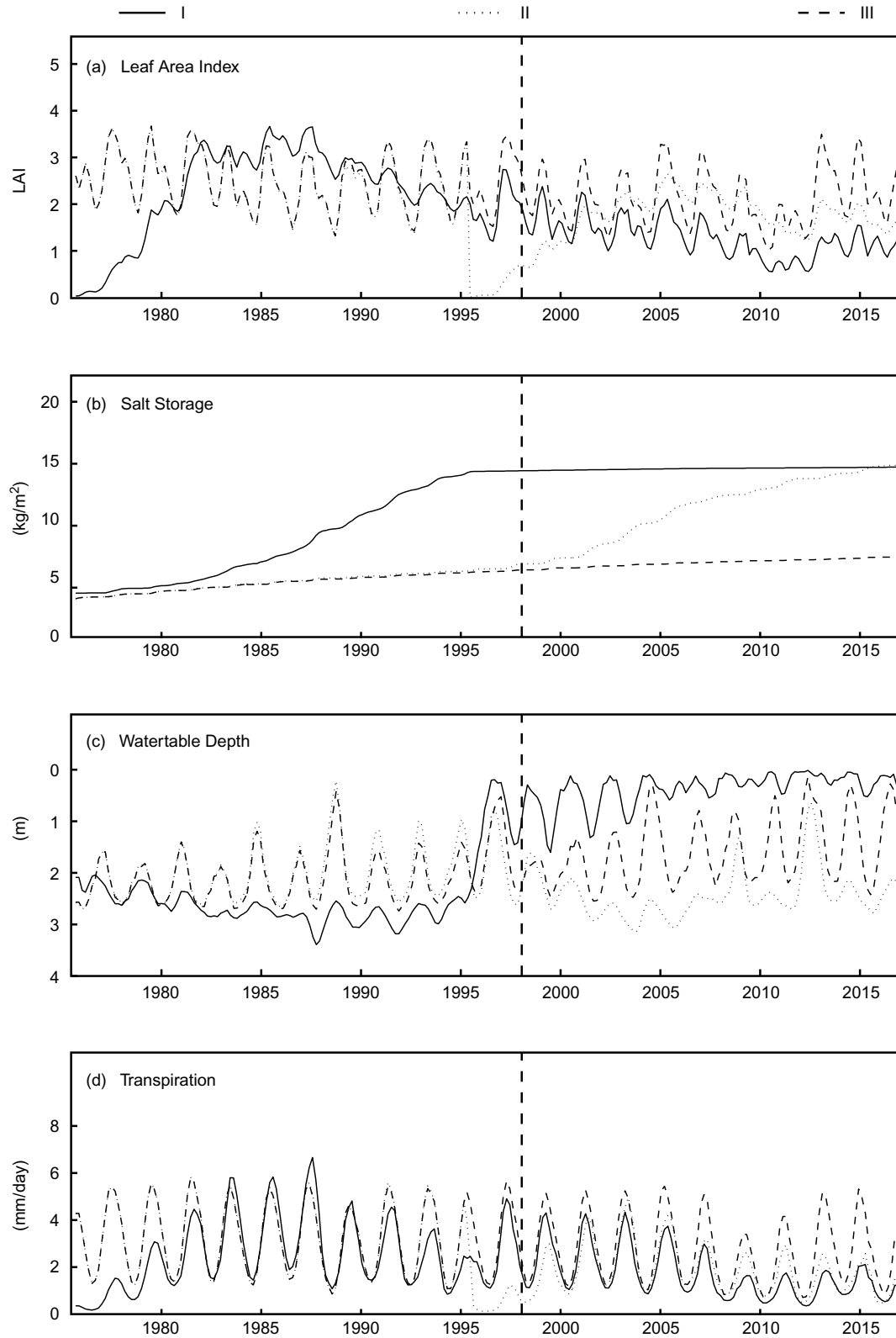


Figure 59. Environmental conditions for first and second rotation plantations at Kyabram, with the harvest of the first plantation carried out after 10 years. The data are plotted for three domain elements indicated in Figure 42, with I indicating the first plantation, II the site with the second plantation, and III indicating permanent irrigated pasture. The vertical dashed line indicates the timing of the harvest and second planting.

5.8 Discussion of modelling experiments

5.8.1 Effect of initial watertable depth

While the trees were being irrigated during the first 6 years, plantation growth was not greatly affected by initial watertable level (Figure 43). This is not surprising, as the irrigation should have ensured that the trees received as much water as they required. In the simulations with the initial watertable at 1 and 2 m, the watertable fell after the first year, indicating the immediate benefit for such shallow watertables (Figure 46). However, when the initial watertable was at 4 or 6 m, it remained at that level or rose before falling as the plantation grew and irrigation ceased.

Figures 43 and 44 also showed that, for all groundwater salinities considered, the deeper the watertable, the generally better was LAI and stem carbon growth. When TSS = 700 mg/L there were, however, a few years after irrigation ceased when there was a slightly lesser growth rate from 1985–87. This appeared to come about because the deeper groundwater meant less available moisture for the trees. Also, for all initial watertable depths, the fresher the groundwater, the better the growth. When the groundwater had a TSS = 2000 mg/L, which happens to be about that at Kyabram, depth to groundwater produced a bifurcation in response at depths between 2 and 4 m. This may have been affected by the choice of salt sensitivity value ($\eta = 1$ for these simulations), but by about 1985 there was a significant difference in both LAI and stem growth between watertables at 1 and 2 m and those at 4 and 6 m. This difference increased after the drought in 1994 until the traces started to converge around 2003. There was a similar split in the growths over the high-salinity groundwater from 1983 to 1993, but from then on the growth over the three deeper watertables was better than that over the 1 m watertable.

For the pasture in neighbouring paddocks, the lower the initial watertable, the higher was the LAI (Figure 45). When the groundwater TSS was 6000 mg/L, LAI remained at a steady level throughout the 30 years when the initial watertable was 4 or 6 m below the surface, but showed a gradual downward trend as salt accumulated above the shallower watertables. As pasture leaf area has not been monitored at Kyabram, this long-term trend cannot be confirmed, but there is anecdotal evidence to support it.

Figure 46 illustrated how the salinity of the groundwater impacted on the long-term depth of the watertable. For groundwater with TSS = 700 mg/L, the watertable was permanently lowered under the tree plantation, except for a brief period after planting and during the irrigation. For groundwater with TSS = 2000 mg/L, the watertable was deeper at the end of the simulation than at the start, but it was on a rising trend from about 1993 onwards. For groundwater with TSS = 6000 mg/L, all watertables ended up shallower than their initial level. This was due to the influence of salt accumulation, leading to reduced transpiration and, therefore, reduced groundwater extraction.

5.8.2 Effect of groundwater salinity and salt sensitivity

Figures 47 and 48 illustrate that the groundwater salinity at the Kyabram site and the sensitivity of trees to salt had a significant effect on plantation LAI and stem carbon growth once irrigation ceased. Our results indicate that the lower the salinity in the groundwater, the greater the leaf area and stem growth, regardless of the value assumed for η . The

connection between salt sensitivity and salt concentration is evident. For example, when $\eta = 0.5$ and TSS = 2000 mg/L, both LAI and stem growth generally followed the trend of the trees over the lower salinity (TSS = 700 mg/L) groundwater. Under conditions of $\eta = 0.5$ and TSS = 6000 mg/L, or $\eta = 1$ and TSS = 2000 mg/L, there was a general decline in LAI from the time irrigation ceased. This can also be seen as a lesser ability of the plantation to recover from moisture stress, such as that imposed by the 1994 drought. Prior to then, the LAI and stem growth for $\eta = 1$ and TSS = 2000 mg/L were generally about half-way between the other two traces, but after that time the trends were downward towards the lower (TSS = 6000 mg/L) trace. With $\eta = 3$ (highly salt sensitive), the plantation LAI and stem growth were significantly lower, even for TSS = 2000 mg/L. An interesting feature of the response when $\eta = 0.5$ was the crossover in traces for TSS = 700 mg/L and 2000 mg/L around the year 2002 (Figure 47). This appears to be due to greater transpiration when the groundwater was fresher drying out the profile in the vicinity of the roots, to the extent that growth was limited. When salinity was a little higher, transpiration was inhibited enough to elevate soil moisture content. This would have enhanced unsaturated flow and, with the particular rainfall conditions during the period, resulted in better growth conditions at that time. It is an interesting example of the fact that access to water is still the trees' primary limit on growth, despite salinity in the soil. Total wood production up to that point was still higher when TSS was lower. Under conditions of $\eta = 3$, it appeared that TSS = 2000 mg/L was enough for growth to be slowed, to the extent that it was not significantly different from that when TSS = 6000 mg/L.

In the plant growth module in Topog_Dynamic, trees under moisture (and salinity) stress assimilate less carbon, but allocate a greater proportion of assimilated carbon into root development. The effect of this is illustrated in Figures 47, 48, and 49. The LAI and stem growth traces separated 2 years after irrigation ceased, with LAI and stem carbon reducing as TSS increased, but the root development increased as TSS increased. In Figure 49, the effect of ceasing irrigation can also be seen as an increase in root growth in 1983 as the watertable fell. Over time, however, the reduced LAI and the lower total carbon assimilation rate resulting from the greater salt accumulation reduced root growth. In all cases, except under conditions of $\eta = 0.5$ and TSS = 700 mg/L, the trees reached a stage when root growth plummeted to a new, but steady, level. The more severe the conditions (i.e., the higher η and TSS), the sooner this point was reached, though it did not occur within the 30-year simulation for $\eta = 0.5$ and TSS = 700 mg/L. This appears to be the result of salt accumulation reducing total carbon assimilation, to the point where all parts of the plant suffer. However, root development in these environments is not well understood and, to date, we lack sufficient information to adequately test our model. For this reason, we remain cautious in interpreting this result.

The clustering together of the lower salinity traces in Figures 47 and 48 for $\eta = 0.5$, and the dramatic separation of traces for the high-salinity groundwater implies a 'salinity threshold effect' (Thorburn *et al.* 1995). The impact of the drought period in 1994, when the plantation was aged 18 years, compares with the period of 4–20 years for the impact of salt accumulation to become severe under the dryland conditions discussed by Thorburn *et al.* (1995). These results suggest that although the plantation may continue to grow beyond the year 2007 (age 30 years), growth will be slowing and the response will depend on the magnitude of the salt sensitivity factor, η . The plantation at Kyabram had its LAI following the trace with $\eta = 1$ and TSS = 2000 mg/L. This indicates that η is reasonably represented

with a value of 1 for this plantation under these conditions, and it may continue its gradual decline. If the groundwater were significantly fresher, say at TSS = 700 mg/L, LAI would be between 2.0 and 3.5, and stem growth would be correspondingly greater for at least 30 years. However, if the groundwater had a salinity of 6000 mg/L, it would have begun its decline more or less as soon as irrigation ceased.

The effect of groundwater salinity and vegetation salt sensitivity on salt accumulation and transpiration is shown in Figures 50 and 51. These have feedback effects on each other, as the transpiration leads to salt accumulation, which in turn limits transpiration. The salt accumulation traces all show their steepest ascent early on, when growth peaked. In Figure 54 the effect of η on salt accumulation can be seen, with salt accumulating faster when η is lower. This is because transpiration is higher for trees less sensitive to salt. Figures 52 and 53 show the correspondingly higher LAI and stem growth of the trees with lower η , though a little caution is needed in interpreting these results. Trees that are able to grow in salty conditions usually exhibit slow growth. Their salt tolerance is expressed by their survival, rather than by high growth rates.

5.8.3 Harvesting, rotation, and irrigation impacts

When two plantations were grown in rotation, the model predicted that LAI and stem growth of the second rotation would be slightly less than that of the first, due to the impact of salt accumulation during the first rotation period, even under irrigated pasture (Figure 55). The rate of salt accumulation under the irrigated pasture (at III, Figure 55) was slower than under the trees, and the watertable was shallower. The accumulation of salt, even under the areas that were permanently under irrigated pasture (Figure 56), indicates that the leaching fraction applied was inadequate. Figures 56 and 57 both illustrate the very local hydrologic effects of the plantation at Kyabram. The watertable drawdown only occurs in the area within and immediately surrounding the plantation (about one model element or so). Consequently the salt accumulation is restricted to the area beneath the plantation.

When the first rotation was replaced by irrigated pasture (at I, Figure 55), the new pasture was severely hampered by the salt that had accumulated under the trees. As the watertable rose, when irrigation recommenced, and the salt moved upwards, the LAI of the pasture on the old plantation site dropped, so it could not survive by about the eighth year. This is a sobering result. If this is replicated in the field, and the experiment probably ought to be done, there are severe implications for current strategies recommending widespread short-rotation tree planting in salt-affected and shallow watertable areas. Our results do not indicate export of salt from under the root zone of the pasture when it replaced the first rotation. We expected that the irrigation waters would leach accumulated salt, and mix it with the deeper groundwater. However, modelling indicated that this did not happen, presumably because of the low soil conductivity and because excess water added as a leaching fraction was not enough to maintain the drainage.

Two strategies that may limit salt accumulation under the trees are to irrigate the plantation throughout its growth, or to harvest the first plantation sooner. When the plantation was irrigated throughout its lifetime (Figure 58), there were modest increases in LAI and stem growth and modest reductions in salt accumulation. When the plantation was replaced by irrigated pasture, the lower salt accumulation did result in pasture survival and growth, but it was significantly lower than the permanent pasture surrounding it. The watertable was

still lowered relative to the irrigated pasture, but by substantially less than when the plantation was not irrigated. The decision whether to irrigate the plantation or not must, therefore, be made on economic grounds, taking into account the value of the increased tree production against the cost of the extra water, and the environmental cost of having a shallower watertable.

Harvesting the plantation after only 10 years (Figure 59) also resulted in better pasture growth, but again less than in the surrounding paddocks (which had been under irrigated pasture throughout the period).

In a simulation (not shown here) similar to that shown in Figure 59, but with groundwater salinity at 700 mg/L, pasture growth after replacing the first plantation was significantly higher than in the surrounding paddocks for about 4 years, before falling to lower levels. This suggested that there may be an optimum rotation length, gauged perhaps by weighing increased pasture productivity against an early harvesting of the trees, particularly if this system could be used before the watertable rose too close to the surface or salt accumulated to growth-limiting levels.

We stress that *the modelled system behaviour will change as site conditions vary*. In particular, initial groundwater salinity, soil hydraulic properties, piezometric gradient, and deep aquifer characteristics will all impact on the behaviour of the system. A full sensitivity analysis is needed before our model results can be generalised further.

5.8.4 Conclusions from the modelling experiments

For the existing plantation at Kyabram, our simulations show that most of the watertable level reduction occurred during the period 1985–94, after which it began to rise. If the climate over the next 10 years is similar to that during the first 10 years of the simulation (1977–87), we predict that the watertable will remain at roughly its current level for most of that time, before rising slightly further. Over the same period, LAI and stem growth would be expected to decline.

After the cessation of irrigation, and for different salinities, the model shows separation of LAI and stem growth traces, suggesting that the effect of salt in the soil was significant in reducing subsequent plantation water use and growth. Once the trees have withdrawn available soil moisture, the low soil K_s makes replenishment from the watertable beyond 4 m a slow process, thus compounding the problem for the trees. At a site with higher K_s , this may not be such an issue, as soil moisture may more readily be supplied to the roots and into the plantation from surrounding irrigated fields. However, this greater water supply will also bring with it more salt, and the balance between extra growth from more water and the negative influence of salt accumulation may strongly depend on occasional leaching events.

Our findings suggest that plantations established over low-salinity groundwater will certainly grow for more than 30 years. Over higher salinity groundwater, stress from salt accumulation will result in a loss of plantation drought-resilience. This was illustrated by the response after the 1994–95 drought, when the plantations over the higher salinity groundwater did not recover (Figures 47, 48, and 49). This was also true for low-salinity groundwater conditions when a higher plant salt sensitivity was assumed. We find evidence

for the concept of a 'groundwater salinity threshold' effect on growth. The actual threshold depends on the assumed sensitivity of the trees to salt.

Harvesting a plantation and returning the site to pasture resulted in a severe reduction in pasture growth as a result salt accumulated in the soil. We predict that pasture will no longer grow 8 years after its re-establishment on a harvested plantation site. Perhaps this problem can be overcome by a substantially increased leaching fraction. Irrigation of the plantation and earlier harvest lessened the salt accumulation, but increased the environmental cost of a shallower watertable. Our results suggest that finding the optimal plantation rotation involves a balance between pasture and plantation productivity.

5.9 Current status of the model and future work

Topog_Dynamic has reached operational status, with testing complete for the Kyabram plantation. This test, for a flat site surrounded by irrigated pasture, complements extensive work undertaken at other, mainly steep, forested sites (see, for instance, Vertessy *et al.* 1996a). The model can now be applied to examine the effects and outcomes of alternative plantation management strategies, such as varying plantation density and distribution, and moving plantations between rotations.

Our model simulations show that salt does accumulate in the root zone of the plantation at the right rate. Mechanisms for salt accumulation, lateral sub-surface salt and water movement, and for plantation growth appear to be well represented in the model. However, more effort and further field data are needed to check that our long-term predictions of salt accumulation beneath the plantation are correct.

The most pressing problem to be addressed in future work, and one which has bearing on all of our modelling results, is the assumed sensitivity of plantations and pastures to salt in the soil water. Although some data are available, quantification of the effect is incomplete. A better understanding of the distribution of root growth and water uptake is needed to improve our modelling of this process. This is particularly important for its role in the distribution of salt accumulation within the soil profile. This work should also be followed with further model testing, to explore more fully the response of the trees to other site and climatic conditions. The effect of soil heterogeneity, both vertically and horizontally, also needs to be assessed further. The irrigation strategy for a plantation and surrounding fields can have a significant influence on salt accumulation and tree growth, and testing of more management scenarios is needed. It is desirable that these be coupled to an economic analysis, enabling a more practical interpretation of the results for managers.

6 Conclusions

This study has shown that if plantation density is sufficiently high (so that evaporative demand exceeds infiltration of rainfall into the soil), the trees will use water from a shallow watertable. This will create a groundwater depression beneath the trees. Under such conditions, salt will accumulate in the plantation root zone and the magnitude of that accumulation will be directly related to the net groundwater discharge (difference between transpiration and infiltration) and the groundwater salt concentration. The uptake of groundwater by the plantation will decline as the salt accumulation increases, leading to rises in the groundwater level. The prospects for long-term sustainable plantation growth under net groundwater discharge conditions are poor, unless processes such as leaching and diffusion remove salt from the root zone to balance the accumulation process. Without these balancing processes, net tree groundwater water usage will decline to zero due to salt accumulation. Nevertheless, plantations can effectively negate groundwater recharge.

6.1 *Groundwater impact*

Our field observations of groundwater dynamics at the Kyabram site revealed that:

- the watertable has been lowered significantly beneath the plantation, relative to its level beneath the adjacent irrigated pastures;
- the spatial extent of this watertable lowering is limited to 40 m from the plantation boundary, primarily due to low soil hydraulic conductivities at the site;
- seasonal fluctuations in watertable levels beneath the plantation are greater than beneath the adjacent irrigated pastures;
- the watertable is gradually rising beneath the plantation, due to trees using progressively less groundwater and/or from increased irrigation outside the plantation;
- the hydraulic gradient beneath the plantation is moving vertically upwards and the hydraulic gradient around the plantation is moving laterally inwards.
- plantations can effectively cancel groundwater recharge.

6.2 *Solute accumulation in the unsaturated zone*

Our field observations of salt storage dynamics at the Kyabram site revealed that:

- salt accumulation due to concentrated water extraction has occurred in the root zone, leading to salt bulges near the watertable associated with maximum root density;
- these salt bulges are dynamic, shrinking and expanding on a seasonal basis in response to watertable levels and tree water extraction patterns;
- there is a dry zone within the root zone of the trees that is subject to little or no leaching by infiltrating rain.

6.3 Tree water use and tree growth

Our field observations of transpiration and tree growth at the Kyabram site revealed that:

- tree water use is relatively low, averaging about 300 mm/yr;
- the trees are using more water than is provided by rainfall, indicating that they are taking up groundwater;
- the trees appear to be moisture limited, indicated by low tree water use and leaf area;
- tree growth rates are relatively low* for 20-year-old trees;
- low soil permeability and high planting density appear to be the main limitations to tree growth;
- salt accumulation is reducing the ability of the trees to use the groundwater.

6.4 Modelling

The main conclusions of our modelling work with Topog_Dynamic are that:

- the model can differentiate between plantation water use and that of surrounding irrigated pasture;
- the model can predict the effect of plantation water use on the water balance of the area and particularly on the watertable;
- plantation leaf and stem growth and root dynamics are simulated realistically;
- a site with conditions like those at Kyabram appears to have a time scale of about 20 years (the current age of the plantation) before the effects of salt accumulation and water limitation caused by the low permeability become apparent;
- our predictions are strongly influenced by our assumptions of tree sensitivity to salt in soil moisture, and how this sensitivity varies with reducing available soil moisture;
- the model output can (and should) be used to generate input for economic scenarios and analysis of management and plantation options;
- shorter plantation rotations may alleviate the impact of salt accumulation;
- irrigation of the plantation throughout its rotation would lessen the salt accumulation within the root zone and improve growth rates, but at the environmental cost of a raised watertable relative to that which would occur under a rain-fed plantation, and this would not provide the local sub-surface sink for salt draining from the surrounding irrigated pasture.

* Subsequent to the completion of this work, yield has been estimated as a mean annual increment of about 15 m³/ha/yr; with the best plots of *E. grandis* showing 22 m³/ha/yr).

7 References

- Abbott, M. B., Bathurst, J. C., Cunge, J. A., O'Connell, P. E., and Rasmussen, J., 1986a. An introduction to the European Hydrological System – Systeme Hydrologique Europeen, “SHE”, 1: History and philosophy of a physically-based, distributed modelling system. *J. Hydrol.*, 87: 45–59.
- Abbott, M. B., Bathurst, J. C., Cunge, J. A., O'Connell, P. E., and Rasmussen, J., 1986b. An introduction to the European Hydrological System – Systeme Hydrologique Europeen, “SHE”, 2: Structure of a physically-based, distributed modelling system. *J. Hydrol.*, 87: 61–77.
- Allen, R.G., Jensen, M.E., Wright, J.L., and Burman, R.D., 1989. Operational estimates of reference evapotranspiration. *Agron. J.*, 81: 650–662
- Amoozegar, A., 1989. A compact constant-head permeameter for measuring saturated hydraulic conductivity of the vadose zone. *Soil Sci. Soc. Am. J.*, 53: 1356–1361.
- Aston, A.R., 1979. Rainfall interception by eight small trees. *J. Hydrol.* 42: 383–396.
- Ball, J.T., Woodrow, I.E., and Berry, J.A., 1987. A model predicting stomatal conductance and its contribution to the control of photosynthesis under different environmental conditions. *In Progress in Photosynthesis Research*, Vol. IV. Ed. J. Biggins. Martinus Nijhoff Publishers, Netherlands, pp. 221–224.
- Battaglia, M., Cherry, M.L., Beadle, C.L., Sands, P.J., and Hingston, A., 1998. Prediction of leaf area index in eucalypt plantations: effects of water stress and temperature. *Tree Physiol.*, 18: 521–528.
- Beverly, C.R., 1992. Background notes on the CSIRO Topog model. 1. Details of the numerical solution of the Richards equation in Topog_Yield. CSIRO Division of Water Resources, Tech. Memo. 92/12.
- Bouwer, H., 1989. The Bouwer and Rice slug test – an update. *Ground Water*, 27: 304–309.
- Bouwer, H. and Rice, R.C., 1976. A slug test for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells. *Water Resour. Res.*, 12: 423–428.
- Broadbridge, P. and White, I., 1988. Constant rate rainfall infiltration: a versatile nonlinear model. 1. Analytic solution. *Water Resour. Res.*, 24: 145–154.
- Brutsaert, W.H., 1982. *Evaporation into the atmosphere*. D. Reidel Publishing Company, Dordrecht, Holland.
- Campbell, G.S. and Campbell, M.D., 1982. Irrigation scheduling using soil moisture measurements: theory and practice. *Adv. Irrig.*, 1: 25–42.
- Chapin, F.S., Bloom, A.J., Field, C.B., and Waring, R.H., 1987. Plant response to multiple environmental factors. *BioScience*, 37: 49–57.
- Choudhury, B.J. and Monteith, J.L., 1988. A four-layer model for the heat budget of homogeneous land surfaces. *Q. J. R. Meteorol. Soc.*, 114: 373–398.
- Davis, S.H., Vertessy, R.A., and Silberstein, R., 1999. The sensitivity of a catchment model to soil hydraulic properties obtained by using different measurement techniques. *Hydrol. Proc.*, 13: 677–688.

- Dawes, W. and Short, D.L., 1994. The significance of topology for modeling the surface hydrology of fluvial landscapes. *Water Resour. Res.*, 30: 1045–1055.
- Dawes, W. and Hatton, T.J., 1993. Topog_IRM 1. Model Description. CSIRO Division of Water Resources, Technical Memorandum 93/5, 33 pp.
- Dawes, W. R., Zhang, L., Hatton, T.J., Reece, P. H., Beale, G.T.H., and Packer, I., 1997. Evaluation of a distributed parameter model (TOPOG-IRM) on a small cropping catchment. *J. Hydrol.*, 191: 64–86.
- Domenico, P.A. and Schwartz, F.W., 1990. *Physical and Chemical Hydrogeology*. John Wiley and Sons.
- Edwards, W.R.N. and Warwick, N.W.M., 1984. Transpiration from a kiwifruit vine as estimated by the heat pulse technique and the Penman–Monteith equation. *N. Z. J. Agric. Res.*, 27: 537–543.
- Edwards, W.R.N., Becker, P., and Cermak, J., 1997. A unified nomenclature for sap flow measurements. *Tree Physiol.*, 17: 65–67.
- Gower, S.T. and Norman, J.M., 1991. Rapid estimation of leaf area index in conifer and broad-leaf plantations. *Ecology*, 72: 1896–1900.
- Grantz, D.A. and Meinzer, F.C., 1990. Stomatal response to humidity in a sugarcane field: simultaneous porometric and micrometeorological measurements. *Plant Cell and Environ.*, 13: 27–37.
- Grosenbaugh, L.R., 1979. 3P sampling theory, examples and rationale. Technical Note No. 331, U.S. Department of the Interior, Bureau of Land Management.
- Hatton, T.J. and Dawes, W.R., 1993. Topog_IRM. 2. Sample solutions. CSIRO Div. Water Resour., Tech. Memo. 93/6, 81 pp.
- Hatton, T.J., Catchpole, E.A., and Vertessy, R.A., 1990. Integration of sapflow velocity to estimate plant water use. *Tree Physiol.*, 6: 201–209.
- Hatton, T.J., Walker, J., Dawes, W., and Dunin, F.X., 1992. Simulations of hydroecological responses to elevated CO₂ at the catchment scale. *Aust. J. Bot.*, 40: 679–696.
- Hatton, T.J., Moore, S.J., and Reece, P.H., 1995. Estimating stand transpiration in a *Eucalyptus populnea* woodland with the heat pulse method: measurement errors and sampling strategies. *Tree Physiol.*, 15: 219–227.
- Hatton, T.J., Reece, P., Taylor, P., and McEwan, K., 1998. Does leaf water efficiency vary among eucalypts in water limited environments? *Tree Physiol.*, 18: 529–536.
- Heuperman, A.F., 1995. Salt and water dynamics beneath a tree plantation growing on a shallow watertable. Institute of Sustainable Irrigated Agriculture, Tatura Centre. Department of Agriculture, Energy and Minerals Victoria.
- Jacobs, M.R. 1955. *Growth Habits of the Eucalypts*. Govt. Printer, Canberra, 262 pp.
- Jarvis, P.G., 1981. Stomatal conductance, gaseous exchange and transpiration. Ch. 10 in *Plants and their Atmospheric Environment*, ed. J. Grace, E.D. Ford, and P.G. Jarvis. 21st Symposium, British Ecological Society. Blackwell Scientific Publications: London.

- Jarvis, P.G. and McNaughton, K.G., 1986. Stomatal control of transpiration: scaling up from leaf to region. *Adv. Ecol. Res.*, 15: 1–49.
- Kessler, J. and Oosterbaan, R.J. 1974. Determination of hydraulic conductivity of soils. *In* Drainage Principles and Applications. III: Surveys and Investigations (N.A. de Ridder, ed.). International Institute for Land Reclamation and Improvement (ILRI), Wageningen, The Netherlands. pp. 255–296.
- Khanzada, A.N., Morris, J.D., Ansari, R., Slavich, P.G., and Collopy, J.J., 1998. Groundwater uptake and sustainability of Acacia and Prosopis plantations in southern Pakistan. *Agric. Water Manage.*, 36: 121–139.
- Klein, S.A., 1977. Calculation of monthly average insolation on tilted surfaces. *Solar Energy*, 19: 325–329.
- Landsberg, J.J., 1986. *Physiological Ecology of Forest Production*. Academic Press: London. 191 pp.
- Landsberg, J.J. and Waring, R.H., 1997. A generalised model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance and partitioning. *For. Ecol. Manage.*, 95: 209–228.
- Leuning, R., 1995. A critical appraisal of a combined stomatal–photosynthesis model for C3 plants. *Plant Cell and Environ.*, 18: 339–355.
- Leuning, R., Kriedemann, P.E., and McMurtrie, R.E., 1991. Simulation of evapotranspiration by trees. *Agric. Water Manage.*, 19: 205–221.
- Marcar, N., Crawford, D., Leppert, P., Jovanovic, T., Floyd, R., and Farrow, R., 1995. *Trees for saltland: a guide to selecting native species for Australia*. CSIRO Australia, 72 pp.
- Martin, P., 1989. The significance of radiative coupling between vegetation and the atmosphere. *Agric. For. Meteorol.*, 49, 45–53.
- McDonald, M. C. and Harbaugh, A. W. 1988. MODFLOW, A modular three-dimensional finite difference ground-water flow model. Washington D.C.: U. S. Geological Survey; 1988; Open-file report 83-875. Chapter A1.
- McJannet, D.L. and Vertessy, R.A., 2000. The effect of thinning on the wood production, leaf area index, transpiration, and canopy interception of a plantation susceptible to drought stress. *Tree Physiol.*, in press.
- Meinzer, F.C., Goldstein, G., Holbrook, N.M., Jackson, P., and Cavelier, J., 1993. Stomatal and environmental control of transpiration in a lowland tropical forest tree. *Plant, Cell and Environ.*, 16: 429–436.
- Miller, J.B., 1967. A formula for average foliage density. *Aust. J. Bot.* 15: 141–144.
- Monteith, J.L., 1965. *Evaporation and environment*. Symp. Soc. Exp. Biol., 19: 205–234. Cambridge University Press.
- Monteith, J.L. and Unsworth, M.H., 1990. *Principles of Environmental Physics*, 2nd edition. Routledge, Chapman and Hall, New York, 291 pp.
- Morris, J, Mann, L., and Collopy, J., 1998. Transpiration and canopy conductance in a eucalypt plantation using shallow saline groundwater. *Tree Physiol.*, 18: 547–555.

- Olbrich, B.W., 1991. The verification of the heat pulse velocity technique for estimating sap flow in *Eucalyptus grandis*. Can. J. For. Res., 21: 836–841
- O’Loughlin, E.M., 1986. Prediction of surface saturation zones in natural catchments by topographic analysis. Water Resour. Res., 22: 794–804.
- Penfold, A.R. and Willis, J.L., 1961. The Eucalypts: botany, cultivation, chemistry and utilisation. Interscience Publishers, New York.
- Perroux, K.M. and White, I., 1987. Designs for disc permeameters. Soil Sci. Soc. Am. J., 52: 1205–1215.
- Pook, E.W., 1984a. Canopy dynamics of *Eucalyptus maculata* Hook. I. Distribution and dynamics of leaf populations. Aust. J. Bot., 32: 387–403.
- Pook, E.W., 1984b. Canopy dynamics of *Eucalyptus maculata* Hook. II. Canopy leaf area balance. Aust. J. Bot., 32: 405–413.
- Rauscher, H.M., Isebrands, J.G., Host, G.E., Dickson, R.E., Dickmann, D.I., Crow, T.R., and Michael, D.A. 1990. ECOPHYS: An ecophysiological growth process model for juvenile poplar. Tree Physiol., 7: 255–281.
- Refsgaard, J.C. and Storm, B., 1995. MIKE-SHE, in Computer Models of Watershed Hydrology, ed. V.P. Singh, pp. 809–846, Water Resources Publ., USA.
- Running, S.W. and Coughlan, J.C., 1988. A general model of forest ecosystem processes for regional applications. I. Hydrologic balance, canopy gas exchange and primary production processes. Ecol. Modelling, 42: 125–154.
- Running, S.W. and Gower, S.T., 1991. FOREST-BGC, A general model of forest ecosystem processes for regional applications. II. Dynamic carbon allocation and nitrogen budgets. Tree Physiol., 9: 147–160.
- Shalhevet, J. and Hsiao, T.C., 1986. Salinity and drought: a comparison of their effects on osmotic adjustment, assimilation, transpiration and growth. Irrig. Sci., 7: 249–264.
- Short, D. and Dawes, W.R., 1995. The practicability of using Richards’ equation for general purpose soil-water dynamics models. Environ. Internat., 21: 723–730.
- Silberstein, R.P., Vertessy, R.A., and Morris, J., 1999. Modelling the effects of soil moisture and solute conditions on tree growth and water use. Agric. Water Management, 39: 283–315.
- Skene, J.K.M. and Poutsma, T.J., 1962. Soils and land use in part of the Goulburn Valley, Victoria. Department of Agriculture, Victoria. Technical Bulletin No.14, Melbourne.
- Slavich, P.G., 1997. Modelling groundwater use, salt accumulation and vegetation growth in areas of shallow saline watertables. Ph.D. thesis, Flinders University of South Australia.
- Slavich, P.G. and Petterson, G.H., 1993. Estimating the electrical conductivity of saturated paste extracts from 1:5 soil:water suspensions and texture. Aust. J. Soil Res., 31: 73–81.
- Specht, R.L, Rogers, R.W., and Hopkins, A.J.M., 1981. Seasonal growth and flowering rhythms: Australian heathlands. In: Ecosystems of the World, ed. R.L. Specht, pp.5–13. Elsevier, Amsterdam.
- Stirzaker, R.J. and Passioura, J.B., 1996. The water relations of the root–soil interface. Plant, Cell Environ., 19, 201–208.

- Stone, C. and Bacon, P.E., 1994. Relationships among moisture stress, insect herbivory, foliar cineole content and the growth of river red gum *Eucalyptus camaldulensis*. J. Appl. Ecol., 31: 604–612.
- Talsma, T. and Hallam, P.M., 1980. Hydraulic conductivity measurement of forest catchments. Aust. J. Soil. Sci., 30: 139–148.
- Thorburn, P.J., Walker, G.R., and Jolly, I.D., 1995. Uptake of saline groundwater by plants: An analytical model for semi-arid and arid areas. Plant and Soil, 175: 1–11.
- Vertessy, R.A., Benyon, R.G., O'Sullivan, S.K., and Gribben, P.R., 1995. Relationships between stem diameter, sapwood area, leaf area and transpiration in a young mountain ash forest. Tree Physiol., 15: 559–567.
- Vertessy, R.A., Dawes, W.R., Zhang, L., Hatton, T.J., and Walker, J., 1996b. Catchment scale hydrologic modelling to assess the water and salt balance behaviour of eucalypt plantations. In: K.G. Eldridge, M.P. Crowe and K.M. Old (eds.) Environmental Management: The Role of Eucalypts and Other Fast Growing Species, pp. 110–121.
- Vertessy, R.A. and Elsenbeer, H., 1999. Distributed modeling of stormflow generation in an Amazonian rainforest catchment: effects of model parameterisation. Water Resour. Res., 35: 2173–2187.
- Vertessy, R.A., Hatton, T.J., Benyon, R.J., and Dawes, W.R., 1996a. Long term growth and water balance predictions for a mountain ash (*E. regnans*) forest subject to clearfelling and regeneration. Tree Physiol., 16: 221–232.
- Vertessy, R.A., Hatton, T.J., O'Shaughnessy, P.J., and Jayasuriya, M.D.A., 1993. Predicting water yield from a mountain ash forest catchment using a terrain analysis based catchment model. J. Hydrol., 150: 665–700.
- White, I. and Sully, M.J., 1988. Disc permeameter instruction manual, CSIRO Centre for Environmental Mechanics, Technical report T34, Canberra.
- Wilson, J.B. 1988. A review of evidence on the control of shoot:root ratio, in relation to models. Annals of Botany, 61: 433–449.
- Wu, H., Rykiel, E.J., Hatton, T., and Walker, J., 1994 An integrated rate methodology (IRM) for multi-factor growth rate modelling. Ecol. Modelling, 73: 97–116.
- Zhang, L., Dawes, W.R. and Hatton, T.J., 1996. Modelling hydrologic processes using a biophysical based model – application of WAVES to FIFE and HAPEX-MOBILHY. J. Hydrol., 185: 147–169.
- Zhang, L., Dawes, W.R., Slavich, P.G., Meyer, W.S., Thorburn, P.J., Smith, D.J., and Walker, G.R., 1999. Growth and groundwater uptake responses of lucerne to changes in groundwater levels and salinity: Lysimeter, isotope and modelling studies. Agric. Water Manage., 39: 263–280.