



The effect of **Salt on wood and fibre formation in eucalypts**

**A report for the Rural Industries Research
and Development Corporation**

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Foreword

Secondary salinity involving high, saline water-tables affects large areas of agricultural land in south-eastern and western Australia. Tree planting is one approach for lowering the saline water tables. Such plantations, especially of Tasmanian blue gum (*Eucalyptus globulus* ssp. *globulus*), could become a significant fibre source for the pulp and paper industry.

This report addresses whether growth of *Eucalyptus globulus* ssp. *globulus* in salt-affected environments influences key fibre properties important in paper production.

Research was conducted on plantations near Shepparton, Victoria, irrigated with pumped saline ground water of 5-10 dS m⁻¹, and with pot trials at the School of Forestry, Creswick, Victoria. The combined results indicate that levels of soil salt that do not significantly affect tree growth also have no measurable effect on fibre properties, at least in the first 4 years after planting.

RIRDC's involvement in this project and in the Joint Venture Agroforestry Program, is part of the Corporation's Agroforestry and Farm Forestry Research Program which aims to foster integration of sustainable and productive agroforestry within Australian farming systems. It was funded by three R&D Corporations — RIRDC, LWRRDC and FWPRDC which are principally funded by the Federal Government.

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Peter Core

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Abbreviations

CFTT	Centre for Forest Tree Technology, the research arm of DNRE
DNRE	Victorian Department of Natural Resources and Environment (previously the Department of Conservation and Natural Resources)
EC	electrical conductivity, a measure of salt content
EC _a	apparent electrical conductivity, measured electromagnetically with an EM38
EC _e	electrical conductivity of a saturation soil extract (typical of the dissolved salt levels experienced by plants)
EC _{sat}	see EC _e
EC _{1:1}	electrical conductivity of a 1:1 soil/water extract
EC _{1:5}	electrical conductivity of a 1:5 soil/water extract (a measure of total dissolved salts)
EM38	an instrument for electromagnetic measurement of soil salinity
FAA	formalin:acetic acid:ethanol:water 10:5:50:35 by volume
GLOBU660	Otways seedlot of <i>Eucalyptus globulus</i> ssp. <i>globulus</i>
TDS	total dissolved salts
TSS	total soluble salts
TfP	Trees for Profit foundation
Tt.mod	Tatura site irrigated with moderate salinity ground water
Ti.low	Timmering site irrigated with low salinity channel water
Ti.high	Timmering site irrigated with high salinity ground water

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Executive summary

Salinity, the presence of soluble salts in soils or waters, can be separated into naturally occurring primary salinity, and secondary salinity resulting from human activities such as land development and agriculture. Secondary salinity involving high, saline water-tables affects large areas of agricultural land in Australia, and tree planting is one approach for lowering the saline water tables. Such plantations could become a significant fibre source for the pulp and paper industry, but it is not known whether growth in salt-affected environments will influence key fibre properties important in paper production.

This work therefore examines the wood and fibre properties of Tasmanian blue gum, *Eucalyptus globulus* spp. *globulus*, from trial plantations in the Shepparton region of north-central Victoria that were irrigated with pumped saline ground water. The plantations were established in 1993, and field sampling was carried out from 1995 to 1997. One plot at Timmering was irrigated with fresh channel water with an electrical conductivity (EC) of 0.2 dS m^{-1} , while two plots (one at Tatura and one at Timmering) were irrigated with saline ground water with nominal EC values of 5.0 and 10 dS m^{-1} respectively. Mean soil salinity over the period of study, expressed as the EC of a saturated soil extract (EC_e), was 2.0 dS m^{-1} for the Timmering plot irrigated with fresh water (thus ranging from non-saline to slightly saline soil categories), and 3.3 dS m^{-1} and 4.7 dS m^{-1} for the Tatura and Timmering plots irrigated with saline ground water (thus ranging from slightly saline to moderately saline soil categories). Soil from the Timmering plot irrigated with ground water was on average 2.3-fold as saline as soil from the Timmering plot irrigated with fresh water.

Tree size did not differ significantly between plots at any age. There were no significant differences in tree growth over the period of study between the plot irrigated with ground water at nominal 10 dS m^{-1} and the plot irrigated with fresh water, and the small differences in tree growth that did occur could not be attributed to soil salinity. Although a small negative relationship between tree diameter growth and soil EC was found, there was a small positive relationship between tree height growth and soil EC, and overall no consistent relationship between tree volume growth and soil EC.

Differences in foliar $[\text{Na}^+]$, $[\text{K}^+]$ and $[\text{Cl}^-]$ occurred between the field plots but were not consistent between years, and the highest concentrations of foliar ions were also not always associated with the plot receiving the most saline irrigation water. Significant, positive regression relationships between foliar ion concentrations and soil EC existed in 1996 only, suggesting that in only some years was the soil salt level sufficient to cause a plant response. Basic density of the Tatura plot receiving the moderate salinity irrigation water ($0.40\text{-}0.49 \text{ g cm}^{-3}$) differed from that of the Timmering plots receiving the highest salinity irrigation water ($0.48\text{-}0.49 \text{ g cm}^{-3}$) and the fresh channel water ($0.48\text{-}0.52 \text{ g cm}^{-3}$), which may reflect site-specific effects. There were also no significant relationships between basic density and soil EC, and basic density and foliar ion concentrations, further supporting the conclusion that field salinity had not affected basic density. Salinity also did not affect any fibre morphology parameter: there were no significant differences in fibre length between any of the plots over the period of study, or in fibre diameter or double wall thickness. There were some differences between the plots in the increase in fibre length from year to year but, when fibre morphology parameters of individual trees were compared with soil EC at their base and with foliar $[\text{Na}^+]$, $[\text{K}^+]$ and $[\text{Cl}^-]$, no significant relationships could be established.

In addition to the above field-trial, a pot-trial on 18-month-old *Eucalyptus globulus* spp. *globulus* trees was carried out at the School of Forestry, Creswick, Victoria, applying different saline solutions over a 10-week period. The EC of the potting mixture increased very markedly in the salt-treated trees relative to the controls. Foliar chloride and sodium were also significantly higher in trees on the higher salt treatments (up to 26 mg g⁻¹ Cl⁻ and 12 mg g⁻¹ Na⁺) than in the control trees (up to 3.6 mg g⁻¹ Cl⁻ and 1.3 mg g⁻¹ Na⁺), so the salt treatments had influenced some aspects of tree physiology. There was no significant effect of salt treatment on the mean growth in tree height or diameter, but when regression analyses were applied to test the effects of pot-to-pot variation it was found that tree diameter and volume growth both decreased during the second half of the experiment with increasing EC.

A wound made to the cambium allowed pre-treatment fibres (fibres formed prior to the start of the experiment) to be distinguished from post-treatment fibres (fibres formed during the experiment). Trees on higher salt treatments produced significantly longer, thinner-walled fibres compared to controls, but this pattern also occurred in fibres formed before treatments were imposed, implying that these differences were due to pre-existing differences in the trees unrelated to the salt treatment. Statistical analysis of fibres formed during treatments, taking account of pre-existing differences, found that there was no significant effect of salt treatment on fibre length or wall thickness, although this was possibly because of the low sample size relative to the variation of the experimental material

The controlled application of salt in the 10-week pot trial thus adversely affected tree physiology and may have started to reduce tree growth, but no significant effects on fibre dimensions or wood formation were observed. This confirms the conclusion from the field trials, that levels of soil salt that do not significantly affect tree growth also have no measurable effect on fibre properties, at least in trees up to 4 years old. Higher levels of salt could cause rapid tree decline due to the inability of the trees to exclude the salt, and any processes associated with fibre formation would then probably cease.

1. Introduction

Secondary salinity is a human-induced process where irrigation and/or clearing of native vegetation causes salinisation of previously unaffected soils (Sands 1986). Two types of secondary salinity are recognised, depending on whether a ground-water system is associated with the development and maintenance of salinity (Williamson 1990). Scalds are not associated with a ground-water system, but occur in low rainfall zones (less than 400 mm annual precipitation) where erosion due to excessive grazing exposes a saline or sodic subsoil (Williamson 1990). Saline seeps, by contrast, are associated with ground-water systems, and occur where there is a discharge at the soil surface of ground water containing dissolved salts (Williamson 1990); they can occur in dryland or irrigated areas. The total area of secondary saline soils in Australia, including scalds, non-irrigated saline seeps and irrigated saline soils, was estimated in 1990 to be 4 734 000 ha (Williamson 1990). This area is expanding (Williamson 1990; Anon. 1996), and thus represents a continuing threat to agricultural production, the supply of potable water and the ecology of wetlands (Schofield 1992; Marcar et al 1995).

In order to control and even reduce the area of secondary salinity, elimination of the source of water or the method of salt redistribution needs to occur. In irrigation areas, engineering approaches, involving the use of pumps, wells and ditches have been used (Williamson 1990). However, in dryland areas engineering approaches may not be feasible or affordable, so the control of excess ground-water recharge may be achieved with an environmental approach. Tree planting in both ground-water recharge and discharge areas is one environmental method for controlling rising water tables (Marcar et al 1995), as with access to adequate water eucalypts might transpire 1600 mm annually, while mature pasture transpires 800 mm (Bren 1992; Raper 1998).

Tree planting on farmland to control and reduce secondary salinity problems represents a present opportunity cost to the landowner in terms of area lost to agricultural production. If, however, the pulp or timber resource potential of the trees were to be realised, then there would be a financial as well as environmental benefit to the landowner. Australia currently has a large trade imbalance in pulp and paper products, estimated at \$1 000 000 000 annually. With continuing political pressure to reserve native forests for non-wood uses, the traditional resource base for locally produced product is being reduced. Plantations on salt-affected lands could improve resource availability provided the quality of the fibre produced is satisfactory. However, the effects of a saline environment on the wood and fibre properties of trees have not been determined (Rawlins 1992): specifically, it is not known whether wood properties become affected at different levels of salinity to those at which growth is affected.

The Tasmanian blue gum, *Eucalyptus globulus* ssp. *globulus*, is recognised to provide wood and fibre appropriate for production of highest quality pulp and paper (Downes et al 1997), and many plantations of *E. globulus* are being established across south-eastern Australia. However, *E. globulus* is also slightly to moderately tolerant to salinity (Marcar et al 1995), and was thus chosen for this study. Many wood and fibre properties are important for pulp and paper production, including wood basic density and fibre length, diameter, wall thickness and lumen diameter, and are determined by processes that occur in the vascular cambium, the meristematic zone in the tree stem responsible for wood production. Simple measurement of fibre properties does not explain the causes of any variability, and a better understanding of cambial processes will enable the effects of specific environmental factors upon fibre morphology to be separated.

The specific aims of the study were thus to:

- i) measure the salinity of the environment in which selected trees grew;
- ii) monitor the growth response of the trees to salinity;
- iii) investigate the wood and fibre properties of those trees;
- iv) relate any differences in wood properties to the degree of salinisation of the environment in which they were formed;
- v) distinguish, if possible, direct effects of salinity on wood properties from the effects of altered growth on wood properties.

2. Objective

The objective of the project was to determine the effect, if any, of root-zone salt on key wood and fibre properties important in the production of paper.

3 Experimental design

3.1 *Eucalyptus globulus* field trials

Field measurements for this study were made in established trials where the effects of soil salinity on agroforestry were already being tested. Sites were chosen where the rate of growth of the experimental species, *Eucalyptus globulus*, justified commercial interest in the fibres being produced, but where there was a potential for tree growth to be affected by salinity.

The field trials of *E. globulus* used in this study were selected from plantations in the Shepparton irrigation region after inspection of several other sites in Victoria, and consultation with Dr Jim Morris (Centre for Forest Tree Technology), Mr Des Stackpole (Department of Natural Resources and Environment), Dr Nico Marcar (CSIRO Forestry & Forest Products) and Dr Arnis Heislars (Trees for Profit). The Shepparton plantations had been established by the Trees for Profit foundation to demonstrate the commercial potential of eucalypts grown on farms for land and water care.

To assess if salt had any effect on fibre properties, it was necessary to measure trees on a relatively high salt treatment, and compare them with trees of the same age, location, species and provenance on a low or zero salt treatment. The Timmering Trees for Profit plantation site met this requirement, with the following two irrigation treatments being applied to alternate bays of tree plots, each bay containing several rows of trees irrigated simultaneously:

- i) fresh, channel-water irrigation, nominal salinity of 0.2 dS m^{-1} . One plot of *E. globulus* spp. *globulus* (hereafter denoted as Ti.low) was selected from this irrigation regime;
- ii) saline, ground-water irrigation, nominal salinity of 10.0 dS m^{-1} . One plot of *E. globulus* spp. *globulus* (hereafter denoted as Ti.high) was selected from this irrigation regime.

The Trees for Profit plantation site at Tatura provided a third level of salt treatment, halfway between the two treatments available at Timmering. A single irrigation treatment, with saline ground water of a nominal salinity of 5.0 dS m^{-1} , was applied across the Tatura entire site. The confounding effect on data interpretation of this second site, with potentially different soil and weather conditions, was recognised in the analyses. A single plot of *E. globulus* spp. *globulus* from the Tatura site (hereafter denoted as Tt.mod) was selected for the present study. A replicate plot showing impaired tree growth was also sampled in 1997.

Sampling at these sites took place in Jan 1995, 1996 and 1997. In Jan 1995, nine trees from each plot were randomly selected, providing a total of 27 sample trees, and measurements and sampling in subsequent years were repeated on the same trees. At the 1996 sampling, one tree at the Tt.mod plot and another at the Ti.high plot had fallen over, and were left out of the sampling program in that and the subsequent year (1997).

The trial designs, establishment information and soil and ground-water characteristics of the Trees for Profit plantation sites have been described in detail elsewhere (Bren et al 1993; Baker et al 1994; Stackpole et al 1995). A brief summary of this site information for the two plantations selected for the present study is provided below.

Timmering

The Timmering site was located approximately 6 km south of Tongala, on the property of D & H Chessum on Everard Road, west of Watson's Road, Timmering. The Trees for Profit plantation covered 7 ha. High watertables, generally 1 to 2 m below the soil surface and with electrical conductivity (EC) levels of approximately 10 dS m⁻¹, characterised the Timmering district (Bren et al 1993; Stackpole et al 1995).

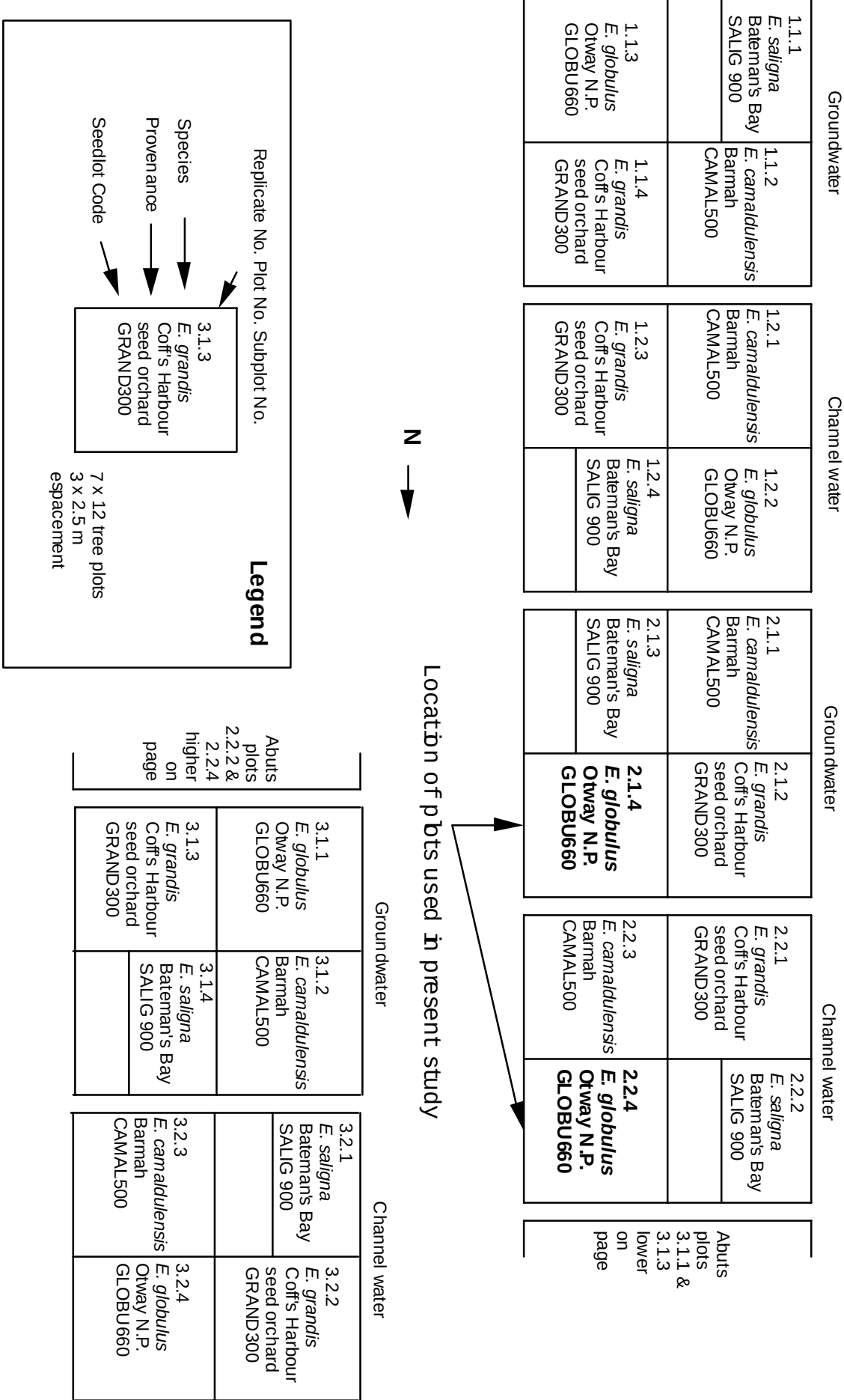
Soils at the Timmering site were heavy clays, known locally as Alta clay loam, and subject to seasonal waterlogging (Stackpole et al 1995). The three soil profiles characterised and described by Bren et al (1993) at the Timmering site were a Wanalta loam in the north-east, and Alta clays in both the north-west and south-east corners. The Wanalta loam in the north-east and the Alta clay in the south-east were both red duplex soils whereas the Alta clay in the north-west was a brown duplex soil (Northcote 1979). All three profiles had alkaline reaction trends. An extensive sand layer occurs at between 4 and 8 m depth.

Twenty-one bores were drilled at the Timmering site for investigation of hydro-geological features (Bren et al 1993). Standing water levels below the natural surface ranged from 0.80 to 1.98 m. EC of these waters ranged from 0.155 to 20.4 dS m⁻¹, with a median value of 5.1 dS m⁻¹. Total soluble salts (TSS%) in the soil water from a selection of 6 of the 21 bores ranged from 0.023 to 0.160 TSS% over the top 4.0 m, equivalent to calculated soil EC_{1:1} values (for 1:1 soil:water mixtures) of 0.383 to 2.67 dS m⁻¹. Bore 4821, from which the groundwater supply was extracted, gave water at EC of 20.2 dS m⁻¹, with 0.051 to 0.162 TSS% which converts to EC_{1:1} values of 0.85 to 2.7 dS m⁻¹.

The site was ripped in late March 1993, laser-graded in May 1993 and mounded straight after (Stackpole et al 1995). Prior to planting, residual and knockdown chemicals were applied.

Four trials were established on the Timmering site, TIs1 (major species demonstration), TIs2 (major species provenance selection), TIs3 (minor species provenance selection) and TIp (cloned *Eucalyptus camaldulensis* and *E. occidentalis*). Figure 3.1 illustrates the arrangement of these trials. Trees were planted in late July 1993, and were irrigated from March 1994 with either pumped saline ground water (nominally taken as being 10 dS m⁻¹) or fresh channel water (0.2 dS m⁻¹), thus allowing direct comparisons between controls and trees exposed to salt (Baker et al 1994). However, consistent application of saline ground water did not occur until the 1995-96 irrigation season (Hamlet & Morris 1996).

Figure 3.1 . Timing Plantation, major species demonstration trial



Tatura

The Tatura site was located approximately 4 km north of the township of Tatura on the property of GA & I Oakes on the Undera Road north of the Midland Highway in the Shepparton irrigation region. The Trees for Profit plantation covered 5.4 ha.

Soils were heavy clays associated with the Mosquito Depression, an intermittently flowing waterway (Stackpole et al 1995). Three soil profiles at Tatura were characterised and described by Bren et al (1993). Two of these profiles, in the north-east and south-west of the site, were classified as Lemnos loam, and the third, to the south-east, was a Goulburn clay. All three profiles were yellow and yellow-grey duplex soils with alkaline soil reaction trends (Northcote 1979).

Twenty bores were drilled at the Tatura site for investigation of hydro-geological features (Bren et al 1993). Standing water levels below the natural surface ranged from 0.5 to 1.9 m. EC of these waters ranged from 0.950 to 16.8 dS m⁻¹, with a median value of 6.1 dS m⁻¹. Total soluble salts (TSS%) in the soil water from a selection of 9 of the 20 bores ranged from 0.027 to 0.227 TSS% over the top 4.0 m, equivalent to calculated soil EC_{1:1} values (for 1:1 soil:water mixtures) of 0.450 to 3.78 dS m⁻¹. Bore 111374, from which the groundwater supply was extracted, gave water at EC of 6.6 dS m⁻¹, with 0.069 to 0.165 TSS% which converts to EC_{1:1} values of 1.15 to 2.75 dS m⁻¹.

Preparation of the site for planting involved laser grading in February 1993, followed by deep ripping in March and rotary hoeing to remove large clods (Stackpole et al 1995). In May 1993, residual and knockdown herbicides were applied.

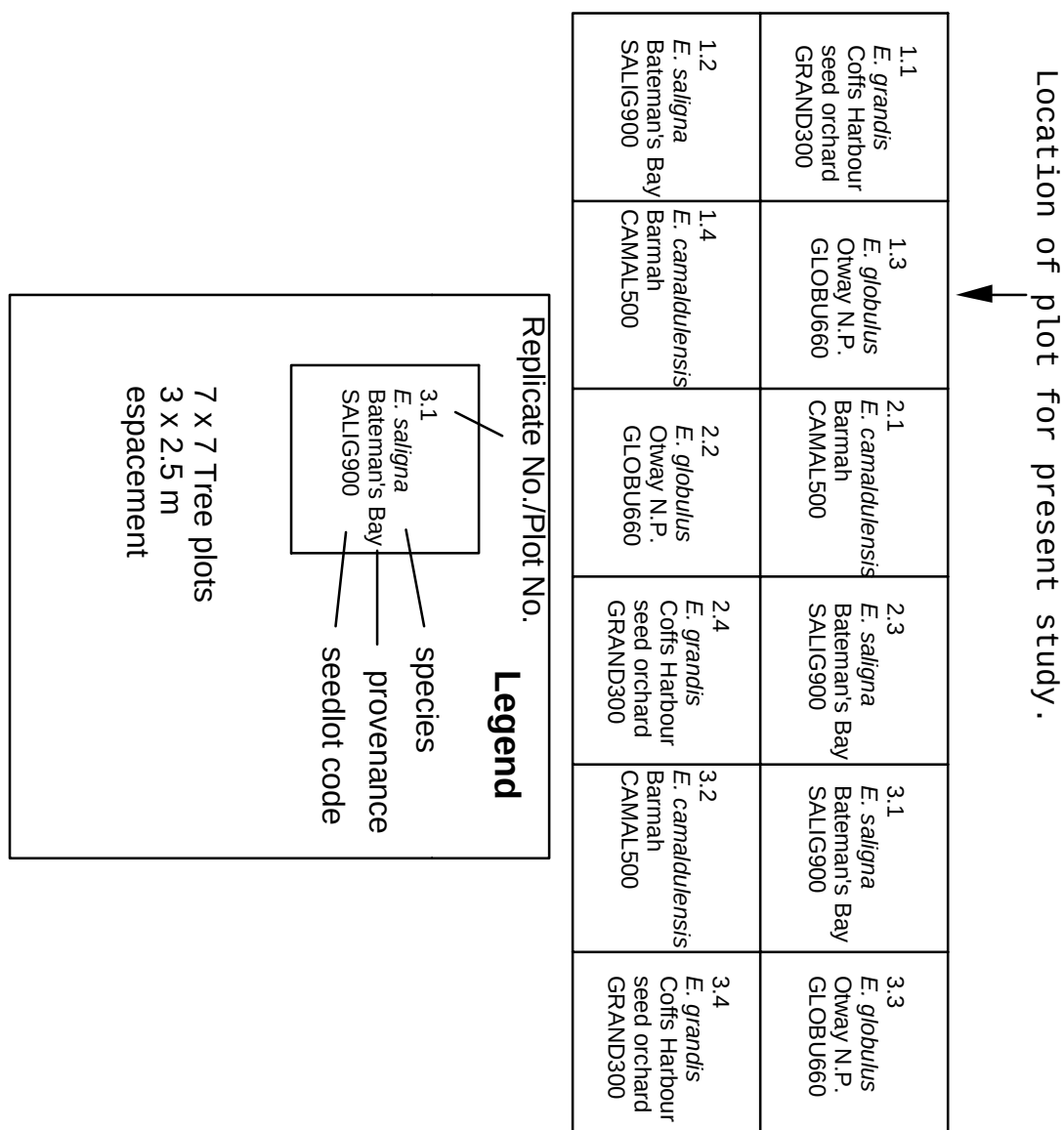
Five trials were established at the Tatura site: TTs1 (major species demonstration), TTs2 (major species provenance selection), TTs3 (minor species provenance selection), TTp (Red Gum provenance and clone selection) and TTi (insects: natural resistance/control investigation). Figure 3.2 illustrates the arrangement of these trials, with the exception of TTL. Planting was carried out in September 1993. Irrigation with pumped saline ground water (nominally 5 dS m⁻¹) commenced two months later. Plants were fertilised with 250 g per tree of Pivot 800 in November 1993. Irrigation by manual pumping was replaced by an automated system in December 1993. For the remainder of summer, irrigation continued at two-weekly intervals.

3.2 *Eucalyptus globulus* pot trial

A pot trial using 18-month-old *E. globulus* ssp. *globulus* trees was conducted at the School of Forestry, Creswick, in late 1996, allowing a more controlled application of salt than was possible in field trials. Seeds were obtained from Ian Bail (CFTT), and comprised 15 individual tree collections (families) from within Otway National Park, Victoria. This was a similar seedlot to the GLOBU660 seedlot used on the Shepparton field sites.

In Feb 1995, seeds were germinated on No.1 Whatman filter paper in disposable plastic Petri dishes. Petri dishes containing seeds were transferred to a growth cabinet on a 12-hr day/night lighting cycle to germinate. Ten days after sowing, cotyledons emerged and the seedlings (4 seedlings/pot) were transferred to 5 L pots filled with a 7/3 (v/v) peat/perlite mix and 15 g of controlled release fertiliser (Osmocote® Plus : 16% N, 3.5% P, 10% K, 1.2% Mg (w/v) with trace elements B, Cu, Fe, Mn, Mo, Zn). Seedlings were grown in a glasshouse with a natural photo-period and manually watered to field capacity every third day.

Figure 3.2. Tatura plantation, species trial design



On 17 and 18 Sep 1995, 164 seedlings were transferred (1 per pot) into 15 L pots filled with fresh potting medium and controlled-release fertiliser. On 21 and 22 Oct 1995, the re-potted seedlings were moved to an outdoor enclosure constructed from star pickets surrounded with 50%-shade shade cloth. The stems were physically supported to reduce the confounding effect of any reaction wood formation.

When the trees were 18 months of age, 48 were randomly selected for the experimental treatments. The experiment was a randomised block design with three replicates, four salinity levels and two volume applications. The four salinity levels were 0 mM NaCl (C, control), 75 mM NaCl (L, low salinity), 150 mM NaCl (M, moderate salinity) and 225 mM NaCl (H, high salinity), and the two volume applications were 3 L and 6 L. *E. globulus* is moderately salt tolerant (Marcar et al 1995), so the moderate salinity level was set at 150 mM NaCl, equivalent to a soil saturated extract (EC_e) of 10 to 15 dS m^{-1} , which is regarded as a

severely saline soil (Marcar 1993). The moderate salt treatment was designed to produce an effect but not one so strong as to result in tree death before they had produced a measurable amount of wood. The other salinity treatments were based around this moderate level, to determine whether there was a threshold value at which effects on fibre properties occurred. The period of growth under these treatments was ten weeks.

The 4 salt treatments – control, low, moderate and high — were applied at two rates, 3 L (low volume) and 6 L (high volume). The 3 L application was designed to just replace soil moisture lost since the previous treatment, thereby gradually increasing salt levels over the course of the experiment. The 6 L application was designed to completely flush out and replace the previous treatment, and maintain a constant salt level in the potting medium. For brevity the individual treatments will be referred to by salinity level and volume of application as C3, C6, L3, L6, M3, M6, H3 and H6; collectively they will be referred to as control, low, moderate and high salt levels, and low and high volume applications.

The first treatment was applied to the trees on 27 Sep 1996 and the following five treatments, up to 31 Oct, were applied once a week. The treatment frequency then was gradually increased to approximately twice a week as the days became warmer and drier (Table 3.1). Final treatments were applied on 5 Dec 1996.

Table 3.1. Dates of application of treatment solutions to experimental trees, pot trial.

Treatment	Date	Days since previous treatment	Duration of experiment (days)
1	27 Sep 1996	0	0
2	4 Oct 1996	7	7
3	11 Oct 1996	7	14
4	18 Oct 1996	7	21
5	24 Oct 1996	6	27
6	31 Oct 1996	7	34
7	5 Nov 1996	5	39
8	9 Nov 1996	4	43
9	13 Nov 1996	4	47
10	16 Nov 1996	3	50
11	19 Nov 1996	3	53
12	22 Nov 1996	3	56
13	26 Nov 1996	4	60
14	28 Nov 1996	2	62
15	2 Dec 1996	4	66
16	5 Dec 1996	3	69

The analyses to be conducted required that foliar and xylary tissues still be alive at the time of harvest. During the course of the experimental treatment, five trees showed symptoms of severe salt stress, including chlorosis and necrosis of leaf tips and margins. They were assessed as unlikely to survive to the completion date of the experiment, and were thus harvested prior to the last scheduled treatment (Table 3.2).

Table 3.2. Prematurely harvested trees, pot trial

Tree number	Treatment	Premature harvest	Duration of experiment (days)
21	M3	20 Nov 1996	54
28	H3	27 Nov 1996	61
36	H6	27 Nov 1996	61
2	H3	2 Dec 1996	66
6	H3	2 Dec 1996	66

4. Trial methodology and rationale

4.1 General

Eucalyptus globulus Labill. ssp. *globulus* was selected for this study because it is a highly desirable pulp species showing fast growth, good tree form characteristics and good wood properties for pulping, including density, fibre morphology, chemical composition and pulp yield (Pereira et al 1995). It is also slightly to moderately salt tolerant (Marcar et al 1995).

Field and pot trials were used to take advantage of the different benefits offered by the two systems. Field trials provide material that better represents real life situations, but controlling variables other than the one of interest is difficult. Very few appropriately established and replicated trials exist in Victoria suitable for analysis of the effect of salt on wood properties. Destructive harvesting was not permitted for the field trials used for this study, limiting the analyses that could be conducted. The pot trial provided the opportunity to impose salt treatments in a more controlled manner than possible under field conditions, and apply salt at higher concentrations than would be allowable for commercial reasons at the field sites. Destructive sampling was also possible for the pot trial.

To assess whether salinity affected wood or fibre properties, the following measurements and samples were collected for both the field trial and the pot trial:

- i) soil samples for determination of soil salinity
- ii) tree height and diameter to monitor growth response to salinity
- iii) foliage samples for analysis of salt uptake
- iv) stem samples for measurement of wood and fibre properties.

4.2 Soil salinity

Assessing the effects of salinity on plant growth requires a measure of the concentration of soluble salts in the soil water at some reference soil water content (Slavich & Petterson 1993). For plant response purposes it would be preferable to perform the analysis at field capacity (the soil water content after drainage from a state of saturation has practically ceased), as this would provide a measure of the concentration of soluble salts in the maximum available soil water.

However, it is difficult to obtain samples of soil solutions at usual field water contents (Rayment & Higginson 1992a), and instead the saturation water content is commonly used as this is the lowest reproducible soil:water ratio from which sufficient sample can be readily removed for analysis (Richards 1954; Shaw 1985). Salinity is thus generally assessed by measuring the electrical conductivity (EC) of soil-water suspensions, with the electrical conductivity of a saturation extract being denoted as EC_e . A 1:5 soil:water ratio is also widely used in Australia (Rayment & Higginson 1992b), and the electrical conductivity of such an extract, denoted as $EC_{1:5}$, provides an easily obtained estimate of the total quantity of soluble salts per unit weight of soil.

Field trials

Soil electrical conductivity ($EC_{1:5}$) data for 1994 and 1995 were provided by CFTT staff of Centre for Forest Tree Technology (CFTT), the research arm of the then Victorian Department of Conservation and Natural Resources. The data came from forty soil cores collected in each replicate block at Tatura (comprising four 7 x 7 tree plots) or replicate plot

at Timmering (comprising 7 x 12 tree sub-plots), divided into 0-10 cm and 10-20 cm portions, bulked over depth and sub-sampled for analysis. However, the CFTT data was not specific to the plots or trees sampled for the present study.

In 1996 and 1997, soil samples for determination of $EC_{1:5}$ were therefore collected concurrently with measurement and sampling of the 9 trees in each plot. Two 50-mm-diameter soil cores were extracted by hand auger to 20-cm depth near the base of each sampled tree, one core from the planting mound and the other in the adjacent irrigation bay. Each core was divided into 0-10 cm and 10-20 cm portions.

Pot trial

Samples of potting medium (hereafter referred to as soil) were collected just prior to the start (25 Sep 1996), approximately halfway (4 Nov 96) and a few days after the end (6 Dec 96) of the experiment. To avoid excessive root disturbance, soil was sampled from only the surface 10 cm, using a hand-held 50-mm-diameter soil auger.

4.3 Tree growth

One of the earliest signs of salt damage in salt-sensitive eucalypts is a marked reduction in growth (Morris 1980). This is caused by several major problems confronting plants growing in a saline soil (Marschner 1986; Sands 1986; Salisbury & Ross 1992; Glenn et al 1997):

- i) a larger negative osmotic potential (increased osmotic pressure) of the soil water, leading to water stress in the plant;
- ii) high concentrations of potentially toxic ions such as chloride and sodium, or deleterious combinations of ions such as a high Na^+ / Ca^{2+} ratio;
- iii) disruption by excess Na^+ of the uptake of ions important to plant nutrition such as K^+ and Ca^{2+} .

Plants can deal with a highly saline soil solution either by excluding the salt, at the risk of developing a within-plant water deficit, or by absorbing the salt at the risk of ion toxicity and nutritional imbalances (Greenway & Munns 1980; Marschner 1986). Whatever mechanism the plant adopts to cope with elevated salinity, it requires energy expenditure that would otherwise have been used in normal growth (Keiper et al 1998).

Field trials

To monitor whole-plant response to salinity in the present study, total height, and diameter at 20% of total height, were measured in Jan 1995, 1996 and 1997. Diameters were measured at 20% height as fibre properties at this height are the most representative of whole-tree values (Downes et al 1997). Tree volume was estimated from $1/3 * \text{tree height} * \text{diameter}^2$ (Hamlet & Morris 1996).

Pot trial

On 23 Sep 1996, four days prior to the commencement of the experiment, the height of each tree was measured with telescoping fibreglass height poles. The diameter at 20% height was measured across the north-south axis of each tree with digital vernier callipers. A small mark of Liquid Paper® was placed on the north side of the stem at the diameter measurement point, which allowed re-measurement at exactly the same point approximately halfway through the experiment (5 Nov 96) and at the end of the experiment (5 Dec 96). Tree height was also remeasured on these dates. Volume was again estimated from $1/3 * \text{tree height} * \text{diameter}^2$.

4.4 Salt uptake

Analysis of foliage for concentrations of soluble salts, $[\text{Na}^+]$, $[\text{K}^+]$ and $[\text{Cl}^-]$, provides a measure of within-tree salinity. It complements soil EC measurements, and provides an alternative measure of the differences between treatments in the salinity experienced by the trees. Whereas the soil EC data is measured at only a few locations for each tree in an attempt to monitor the effects of the irrigation or experimental treatments on soil salinity, within-tree salinity incorporates the responses of the whole rooting zone to soil salt. The tissue analyses thus not only removed the problems of collecting soil samples that accurately represented the whole rooting zone, but also removed the problems encountered in interpreting the meaning of soil chemical data in terms of plant growth. However, only some plant responses to salinity will manifest in elevated foliar ion concentrations: successful ion exclusion may take energy and retard growth, but foliar ion concentrations would be unaltered.

Field trials

Foliage samples were collected from the north side of the upper third of the tree canopy, and comprised most recent fully expanded leaves. Leaves were separated from petioles in the field, immediately placed in snap-lock plastic bags, and placed on ice for transfer to the laboratory. In the first year of sampling, when the trees were 16 and 18-months old (Tatura and Timmering sites, respectively), not all had developed mature foliage. For trees with only juvenile foliage, the foliage sample was collected as above but, for those with both juvenile and adult foliage, a sample of adult foliage was collected from the top third of the canopy and a sample of juvenile leaves was collected from as near as possible to this point on the canopy. Adult and juvenile foliage was analysed separately.

Pot trial

Foliage samples were collected at the completion of the experiment on 6 Dec 1996. Twelve leaves were taken from the north side of the upper third of the crown of each tree, and comprised the most recently fully expanded leaves. All leaves were still of the juvenile form. Leaves were removed from petioles, transferred to snap-lock plastic bags, and placed on ice for transfer to the laboratory.

4.5 Wood basic density

Wood basic density is the ratio of oven-dry mass to green volume, and expresses the relationship between cell wall material and voids, as well as being a measure of the absolute density of the cell wall material (Sandercock et al 1995). Differences in basic density are due to wood anatomical differences, plus the presence of resins, polyphenols and gums, and density has been considered as one of the most significant wood properties determining end use (Bamber & Burley 1983). Although the value of using basic density for predicting the suitability of eucalypt wood for various end products has been questioned (Sandercock et al 1995; Downes et al 1997), it continues to be quoted (Banham 1995; Williams et al 1995; Clark et al 1998) probably because of the ease and speed with which it can be determined. Basic density was used in the present study to flag changes occurring at the cellular level.

Field trials

Stem samples for determination of basic density were extracted from the north side of each tree near the diameter measurement point, with a 5-mm-diameter increment corer at right angles to the stem axis and aligned north-south through its pith (centre). The cores were immediately placed in vials of ethanol to maintain green volume and prevent fungal contamination.

Pot trial

Basic density was not measured in the *Eucalyptus globulus* pot trial as it was considered too coarse a measure for the small amount of wood formed during the experimental treatments.

4.6 Fibre morphology

Wood fibres are the primary raw material in pulp and paper, and measurement of their morphology was a central part of the present study. Variation in fibre dimensions (fibre length, fibre diameter, lumen diameter and wall thickness) directly affects paper quality (Sandercock et al 1995; Downes et al 1997).

Fibre length is important in the paper properties of tearing resistance and folding endurance, and shorter fibres will result in paper inferior in these characteristics (Bamber 1985). Shorter fibres do confer some advantages over longer fibres in paper production, however, as longer fibres are more likely to become entangled during the papermaking process leading to the formation of flocs and variation in sheet opacity (Higgins 1969).

Cross-sectional fibre dimensions (diameter, wall thickness and lumen diameter) are important in papermaking because they influence the ease of fibre collapse, which improves fibre-fibre bonding in the paper sheet. For a given fibre diameter, those with thinner walls will collapse more readily during pressing and drying stages of paper manufacture, giving a high relative bonded area and better mechanical properties (Higgins 1969).

Field trials

Samples for examination of fibre morphology were collected from the north side of each stem, near the diameter measurement point, with a 5-mm-diameter increment corer oriented at right angles to the stem axis and aligned north-south through its pith (centre). The cores were immediately placed in vials of ethanol to maintain green volume and prevent fungal contamination.

Pot trial

A cambial marker allowed xylem formed before and after treatments to be distinguished in tissue sections. The various methods of marking xylem growth were reviewed by Ridoutt (1995), who found cambial wounding with fine needles to be a successful method for *E. globulus*. This method was introduced by Wolter (1968) who tested it on a softwood species (*Pinus resinosa* Ait.), and its efficacy for marking xylem growth in hardwoods was tested and found satisfactory by Kuroda & Shimaji (1984).

On 25 Sep 1996, two days before treatments commenced, a small wound was made to the cambium of all experimental trees. Sterilised 400- μ m stainless steel needles (Asta Ento Pins, Newey Goodman Ltd, England) were inserted just above the point of diameter measurement (20% of total tree height) on the north side of each stem, until resistance was met. The needles were immediately removed to allow wound formation to commence. The point of insertion was marked with Liquid Paper® to ensure it could be remeasured at the end of the experiment.

A stem disc, approximately 20-mm thick (longitudinally) and including the needle insertion point, was removed from the stem at the completion of the experiment. To prevent damage to the soft tissue of the cambium, strips of bark 3-4 mm wide, were carefully removed with single-edge razor blades from above and below the wound point. Saw cuts to remove the disc from the stem were made at the locations where the bark had been stripped. The discs were then immediately fixed in FAA (formalin:acetic acid:ethanol:water 10:5:50:35 by volume).

Two sets of samples were collected to determine whether salt had affected fibre morphology. One set was used to make between-treatment comparisons. The second set was used to make before-treatment and after-treatment comparisons, and so was separated into fibres formed before and after treatment within each tree.

4.7 Cambium

The cambium is the area of actively dividing cells (meristem) in the stem of vascular plants undergoing secondary growth. It is responsible for the formation of secondary xylem, collectively referred to as wood, and comprising tissue involved in water and nutrient transport within the plant and tissue providing structural support. The vascular cambium also gives rise to secondary phloem, which includes tissue responsible for transport of sugars from the canopy. The cambium consists of two cell types: fusiform initials and ray initials (Panshin & de Zeeuw 1970). In the cambium of eucalypts, fusiform cambial cells differentiate into longitudinally oriented cells, namely vessel elements, longitudinal parenchyma, vasicentric tracheids and fibre tracheids (fibres), while cambial ray cells give rise to horizontally oriented cells, namely ray parenchyma (Ridoutt & Sands 1995).

Fibre dimensions are influenced by both the dimensions of the fusiform initials and the changes that occur during their differentiation into mature fibres (Ridoutt & Sands 1993). The differentiation of fusiform initials into mature fibres involves cell enlargement, both radially and longitudinally, concurrently with primary wall formation, followed by secondary wall deposition and lignification (Ridoutt & Sands 1994). The non-lignified contents of the cells then undergo autolysis, hence the mature lignified fibre is incapable of subsequent anatomical changes (Ridoutt 1995). It is therefore during the differentiation process that environment can affect the morphology of the fully differentiated fibre. If an effect of salt treatment on fibre morphology were to be found in the present study, variability in the cambial initials and/or in the processes of differentiation may help explain it.

Field trials

Wood samples with bark and intact cambium were carefully removed using razor blades and a chisel (Ridoutt & Sands 1994) from near the point of diameter measurement (20% of total tree height) on the north side of each tree. The samples were immediately fixed in vials of FAA for transport to the laboratory.

Pot trial

A sample of intact cambium was obtained from the stem disc removed from each tree for examination of fibre morphology.

5. Analyses

5.1 Soils

Field and pot trials

Electrical conductivity of 1:5 soil/water extracts ($EC_{1:5}$) was determined on field and pot trial samples according to the method of Rayment and Higginson (1992a). Electrical conductivity was measured at 25 C using a Radiometer (Copenhagen) conductivity meter. A tree mean EC value was calculated from the average of the values measured on the four soil samples collected at the base of each tree.

To enable comparison with other field trials, saturated pastes were prepared for representative soil samples from each field plot and their conductivity measured, which allowed a conversion factor to be calculated for estimating EC_e from $EC_{1:5}$. Four of the 1996 soil samples from each plot were selected for EC_e determination, one mound 0-10 cm, one mound 10-20 cm, one irrigation bay 0-10 cm and one irrigation bay 10-20 cm. The air-dry weight of the samples was determined, then approximately 10 g of air-dried soil was accurately weighed into pre-weighed tins and dried at 105 C to constant weight. Air-dry moisture was calculated as:

$$\text{air-dry moisture \%} = (\text{air-dry weight} - \text{oven-dry weight}) \times 100\% / \text{oven-dry weight}.$$

An approximate saturation paste was prepared according to method 2D1 of Rayment & Higginson (1992a), the saturated pastes were extracted by centrifuge, and the electrical conductivities of the resultant extracts were measured to give the soil EC_e . The EC_e values for the representative soil samples were divided by their corresponding $EC_{1:5}$ values, and these four ratios were averaged to provide conversion factors for $EC_{1:5}$ to EC_e for each plot. The conversion factors were then applied to the average $EC_{1:5}$ for each tree of each plot.

Saturated pastes were not prepared for the pot trial as the aim was to make comparisons between the treatments within the trial, and not with different sites or other trials. The artificial composition of the potting medium used would also make comparisons with field soils invalid.

The moisture content of pot-trial soil samples collected after 38 days (4 Nov 1996) and at the end of the experiment (9 Dec 1996) was also measured according to method 2B1 of Rayment & Higginson (1992c). A fresh, representative subsample of soil was weighed to the nearest milligram, dried to constant weight at 105 C and reweighed. Moisture content was calculated using the formula:

$$\text{moisture content (\%)} = (\text{fresh weight} - \text{oven-dry weight}) / (\text{oven-dry weight}) \times 100\%$$

5.2 Tree growth

Field trials

Tree growth (height, diameter and stem volume increments) was calculated for 1995–1996, 1996–1997 and the entire study period, 1995–1997.

Pot trial

For the analyses that were to be conducted, it was essential that foliar and xylary tissues still be alive at the time of harvest. Five trees were harvested prior to the last experimental treatment (Table 3.2) because they were showing symptoms of severe salt stress and were assessed as unlikely to survive to the end of the experiment. Therefore tree growth (height, diameter and stem volume increments) was expressed on a daily rate to enable comparisons between all trees, regardless of their final harvest date.

5.3 Foliar analyses

Field and pot trials

Leaf samples were washed free of external salt by agitating with 80 mL of double distilled water for 30 s. The washed samples were then placed in paper bags and dried in a forced-draft oven at 70 C to constant weight (48 hours). Fresh and oven-dry weights were measured to the nearest milligram. Dried leaves were ground to a fine powder. Two-hundred milligrams of dried, ground sample were weighed into graduated 50-mL digest tubes to which 30 mL of 18-M Ω water (Millipore, Bedford, MA, USA) was added. Samples were gently boiled on a Windrift Instruments (Welshpool, Wales) digestion block for an hour, cooled and made up to 50 mL (method modified from Johnson et al 1985). The resulting extracts were filtered through 0.45- μ m PTFE syringe filters (Alltech Associates Aust, Baulkham Hills, Sydney, Australia) and refrigerated in 70-mL polystyrene sample jars (Disposable Products, Ingle Farm, South Australia) prior to analyses.

Na⁺ and K⁺ were determined by flame-emission spectroscopy on a Corning 400 flame photometer. Cl⁻ was determined by capillary ion analysis using a Waters Quanta 4000 capillary electrophoresis system, in conjunction with Waters Millennium Chromatography Manager software.

5.4 Basic density

Field trials

One of the two wood cores collected from each tree was prepared for determination of basic density. Core green volumes were determined by water displacement (Olesen 1971). Cores were then oven-dried at 105 C for 48 hours, cooled in a desiccator and weighed to the nearest milligram. Basic density was calculated as the ratio of oven-dry mass to green volume.

5.5 Fibre morphology

Field trials

The second of the increment cores from each tree was used for determination of fibre length. Cores were taken at 20% height as fibre properties at this height are the most representative of whole-tree values (Downes et al 1997). The north half of the core (pith to bark) was macerated using Franklin's method (Franklin 1945) by gently boiling for 1 hour in equal quantities of glacial acetic acid and hydrogen peroxide (100 vol). Fibre lengths were measured using an automated optical analyser, the Kajaani FS-200 (Kajaani Electronics Ltd.). Measurement of fibre length by the FS-200 unit is based on the ability of the fibres to change the direction of polarised light (Carvalho et al 1997).

More detailed investigation of fibre morphology was made on the 1997 field samples, in addition to automated fibre length measurement. A representative subsample of the fibre

macerate for each tree was stained with 1% aqueous safranin. A drop of stained fibres was mounted on a slide, and the length, fibre diameter and lumen width of 50 randomly selected and intact fibres were measured using an Olympus BH-2 research microscope fitted with an eyepiece scale, in conjunction with a calibrated slide. Lumen width was subtracted from fibre diameter to derive fibre double wall thickness for each fibre.

Pot trial

Samples for examination of fibre morphology were taken from the north side of each stem disc. Bark and loose cambial tissue were removed, as only the morphology of fully differentiated xylem fibres was of interest. The cleaned section of the stem disc was mounted in a sledge microtome, and thick sections were cut to provide the following samples:

- i) the last 100 μm of xylem formed just before completion of the experiment;
- ii) xylem formed during the experimental period (27 Sep to 6 Dec 1996), the extent of which was deduced from measurements made on thin sections cut through the needle wound zone;
- iii) 500 μm of xylem formed prior to commencement of the experiment.

The "last 100- μm " sample (i) was collected to obtain a preliminary estimate of differences in fibre morphology between treatments. Although this sample was collected prior to the determination of post-treatment xylem growth (see Section 5.6), subsequent measurements of overbark stem diameter growth indicated that the last 100 μm of xylem would all have been formed during the experimental period.

Samples (ii) and (iii) allowed comparison of fibres formed within each tree before and after treatment. The "post-treatment fibres" sample (ii) was defined by the radial production of xylem during the experiment, as measured from the position of needle wounds on thin sections (see Section 5.6). The "pre-treatment fibres" sample was more difficult to define, as there was no common feature in the growth-ring patterns of the stem discs to enable an identical growth period to be determined in each tree. In lieu of this, a 500- μm thick sample, from immediately behind the point identified as the position of the cambial initials at the time of needle insertion, was cut from each stem disk for analysis of pre-treatment fibres. This relatively thick sample was taken to smooth out within-ring and between-ring variation in fibre morphology (Bisset & Dadswell 1949; Bisset & Dadswell 1950; Downes et al 1997; Mitchell & Denne 1997).

Macerates of these fibre samples were prepared as described above for the field-trial samples, and parameters of fibre morphology were measured manually with the microscope.

5.6 Cambium

Field trials

Samples of intact cambium were dehydrated through an ethanol series. Suitably trimmed pieces were embedded in acrylic resin (LR White, London Resin Company Ltd), sectioned at 5 μm in transverse section, and stained with toluidine blue (O'Brien et al 1964).

Pot trial

A radial wedge including the needle insertion point, and measuring approximately 6 mm tangentially at its outer face and 5 mm radially, was removed from each stem disc and transferred to 70% ethanol. The sample was prepared, sectioned through the needle wound, and stained as for the field trial samples. The amount of xylem formed during the experiment

was measured, after Kuroda and Shimaji (1984), as the distance from the middle of the cambial zone at the end of the experiment, to the point within the injury deduced as being the location of the cambial initials when the needle wound was made at the commencement of the experiment.

5.7 Statistical analysis

Field trials

One-way analyses of variance (ANOVA) were used to test for differences between the field plots in measured parameters. Fisher's Protected Least Significant Difference (PLSD) multiple comparison procedure was used to evaluate differences between means, using SuperAnova software (Abacus Concepts Inc., Berkeley, CA 1989).

Paired t-tests were performed to examine the statistical significance of differences in ion concentrations between juvenile and adult foliage sampled in Jan 1995, using the Statview software (Abacus Concepts Inc., Berkeley, CA 1992).

Simple linear regression was performed between tree parameters (growth, foliar ion concentration, basic density and fibre morphology) and electrical conductivity measured on the soil samples, using the Statview software (Abacus Concepts Inc., Berkeley, CA 1992).

Sub-division of Tatura site

Site and tree parameters for the two plots were compared with t-tests. Simple linear regression was used to analyse relationships between soil salinity data at the base of each tree, tree growth and foliar ion concentrations. Wood and fibre properties were compared to soil salinity and tree growth data using simple correlation analysis. All statistical procedures were performed using the Statview software (1992 Abacus Concepts, Inc.).

Pot trial

Two-factor analyses of variance (salt level and volume applied) were performed for each measured parameter using the SuperAnova software (Abacus Concepts Inc., Berkeley, CA 1989). Fisher's Protected Least Significant Difference (PLSD) multiple comparison procedure was used to evaluate differences between means where interaction effects were not significant. Where the volume treatment did not have a significant effect on a parameter, measurements for the high and low volumes were combined for each salt treatment, and a one-way analysis of variance was performed.

Simple linear regression was performed between tree parameters (growth, foliar ion accumulation and fibre morphology) and electrical conductivity measured on the final soil samples, using the Statview software (Abacus Concepts Inc., Berkeley, CA 1992).

The relationship between radial xylem production and overbark stem diameter growth was tested with simple linear correlation, using the Statview software (Abacus Concepts Inc., Berkeley, CA 1992).

Paired t-tests were performed to examine the statistical significance of differences in fibre morphology between pre-treatment and post-treatment fibres, using the Statview software (Abacus Concepts Inc., Berkeley, CA 1992).

Analysis of covariance was performed on the post-treatment fibre morphology, using the parameters of pre-treatment fibre morphology as covariates, with the SuperAnova software (Abacus Concepts Inc., Berkeley, CA 1989).

6. Results

6.1 Field trials

Soil salinity

Soil electrical conductivity data ($EC_{1:5}$, determined on 1:5 soil/water extracts) for the three plots are in Table 6.1. The data is split into three parts:

- pooled Centre for Forest Tree Technology (CFTT) data for 1994 and 1995 (Table 6.1a). This is soil $EC_{1:5}$ data for entire replicate blocks at Tatura or replicate plots at Timmering but is here assigned to the actual plots sampled in the present study (Ti.low, Tt.mod and Ti.high), on the assumption that the replicate block or plot values are representative of the individual plots within them. In addition, there was no measure of variability associated with this data as soil samples were bulked. However, the data do provide useful baseline information on general trends in plot salinity;
- data (means of individual tree values) collected in this work in 1996 and 1997 (Table 6.1b). These data are averages of 4 determination for each individual tree, and so were amenable to statistical analysis;
- plot averages for all years, 1994 to 1997 (Table 6.1c).

In addition, Table 6.1d shows the plot average EC_e values for all years, 1994 to 1997, calculated from the plot average $EC_{1:5}$ data in Table 6.1c.

For 1994–1995, soil $EC_{1:5}$ values decreased in the order Tt.mod > Ti.high > Ti.low (Table 6.1a), with overall means of 0.29, 0.22 and 0.12 dS m⁻¹ respectively. Soil $EC_{1:5}$ was higher in the 0-10 cm sample at the two Timmering plots in 1994 compared to the 10-20 cm sample, whereas for the Timmering plots in 1995 or the Tatura plot in either year there was little difference in EC between the two soil depths.

The trend in soil $EC_{1:5}$ across the three plots for 1996–1997 was in the order Ti.high > Tt.mod > Ti.low (Table 6.1b), with overall means of 0.34, 0.26 and 0.13 dS m⁻¹ respectively. For this period, soil $EC_{1:5}$ was more often higher at 0-10 cm depth, although the difference was least marked for plot Ti.high, and was more often higher in the planting mound than in the irrigation bay.

Table 6.1. Soil electrical conductivity, field trial. All data in dS m⁻¹**a) 1994-95 EC_{1:5} data from CFTT**

		Ti.low	Tt.mod	Ti.high
1994	0-10 cm	0.19	0.35	0.34
	10-20 cm	0.07	0.33	0.18
1995	0-10 cm	0.11	0.21	0.18
	10-20 cm	0.11	0.26	0.19
1994&95	mean 0-10 cm	0.15	0.28	0.26
	mean 10-20 cm	0.09	0.30	0.19
	overall mean	0.12	0.29	0.22

b) 1996-97 EC_{1:5} data, this work

			Ti.low	Tt.mod	Ti.high
1996	mound	0-10 cm	0.182	0.272	0.362
	mound	10-20 cm	0.203	0.203	0.395
	bay	0-10 cm	0.191	0.136	0.519
	bay	10-20 cm	0.142	0.148	0.401
1997	mound	0-10 cm	0.104	0.609	0.380
	mound	10-20 cm	0.076	0.200	0.341
	bay	0-10 cm	0.066	0.255	0.144
	bay	10-20 cm	0.054	0.228	0.172
1996&97	mean 0-10 cm		0.136	0.318	0.351
	mean 10-20 cm		0.119	0.195	0.327
	mean mound		0.141	0.321	0.370
	mean bay		0.113	0.192	0.309
	overall mean 96-97		0.13	0.26	0.34

c) 1994-97 mean EC_{1:5} values

	Ti.low	Tt.mod	Ti.high
1994	0.13	0.34	0.26
1995	0.11	0.24	0.19
1996	0.18	0.19	0.42
1997	0.08	0.32	0.26
overall mean 94-97	0.12	0.27	0.28

d) 1994-97 mean EC_e values. Data determined from EC_{1:5} values and plot-specific calibration values

	Ti.low	Tt.mod	Ti.high
1994	2.12	4.18	4.35
1995	1.80	2.89	3.09
1996	2.93	2.33	7.01
1997	1.23	3.97	4.33
overall mean 94-97	2.0	3.3	4.7

Average soil EC_{1:5} values for 1996, 1997 and the 1996-1997 change are also shown in Figure 6.1. One-way analyses of variance revealed highly significant differences between plots in both years ($p = 0.0001$ for both years) and a highly significant plot difference for the change

in soil $EC_{1:5}$ from 1996 to 1997 ($p = 0.0002$). In 1996, soil $EC_{1:5}$ was significantly higher for plot Ti.high than either of the other two plots whereas, in 1997, there was no significant difference between Tt.mod and Ti.high but they both had higher soil $EC_{1:5}$ values than Ti.low. The change in soil $EC_{1:5}$ from 1996 to 1997 was significantly greater for Tt.mod, where it increased by an average of 0.133 dS m^{-1} , than for Ti.low and Ti.high, where it decreased by 0.104 and 0.160 dS m^{-1} respectively (Figure 6.1).

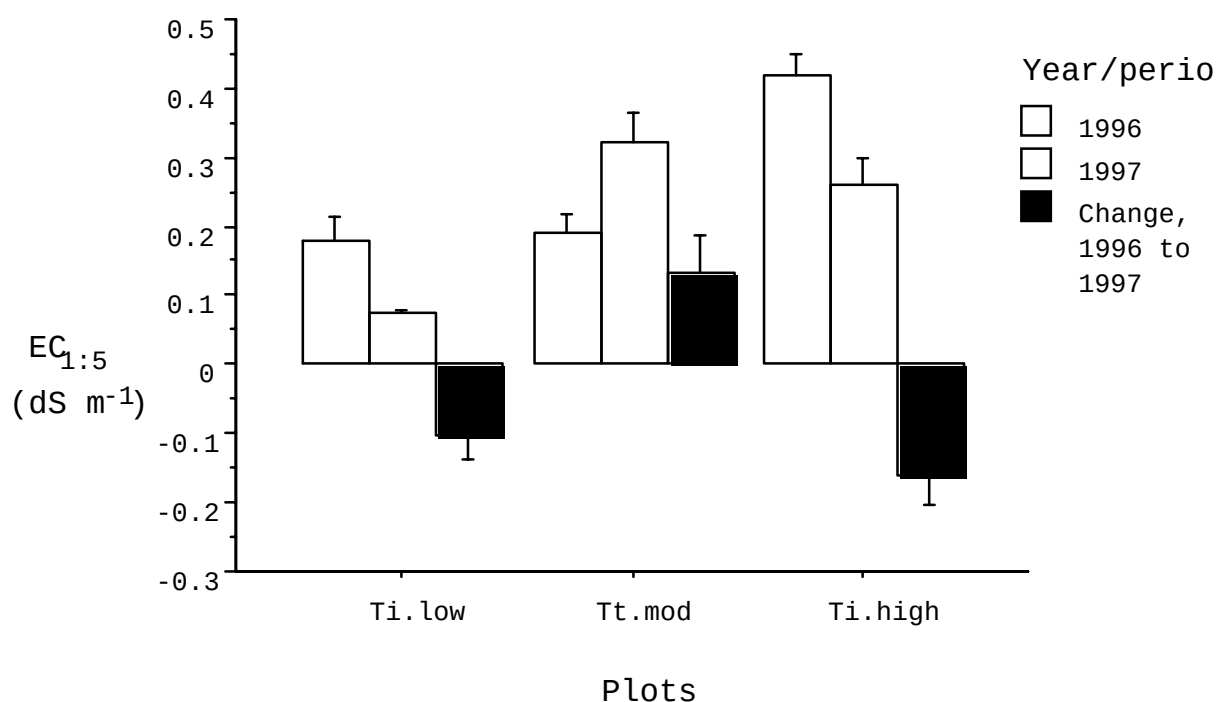


Figure 6.1. Average soil electrical conductivity values, field plots. Data for 1996 and 1997, and the change in EC from 1996 to 1997. Bars indicate standard error of the mean.

Average soil $EC_{1:5}$ values for the three plots from 1994 to 1997 are in Table 6.1c. There was a decline in soil $EC_{1:5}$ on all plots from 1994 to 1995, although it was very small for plot Ti.low. From 1995 to 1996, values increased at Ti.low and Ti.high, but decreased for Tt.mod. This pattern reversed from 1996 to 1997, with soil $EC_{1:5}$ decreasing at both Ti.low and Ti.high, but increasing at Tt.mod (Table 6.1c). The overall mean soil $EC_{1:5}$ averaged over 1994-97 shows that the two saline-irrigated plots Tt.mod (0.27 dS m^{-1}) and Ti.high (0.28 dS m^{-1}) have similar soil $EC_{1:5}$ values, but that these are about 2.3-fold higher than that recorded for the freshwater-irrigated plot Ti.low (0.12 dS m^{-1}). It can therefore be concluded that salt accumulation was occurring as a result of the saline irrigation treatments, but the two different irrigation salinities have not resulted in a marked difference in soil $EC_{1:5}$.

Electrical conductivities of saturated soil extracts (EC_e) for the three plots for each year from 1994 to 1997 were calculated from the $EC_{1:5}$ data, and are shown in Table 6.1d. The use of plot-specific calibration values to convert $EC_{1:5}$ to EC_e altered the relative magnitudes of salinities measured at Tatura and Timmering. Compared to the soil salinity classes of Marcar et al (1995), plot Ti.low (mean 2.0 dS m^{-1} , ranging from 1.2 - 2.9 dS m^{-1}) ranged from non-saline to slightly saline over the 1994 to 1997 period, whereas both plots Tt.mod (mean 3.3 dS m^{-1} , ranging from 2.9 - 4.2 dS m^{-1}) and Ti.high (mean 4.7 dS m^{-1} , ranging from 3.1 - 7.0 dS m^{-1}) ranged from slightly to moderately saline.

Tree growth

Average tree growth parameters 1995–1996, 1996–1997 and 1995–1997 are presented in Table 6.2 and Figure 6.2a-c. One-way analyses of variance found significant plot differences for height growth for both 1995–1996 and 1995–1997 ($p = 0.0004$ and $p = 0.0279$, respectively). Diameter growth for 1996–1997 also differed significantly between plots ($p = 0.0174$) but there were no significant plot differences for volume growth in any period. Comparison of plot means for tree growth found significantly greater height growth from 1995–1996 for Ti.high than both Tt.mod and Ti.low whereas for 1995–1997 height growth was greater for Ti.high than Tt.mod only. Diameter growth 1996–1997 was greater for both Ti.low and Ti.high compared to Tt.mod, but for 1995–1997 only Ti.low was significantly greater than Tt.mod.

Table 6.2. Average tree diameters, heights and volumes, field trial.

a) Average diameters (mm; $\pm$ standard error)

Site	1995	1996	1997
Ti.low	59.7 (± 2.9)	86.7 (± 3.5)	108.8 (± 4.0)
Tt.mod	57.1 (± 3.1)	81.6 (± 4.7)	94.8 (± 5.4)
Ti.high	57.9 (± 1.5)	77.6 (± 4.9)	104.0 (± 5.0)

b) Average heights (m; $\pm$ standard error)

Site	1995	1996	1997
Ti.low	4.1 (± 0.2)	6.8 (± 0.2)	8.9 (± 0.4)
Tt.mod	4.3 (± 0.2)	6.5 (± 0.3)	8.6 (± 0.4)
Ti.high	3.8 (± 0.1)	7.4 (± 0.2)	9.3 (± 0.3)

c) Average volume ($\text{m}^3 \times 10^3$; $\pm$ standard error)

Site	1995	1996	1997
Ti.low	5.0 (± 1.0)	18.0 (± 2.0)	36.0 (± 4.0)
Tt.mod	5.0 (± 1.0)	15.0 (± 2.0)	27.0 (± 4.0)
Ti.high	4.0 (± 0.4)	15.0 (± 2.0)	34.0 (± 4.0)

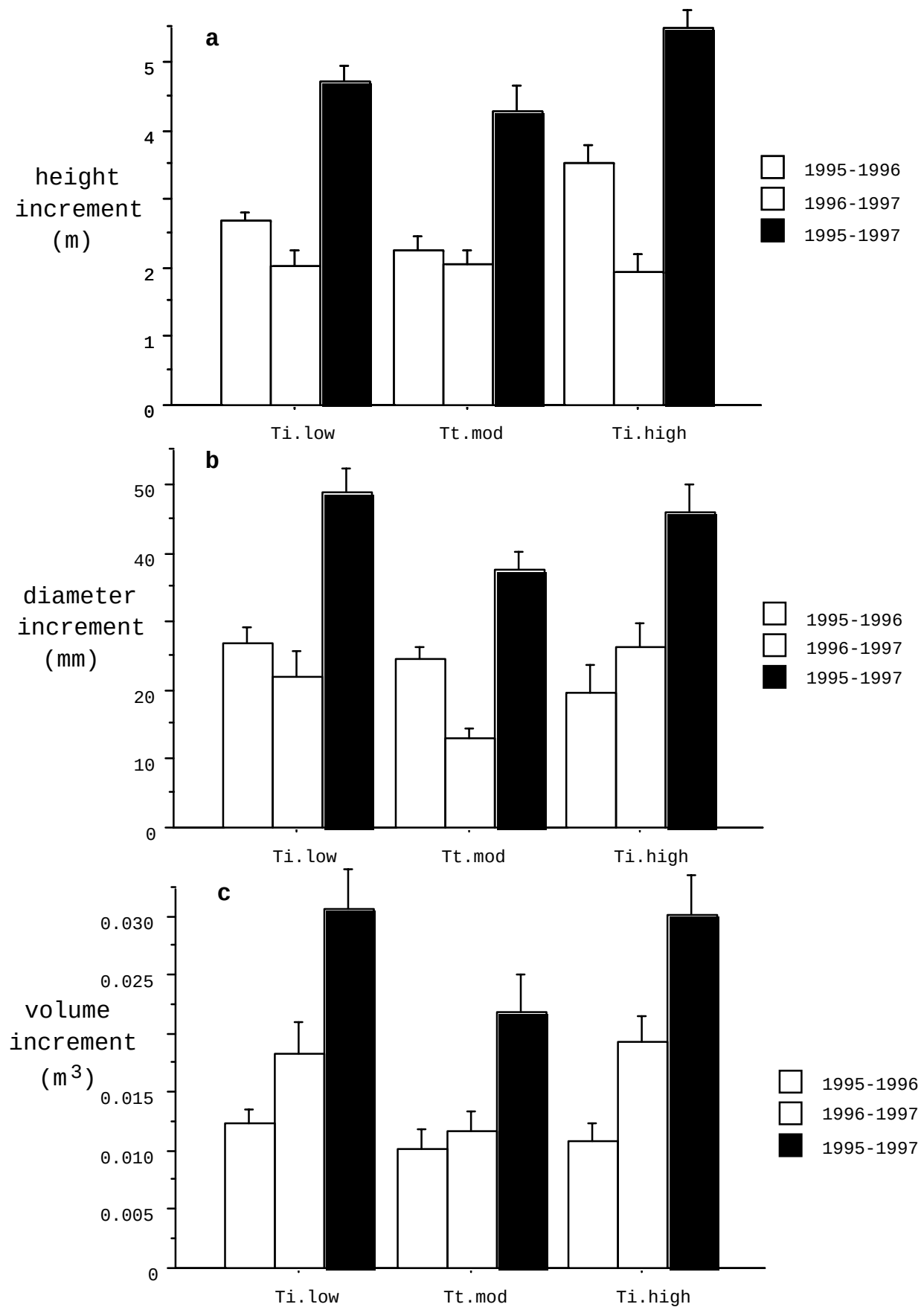


Figure 6.2. Average tree growth, field plots. Data from 1995 to 1996, 1996 to 1997 and 1995 to 1997. Bars indicate standard error of the mean.

The size and growth of individual trees was compared with average soil $EC_{1:5}$ at their base in 1996 and 1997. Improved sensitivity was expected because this test removed the smoothing effect of plot averages on variation between trees. Regressions of tree diameter and tree volume in 1996 on soil $EC_{1:5}$ in 1996 were not significant, but the regression of tree height in 1996 on tree soil $EC_{1:5}$ in 1996 was significant ($p = 0.0296$), with 19% of the variation in tree height explained by the equation:

$$\text{tree height} = 2.41 EC_{1:5} + 6.28 \quad \text{tree height, m; } EC_{1:5}, \text{ dS m}^{-1}.$$

Regression of tree diameter in 1997 on soil $EC_{1:5}$ in 1997 was highly significant ($p = 0.0048$), with 30% of the variation in diameter explained by the equation:

$$\text{tree diameter} = -56.29 EC_{1:5} + 114.78 \quad \text{tree diameter, mm; } EC_{1:5}, \text{ dS m}^{-1}.$$

Tree volume in 1997 was also significantly related to soil $EC_{1:5}$ in 1997 ($p = 0.0290$), with 19% of the variation in volume explained by the equation:

$$\text{tree volume} = -0.035 EC_{1:5} + 0.04 \quad \text{tree volume, m}^3; EC_{1:5}, \text{ dS m}^{-1}.$$

Tree growth 1996–1997 was also compared to the change in soil $EC_{1:5}$ 1996–1997 ($\Delta EC_{1:5}$). There was no significant regression relationship between height growth 1996–1997 and the change in soil EC over the same period. The regression of diameter growth 1996–1997 with $\Delta EC_{1:5}$ was significant ($p = 0.0442$), with 16% of the variation in diameter growth explained by the equation:

$$\text{diameter growth} = -23.05 \Delta EC_{1:5} + 19.59 \quad \text{diameter growth, mm; } \Delta EC_{1:5}, \text{ dS m}^{-1}.$$

Tree volume growth 1996–1997 was also significantly related to $\Delta EC_{1:5}$ ($p = 0.0146$), with 23% of the variation in volume growth explained by the equation:

$$\text{volume growth} = -0.02 \Delta EC_{1:5} + 0.016 \quad \text{tree volume growth, m}^3; \Delta EC_{1:5}, \text{ dS m}^{-1}.$$

Foliar salt – 1995 sample: juvenile and adult foliage

Six trees in plot Ti.low, seven trees in plot Tt.mod and eight trees in plot Ti.high carried both juvenile and adult foliage in 1995. Foliar ion concentrations in juvenile and adult foliage were compared for all trees carrying both foliage types (Figure 6.3). Across all three plots t-tests revealed significant differences in $[Na^+]$ and $[K^+]$ ($p = 0.0429$ and $p = 0.0006$, respectively) between adult and juvenile foliage. Sodium levels were higher in the juvenile foliage (mean difference 24 mmol kg^{-1} leaf dry weight) whereas $[K^+]$ was higher in the adult foliage (mean difference 101 mmol kg^{-1} leaf dry weight). There was no significant difference for $[Cl^-]$.

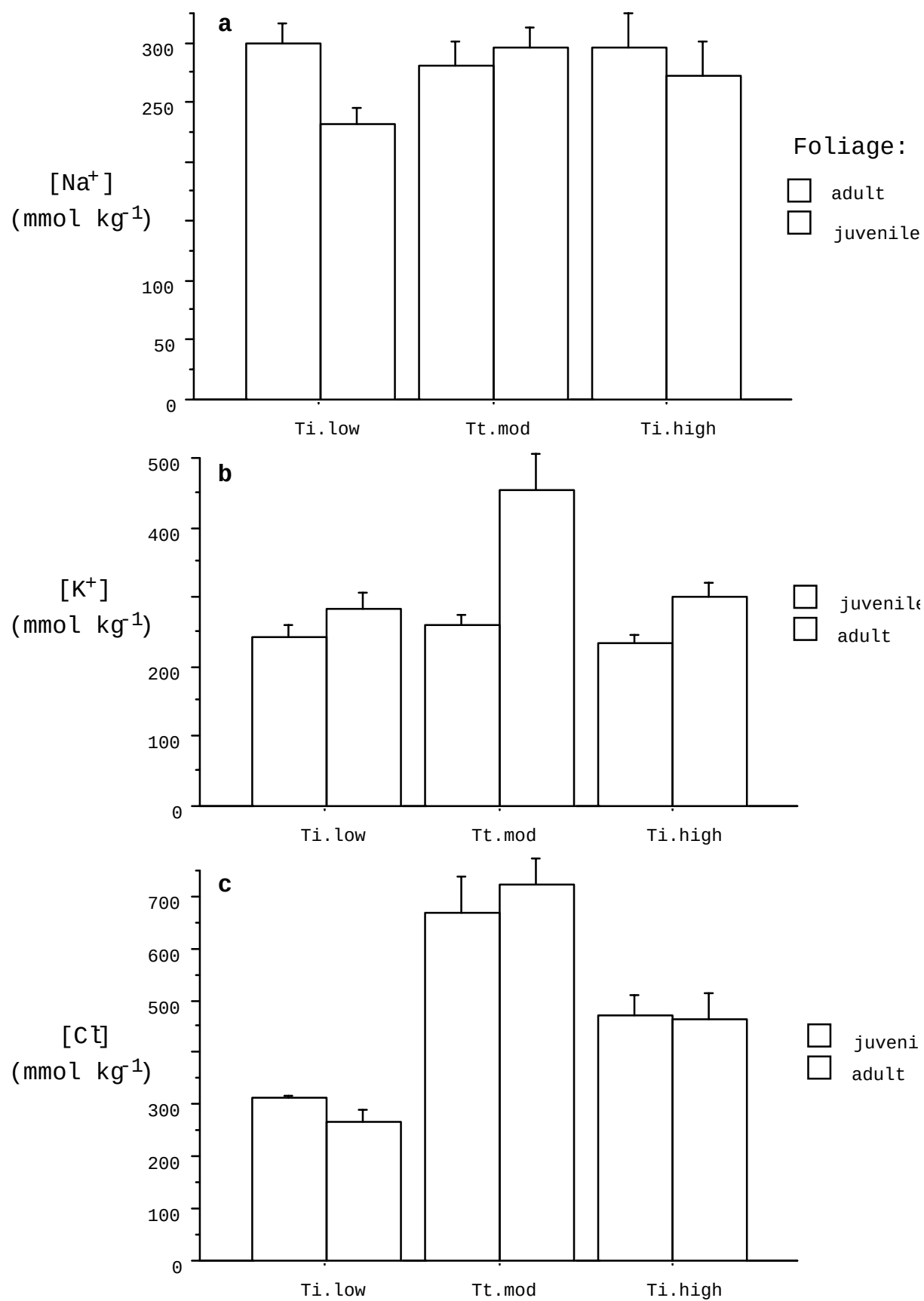


Figure 6.3. Foliar ion concentrations, 1995 juvenile and adult foliage, field plots. Bars indicate standard error of the mean.

Within each of the plots, the difference for foliar $[\text{Na}^+]$ was significant for Ti.low and Ti.high ($p = 0.0098$ and $p = 0.0473$, respectively) but not for Tt.mod ($p = 0.499$). Potassium concentrations were significantly different for Tt.mod and Ti.high ($p = 0.0099$ and $p = 0.0444$, respectively), but not for Ti.low ($p = 0.0822$). There were no differences within any of the plots for chloride.

Foliar salt – between-plots comparison 1995, 1996 and 1997, adult foliage only

Average foliar ion concentrations ($[\text{Na}^+]$, $[\text{K}^+]$ and $[\text{Cl}^-]$) for the three plots in Jan 1995, 1996 and 1997 are in Figure 6.4. No $[\text{Cl}^-]$ data is available for 1996. There was a decline in concentrations of all three ions across all plots from the first year of sampling, 1995, to subsequent years (Figure 6.4).

In 1995, differences in $[\text{K}^+]$ and $[\text{Cl}^-]$ between the plots were significant ($p = 0.0251$ and $p < 0.0001$, respectively) but for $[\text{Na}^+]$ there were no significant plot differences ($p = 0.0702$). Foliar $[\text{K}^+]$ was significantly higher for Tt.mod than either Ti.low or Ti.high, whereas for $[\text{Cl}^-]$ differences between the plots were in the order Tt.mod > Ti.high > Ti.low.

Between-plot differences in $[\text{Na}^+]$ were significant in 1996 ($p = 0.0011$). Foliar $[\text{Na}^+]$ was significantly higher for Ti.high than either Tt.mod or Ti.low. There were no significant differences ($p = 0.0543$) between plots in foliar $[\text{K}^+]$ for the 1996 samples. In 1997, both $[\text{Na}^+]$ and $[\text{K}^+]$ differed significantly between the plots ($p = 0.0102$ and $p = 0.0352$, respectively), but for $[\text{Cl}^-]$ the differences were not significant ($p = 0.235$). Foliar $[\text{Na}^+]$ and $[\text{K}^+]$ were higher for both Ti.low and Ti.high than for Tt.mod.

Basic density

Wood basic density values for the three plots over the three years in which they were measured are provided in Table 6.3 and Figure 6.5a. Values increased each year for all three plots except for plot Ti.low where a small decrease occurred from 1996 to 1997. Little variation occurred from year to year in average basic density on the Ti.high plot, whereas for the Tt.mod plot there was a marked increase from 1995 to 1996 and thereafter only a small increase (Figure 6.5a). The highest basic density values generally occurred at the Ti.low plot.

The changes in basic density 1995–1996, 1996–1997 and 1995–1997 (Figure 6.5b) were examined with one-way analyses of variance. There were significant differences between the plots ($p = 0.0243$) for 1995–1996, and the change in basic density was significantly greater for Tt.mod than for Ti.high (Figure 6.5b). Change in basic density 1996–1997 was much

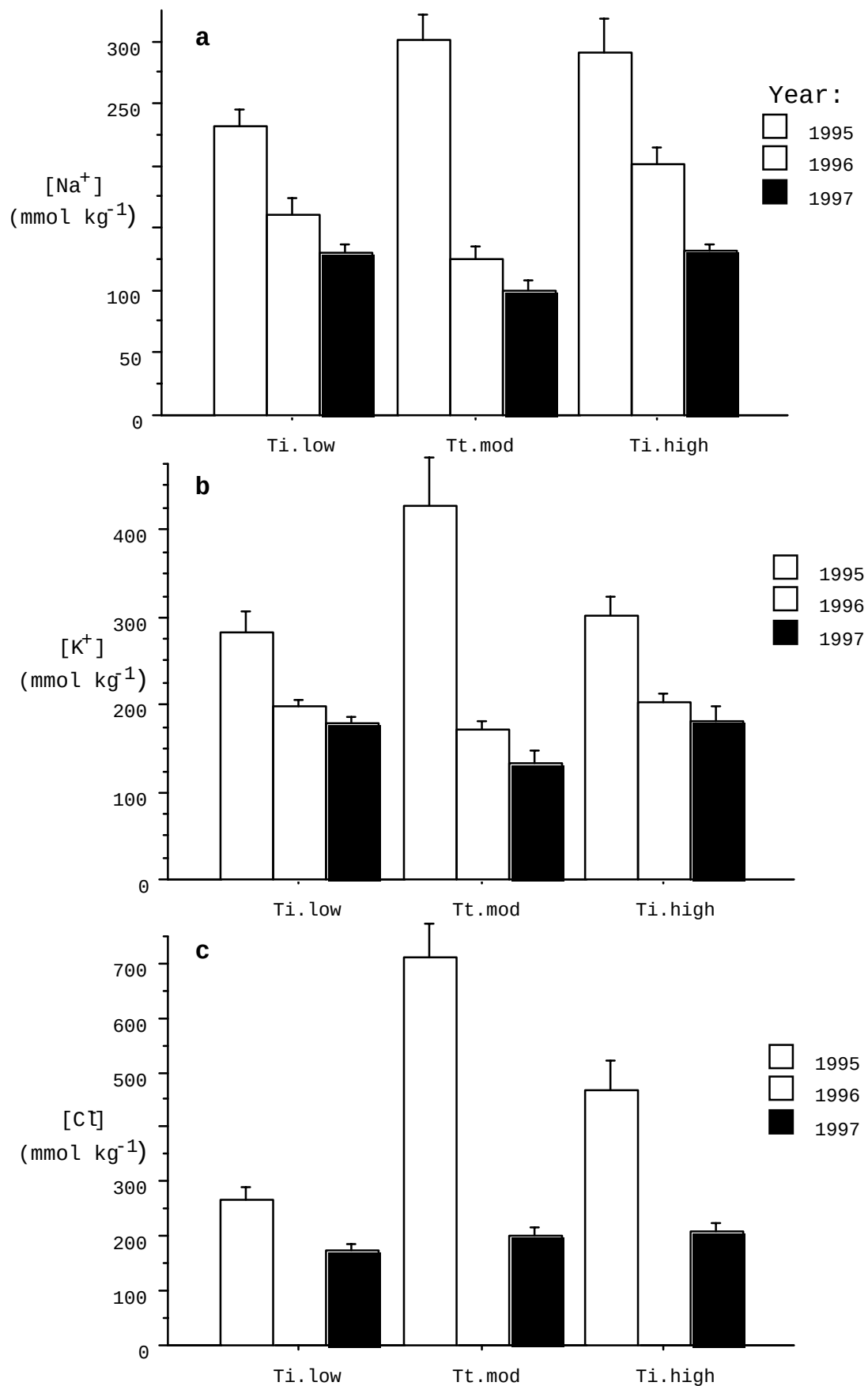
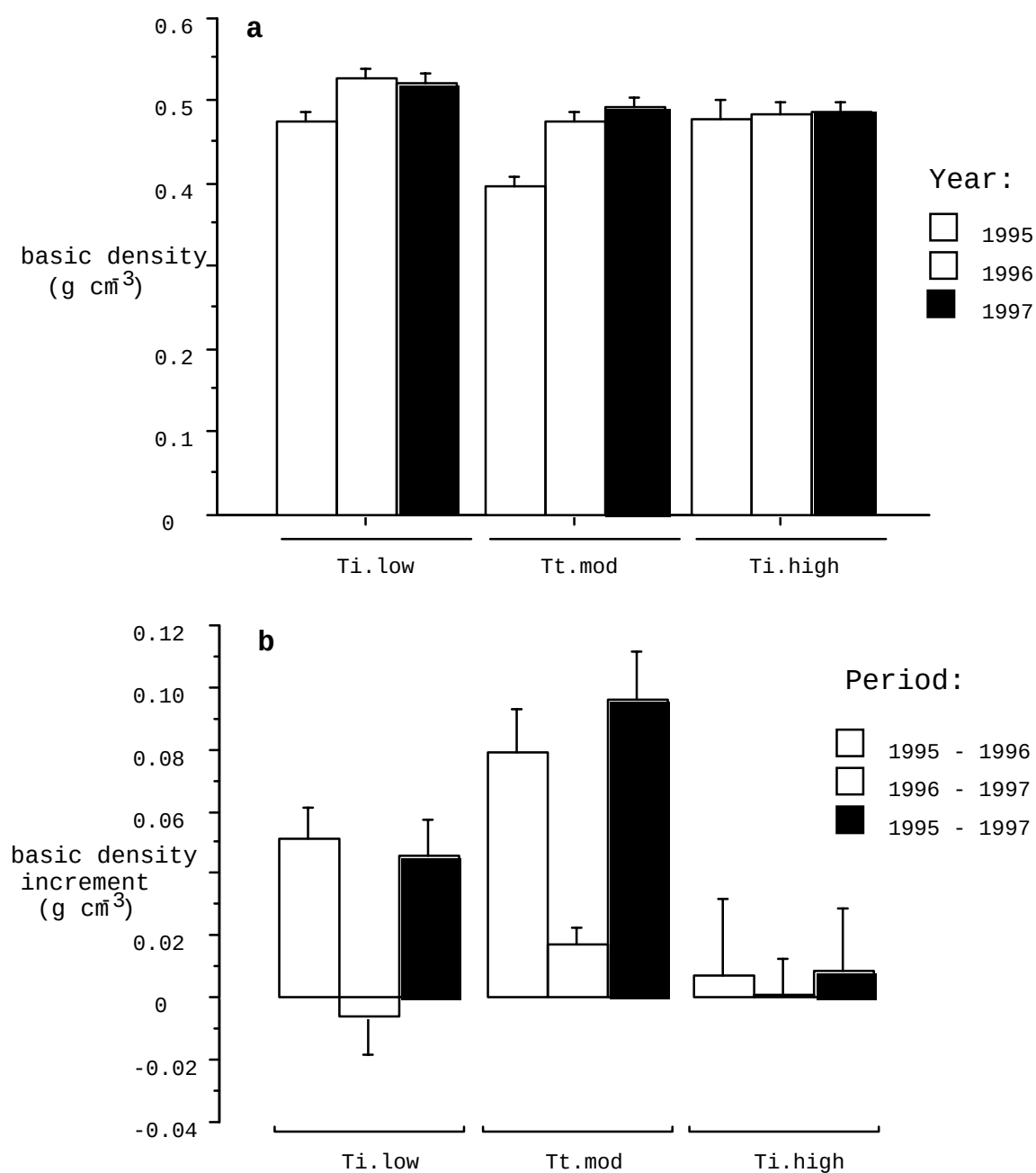


Figure 6.4. Foliar ion concentrations, adult foliage, field plots. Data from 1995, 1996 and 1997. Bars indicate standard error of the mean.



Plots

Figure 6.5. Wood basic density values and increments, field trials. Data from 1995, 1996 and 1997, and changes from year to year. Bars indicate standard error of the mean.

Table 6.3. Average wood basic densities, field trial. Figures in parenthesis are standard errors of the means.

Site/plot	Basic density (g cm^{-3})		
	1995	1996	1997
Ti.low	0.475 (0.013)	0.526 (0.011)	0.520 (0.012)
Tt.mod	0.396 (0.013)	0.475 (0.012)	0.493 (0.012)
Ti.high	0.478 (0.023)	0.485 (0.012)	0.486 (0.012)

smaller than for 1995–1996 (Figure 6.5b) and did not differ significantly between plots ($p = 0.307$). For the combined period 1995–1997, the difference between plots was highly significant ($p = 0.0039$), with the change being much greater for Tt.mod than either Ti.low or Ti.high.

The absence of any significant difference between Ti.low and Ti.high, the two plots receiving the most divergent salinity treatments, prompted a further investigation of relationships between basic density and salinity. Individual tree values for basic density in 1996 and 1997 were compared to average soil $EC_{1:5}$ measured at their base in the same years. These analyses found no significant linear regression relationships between soil $EC_{1:5}$ and basic density in 1996 or 1997. There was no measure of soil salinity associated with the sampled trees in 1995 to determine whether the effect on basic density in this year was related to soil salinity. Basic density values were also compared with simple correlation analyses to within-tree salinity (foliar $[Na^+]$, $[K^+]$ and $[Cl^-]$), but no significant relationships existed.

Fibre length 1995–1997

Fibre length averages for the three plots in 1995, 1996 and 1997 measured with the Kajaani analyser, and the yearly changes in fibre length are presented in Figures 6.6a,b. Comparison of plot means of absolute fibre length using one-way ANOVAs found no significant differences within any year ($p = 0.576$, 0.239 and 0.115 for 1995, 1996 and 1997, respectively).

The changes in fibre length from year to year across all three plots were mostly positive. The increases were quite marked for Ti.high (Figure 6.6b) compared to Tt.mod, while at Ti.low there was a small decrease in average fibre length from 1996 to 1997 (Figure 6.6b). The change in fibre length for the periods 1995–1996, 1996–1997 and 1995–1997 were subjected to one-way analyses of variance. There were no significant differences ($p = 0.269$) between the plots for the 1995–1996 period (Figure 6.6b), but for the 1996–1997 and 1995–1997 periods the plot differences were highly significant ($p = 0.0051$ and $p = 0.0087$, respectively). The increase in fibre length 1996–1997 for Ti.high was significantly greater than for plots Ti.low and Tt.mod. For the 1995–1997 period, fibre length increase for Ti.high was significantly greater than for Tt.mod only (Figure 6.6b).

A more sensitive test of the effect of soil salinity on fibre length was available in the data. Average soil $EC_{1:5}$ at the base of each tree in 1996 and 1997 was compared to fibre length in those years, and the change in $EC_{1:5}$ ($\Delta EC_{1:5}$) 1996–1997 was compared to the change in fibre length for the same period. These analyses found no significant regression relationships between soil $EC_{1:5}$ and fibre length, or $\Delta EC_{1:5}$ and the change in fibre length. Similarly, when fibre length was compared to within-tree salinity (foliar $[Na^+]$, $[K^+]$ and $[Cl^-]$) for 1995, 1996 and 1997, no significant relationships were found.

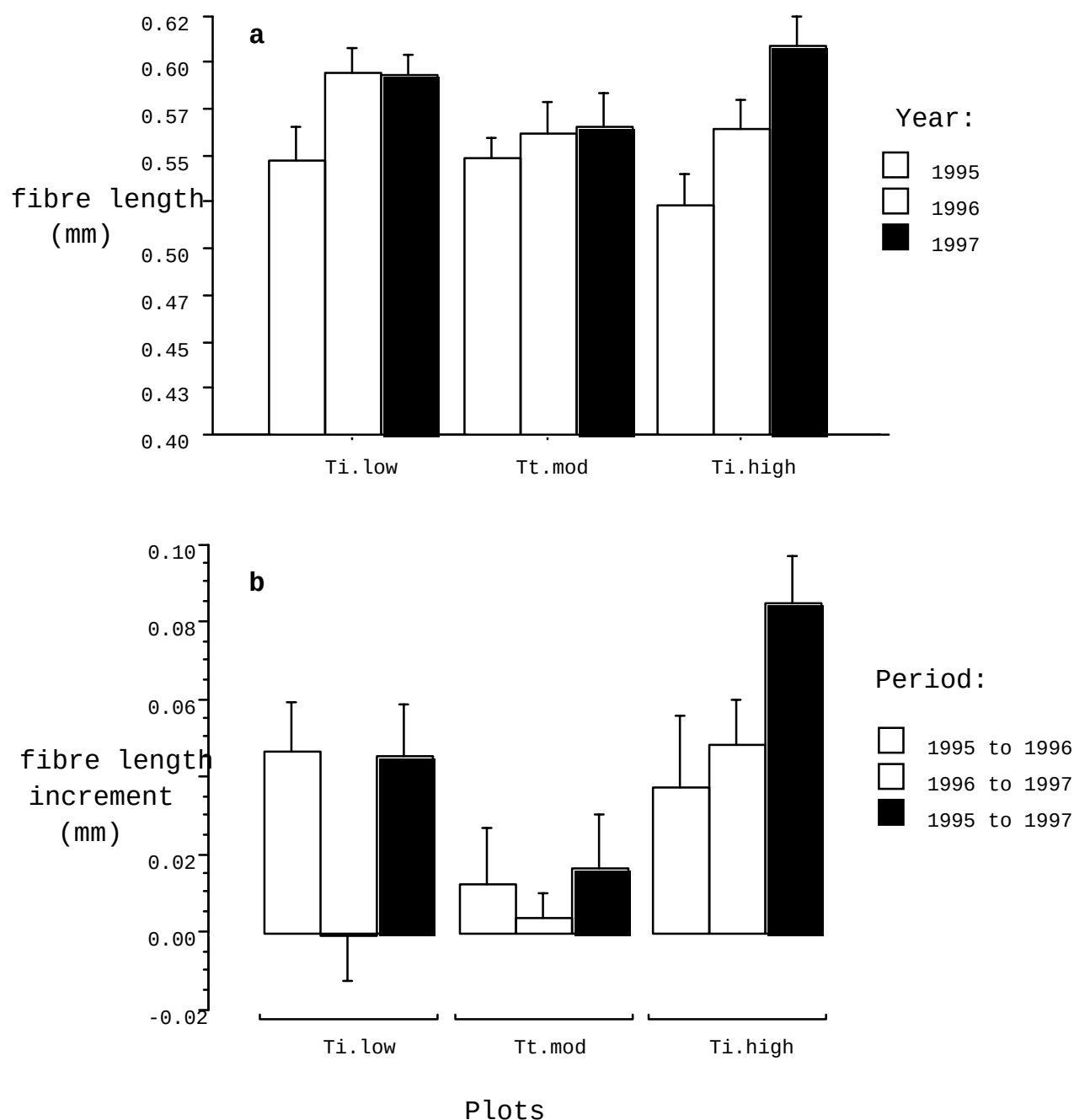


Figure 6.6. Average fibre lengths and increments, field trials. Kajaani data from January 1995, 1996 and 1997. Bars indicate standard error of the mean.

Fibre morphology 1997

Fibre length, diameter and double wall thickness averages measured manually with a microscope for the 1997 samples are in Figure 6.7. One-way analyses of variance found no significant effect of plot for any of these fibre parameters. Comparison of tree averages for these parameters with average soil $EC_{1:5}$ at their base and foliar ion concentration in 1997 also found no significant correlations existed.

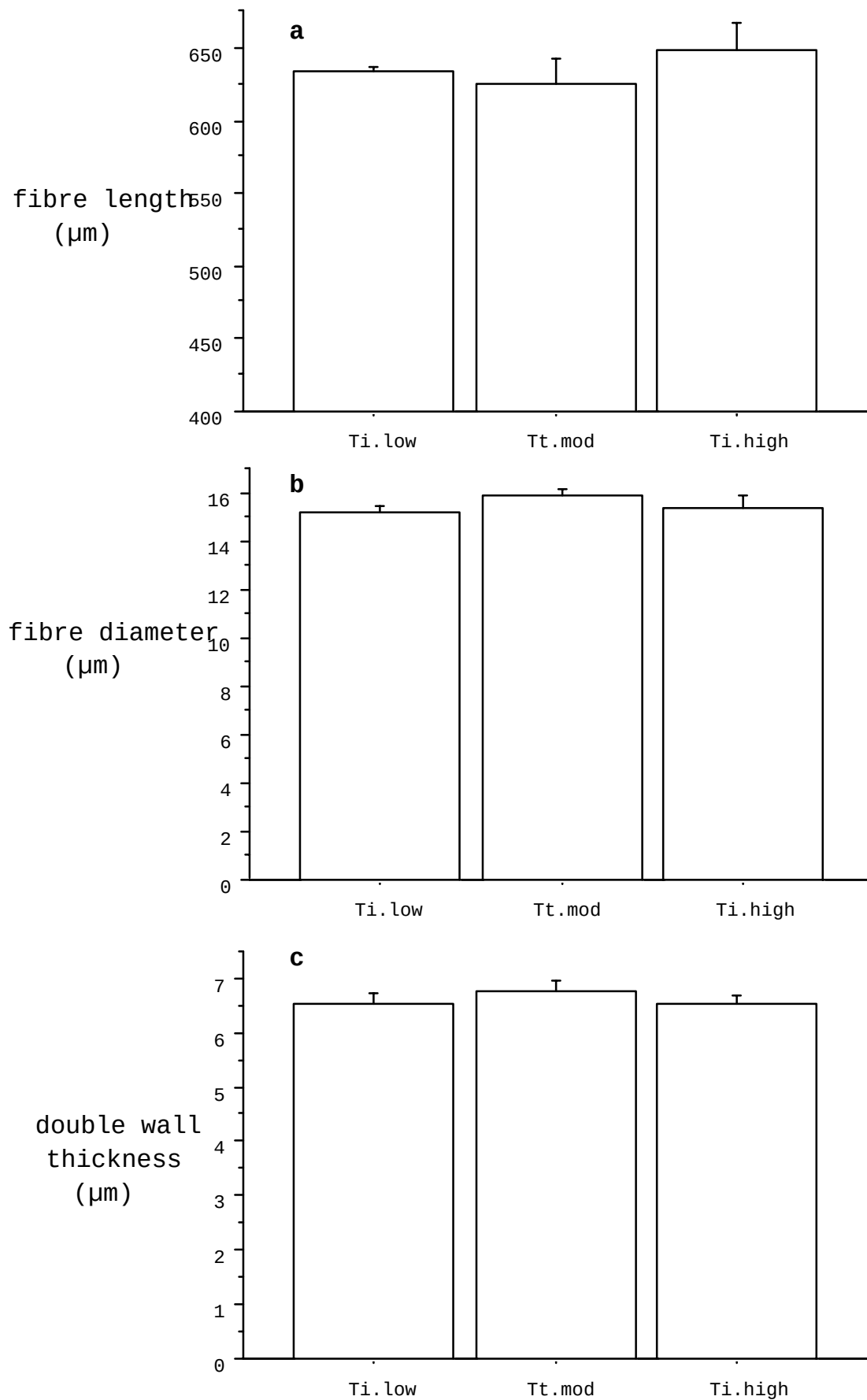


Figure 6.7. Fibre morphology, field plots, January 1997. Bars indicate standard error of the mean.

6.2 Subdivision of the Tatura site

The Tatura Trees for Profit site receives irrigation water of a uniform salinity across the whole site. However, soil salinity data collected by the Centre for Forest Tree Technology (CFTT) in 1996 (Hamlet & Morris 1996) using electromagnetic induction (EM38) sampling indicated that soil salinity varied significantly both within and between replicate plots at the Tatura site. The originally sampled plot at this site (plot 1/3) was located in one of the less saline areas. Therefore, in 1997, an additional and more saline plot (plot 4/3), selected based on the CFTT salinity data, was also sampled. Plot 4/3 is an "end-of-bay" set of trees, a site typically associated with intermittent over-watering or under-watering. Plot naming is based on the numbering system applied in the original establishment of the site. Averages for all parameters measured at the two plots are presented in Table 6.4.

Table 6.4. Comparison of site and tree parameters, plots 1/3 and 4/3, Tatura field site, 1997. All values are means of 9 determinations. Values within each row followed by the same letter are not significantly different ($p \leq 0.05$).

Parameter	Plot 1/3		Plot 4/3	
soil EC _{1:5} (dS m ⁻¹)	0.314	a	0.228	b
soil EC _e (dS m ⁻¹)	3.86	a	2.75	b
total tree height (m)	8.4	a	6.1	b
diameter @ 20% height (mm)	93.0	a	67.8	b
tree volume (m ³)	0.025	a	0.011	b
foliar Na ⁺ (mol kg ⁻¹ leaf dry weight)	0.106	a	0.098	a
foliar K ⁺ (mol kg ⁻¹ leaf dry weight)	0.148	a	0.122	a
foliar Cl ⁻ (mol kg ⁻¹ leaf dry weight)	0.218	a	0.190	a
basic density (kg m ⁻³)	488	a	519	a
length-weighted fibre length ¹ (mm)	0.57	a	0.53	a
fibre length ² (μm)	632	a	610	a
fibre diameter (μm)	16.0	a	16.4	a
fibre double wall thickness (μm)	6.6	a	6.7	a

¹ measured using Kajaani FS-200

² measured microscopically

Soil salinity

Soil electrical conductivities of 1:5 soil/water extracts (EC_{1:5}) and of saturation extracts (EC_e) were significantly higher in 1997 for plot 1/3 than plot 4/3 (Table 6.4).

Tree growth

Total tree height, diameter at 20% height and volume were all significantly greater in 1997 for plot 1/3 than for plot 4/3 (Table 6.4). Regressions of these growth traits on soil EC_{1:5} were not significant.

Foliar salt

Foliar concentrations of Na^+ , K^+ and Cl^- in 1997 did not differ significantly between the two plots (Table 6.4). No significant regression relationships were found between foliar ion concentrations and soil $\text{EC}_{1:5}$.

Wood basic density

Basic density measured in 1997 did not differ significantly between the two plots (Table 6.4). Simple linear correlation analysis did not find any significant relationship between basic density and soil $\text{EC}_{1:5}$. There was a significant ($p = 0.0459$) negative correlation ($r = -0.47$) between basic density and tree height.

Fibre morphology

Fibre length, measured by both methods, did not differ significantly ($p \leq 0.05$) between the two plots. Results from the two methods were strongly correlated ($r = 0.755$, $p = 0.0001$), but estimates made using the microscope were significantly greater ($p < 0.0001$) than those made with the FS-200 (mean difference = $72 \mu\text{m}$). There were no significant correlations between soil $\text{EC}_{1:5}$ and fibre length measured with the FS-200 or by microscope. No growth traits were correlated with either measure of fibre length.

Fibre diameter did not differ significantly between the plots (Table 6.4), and simple correlation analysis did not reveal any significant relationships with soil $\text{EC}_{1:5}$ or tree growth traits. Similarly, there was no significant difference in fibre double wall thickness between the two plots (Table 6.4), and simple correlation analysis did not reveal any significant relationships with soil $\text{EC}_{1:5}$ or tree growth traits.

6.3 Pot trials

Soils – Moisture content

On 30 Oct 96, several of the trees were wilting. Most of the wilting trees were on the control and low salt treatments. By contrast, wilting was not observed in the trees on the moderate and high salt treatments. The soil of the wilting trees on this day, 6 days since the last treatment, appeared quite dry compared to that of the trees that were not wilting.

The moisture contents of samples collected on 4 Nov 1996 confirmed quantitatively that the potting medium in the controls was drier than that in any of the salt treatments (Figure 6.8a). There was a significant difference between the salt treatments ($p = 0.0014$) and between the two volume applications ($p = 0.0065$). The interaction between these two factors was not significant ($p = 0.337$). All the elevated salt treatments had significantly higher moisture contents than the controls, and application of solutions at the higher volume also resulted in significantly higher moisture contents.

The increased frequency of application of treatments during the second half of the experiment, increased soil moisture content across all treatments (Figure 6.8b), but differences between the treatments were still significant ($p = 0.0104$). Moisture contents were significantly higher (at the 5% significance level) for the low, medium and high salt treatments than for the controls. There was no effect of volume of solution applied ($p = 0.366$) nor was there a significant salt by volume interaction ($p = 0.771$).

Soil salinity

The change in soil $EC_{1.5}$ from the start to the end of the experiment differed significantly ($p = 0.0001$) between the treatments. Whereas there was a small decrease in soil $EC_{1.5}$ from the start to the end in the controls (Figure 6.9), the low, moderate and high salt treatments all displayed a very marked increase. The difference between the controls and the elevated salt treatments was significant at the 5% level. There was also a significant difference amongst the elevated salt treatments, with the high salt treatment showing a significantly greater increase in soil $EC_{1.5}$ (at the 5% level) than the moderate salt treatment. There was no significant effect of volume ($p = 0.155$) on the change in soil $EC_{1.5}$ from start to end, nor was there a significant salt by volume interaction ($p = 0.450$).

Tree growth – general

Daily mean tree diameter, height and volume growth are illustrated for all the individual trees in Figure 6.10, and as treatment means in Figure 6.11. Diameter and height growth rates differed significantly ($p = 0.0063$ and $p = 0.0216$, respectively) between treatments. However, there was no significant effect of salt on tree volume growth rate ($p = 0.1274$), and salt-by-volume interactions were not significant for any of the parameters of tree growth. On the other hand, the volume of solution applied had a significant effect on diameter, height and volume growth ($p = 0.0356$, 0.0053 and 0.0003 , respectively), with values being significantly higher for the high-volume than the low-volume application.

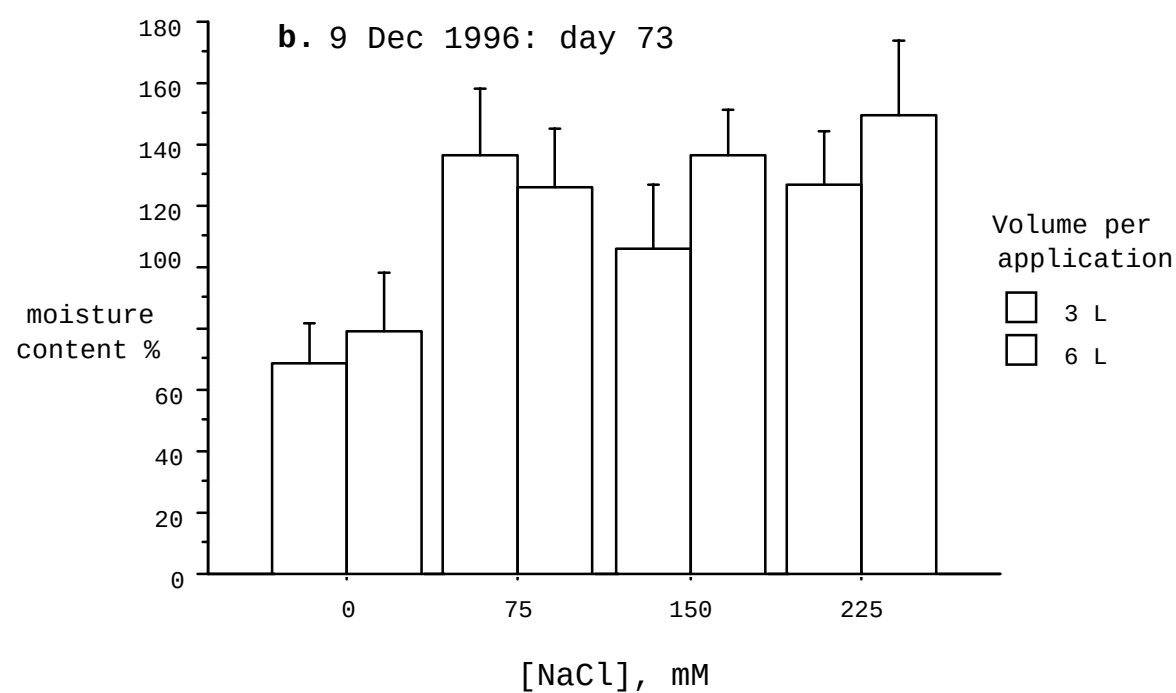
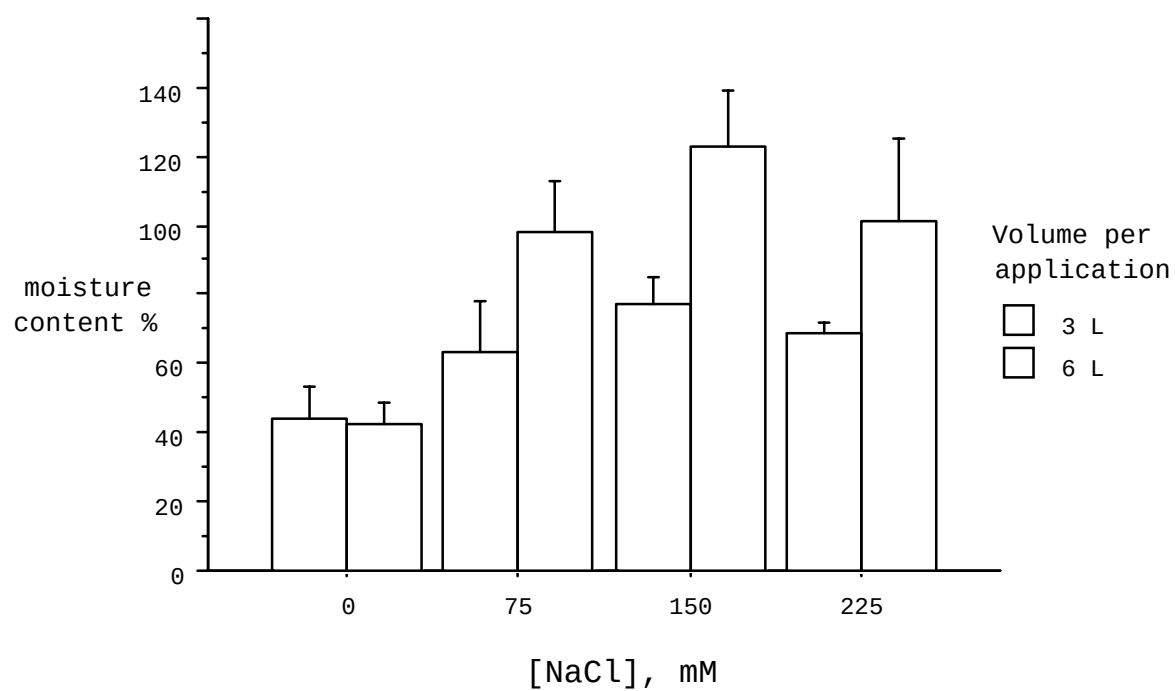


Figure 6.8. Soil moisture contents, pot trial. Data from days 38 and 73. Error bars indicate standard error of the mean

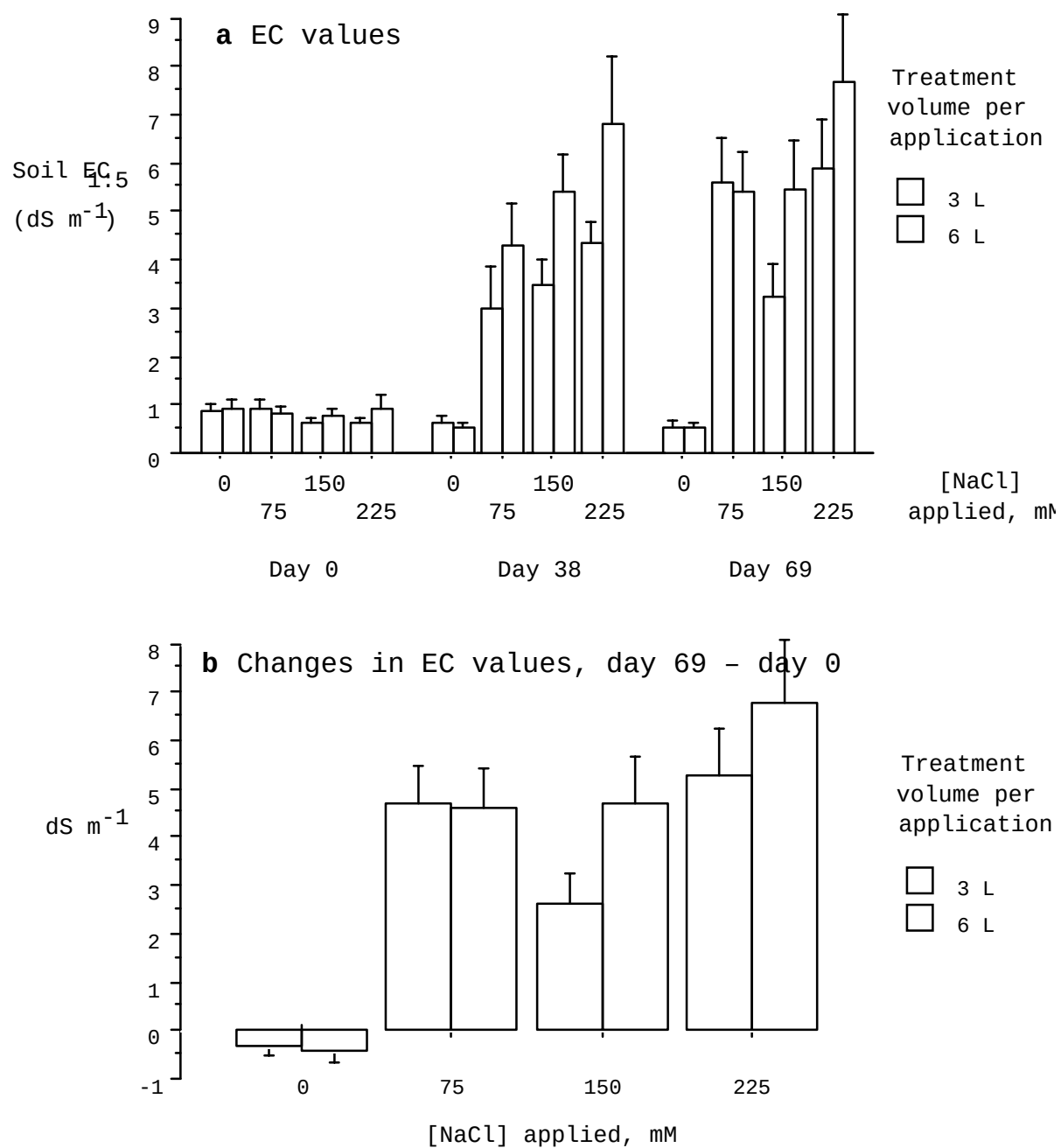


Figure 6.9. Soil EC values and increments, pot trial. Error bars are standard errors

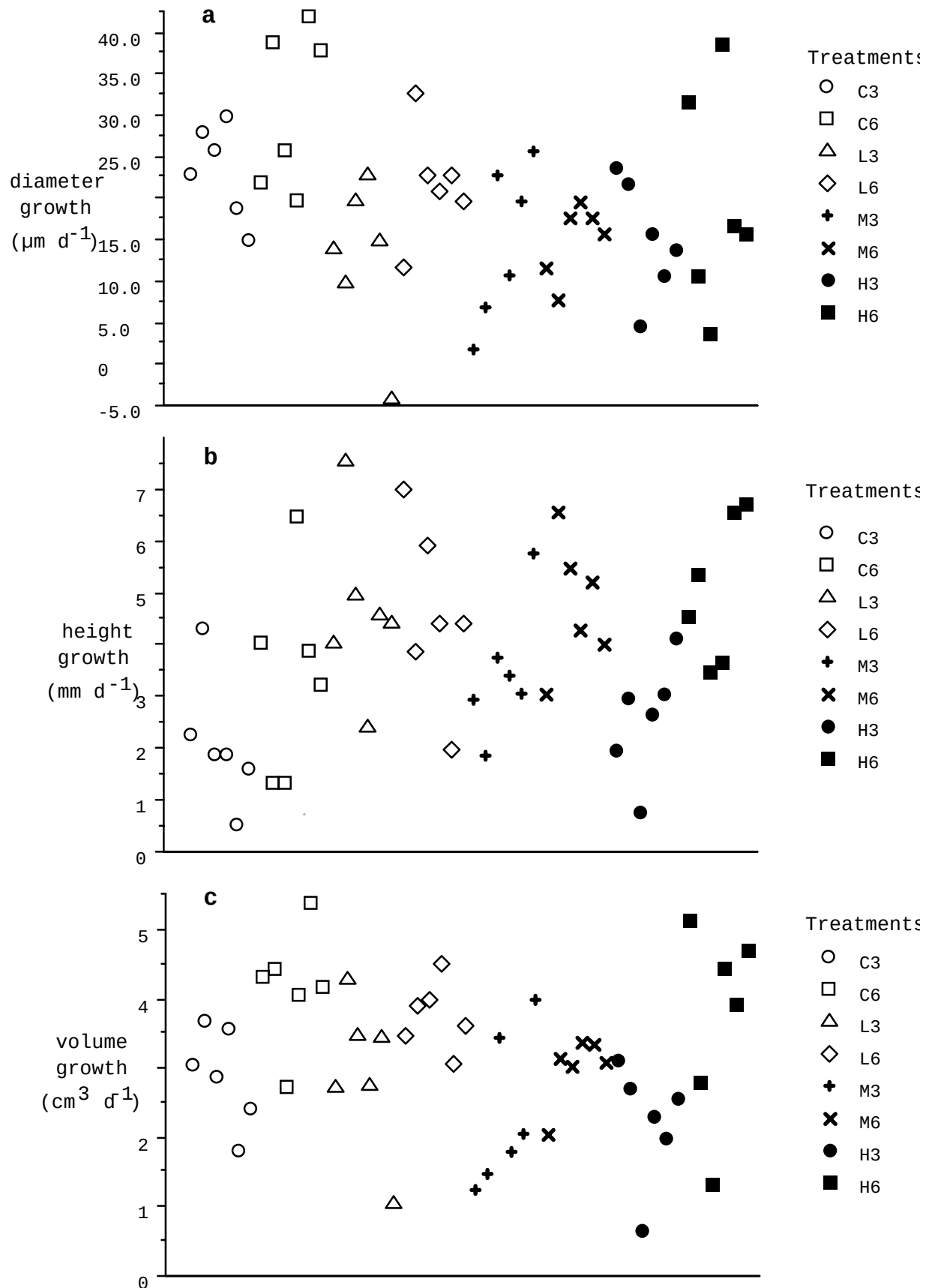


Figure 6.10. Mean daily growth rates, pot trial: scattergrams of individual tree data for average daily diameter, height and volume growth.

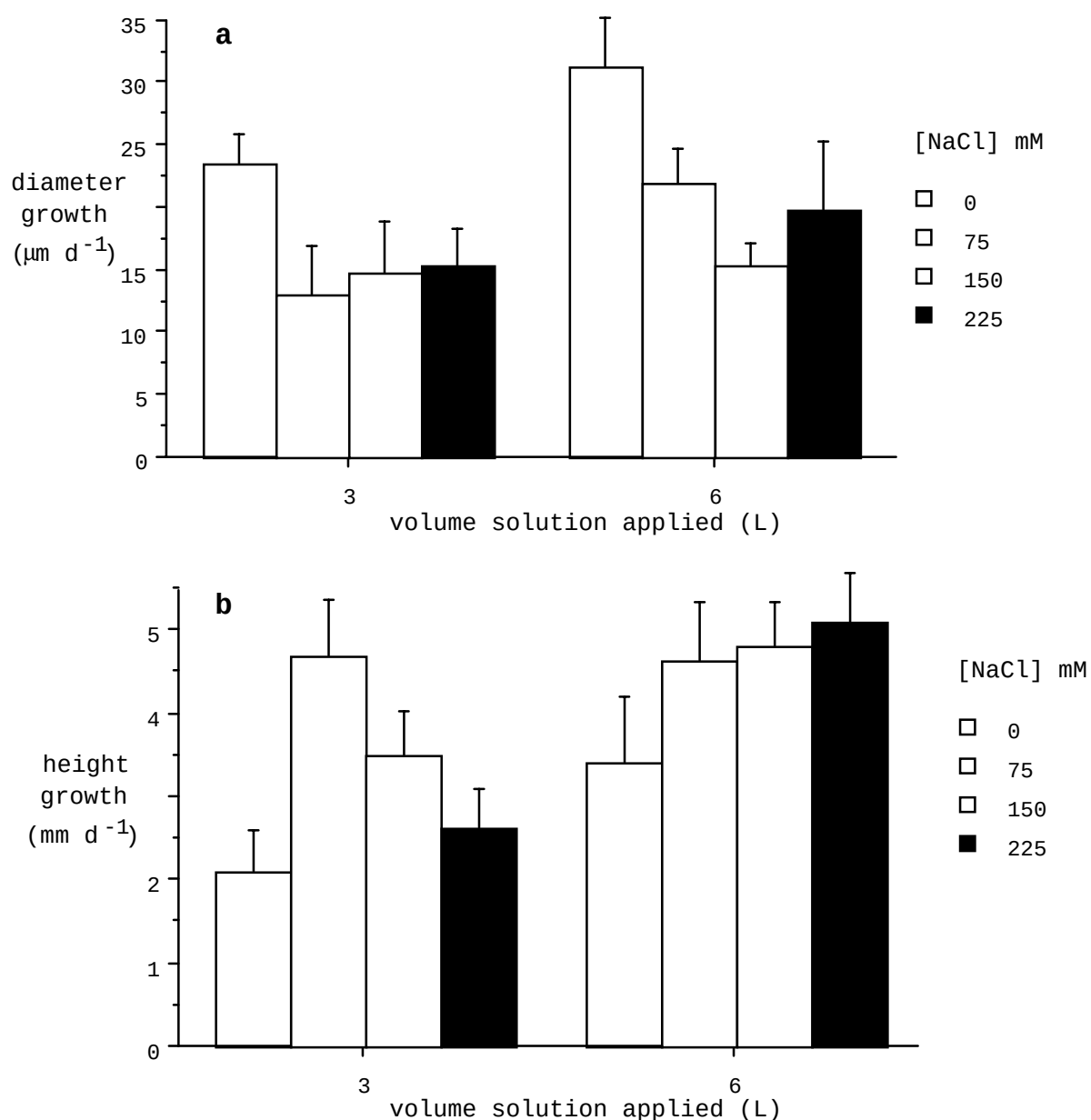


Figure 6.11. Mean daily growth rates, pot trial: treatment means for average daily diameter and height growth. Bars represent standard errors.

Diameter growth was significantly less (at the 5% level) for all the salt treatments than for the controls growing on fresh water (Figure 6.11a), whereas height growth was significantly greater (at the 5% level) in the low and moderate salt treatments than in the controls (Figure 6.11b). A regression of average daily diameter growth on final soil EC was highly significant ($p = 0.0040$) but only 17% of the variation in diameter growth was explained by the equation:

$$d = 24.8 - 1.27 \text{ EC}_{1:5 \text{ final}}$$

d , average daily diameter growth, $\mu\text{m d}^{-1}$
 $\text{EC}_{1:5 \text{ final}}$, $\text{EC}_{1:5}$ at the end of the experiment, dS m^{-1} .

Simple regressions between final EC and height or volume growth were not significant at the 5% level.

Post-treatment radial xylem growth

The wound made to the cambium at the commencement of the experiment was subsequently located in the xylem of 19 of the 48 experimental trees. The failure to locate the wound in the stems of the other trees was attributed to a combination of the following:

- i) insufficient pressure being exerted on the needle, resulting in the needle not penetrating into the cambium
- ii) the radial wedge removed from the stem section failing to include the wound area, due to the needle not being inserted into the tree perpendicular to the stem
- iii) the wound being deeper in the stem than the depth from which the radial wedge was extracted.

The 19 trees in which the wound was found, and their treatment groups, are listed in Table 6.5. Wood formation during the experiment was assessed both by radial (half-diameter) growth over bark and by radial xylem production measured from the thin sections cut through the wound zone (Table 6.6). Radial xylem production ranged from 104 to 560 μm , whereas overbark diameter growth during the same period ranged from 160 to 2330 μm . A plot of radial growth against over-bark diameter growth (Figure 6.12) revealed little relationship between the two measures, whether or not outliers were removed, and correlation analysis confirmed the absence of any statistically significant relationship ($p = 0.816$, $r = 0.058$).

Neither growth measured from thin sections, nor growth measured from over-bark measurements, was significantly related to the salt or volume treatment applied. The regression of radial growth over bark on soil EC was significant ($p = 0.0169$) and 29% of the variation in radial growth over bark was explained by the equation:

$$r = 852.96 - 59.56 \text{ EC}_{1:5 \text{ final}} \quad r, \text{ radial growth over bark, } \mu\text{m}$$

$\text{EC}_{1:5 \text{ final}}, \text{ EC}_{1:5} \text{ at the end of the experiment, dS m}^{-1}$.

Table 6.5. Trees in which cambial wound was located, pot trial.

Treatment	Tree numbers
C3	29, 41, 44
C6	no trees
L3	13
L6	10, 27
M3	1, 20, 21, 30, 48
M6	31, 33
H3	6, 19, 25, 43
H6	22, 4

Table 6.6. Mean over-bark radial growth, and radial production of xylem measured from thin sections, pot trial. Radial growth was calculated as 0.5 x diameter growth.

Treatment	Tree number	Mean over-bark radial growth (μm)	Radial xylem production (μm)
C3	29	940	104
	41	1105	200
	44	710	200
L3	13	520	200
L6	10	430	216
	27	750	240
M3	1	80	184
	20	840	376
	21	320	136
	30	730	560
	48	940	104
M6	31	725	160
	33	640	192
H3	6	770	144
	19	165	192
	25	580	112
	43	495	240
H6	4	1165	144
	22	160	136

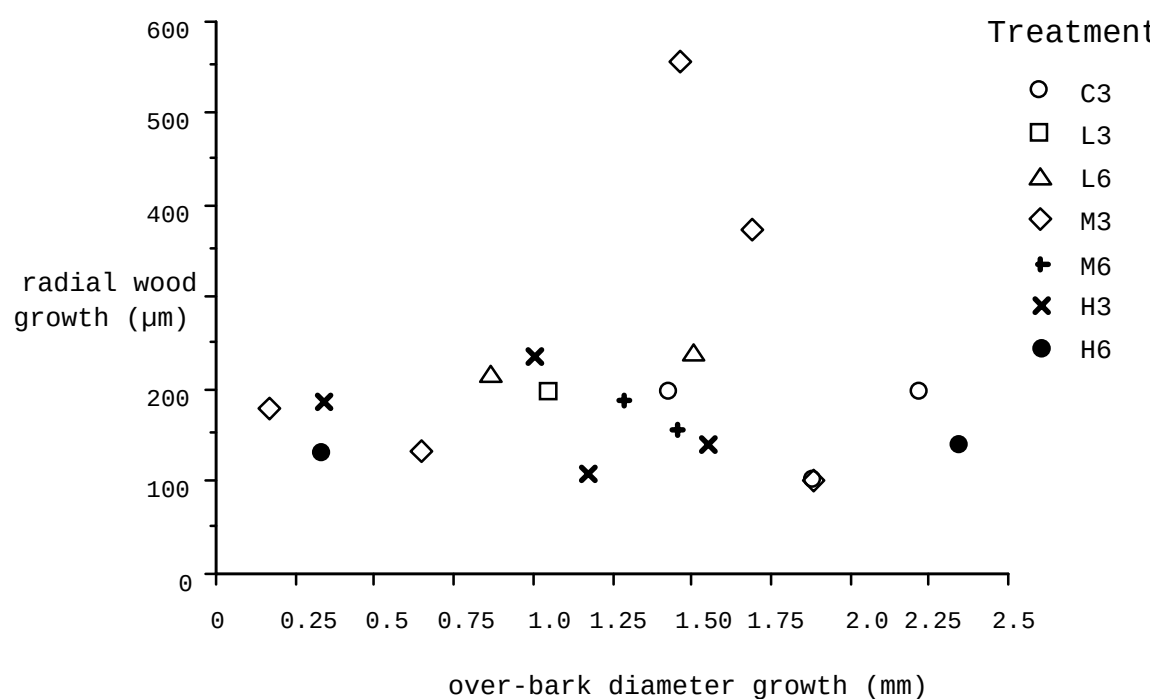


Figure 6.12. Radial xylem production and over-bark diameter growth, pot trial. Individual tree data.

Foliar salt

Foliage samples collected at the end of the experiment were analysed for foliar ion concentrations, $[\text{Cl}^-]$, $[\text{Na}^+]$ and $[\text{K}^+]$. There was a clear effect of salt treatment on foliar accumulation of both Na^+ and Cl^- (Figure 6.13a,b) but less effect was evident for K^+ (Figure 6.13c) especially if two outlier trees were discarded. The volume of solution applied did not strongly influence foliar ion concentrations.

The effect of salt was highly significant ($p < 0.0001$) for both $[\text{Cl}^-]$ and $[\text{Na}^+]$. There was a significant effect of volume of solution applied for $[\text{Na}^+]$ ($p = 0.0321$), but not for $[\text{Cl}^-]$ ($p = 0.370$). There was no significant interaction between salt level and volume applied for either ion. Foliar $[\text{Cl}^-]$ and $[\text{Na}^+]$ were significantly less in the control treatment (at the 5% level) than in all the salt treatments, and were significantly higher (at the 5% level) for the moderate and high salt treatments compared to the low salt treatment.

The positive effect of salt on foliar accumulation of K^+ was also highly significant ($p = 0.0071$; $p < 0.0001$ if the two outlier trees in the H6 treatment were discarded). There was no significant effect of volume of solution applied on foliar $[\text{K}^+]$, nor was there a significant interaction between salt and volume. Foliar $[\text{K}^+]$ was significantly higher (at the 5% level) in all the salt treatments than in the controls, but there were no significant differences between any of the salt treatments.

The highly significant effect of salt treatment on both final soil EC and foliar ion concentrations suggested a relationship between these two parameters. Separate regressions of $[\text{Cl}^-]$ and $[\text{Na}^+]$ on final EC were both highly significant ($p = 0.0004$ and $p = 0.0002$, respectively). For $[\text{Cl}^-]$, 24% of its variation was explained by the equation:

$$[\text{Cl}^-] = 211.35 + 43.41 \text{ EC}_{1:5 \text{ final}} \quad [\text{Cl}^-], \text{ foliar } \text{Cl}^-, \text{ mmol kg}^{-1} \text{ leaf dry weight}$$

$\text{EC}_{1:5 \text{ final}}, \text{ EC}_{1:5} \text{ at the end of the experiment, dS m}^{-1}.$

For $[\text{Na}^+]$, 27% of its variation was explained by the equation:

$$[\text{Na}^+] = 143.14 + 32.57 \text{ EC}_{1:5 \text{ final}} \quad [\text{Na}^+], \text{ foliar } \text{Na}^+, \text{ mmol kg}^{-1} \text{ leaf dry weight.}$$

The regression of foliar $[\text{K}^+]$ on final EC was also highly significant and positive, with the two outlying values (see above) either included ($p = 0.0007$) or excluded ($p = 0.0003$). A greater proportion of the variation in $[\text{K}^+]$ (26% compared with 22%) was explained with the outliers omitted, equation (i), than with them included, equation (ii):

$$\begin{aligned} \text{i) } [\text{K}^+] &= 129.87 + 6.57 \text{ EC}_{1:5 \text{ final}} & [\text{K}^+], \text{ foliar } \text{K}^+, \text{ mmol kg}^{-1} \text{ leaf dry weight} \\ \text{ii) } [\text{K}^+] &= 109.90 + 15.38 \text{ EC}_{1:5 \text{ final}} \end{aligned}$$

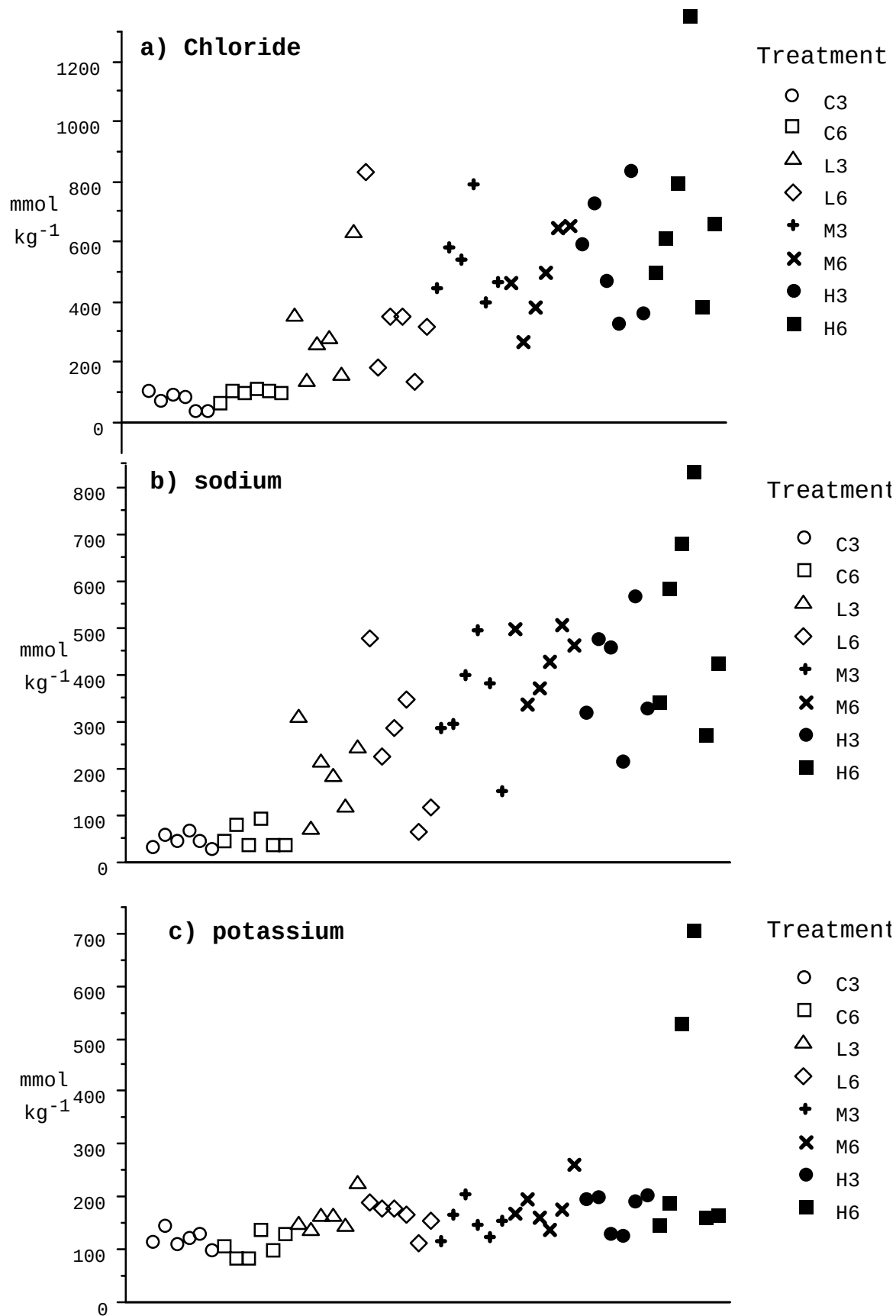


Figure 6.13. Foliar ion concentrations, pot trials. Scattergrams of foliar chloride, sodium and potassium concentrations in individual trees, split by treatment.

Fibre morphology - last 100 μm

The fibre parameters (length, diameter and double wall thickness) measured for each treatment class are presented in Fig. 6.14. These measurements were not influenced significantly by the volume of applied saline solution, so the measurements for each high-volume and low-volume treatment were combined in the statistical analysis.

The effect of salt was highly significant for fibre length and double wall thickness ($p = 0.0002$ and $p = 0.0001$, respectively), with fibre length increasing and double wall thickness decreasing with applied salinity. There was no significant effect on fibre diameter ($p = 0.697$), and there was no significant salt-by-volume interaction for any of the fibre parameters. Fibre length was significantly less (at the 5% level) in the controls than in any of the salt treatments (Figure 6.14a) whereas double wall thickness was significantly less (at the 5% level) in the moderate and high salt treatments compared to the control and low salt treatments (Figure 6.14c).

Fibre parameters were also compared to tree growth during the treatments. Only one significant ($p = 0.0072$) correlation was found, a negative correlation between diameter growth and fibre length ($r = -0.380$).

Fibre morphology – pre- and post-treatment fibres

Fibres formed in the presence of salt (post-treatment) were compared to those formed in its absence (pre-treatment), for each of the 19 trees in which the cambial wound was located. Data for the volume treatments within each salt level were combined, following the finding above that there was no significant effect of treatment volume for any fibre parameter. Parameter means for post-treatment and pre-treatment fibres, and the difference between these for each applied salt treatment, are given in Figure 6.15.

There were similar trends across the treatments in fibre length and double wall thickness for both the pre-treatment and post-treatment samples, with length increasing and double wall thickness decreasing with higher salt treatment. For both parameters, the dimensions of the pre-treatment fibres were slightly greater than for the post-treatment fibres, however paired t-tests found that for fibre length the difference was not significant, either across all treatments or within treatments. The mean difference in double wall thickness ($0.57 \mu\text{m}$) between pre-treatment and post-treatment fibres across all treatments was significant ($p = 0.001$), but within treatments the differences were not significant. Fibre diameter was similar across all treatments and the differences between pre-treatment and post-treatment fibres were small (Figure 6.15). For fibre length and fibre diameter there were no significant differences between pre- and post-treatment samples, either across all treatments or within treatments.

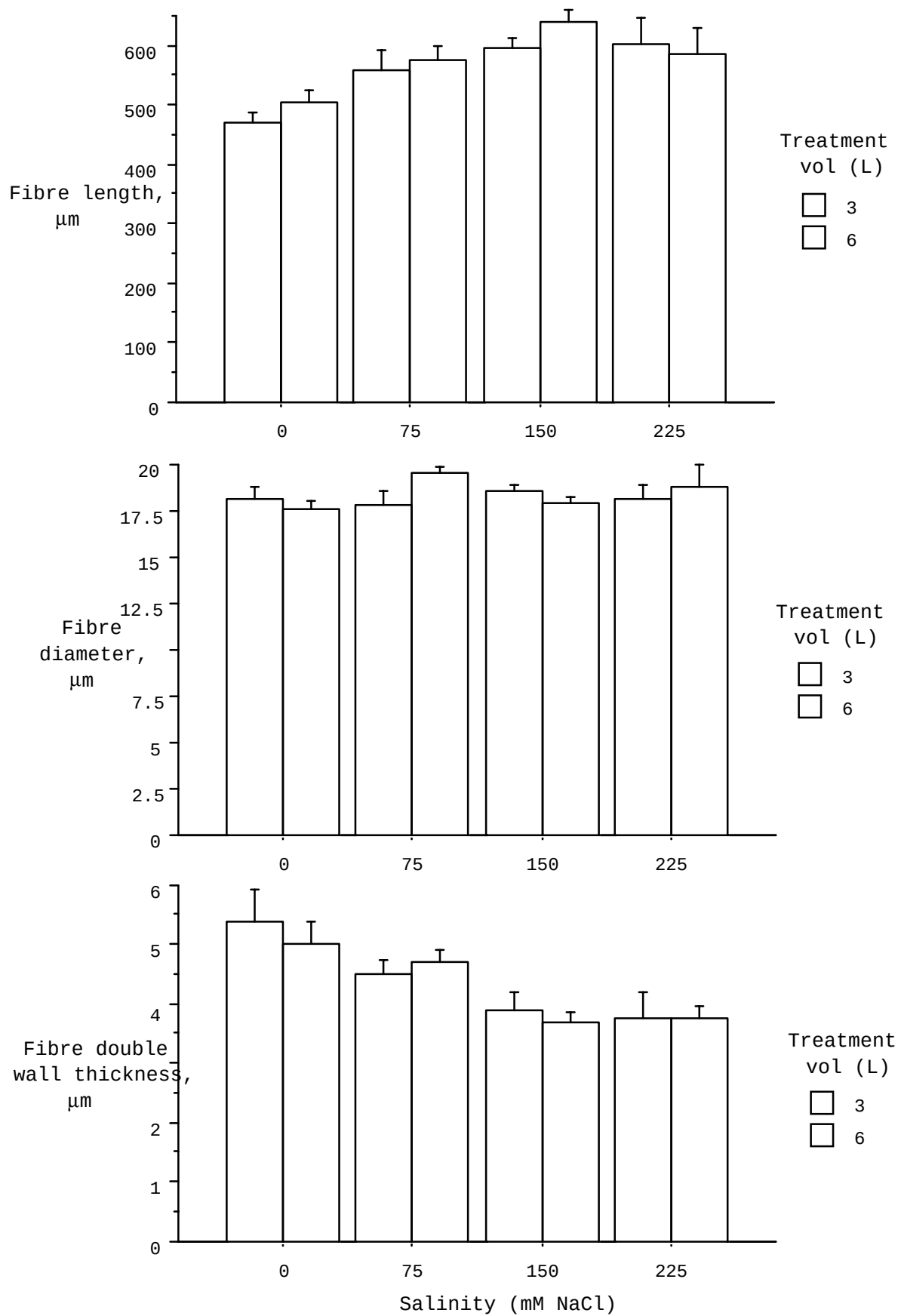


Figure 6.14. Fibre morphology, pot trial. Data are treatment means separated by different applied salinity concentrations and volumes. Error bars are standard errors.

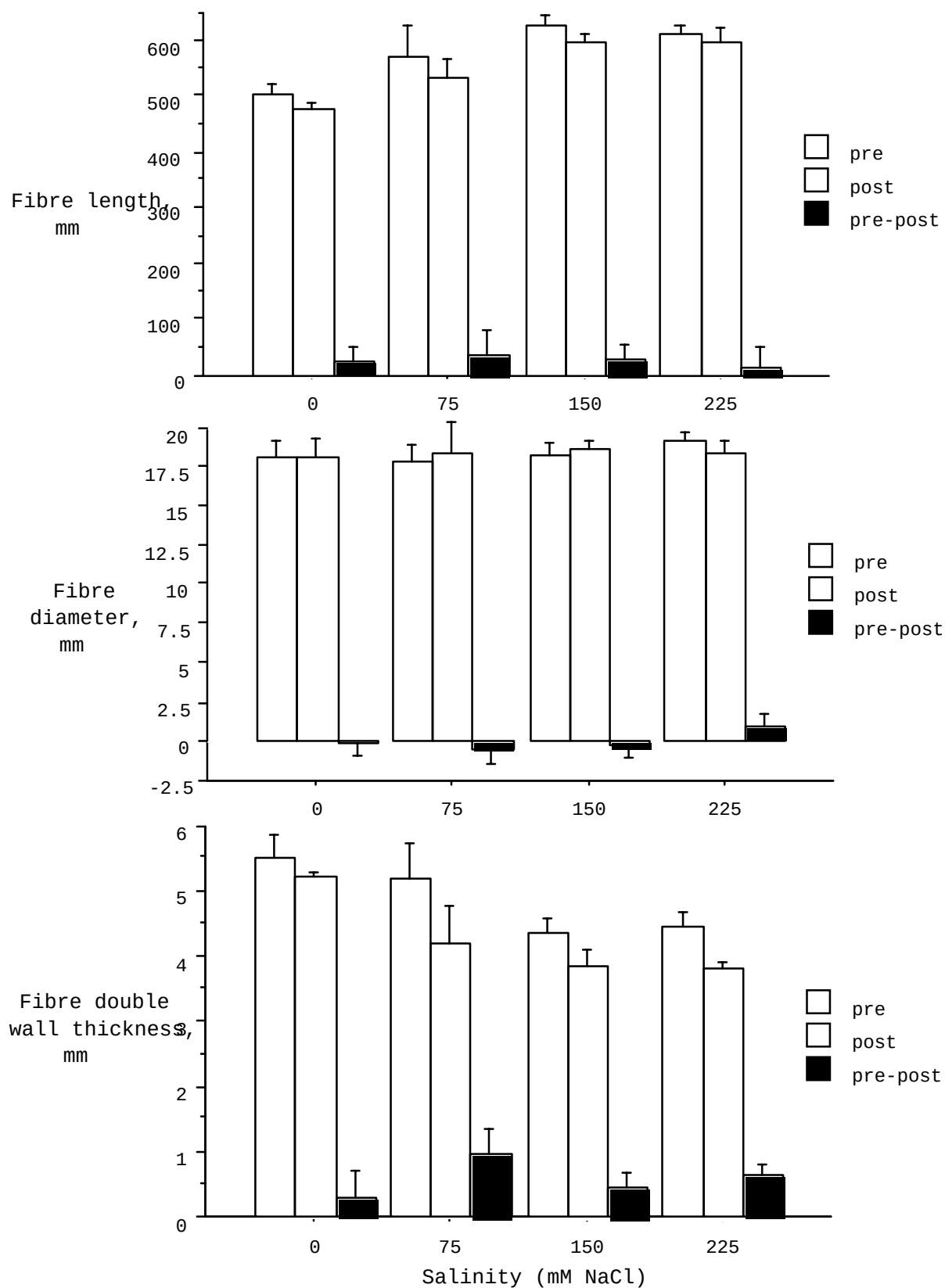


Figure 6.15. Pre-treatment and post-treatment fibre morphology, pot trial. Data are treatment means separated by different applied salinity concentrations. Error bars are standard errors. Pre-post, differences due to treatment.

These results suggested that the treatment differences found in the last-100- μm sample were the result of differences present prior to imposition of the salt treatments. Analyses of covariance were thus performed with pre-treatment values as covariates, which recognised the contribution of pre-treatment fibre morphology to variation in post-treatment fibre morphology. The analyses found no significant effect of salt on post-treatment fibre double wall thickness, length or fibre diameter ($p = 0.119, 0.311$ and 0.620 , respectively).

7. Discussion

7.1 Soil salinity

The two field plots irrigated with saline ground water had significantly higher soil salinities than the plot irrigated with fresh channel water, but had not become more than moderately saline by the end of this study in 1997. Year-by-year variability was such that the plot nominally receiving the highest salinity irrigation water, Ti.high, did not have the most saline soil in each year of the study. This could partly be explained by the variable salinity of the ground water at this plot (Bren et al 1993), or by differences in irrigation scheduling by the landowners of the two sites. High tree-to-tree variations also increase the variability in the data. The lower salinities of surface soil from both Timmering plots in spring 1997 compared to spring 1996 could be due to large amounts of winter rain received in 1996-97.

Overall mean salinities for 1994-97, a period over which no definite trend of increasing salinity could be distinguished, were measured as $EC_{1:5}$ values of 0.12, 0.27 and 0.28 dS/m for Ti.low, Tt.mod and Ti.high respectively, which using plot-specific calibration values equates to EC_e values of 2.0, 3.3 and 4.7 dS/m. The following soil salinity classes, based on EC_e values, are commonly recognised (Marcar et al 1995):

non-saline	$EC_e < 2 \text{ dS m}^{-1}$
slight	$EC_e 2\text{-}4 \text{ dS m}^{-1}$
moderate	$EC_e 4\text{-}8 \text{ dS m}^{-1}$
severe	$EC_e 8\text{-}16 \text{ dS m}^{-1}$
extreme	$EC_e > 16 \text{ dS m}^{-1}$

Compared to this classification, plot Ti.low was non-saline to slightly saline, whereas plot Tt.mod was slightly saline and plot Ti.high was moderately saline.

Pot-trial salt treatments had a marked effect on potting medium salinity relative to the control, although the quantity of salt solution applied at each treatment was not important. The highest pot-trial salt treatment, 225 mM NaCl, gave a much higher average soil $EC_{1:5}$ (6.8 dS m^{-1} at the end of the experiment) compared to the two field plots treated with saline ground water from 1994 to 1997 (averages of 0.27 and 0.28 dS m^{-1} for Tt.mod and Ti.high, respectively).

7.2 Tree growth and salinity

Differences between treatments in tree growth could not conclusively be attributed to the effects of salinity in either the field plots or the pot trials. In both trials, there was no significant effect of plot or treatment on tree volume growth. There were significant plot and treatment effects on height and diameter growth for both field and pot trials, and in both cases greater height growth was associated with plots or treatments receiving higher salt, whereas reduced diameter growth was associated with plots or treatments receiving higher salt. Some of these plot and treatment effects were confirmed with significant regressions of individual tree growth on soil or potting medium $EC_{1:5}$. For height growth in the field, the regression relationship with $EC_{1:5}$ was positive but for the pot trials the relationship was not significant. There were significant, negative regression relationships for diameter growth and $EC_{1:5}$ in both the field and pot trials, whereas for volume growth, significant within-plot negative

regression relationships with EC_{1:5} existed only for the field trials. The effect of salt on the growth of non salt-tolerant plant species is generally expected to be adverse above a certain threshold value of salt, and the positive relationship between EC_{1:5} and height observed at the individual tree and plot levels for the field trial, and at the treatment level for the pot trial, therefore appears anomalous.

The explanation for the field trials could be that the species under study, *Eucalyptus globulus*, ssp. *globulus*, is moderately salt tolerant (Marcar et al 1995), and has yet to be affected by salt as none of the plots were more than just moderately saline. The growth differences observed could then have more to do with other factors such as differences in irrigation quantities rather than irrigation salinities, especially between the two plantation sites, Timmering (where plots Ti.low and Ti.high are located) and Tatura (where plot Tt.mod is located). Irrigation with saline ground water for a longer period than the present study may result in considerably higher soil salinities at the field plots, and a subsequent effect on tree growth that could more confidently be attributed to salinity. However, for the present study, the confounding effects of winter rainfall, irregular irrigation scheduling, and a significant salt tolerance, have not provided a conclusive and significant effect of salinity on growth of the *E. globulus* plots.

We thus do not confirm the earlier report of Hamlet & Morris (1996), who reported significant negative correlation between growth and salinity at 1.5 years after planting, and strong site-specificity in the extent of salt-sensitivity. The trees we sampled were 1.5, 2.5 and 3.5 years old, and our sampling protocols and analytical methodologies were substantially different. Additionally, further recent work by Turnbull and Read (unpublished), confirms our results even more strongly: at 5.5 years after planting, soil salinity (EM38) is not correlated with either individual or plot mean tree growth in either the Timmering or Tatura plantations.

For the pot trial, the greater water use of trees on the control and low-salt treatments compared to trees on higher salt treatments led to the temporary droughting of the trees on the control and low-salt treatments on transfer to a fixed-volume irrigation schedule, and this probably accounts for the reduced height growth associated with the controls. It was thus equally difficult to attribute growth effects in the pot trial to salinity. It also appears, though, that *E. globulus* in relatively saline pots continued to grow despite increasing salt loads, until within-tree salt levels resulted in the death of the tree, which is a response typical of most salt-sensitive crops above their threshold soil salt tolerance. This contrasts with concurrent observations made on *E. camaldulensis* in a parallel study (data not included): *E. camaldulensis* is regarded as one of the more salt tolerant eucalypts, and in response to salt treatment almost stopped growing, but in so doing was able to control within-tree salt loads, and continued to survive.

7.3 Salt uptake

Differences in foliar [Na⁺], [K⁺] and [Cl⁻] occurred between the field plots for each year they were measured, but the differences were not consistent each year and the highest concentrations of foliar ions were not always associated with the plot receiving the most saline irrigation water. Comparison of foliar ion concentrations with soil EC found significant and positive regression relationships in 1996 for [Na⁺] and [K⁺], but no such relationships were found for 1997. The highest foliar ion concentrations were found in the first year of this study, consistent with juvenile leaves or leaves on younger trees accumulating more salt than adult leaves or leaves on older trees.

By contrast, foliar $[\text{Na}^+]$, $[\text{K}^+]$ and $[\text{Cl}^-]$ increased consistently with increasing application of NaCl in the pot trial, which reached much higher soil EC values than obtained in the field. Regression relationships between all three ions and soil EC were highly significant and positive in the pot trial. The high within-tree salt loads seen in the pot trial trees, and the clearer relationship between salt treatment and salt uptake, suggests that important features of trees in the field, such as the lack of restriction to their root systems and the access to fresh water derived from precipitation, may be linked to their avoidance of high within-tree salt loads.

7.4 Basic density

The highly significant differences between the field plots in the change in basic density over the period 1995-97 could not be related to salinity. This change was greater for plot Tt.mod than both Ti.low and Ti.high, but between the latter pair no difference was found. Comparison of basic density values for individual trees with soil EC measured at their base and with foliar $[\text{Na}^+]$, $[\text{K}^+]$ and $[\text{Cl}^-]$ also failed to establish any relationship. A site effect is thus inferred.

7.5 Fibre morphology

Salinity imposed in the field by irrigation treatments, and that applied to trees in the pot trial, did not affect fibre morphology.

In the field trials, fibre length averages for each year of measurement did not differ between plots. Additional measures of fibre morphology made on the 1997 samples, including fibre diameter and double wall thickness, as well as fibre length, also did not differ between the plots. There were, however, differences between the plots in the increase in fibre length for 1996–1997 and 1995–1997. For the former period, the increase was greater for Ti.high than either Tt.mod or Ti.low whereas, for the latter period, the increase for Ti.high was greater than that for Tt.mod only. The absence of a difference between either of the saline groundwater treated plots and the freshwater-irrigated plot Ti.low for 1995–1997 suggested that the difference observed was not related to salinity. This was tested by comparing parameters of fibre morphology for individual trees with soil EC measured at their base, and with foliar $[\text{Na}^+]$, $[\text{K}^+]$ and $[\text{Cl}^-]$. The absence of any significant relationships between parameters of fibre morphology with salinity internal or external to the trees led to the conclusion that salinity did not affect fibre morphology in the field trial.

An initial sample of fibres from the pot trial, comprising the last-formed 100 μm of xylem from each tree, appeared to show a significant effect of salt treatment on fibre length and double wall thickness, with trees on higher salt treatments having significantly longer, thinner-walled fibres compared to controls. However this pattern was also observed in fibres formed in these trees but before treatments were imposed, suggesting that the differences were unrelated to salt treatments but were due to pre-existing differences. Covariance analysis, which took account of the variability in post-treatment fibre morphology due to pre-treatment morphology, found that there was no significant effect of salt treatment on fibre morphology.

7.6 Separation of Tatura site into 2 plots

There were distinct differences in tree growth and salinity between two replicate plots at Tatura, but no link between these parameters could be established. The replicate plot, plot 4/3, was an "end-of-bay" set of trees, a site typically associated with intermittent over-watering or under-watering, and contains shorter trees than the first plot sampled, plot 1/3.

The increase in soil salinity observed by Hamlet and Morris (1996) towards the end of the irrigation bays, and specifically in plot 4/3, was also not corroborated in the present study.

Significantly higher soil salinity was recorded for Tatura plot 1/3 in Jan 1997 compared to plot 4/3, but this was not reflected in tree growth or foliar ion concentrations. Tree heights, diameters and volumes were all significantly greater for plot 1/3 than for plot 4/3, while foliar concentrations of $[Na^+]$, $[K^+]$ and $[Cl^-]$ did not differ. When $EC_{1:5}$ data was converted to EC_e , both plots had soil salinities in the slightly saline class of Marcar et al (1995). *Eucalyptus globulus* is moderately salt tolerant (Marcar et al 1995), and hence the difference in soil salinity between the two plots might not be important in terms of plant response. There were also no correlations between any individual tree parameters and soil salinity measured at their base.

It is concluded that the observed differences in tree growth between the two plots were due to factors other than soil salinity measured in Jan 1997. Salinity at depth (>20 cm) was not measured in the present study. However, any differences of salinity at greater depth had little effect on the trees as leaf ion concentrations did not differ significantly between the two plots.

Differences in tree growth had no significant effect on fibre properties between the two plots. There was, though, a significant negative correlation between tree height and basic density. This concurs with the assertion of Higgins (1984) who reported a general acceptance of lower than normal growth rates being associated with higher basic densities. A contrary view was provided by Hillis (1984) who concluded that density of eucalypt woods is not influenced by or significantly correlated with growth rate. In a more recent review, Downes et al (1997) found that of the three possible relationships between wood density and growth rates – positive, negative or no correlation – most reports identified a negative correlation. The negative correlation of basic density with tree height in the present study did not translate to a significant difference between plots in basic density.

The increase in soil salinity towards the end of the irrigation bays at Tatura observed by Hamlet and Morris (1996) in surveys in Jul 1995 and Feb 1996 was not detected in sampling for the present study in Jan 1997. A trend in the opposite direction was seen, with significantly higher soil salinity recorded in plot 1/3 at the head of the irrigation bay, than for plot 4/3 at the end of the bay. A number of factors could account for this discrepancy. Eleven months had elapsed between the Feb 1996 survey of Hamlet and Morris (1996) and our Jan 1997 survey, and during this time leaching winter rains could have redistributed salts. The 1996/97 summer irrigation season also could have altered salinity profiles across the site. Further, the differences between the two surveys in the spatial trends of soil salinity could be explained by the use of different measurement methods that sample salt at different depths. The present study used samples collected from the surface 20 cm of soil for preparation of 1:5 soil/water extracts, on which electrical conductivity was measured directly. Hamlet & Morris (1996) measured soil electrical conductivity indirectly with an electromagnetic induction meter (a Geonics EM38). This instrument records apparent soil electrical conductivity (EC_a) (Bennett & George 1995). In the horizontal measurement mode (EM38H) 75% of the signal is estimated to come from the top 1.0 m of a uniform soil, whereas in the vertical measurement mode (EM38V) 75% of the signal is estimated to come from the top 1.8 m (Bennett & George 1995).

7.7 Salinity effects on pulping and paper-making properties

A concurrent study by Dr Noel Clark, CSIRO Forestry and Forest Products, investigated the pulping and paper-making properties of a range of eucalypts grown on dryland and irrigated sites within and outside the Murray-Darling basin (Clark 1998; Clark et al 1998). *Eucalyptus camaldulensis* was the only species analysed from sites of a range of salinities. The small observed reductions in growth due to salinity in trees 6-14 years old were associated with increased wood density and a reduced bleached Kraft pulp yield, but changes were very small compared to changes due to fertilisation, which increased growth while altering wood quality.

Overall, Clark concluded that the effects of salinity were similar to the effects of reduced water availability. However, if growth were unaffected due to the low level of soil salinity compared to the tolerance expressed by the trees, then differences in pulpwood properties were less likely to be significant. This last conclusion is very similar to the conclusions of this work, that wood and fibre properties are unaffected under conditions where tree growth is also unaffected.

8. Implications

The primary implication from the present study is that establishment of plantations of *Eucalyptus globulus* ssp. *globulus* on land irrigated with pumped saline groundwater of 5-10 dS/m appears to be a feasible proposition, at least for the first four years. No tree growth reductions were observed in the first 4 years after planting, nor any fibre morphological differences that could reduce timber values for fibre production. Direct comparisons between controls and trees exposed to salt were especially clear at the Timmering site, which uses irrigation waters of both low and high salinity.

This assessment is made purely on a physiological basis, with no reference to economic constraints outside the scope of the present study. The assumed establishment of a major wood-fibre industry at Shepparton, harvesting young trees for fibre rather than growing any on for sawlogs (Bren 1992), was based on precedents with eucalypts in Portugal, and poplars in Oregon, but such a large, local chip or pulp market has not been established. However, the recent entry of a major Japanese company into the region, initially establishing plantations for pulp at 500 ha per year, for export of chips through the port of Melbourne, suggests that haulage costs may not prevent development of an economic industry.

This assessment also assumes no gross change in climatic conditions, and particularly that sufficient leaching winter rain is available to move accumulated surface salt back down to the water table. Overall, no definite trend of increasing salinity could be distinguished over the irrigation period 1994-97, but mean EC_e values for this period were calculated as 2.0, 3.3 and 4.7 dS/m for the 3 sites Ti.low, Tt.mod and Ti.high respectively, indicating higher salinity on the soils irrigated with more saline water. These data put the soils in the slightly saline (Ti.low, Tt.mod) or moderately saline (Ti.high) classes of Marcar et al (1995). Studies over a longer period would be needed to establish if this is also the long-term conclusion.

The combined results from the field and pot trials indicate that the moderately salt tolerant *Eucalyptus globulus* will suffer negligible or minor growth reductions on soils irrigated to a moderately saline level, at least for the first four years after planting, and will produce fibres of similar morphology to trees grown in the absence of salt. As soil salinity increases above the moderate level, the trees will continue to grow provided sufficient water is still available, but internal salt levels will increase to the point where tree death will result. Based on the pot trial, where such internal salt levels were achieved, the decline and death of the trees will occur before any effect on fibre morphology.

9. Recommendations

The most important recommendation is for continued monitoring of the Timmering site, to determine whether soil salinity increases further under saline irrigation, and whether tree growth and wood and fibre characteristics continue to be unaffected by irrigation water salinity, up to harvest age. To this end, one author (SMR), together with BForSc student Tarryn Turnbull, has resampled the Timmering site at Jan 99, 5.5 years after establishment. The site is now managed by CFTT, subject to funding.

10. References

- Anon (1996) Western Australian salinity action plan. A report produced on salinity for Agriculture Western Australia, Department of Conservation and Land Management, Department of Environmental Protection, and Waters and Rivers Commission, Western Australia.
- Baker T, Bail I, Borschmann R, Hopmans P, Morris J, Neumann F, Stackpole D, Farrow R (1994) Commercial tree-growing for land and water care. 2: Trial objectives and design for pilot sites. A report produced by the Centre for Forest Tree Technology for the Trees for Profit Research Centre, University of Melbourne.
- Bamber RK (1985) The wood anatomy of eucalypts and papermaking. *Appita* 38: 210-216
- Bamber RK, Burley J (1983) The wood properties of Radiata Pine. Commonwealth Agricultural Bureau.
- Banham PW (1995) Pulpwood qualities required for the cold soda pulping process. In: BM Potts, NMG Borralho, JB Reid, RN Cromer, WN Tibbits, CA Raymond (eds.), *Eucalypt plantations: Improving fibre yield and quality*. Proceedings CRC-IUFRO Conference, pp. 1-4. CRC for Temperate Hardwood Forestry: Hobart.
- Bennett DL, George RJ (1995) Using the EM38 to measure the effect of soil salinity on *Eucalyptus globulus* in south-western Australia. *Agricultural Water Management* 27: 69-86
- Bisset IJW, Dadswell HE (1949) The variation of fibre length within one tree of *Eucalyptus regnans*, F.v.M. *Australian Forestry* 13: 86-96
- Bisset IJW, Dadswell HE (1950) The variation in cell length within one growth ring of certain angiosperms and gymnosperms. *Australian Forestry* 14: 17-29
- Bren L, Hopmans P, Gill B, Baker T, Stackpole D (1993) Commercial tree-growing for land and water care. 1: Soil and groundwater characteristics of the pilot sites. A report produced by the Centre for Forest Tree Technology for the Trees for Profit Research Centre, University of Melbourne.
- Bren LJ (1992) Irrigation and Water Factors in "Trees for Profit". In: Proceedings of the Seminar on Commercial Tree-growing for Land and Water Care in Some Irrigation and Associated Dryland Areas in the Murray-Darling Basin, pp. 45-52. CSIRO Division of Forest Products, Clayton, Victoria, 10 July 1992.
- Carvalho MG, Ferreira PJ, Martins AA, Figueiredo MM (1997) A comparative study of two automated techniques for measuring fibre length. *TAPPI Journal* 80: 137-142
- Clark NB (1998) The pulpwood quality of trees grown in the Murray-Darling Basin. PhD thesis, University of Melbourne.
- Clark NB, Read SM, Vinden P (1998) The effects of drought and salinity on wood and kraft pulps from young plantation eucalypts. *Appita Journal* 52: 93-97

Downes GM, Hudson IL, Raymond CA, Dean GH, Michell AJ, Schimleck LR, Evans R, Muneri A (1997) Sampling plantation eucalypts for wood and fibre properties. CSIRO Publishing.

Franklin GL (1945) Preparation of thin sections of synthetic resins and wood resin composites and a new macerating method for wood. *Nature* 155: 51

Glenn EP, Brown JJ, Khan MJ (1997) Mechanisms of salt tolerance in higher plants. In: AS Basra, RK Basra (eds) Mechanisms of environmental stress resistance in plants. Harwood Academic Publishers, pp. 83-110.

Greenway H, Munns R (1980) Mechanisms of salt tolerance in non-halophytes. *Annual Review of Plant Physiology* 31: 149-190

Hamlet A, Morris J (1996). Effects of salinity on the growth of four *Eucalyptus* species on irrigated sites in northern Victoria. A report produced by the Centre for Forest Tree Technology for the Trees for Profit Research Centre, University of Melbourne.

Higgins HG (1969) The long and short of papermaking. *The Australian Timber Journal* 35: 24-39

Higgins HG (1984) Pulp and Paper. In: Hillis W.E., Brown A.G. (eds) *Eucalypts for Wood Production*. CSIRO Publications and Academic Press Australia, pp. 290-316.

Hillis WE (1984) Wood quality and utilization. In: *Eucalypts for Wood Production*. CSIRO Australia / Academic Press, pp. 259-289.

Johnson AD, Simons JD, Hansen RW, Daniel RA (1985) Chemical procedures for the analysis of plant material: multielement, oil, sugars and gum. Technical memorandum for the CSIRO Division of Tropical Agronomy.

Keiper FJ, Chen DM, DeFilippis LF (1998) Respiratory, photosynthetic and ultrastructural changes accompanying salt adaptation in culture of *Eucalyptus microcorys*. *Journal of Plant Physiology* 152: 564-573

Kuroda K, Shimaji K (1984) The pinning method for marking xylem growth in hardwood species. *Forest Science* 30: 548-554

Marcar NE (1993) Waterlogging modifies growth, water use and ion concentrations in seedlings of salt treated *Eucalyptus camaldulensis*, *Eucalyptus tereticornis*, *Eucalyptus robusta*, and *Eucalyptus globulus*. *Australian Journal of Plant Physiology* 20: 1-13

Marcar NE, Crawford D, Leppert P, Jovanovic T, Floyd R, Farrow R (1995) *Trees for Saltland. A guide to selecting native species for Australia.* CSIRO Australia.

Marschner H (1986) *Mineral Nutrition of Higher Plants*. Academic Press.

Mitchell MD, Denne MP (1997) Variation in density of *Picea sitchensis* in relation to within-tree trends in tracheid diameter and wall thickness. *Forestry* 70: 47-60

Morris JD (1980) Factors affecting the salt tolerance of Eucalypts. In: Eucalypt dieback in forests and woodlands. CSIRO, pp. 190-204.

Northcote KH (1979) A factual key for the recognition of Australian soils. Rellim Technical Publications.

O'Brien TP, Feder N, McCully ME (1964) Polychromatic staining of plant cell walls by toluidine blue O. *Protoplasma* 59: 368-373

Olesen PO (1971) The water displacement method. A fast and accurate method of determining the green volume of wood samples. *Forest Tree Improvement* 3: 3-23

Panshin AJ, de Zeeuw C (1970) Textbook of wood technology. Structure, identification, uses and properties of the commercial woods of the United States and Canada. McGraw-Hill Book Company, 3rd ed.

Pereira H, Almeida MH, Tome M, Pereira JS (1995) *Eucalyptus globulus* plantations: Genetic, silvicultural and environmental control of fibre yield and quality. In: BM Potts, NMG Borralho, JB Reid, RN Cromer, WN Tibbits, CA Raymond (Ed.), *Eucalypt plantations: Improving fibre yield and quality. Proceedings CRC-IUFRO Conference*, pp. 46-48. Hobart, Australia. Cooperative Research Centre for Temperate Hardwood Forestry.

Raper GP (1998) Agroforestry water use in Mediterranean regions of Australia. In: *Water and Salinity Issues in Agroforestry*, No. 2. RIRDC, Canberra, 71 pp.

Rawlins B (1992) Trees grown for land care, water care and profit in the Murray-Darling Basin: the forest products perspective. In: *Commercial tree-growing for land and water care in some irrigation and associated dryland areas in the Murray-Darling Basin*, pp. 1-13. CSIRO Division of Forest Products, Clayton, Victoria. Trees for Profit Research Centre.

Rayment GE, Higginson FR (1992a) Saturation Extracts. In: R Leydon (eds) *Australian laboratory handbook of soil and water chemical methods*. Inkata Press, pp. 127-136.

Rayment GE, Higginson FR (1992b) Electrical Conductivity. In: *Australian Laboratory Handbook of Soil and Water Chemical Methods*. Inkata Press, pp. 15-16.

Rayment GE, Higginson FR (1992c) Moisture Content. In: R Leydon (eds) *Australian laboratory handbook of soil and water chemical methods*. Inkata Press, pp. 10-14.

Richards LA (1954) Diagnosis and improvement of saline and alkali soils. *Handbook for the United States Salinity Laboratory Staff*, United States Department of Agriculture.

Ridoutt B, Sands R (1995) The vascular cambium: its significance for improving fibre yield and quality. In: BM Potts, NMG Borralho, JB Reid, RN Cromer, WN Tibbits, CA Raymond (eds.), *Eucalypt plantations: Improving fibre yield and quality. Proceedings CRC-IUFRO Conference*, pp. 124-127. Hobart. Cooperative Research Centre for Temperate Hardwood Forestry.

Ridoutt BG (1995) Physiology of fibre development in *Eucalyptus globulus*. PhD thesis, University of Melbourne.

Ridoutt BG, Sands R (1993) Within-tree variation in cambial anatomy and xylem cell differentiation in *Eucalyptus globulus*. *Trees Structure and Function* 8: 18-22

Ridoutt BG, Sands R (1994) Quantification of the processes of secondary xylem fibre development in *Eucalyptus globulus* at two height levels. *International Association of Wood Anatomists Journal* 15: 417-424

Salisbury FB, Ross CW (1992) *Plant Physiology*. Wadsworth Publishing Company, 4th ed,

Sandercock CF, Sands R, Ridoutt BG, Wilson LF, Hudson I (1995) Factors determining wood microstructure in Eucalypts. In: BM Potts, NMG Borralho, JB Reid, RN Cromer, WN Tibbits, CA Raymond (eds.), *Eucalypt plantations: Improving fibre yield and quality*. Proceedings CRC-IUFRO Conference, pp. 128-135. Hobart, Australia. Cooperative Research Centre for Temperate Hardwood Forestry.

Sands R (1986) Drought and salt. In: HR Wallace (eds) *The ecology of the forests and woodlands of South Australia*. Government Printer South Australia, pp. 242-247.

Schofield NJ (1992) Tree planting for dryland salinity control in Australia. *Agroforestry Systems* 20: 1-23

Shaw RJ (1985) Soil Salinity. In: Identification of soils and interpretation of soil data. Refresher Course in Soil Science, pp. 145-174. Brisbane. Australian Society of Soil Science Incorporated, Queensland Branch.

Slavich PG, Petterson GH (1993) Estimating the electrical conductivity of saturated paste extracts from 1:5 soil:water suspensions and texture. *Australian Journal of Soil Research* 31: 73-81

Stackpole D, Borschmann R, Baker T (1995) Commercial tree-growing for land and water care. 3. Establishment of pilot sites. A report produced by the Centre for Forest Tree Technology for the Trees for Profit Research Centre, University of Melbourne.

Williams MD, Beadle CL, Turnbull CRA, Dean GH, French J (1995) Papermaking potential of plantation Eucalypts. In: BM Potts, NMG Borralho, JB Reid, RN Cromer, WN Tibbits, CA Raymond (eds.), *Eucalypt Plantations: Improving Fibre Yield and Quality*. Proceedings CRC-IUFRO Conference, pp. 73-78. CRC for Temperate Hardwood Forestry: Hobart.

Williamson DR (1990) Salinity-an old environmental problem. In: I Castles (eds) *Year Book Australia 1990*. Commonwealth of Australia, pp. 202-211.

Wolter KE (1968) A new method for marking xylem growth. *Forest Science* 14: 102-104