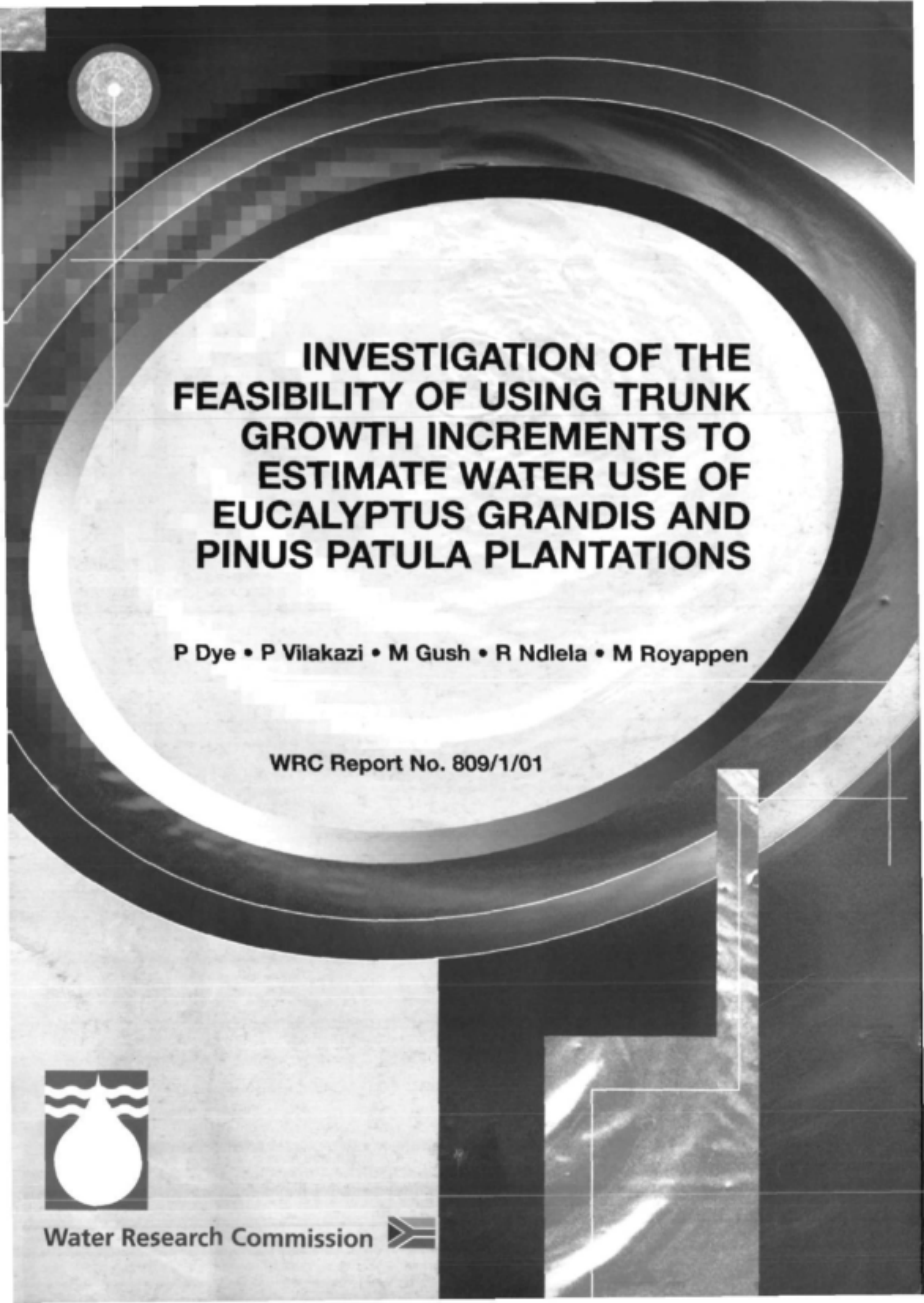

INVESTIGATION OF THE FEASIBILITY OF USING TRUNK GROWTH INCREMENTS TO ESTIMATE WATER USE OF EUCALYPTUS GRANDIS AND PINUS PATULA PLANTATIONS

P Dye • P Vilakazi • M Gush • R Ndlela • M Royappen

WRC Report No. 809/1/01

Water Research Commission

Investigation of the feasibility of using trunk growth increments to estimate water use of *Eucalyptus grandis* and *Pinus patula* plantations

Report to the Water Research Commission and the Department of Water Affairs and Forestry

By

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EXECUTIVE SUMMARY

Background

The water use of forest plantations remains a topical subject in light of recent changes to water law, as well as continuing debate over the hydrological impacts of various types of land use. While sap flow and micrometeorological techniques exist to allow direct measurement of forest water use, their usefulness in resolving land use disputes is currently limited for the following reasons:

- They are complex, and expensive in terms of both equipment and time. Funds are mostly insufficient to permit measurements of water use over a useful period of time. Measurements can generally only be sustained for a small fraction of a forest rotation.

- Forest water use is known to be affected by a wide range of weather, forest stand and site factors, and therefore our ability to extrapolate from relatively few research sites to the entire forestry region is limited. Growth and water use is especially sensitive to the availability of soil water at a site, which is mostly impractical to measure because of deep rooting depths, highly variable stoniness and depth to bedrock, and uncertainty over lateral soil water flow.

An alternative approach to the estimation of plantation water use was suggested by the results of a previous investigation into the relation between annual trunk volume increments and cumulative annual water use of *Eucalyptus grandis* trees. The study was conducted in Kruisfontein Plantation (White River district, Mpumalanga), and involved a full year of growth and sap flow measurement in 17 trees growing on a wide range of site quality. A surprisingly tight, linear relation was found between annual volume growth increment and cumulative annual sap flow (Figure 1), suggesting that this measure of the efficiency of water use did not differ significantly among the trees. Further data from a *Pinus patula* experiment in the White River area (Witklip Plantation) revealed a similar efficiency of water use.

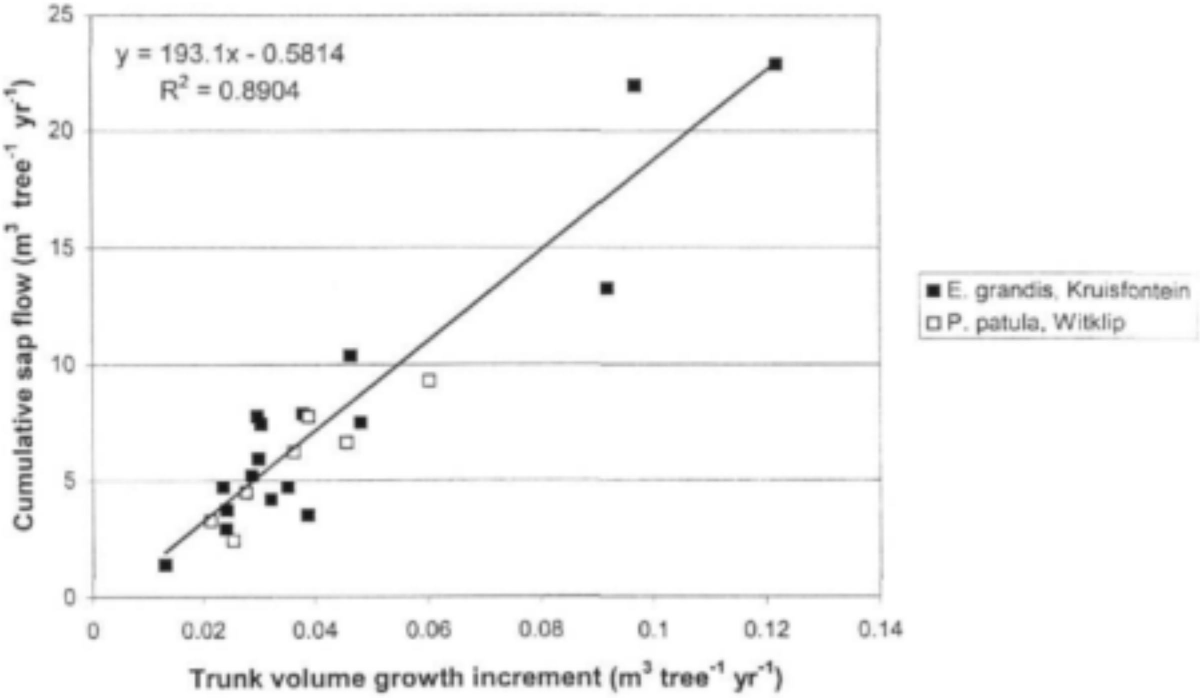

Figure 1. The relation between annual trunk volume growth increment and annual cumulative sap flow recorded in sample trees of *E. grandis* and *P. patula* at Kruisfontein and Witklip plantations, White River.

These results suggest that annual water use may be predicted from growth increment with useful accuracy. Forest growth increments are relatively easy to measure, and are known for most forestry compartments throughout the national forestry estate. A simple correlation to annual water use would bring much clarity to the issue of forest impacts on regional water supply.

Project objective

The Kruisfontein sample trees were mostly 6-years old, and no data were available to determine whether the relationship holds over an entire rotation. The purpose of this study was to examine the correlation in more detail in a selection of *E. grandis* and *P. patula* trees representing a wider range of age, site quality, management regime and climate. The *P. patula* study was funded by the Department of Water Affairs and Forestry. In view of the similarity of the two projects, it was agreed between the WRC and DWAF that the results should be reported together in a single publication.

Data collection

Two adjacent sample trees representing dominant and suppressed size classes were selected in seven *E. grandis* and five *P. patula* forest compartments. These sites were all situated within an 80 km radius of Pietermaritzburg, and covered a range of altitude and tree age. Heat pulse probes were implanted into the sapwood of each tree to monitor hourly sap flow rates over 12 months. Annual trunk volume growth increment was calculated from diameter and height measurements at the start and end of the 12 months. A full year of sapflow data of acceptable quality was recorded at nine of the sites.

Results

The data were analysed together with water use efficiency (WUE) data obtained in five previous studies. The combined plot of data points (Figure 2) displays a more variable and curvilinear trend than suggested by the original Kruisfontein data, and physiological reasons for the non-linearity and variable WUE are reviewed. These results support some recent physiological evidence that the relation between above-ground growth and amount of water transpired may be significantly affected by altered patterns of carbon allocation by trees, with a greater proportion allocated to roots in trees that are stressed. Data reported here have yielded particularly clear evidence that the WUE of forest plantations is influenced by rainfall distribution. *Eucalyptus* clones sampled in the Kwambonambi district showed a distinctly lower WUE than the remaining sample trees, and this difference is attributed to a severe growing-season drought during the period of measurement.

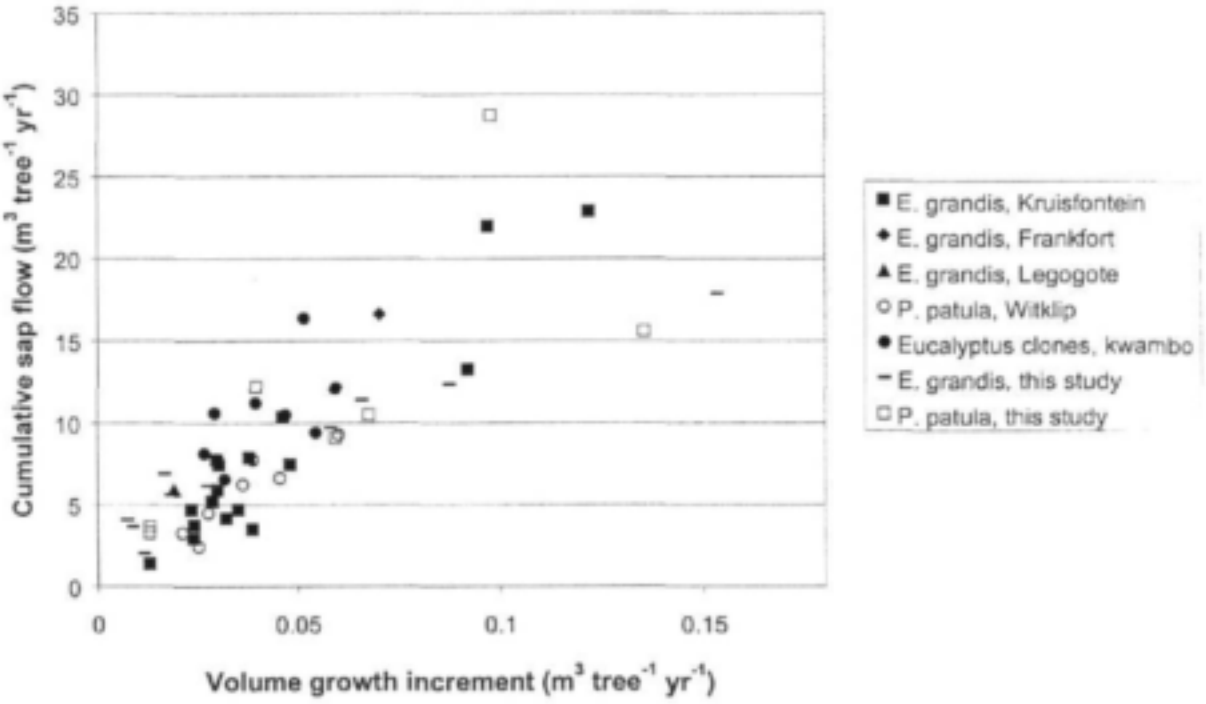

Figure 2. The relation between the annual trunk volume growth increment and the annual cumulative sap flow of sample trees in all the available WUE data sets.

The data reviewed in this report usefully define the range of WUE displayed by sample trees in a wide range of *Eucalyptus grandis* and *Pinus patula* stands, bringing greater clarity to this question, and providing an improved basis for comparisons of WUE with alternative crops. Such comparisons are already underway (e.g. WRC project no. 1133).

Recommendations for future research

In view of the growing trend of plantation establishment by small-scale emergent growers in areas considered marginal for forestry (DWAF, 1997), we believe that it is now timely to extend WUE research to investigate the scope for improving wood production and minimizing drought risk in such areas. Given the range of WUE encountered in this study (Figure 2), it is appropriate to consider to what extent it can be altered through selection of appropriate genotypes and perhaps management strategy. Research should be focussed on *Eucalyptus* species for two reasons. Firstly, they are the preferred species in areas of relatively low rainfall that are marginal for forestry and where a high WUE would be most beneficial. Secondly, much physiological diversity is known to exist among *Eucalyptus* hybrid clones that are already widely planted in South Africa. The scope for improving WUE through an appropriate tree breeding and selection process is believed to be great. The challenge will be to tease apart the genetic and environmental influences on tree WUE for a range of clones and plantation sites.

This study has revealed the need for a new methodology in forest WUE research. Long-term monitoring of sap flow by the heat pulse technique is fraught with risks. These have included malfunction or theft of equipment, unscheduled clearfelling of sample trees, and occasional uncertainty over the long-term development of wounded sapwood tissue following probe insertion. Sustaining high-quality measurements of sap flow over a full year has proved difficult and a number of sample trees had to be abandoned. We believe that further advances in our understanding of WUE will flow from the use of process-based models of forest growth and water use, which allow the separate influences of weather, stand characteristics and site conditions on carbon allocation patterns and transpiration rates to be assessed. Such models, when validated against appropriate short-term measurements of critical physiological parameters such as sap flow rates, leaf area index, canopy temperatures and growth rates, will greatly improve our understanding of the link between growth and water use. One such model (3-PG) shows much promise in this regard (Dye, 2000a), and is undergoing further testing in WRC project 1194.

Capacity building

This project provided an opportunity to train four junior scientists and technicians in the theory, instrumentation, and data analysis procedures associated with the heat pulse velocity technique. These skills were efficiently applied by the project team to subsequent projects (WRC projects 808, 1194).

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1. INTRODUCTION

The water use of forest plantations remains a topical subject in light of recent changes to water law, as well as continuing disputes over the hydrological impacts of various types of land use. While sap flow and micrometeorological techniques exist to allow direct measurement of forest water use, their usefulness in resolving land use disputes is currently limited for the following reasons:

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An alternative approach to the estimation of plantation water use was suggested by the results of an investigation into the relation between annual trunk volume increments and cumulative annual water use of *Eucalyptus grandis* trees (Dye, 1996). The study was conducted in Kruisfontein Plantation (White River district, Mpumalanga), and involved monitoring growth and sap flow rates for a full year in 17 trees growing on a wide range of site quality. A surprisingly tight, linear relation was found between annual volume growth increment and cumulative annual sap flow, suggesting that this measure of the efficiency of water use did not differ significantly among the trees. Further data from a *Pinus patula* experiment in the White River area (Witklip Plantation) revealed a similar efficiency of water use (Figure 1.1).

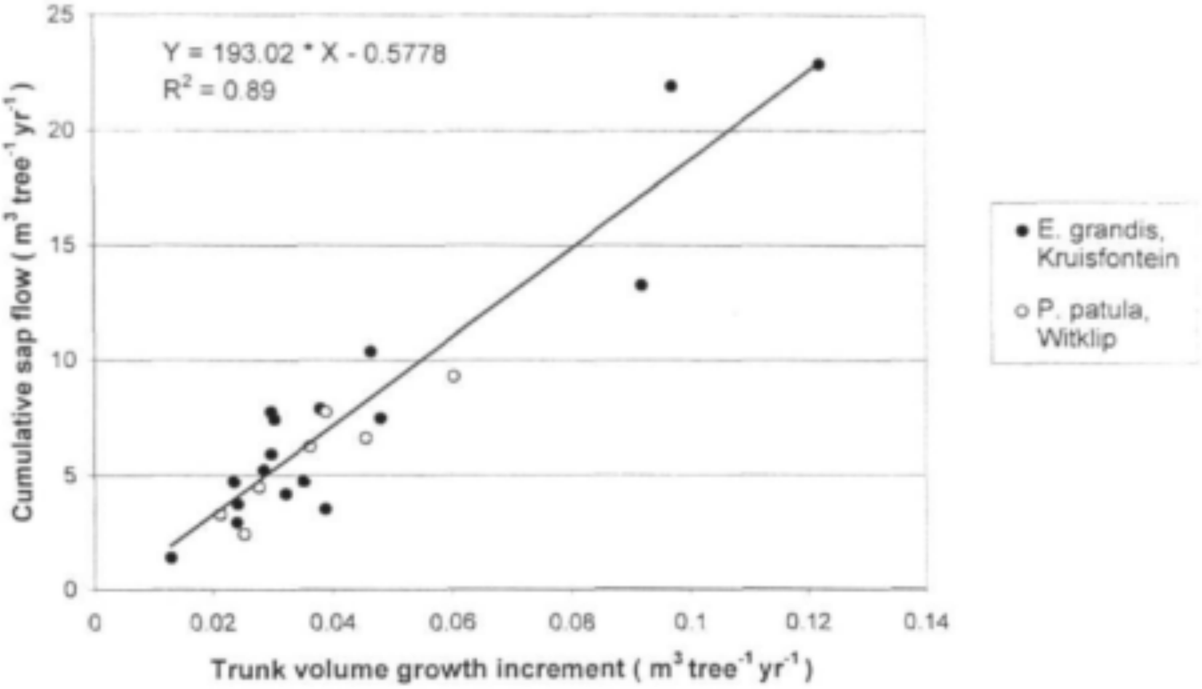

Figure 1.1 The relation between annual trunk volume growth increment and annual cumulative sap flow recorded in sample trees of *E. grandis* and *P. patula* at Kruisfontein and Witklip plantations, White River

These results suggest that annual water use may be predicted from growth increment with useful accuracy. Forest growth increments are relatively easy to measure, and may be estimated for most forestry compartments throughout the national forestry estate. A simple correlation to annual water use would bring much clarity to the issue of forest impacts on regional water supply.

1.1 Project objective

The Kruisfontein sample trees were mostly 6-years old, and no data are available to determine whether the relationship holds over the entire rotation period. The objective of this study was to determine the degree of correlation between trunk volume growth increment and cumulative sap flow in a selection of *E. grandis* and *P. patula* trees representing a wide range of tree age, site quality, climate and management regime. The *P. patula* study was funded by the Department of Water

Affairs and Forestry. In view of the similarity of the two projects, it was agreed between WRC and DWAF that the results should be reported together in a single final publication.

2. METHODS

2.1 Site and tree selection

Seven *E. grandis* and six *P. patula* forest compartments were selected within a radius of 80 km from Pietermaritzburg, to cover a wide range of tree age, site quality and management regime. A number of these had to be abandoned before a full year of data could be collected, due to theft of equipment and corrosion of heat pulse probes caused by gum exudation. Details of those sites yielding a full year of data are summarized in Tables 2.1 and 2.2.

Table 2.1 Details of seven *E. grandis* and six *P. patula* compartments in which the sample trees were chosen.

Species	Compartment	Plantation	Age (yrs)	Establishment
E. grandis	A21	Shafton	5	Non-coppice
E. grandis	C1b	Shafton	11	Non-coppice
E. grandis	A69	Mount Desire	2	Non-coppice
E. grandis	C28	Mount Desire	7	Non-coppice
E. grandis	B27a	Mount Desire	11	Non-coppice
E. grandis	A66	Mount Desire	4	Coppice
E. grandis	A46	Mount Desire	7	Coppice
P. patula	C05B	Gilboa	4	-
P. patula	B15	Gilboa	8	-
P. patula	C13c	Gilboa	14	-
P. patula	Q5	The Start	4	-
P. patula	C52	De Magtenburg	9	-
P. patula	C41	De Magtenburg	16	-

Table 2.2 Site characteristics associated with the compartments in which sample trees were located.

	Pinus patula			*Eucalyptus grandis*		
Site attribute	Gilboa	De Magtenburg	The Start	Shafton	Mount Desire (Eston)	Reference
Mean annual precipitation (mm / year)	850	1125	1198	1000	800	1
Mean annual temperature (^{o}C)	13.5	16.4	16.7	16.7	17.6	1
Altitude (m.a.s.l.)	1530	1130	1130	1130	920	
Lithology	Shale	Shale	Sandstone	shale	dolerite/sandstone	1
Site index (m @ 5 years) *	19	19	19	19	14	2
Mean annual increment (m^3 / ha / year @ 10 years)	16-20	16-20	16-20	28	14	2
Site quality class	III	III	III	II	IV	SAPPI
Land type	-	235	234	223	114	1

* This site index is numerically equal to the mean top height attained by the trees after five years from the time of planting. Top height is defined as the mean height of the 20% largest tree diameters at breast height .

1. Pallett, R.N. and Mitchell, A.G. 1993. Forest land types of the Natal region. SAPPI Forests Research (unpublished).
2. Coetzee, J. 1997. Mensuration of hardwoods. ICFR Annual Report for 1997, p 115.

Two adjacent trees showing contrasting breast height diameters (DBH) were selected within each compartment to represent dominant and suppressed trees. These sample trees were carefully chosen for symmetrical crowns, an even surrounding canopy density, few residual lateral branches at breast height, and an absence of trunk deformities or signs of disease.

2.2 Sap flow measurement

2.2.1 Heat pulse measurement

The heat pulse technique was used to record hourly sap flow rates in all sample trees. Using a 20 mm–thick drill jig, three vertically aligned holes were drilled radially into the sapwood at several positions around the trunk, using a 1.85 mm drill bit. The purpose of the jig was to ensure that the holes were exactly parallel to each other. A line heater was inserted into the central hole, while temperature-sensing probes were implanted 10 mm above and 5 mm below the heater. The line heater consisted of a steel tube with an outside diameter of 1.8 mm. Temperature probes consisted of a single thermistor sealed within a Teflon tube of similar diameter. Each sensor probe pair thus gave a point estimate of sapwood temperature. Each thermistor pair was connected in a Wheatstone bridge configuration and automatically zeroed before each heat pulse initiation. The logger was programmed to apply a current of 30 amps lasting 0.8 s to each heater probe. Heat pulse velocity (*u*)) was measured for each probe set using the compensation technique (Huber and Schmidt, 1937; Swanson, 1974). The temperature rise was measured at distances X_u upstream and X_d downstream from the heater, and *u* was calculated as follows:

$$u = (X_u + X_d) / 2t \tag{1}$$

where *t* is the time delay for the temperatures at points X_u and X_d to become equal. The heat pulse velocity is calculated from the time taken for the pulse to travel the distance of 2.5 mm, i.e. the distance between the heater and a point midway between the thermistors.

Heat pulse velocities were corrected for sapwood wounding caused during the drilling procedure. Swanson and Whitfield's (1981) wound correction coefficients were used to derive corrected heat pulse velocities (u'). The correction takes the form:

$$u' = p + qu + r(u)^2 \qquad \textbf{(2)}$$

where p, q and r are the correction coefficients appropriate to the measured wound size, diameter of Teflon probes, and probe separation distances, respectively.

2.2.2 Sap flow calculation

The corrected heat pulse velocities were converted to sap flux (v) using the following equation (Marshall, 1958):

$$v = \rho_b (m_c + c_{dw})\, u' \qquad \textbf{(3)}$$

where ρ_b is dry wood density, m_c is the moisture fraction of sapwood, and c_{dw} is the specific heat of dry wood, assumed constant at 0.33 (Dunlap, 1912). Total sap flow was then calculated as the product of mean sap flux density and sapwood area.

At the conclusion of each experiment, trunk segments containing the drilled holes were removed to the laboratory to measure the sapwood properties required to calculate sap flow from null-balance times. The four or eight sections of the tree trunk containing the probe implantation holes were excised and re-cut longitudinally at the particular radial depth below the cambium where the thermistor was originally positioned. The exposed, fresh face was shaved smooth using a microtome to allow precise measurement of probe separation distances and wound widths. These were typically -5 mm between the heater probe and the lower thermistor, and 10 mm between the heater probe and the upper thermistor probe, yielding a X_u-X_d/2 = 2.5 mm. Measurements of wound widths were taken midway between the line heater position and both the upper and lower thermistors. An average width was applied to the probe set.

Measurements of sapwood moisture fraction were performed in the field at the time the trees were felled. Three samples of sapwood were removed from a section of trunk close to breast height. A portable electronic scale was used to record fresh mass of each sapwood sample immediately after its removal from the trunk. The immersed weights of the samples were also recorded in the field in the following manner. A small container of water of a size sufficient to hold the sapwood samples was placed on the balance. A laboratory clamp stand was set up next to the balance, and a sharp pointed seeker was clamped to position its point 2-3 mm below the water surface. The balance was then zeroed. The seeker was unclamped and impaled into the sapwood sample, and then replaced to completely immerse the sapwood sample under water. No part of the sample was allowed to touch the sides or bottom of the water container. A new weight was immediately recorded, and using Archimedes' principle, taken to be equivalent to the weight of water displaced. Assuming a specific gravity of water of 1000 kg m^{-3}, the immersed weight in grams was assumed equal to the sample volume in cubic centimetres. The sapwood samples were subsequently brought back to the laboratory, where they were oven-dried to constant weight, before their dry mass was recorded. Moisture fraction was calculated as (fresh weight - dry weight) / dry weight, while basic wood density was calculated as dry weight / volume of the freshly excised section of wood.

A modified sap flow analysis procedure was followed in the case of the *P. patula* trees. In a prior HPV validation study on this species (Dye *et al.*, 1996), HPV sap flow estimates were compared to cut-tree uptake rates, and found to overestimate true sap flow by an average of 49%. This bias was attributed to heat averaging across non-conducting latewood rings. However, water uptake was highly correlated to the product of under-bark cross-sectional area and wound-corrected mean HPV. The following empirical relation was based on 14 cut-tree experiments, and was used in this study:

$$Y = 0.11819 + 0.0000044 * X \quad (R^2 = 0.79) \qquad \textbf{(4)}$$

where Y is whole-tree sap flow ($l\ h^{-1}$) and X is the cross-sectional area of the entire trunk (mm^2). Measurements of sapwood moisture fraction and basic density are not required in this procedure, but wound widths must still be corrected for.

2.2.3 Probe implantation depths

Table 2.3 summarises the probe depths chosen for each sample tree in the study. Depths are measured from the cambium inwards, and therefore exclude the bark. Previous experience has shown that sapwood is mostly 30 to 40 mm thick in all ages of *E. grandis* trees. Implantation depths were therefore chosen to sample this region of the trunk. Four probe sets were implanted into sample trees representing early and mid-rotation trees, while the large and small trees representing end of rotation stands received eight and four probe sets, respectively. Thermistors were implanted to depths of approximately 4, 9, 16 and 24 mm below the cambium. Where eight probe sets were implanted in the larger trees, these implantation depths were repeated twice. This sampling arrangement has been shown to result in good estimates of sap flow in *E. grandis* (Olbrich, 1991). All thermistor probes were repositioning after six months, since they come to lie progressively deeper as the sapwood grows outwards.

In the case of the *P. patula* trees, thermistor probes were implanted in a stratified random manner (Dye *et al.*, 1991). Three quarters of the available probes were implanted to random depths within the outer half of the trunk, while the remaining probes were implanted to random depths within the inner half of the trunk. Heartwood was found to be small over the range of tree sizes used in this study, and so no account was taken of heartwood presence.

All data loggers were programmed to record null balance times every hour between

Table 2.3 Probe implantation depths chosen in the sample trees.

			Small tree										Large tree									
Site	Species	Age at start (yr)	Depth below cambium (mm)								*DBH* (mm)	*Ht* (m)	Depth below cambium (mm)								*DBH* (mm)	*Ht* (m)
A21	*E. grandis*	5	4	9	16	25					110	18.72	4	9	16	25					177	19.75
C1B	*E. grandis*	11	4	9	16	23					200	27.69	4	9	16	23	4	9	16	23	250	28.69
A69	*E. grandis*	2	4	9	16	25					62	6.88	4	9	16	25					83	7.27
C28	*E. grandis*	7	4	9	16	24					123	17.70	4	9	16	24					182	19.10
B27A	*E. grandis*	11	4	9	16	23					149	18.50	4	9	16	23	4	9	16	23	256	21.36
A66	*E. grandis*	4	4	9	16	23					105	12.00	4	9	16	23					135	14.34
A46	*E. grandis*	7	4	9	16	23					132	15.84	4	9	16	23					169	15.70
Q5	*P. patula*	4	14	25	17	18	19	27			78	5.67	18	18	22	23	27	50			111	7.0
C52	*P. patula*	9	30	34	17	29	19	50			120	12.09	20	50	47	50	48	88			182	13.75
C41	*P. patula*	16	15	42	10	41	43	20	51	80	212	20.30	27	38	54	45	7	42	72	80	294	21.06
CO5B	*P. patula*	4	9	20	12	22					72	6.27	20	24	7	19	9	6	40	36	120	8.00
B15	*P. patula*	8	17	22	9	27	12	33			130	9.80	17	22	9	27	12	49			215	13.65
C13C	*P. patula*	14	51	20	14	15	46	21	73	87	250	15.10	32	43	59	50	12	19	77	89	314	17.70

04h30 and 21h30 over the year. The sites were visited at fortnightly intervals to download data and check battery voltages and equipment.

2.2.4 Heat pulse data analysis procedure

The following data analysis procedure was followed. The raw data were first examined using a custom-developed Visual Basic analysis programme to identify probes with missing or faulty data, those with long null-balance times, and those exhibiting poor correlation with other probe sets. Missing or poor quality data were patched using simultaneous data from another probe set with which it is most highly correlated. Long null-balance times that indicate slow sap flow rates were sometimes recorded by the deepest probes, indicating close proximity to heartwood. These probes were excluded where the number of missing data was high. Patched files were then saved and subsequently read again during the calculation of sap flow. The analysis programme calculated hourly sap flow for the tree, and saved the output in three files containing the hourly sap flow rates, daily total sap flow, and the parameters used in the calculations. The daily data files were then concatenated, and partial days at the start and end of files were joined appropriately. These files were checked as follows:

- The whole-year pattern was examined to check for unusually high and low values, and marked discontinuities across the original files.
- Broadly similar patterns of daily sap flow were expected from the larger and smaller trees.
- Readings taken at times when transpiration rates were not reduced by soil water deficits were plotted against mean daily vapour pressure deficit (VPD). High correlations are typical under these conditions, and suspect logger data are immediately apparent.

Where suspect data were identified, they were removed and replaced with patched data.

Daily mean VPD was calculated from hourly temperature and relative humidity data recorded by Hobo sensors installed at C28 (Mount Desire), A21 (Shafton) and C05b (Gilboa). These sensors were mounted 2 m above ground on the south-facing side of a non-sample tree. They were protected from rain by a plastic hood that permitted good lateral movement of air around the sensors. Hourly VPD was averaged over the period from 06h00 to 18h00.

2.3 Trunk growth measurement

Accurate measurements of diameter and height were made at the start of sap flow monitoring. Diameters were recorded at marked positions at 1.3, 4, 8 and 11 metres above the ground. Heights were measured using a graduated measuring rod with a length of 15 m. Where the trees were taller than 15 m, a set of three linked tree ladders was connected and strapped to the tree trunk. The measuring rod was then raised to a height where it was level with the top of the tree. The height of the base of the rod above the ground was measured, and added to the rod length. Diameter and height measurements were repeated at the end of the 12-month measurement periods, with the purpose of calculating volume growth increments from a geometrical analysis of each segment of trunk.

Past experience has revealed difficulties in recording accurate annual diameter increments in this way. Bark shedding is a feature of *E. grandis*, and this not only alters the trunk girth, but also removes the earlier mark on the bark indicating the exact measurement height. The bark of older *P. patula* trees is very rough, and errors in measuring diameters are easily incurred. An alternative backup means of estimating trunk volume from breast height girth changes recorded with fixed dendrometers was adopted after bark-shedding problems were experienced. The design of these dendrometers is described in detail by Liming (1957). Briefly, Dymo stainless steel tape was wrapped around a smoothed section of the trunk, and kept under tension by a spring fixed to both ends. A cut-out section of the tape where the ends overlap allowed both ends to be visible, and a reference scratch mark was made at each site visit by which a change in girth by the next visit could be measured. These girth increments were measured with an 7 X eyepiece fitted with a graduated scale. Flaking bark was kept in position under the band. Tree volume increment was calculated from the DBH and height measurements at the start and end of the sap flow record, using the DeMaerschalk model for *E. grandis* (described by Coetzee, 1992), and the segmented polynomial model of Max and Burkhart (Kotze, 1995) for *P. patula*.

2.4 Leaf mass measurements

At the conclusion of sap flow measurements in each compartment, sample trees were felled to determine the sapwood properties required for the sap flow calculations. All leaves were stripped from the trees and their fresh mass weighed immediately in the field. Sub-samples were brought back to the laboratory where their fresh and oven-dry mass was recorded. The sub-sample ratio of fresh to dry mass was used to estimate the total dry leaf mass of the trees on the basis of their total fresh mass.

3. RESULTS

3.1 Tree and sapwood properties

At the conclusion of measurements at those sites where a full year of data was collected, various tree characteristics were recorded for sap flow calculation and data interpretation. These are summarized in Table 3.1. Figure 3.1 shows the relation between DBH and sapwood area for *E. grandis* and *P. patula*. *P. patula* has markedly less heartwood than *E. grandis*, but the sapwood area includes latewood rings in which no sap flow occurs.

Table 3.1 Whole-tree and sapwood properties recorded at the conclusion of sap flow measurement.

		At end			Sapwood properties				
Compt	Tree size	Age (yrs)	DBH (mm)	Height (m)	Area (mm^2)	Density (kg/m^3)	Moisture fraction	Mean wound width (mm)	Leaf dry mass (kg)
A21	L	6	194	23.00	15007	0.45	1.10	7.5	6.94
	S	6	120	20.85	7330	0.44	1.14	5.8	1.97
C1b	L	12	260	33.50	19784	0.56	1.11	3.4	11.40
	S	12	204	30.90	16738	0.46	1.30	3.3	3.49
A69	L	3	107	11.25	8967	0.45	0.73	2.7	5.99
	S	3	78	9.80	4613	0.49	0.81	2.7	1.84
C28	L	8	194	22.10	16903	0.47	1.12	5.2	4.87
	S	8	132	20.00	9888	0.45	1.18	5.0	2.54
B27a	L	12	266	24.60	18346	0.47	1.02	2.9	12.16
	S	12	150	19.96	7807	0.44	0.93	2.9	2.05
A66	L	5	154	15.62	11708	0.57	0.70	3.5	3.76
	S	5	119	13.00	8268	0.41	0.80	3.9	2.34
A46	L	8	181	16.80	12307	0.45	1.09	2.8	3.92
	S	8	141	16.50	9154	0.48	0.77	2.9	3.00
Q5	L	5	130	9.00	19856	-	-	4.2	11.77
	S	5	103	7.40	11882	-	-	3.3	18.98
C52	L	10	199	14.60	28025	-	-	4.0	7.36
	S	10	127	13.30	12542	-	-	3.4	4.11
C41	L	17	308	22.40	69959	-	-	3.9	28.27
	S	17	225	22.20	36197	-	-	3.5	8.13
C05b	L	5	139	8.19	12998	-	-	5.0	7.03
	S	5	97	7.60	6649	-	-	5.0	6.09
B15	L	9	231	15.30	38243	-	-	2.0	13.15
	S	9	136	11.20	15382	-	-	3.0	3.81
C13c	L	15	359	27.23	269710	-	-	-	-
	S	15	259	19.81	50845	-	-	-	-

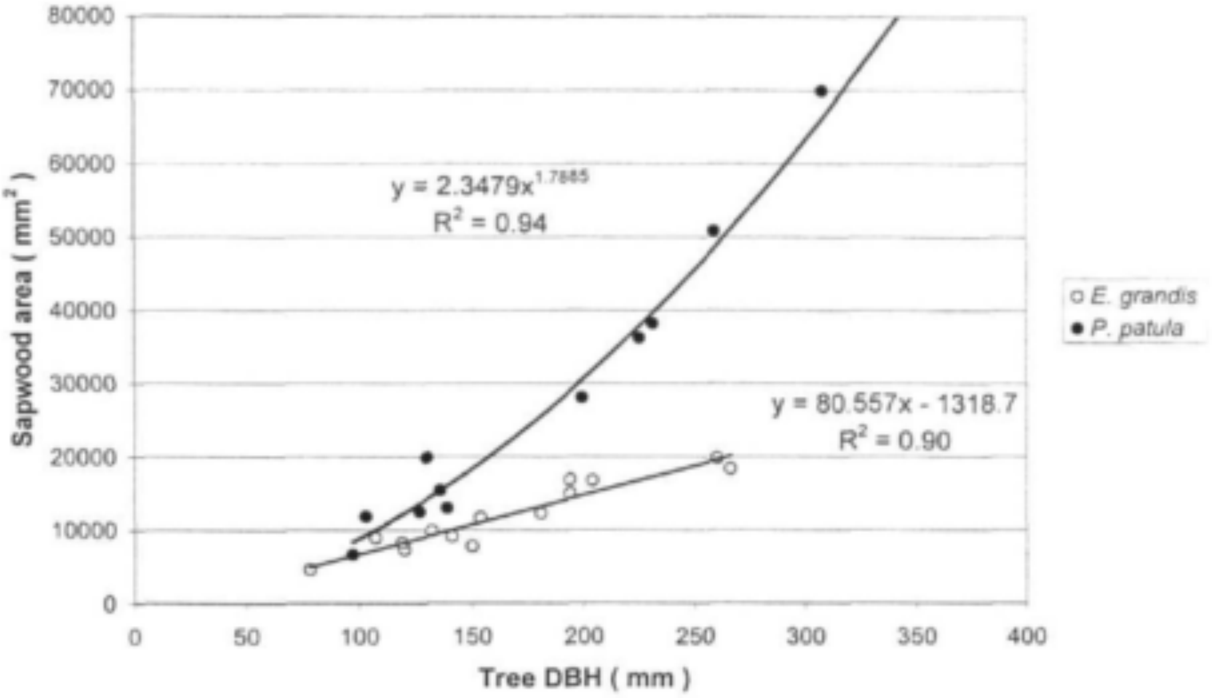

Figure 3.1 The relation between DBH and sapwood area for *E. grandis* and *P. patula* sample trees

Figure 3.2 shows the relation between DBH and dry leaf mass for both species. This correlation is especially poor for *P. patula,* which is subject to pruning, but also displays highly variable branching and canopy density.

The sapwood moisture fraction recorded in the *E. grandis* sample trees averages 0.99. The measurements per tree and per sapwood replicate sample are shown in Figure 3.3. There is a suggestion that moisture fraction is lowest in the Mount Desire trees, which would support an earlier finding that the sapwood moisture fraction in eucalypts growing on relatively dry sites is less than in trees growing in more mesic sites (Dye *et al.*, 1997a). However, as the Mount Desire trees were felled during the winter, the possibility of a seasonal effect cannot be ruled out. Sapwood density averages 0.47.

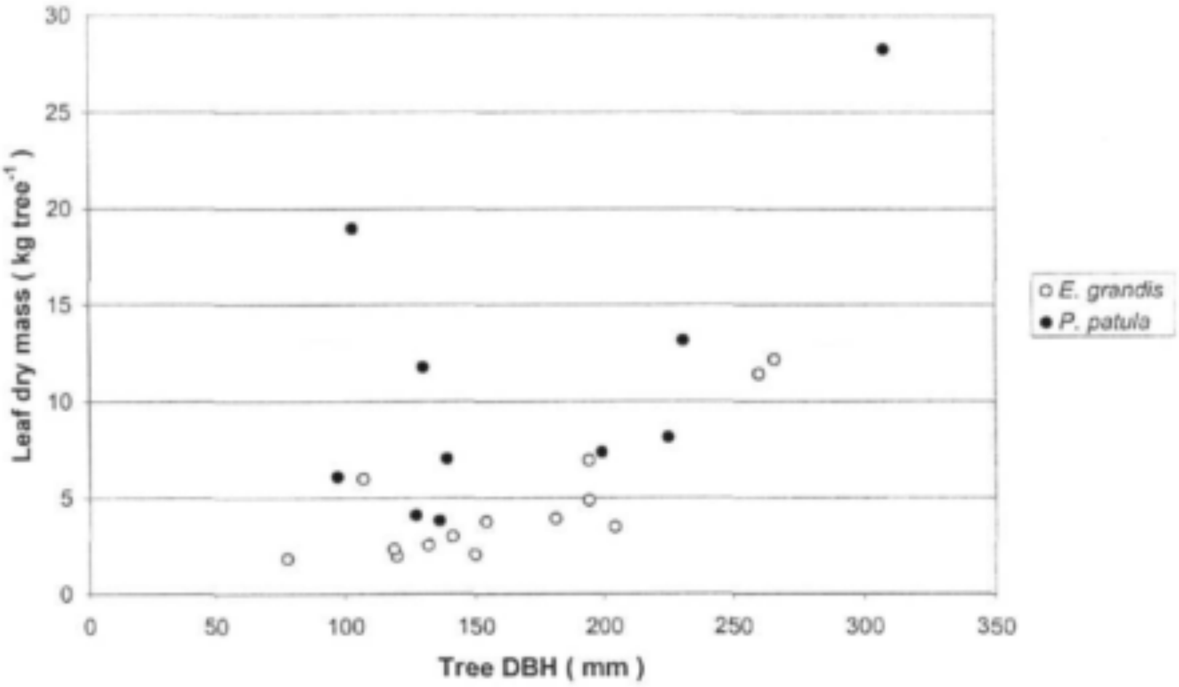

Figure 3.2 The relation between DBH and leaf dry mass for *E. grandis* and *P. patula* sample trees

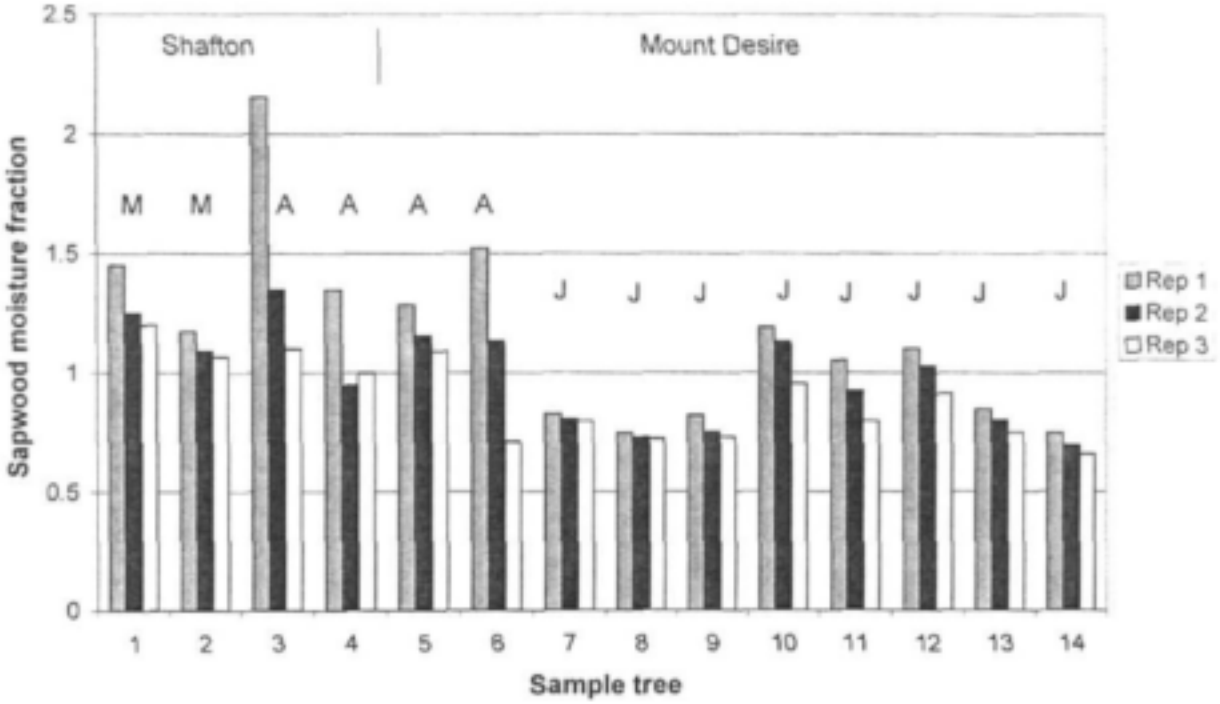

Figure 3.3 Sapwood moisture fraction recorded in replicate wood samples excised from the *Eucalyptus* sample trees. The month of harvest (March, April and June) is indicated

3.2 Patterns of sap flow and trunk growth

Typical annual patterns of daily sap flow for *E. grandis* and *P. patula* are shown in Figures 3.4 and 3.5, respectively. Mid-summer values are characteristically highest, due to long day lengths and high VPD associated with higher temperatures. Winter sap flow rates are much reduced, not only by day-length and VPD, but also by soil water deficits. Winter rains at C28 caused sap flow to briefly increase, but this declined shortly after as the soil water was used up. Such responses are typical of *E. grandis* (Dye *et al.*, 1997b).

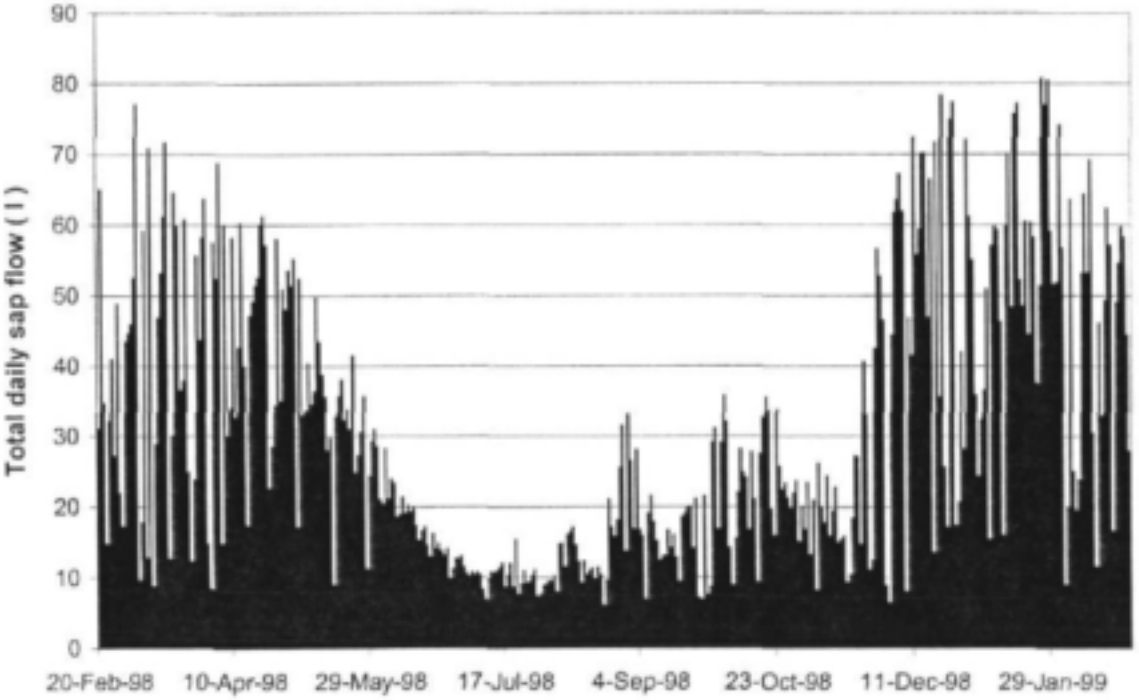

Figure 3.4 The pattern of daily sap flow recorded in the larger *E. grandis* sample tree at C28

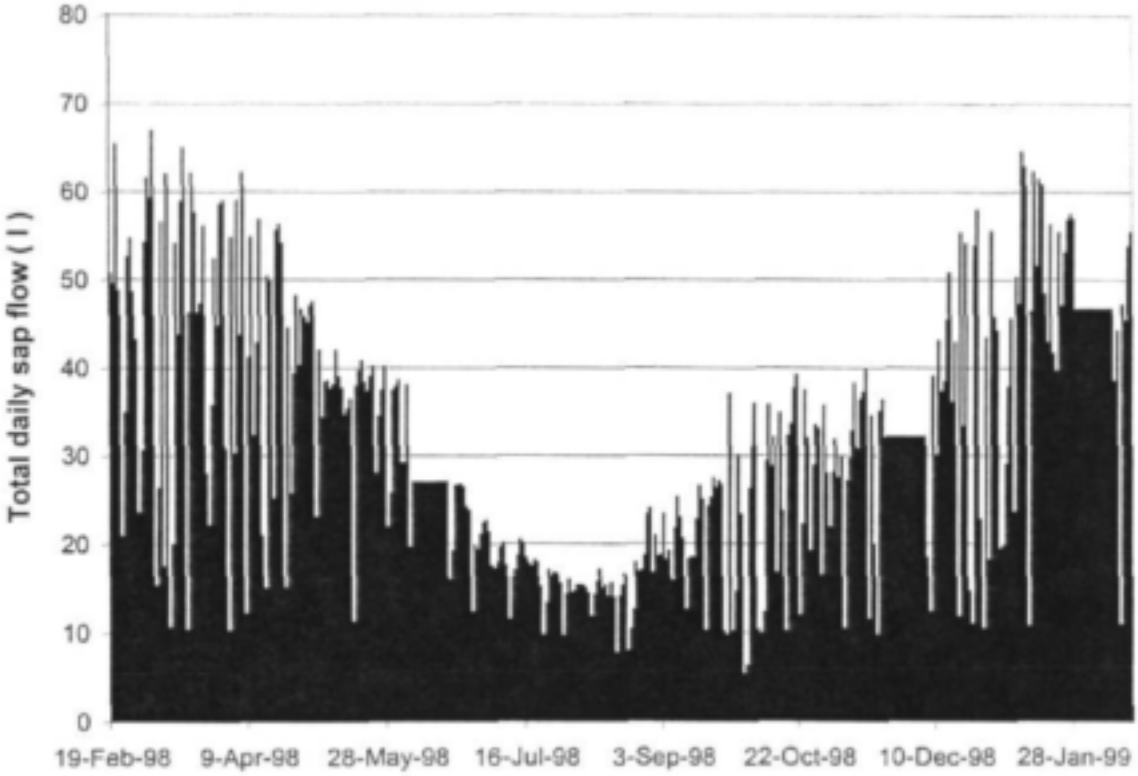

Figure 3.5 The pattern of daily sap flow recorded in the smaller *P. patula* sample tree at C41. Periods of sap flow data loss are patched with average flow rates calculated for periods on either side of the data gap

A trend of diminishing sap flow over the 12 months following probe implantation was observed in some of the sample trees (Figure 3.6). This was not caused by observable changes in sapwood area or progressively deeper probe positions in the sapwood, both of which were accounted for. Previous experience with these species has not yielded any evidence that wound size increases over time. We contend that the trend is not attributable to a progressive increase in sample error, but rather reflects a real reduction in flow rate in the tree. Possible causes are many, but no evidence exists to suggest any particular one.

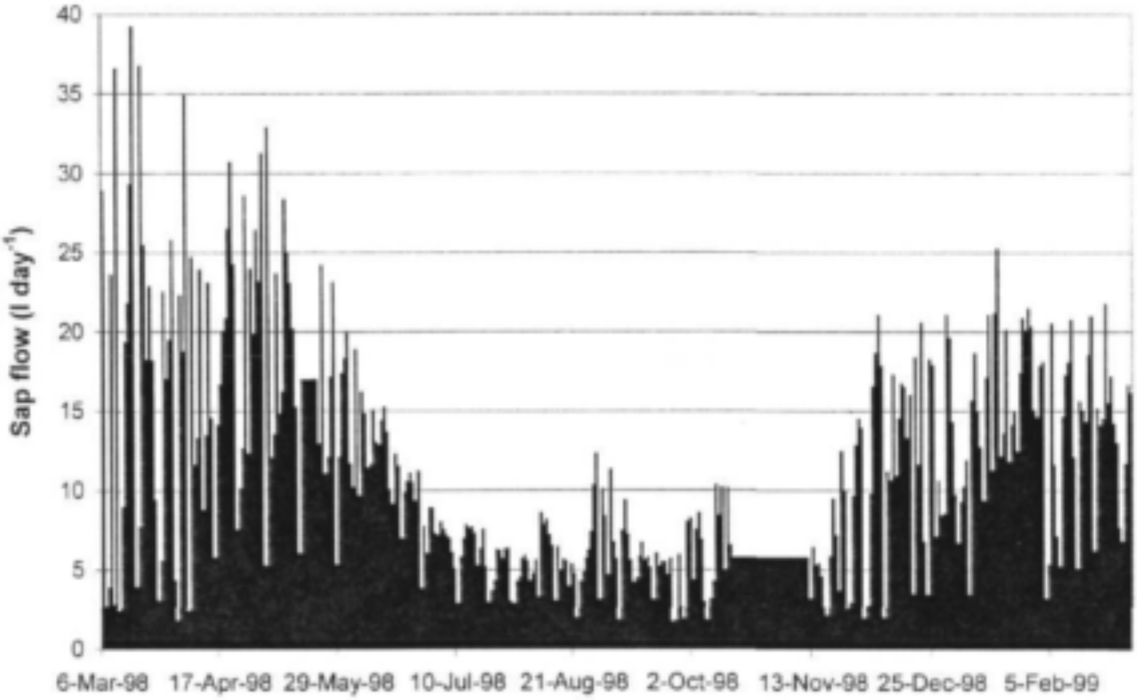

Figure 3.6 The pattern of daily sap flow recorded in the smaller sample tree in A66. A period of sap flow data loss is patched with an average flow rate calculated for periods on either side of the data gap

The data record from Q5 proved to be too sparse and variable to allow confident estimation of annual sap flow. The A21 data record was unusual, indicating realistic sap flow rates in the first month, but a rapid reduction thereafter to very low rates. The wound width for these trees was found to be unusually large (Table 3.1), suggesting either a marked degree of spirality in the sapwood, or else an enhanced wounding response to the drilling caused by xylem anatomical features.

As an approximate check on the absolute value of sap flow rates, average peak daily sap flow recorded in the large and small sample trees was scaled up according to the density of trees measured in a 625 m^2 sample plot at seven sites. Table 3.2

summarises these estimates, which are realistic for unstressed, full-canopied forests (Landsberg, 1999b). The only exception is C1b, where the sample trees appear not to have adequately represented the trees in the stand.

Table 3.2 Approximate peak daily plot sap flow based on peak daily sap flows in the two sample trees, and tree density in their vicinity.

Compartment	Maximum sap flow (mean of two trees), (l day^{-1})	Stems per hectare	Mean maximum sap flow (mm day^{-1})
C1b	95	1296	12.3
C28	70	1120	7.8
A66	60	1344	8.1
C52	65	1024	6.7
C41	150	528	8.1
C05b	100	832	8.3
B15	40	1152	4.6

Figure 3.7 shows a reasonably distinct trend in the relation between total leaf mass of the sample trees at the end of sap-flow measurements, and the cumulative sap flow over the previous 12 months. This trend is expected to be non-linear, as an increasing degree of self-shading occurs as canopy size increases.

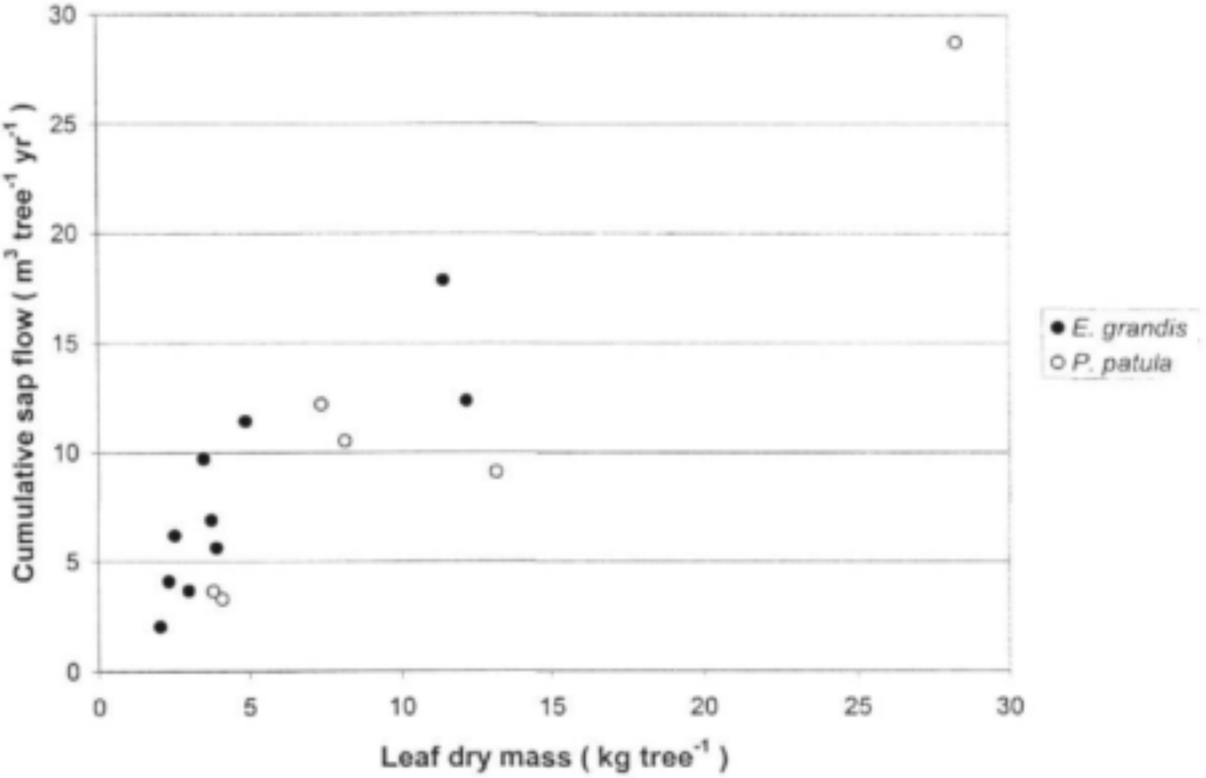

Figure 3.7 The relation between total leaf dry mass at time of harvest, and the cumulative sap flow over the previous 12 months, for the E. *grandis* and *P. patula* sample trees

Figures 3.8 and 3.9 illustrate typical patterns of trunk growth in *E. grandis* and *P. patula*, respectively. Growth slows or ceases altogether during the dry winter, but resume strongly during the wet summer months.

3.3 Annual water use efficiency

Table 3.3 summarises the annual cumulative sap flow and annual volume growth increments recorded in sample trees at those site yielding good quality sap flow data.

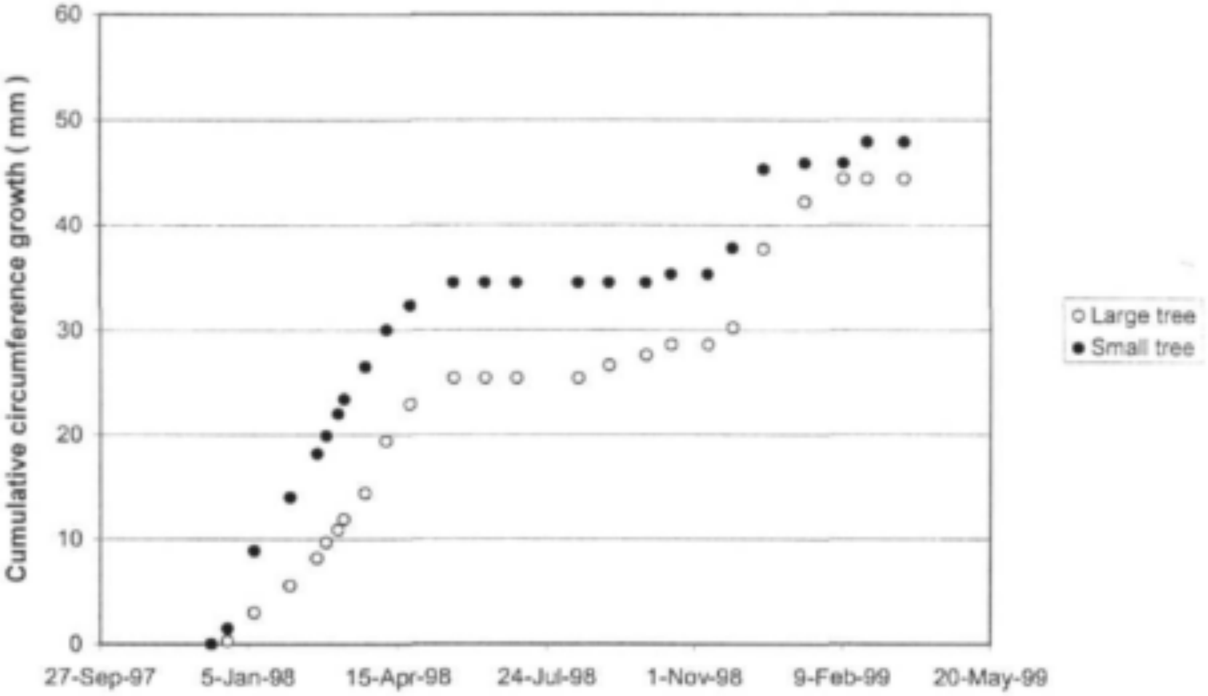

Figure 3.8 Circumference growth shown by dendrometers fitted to two sample *E. grandis* trees at C28

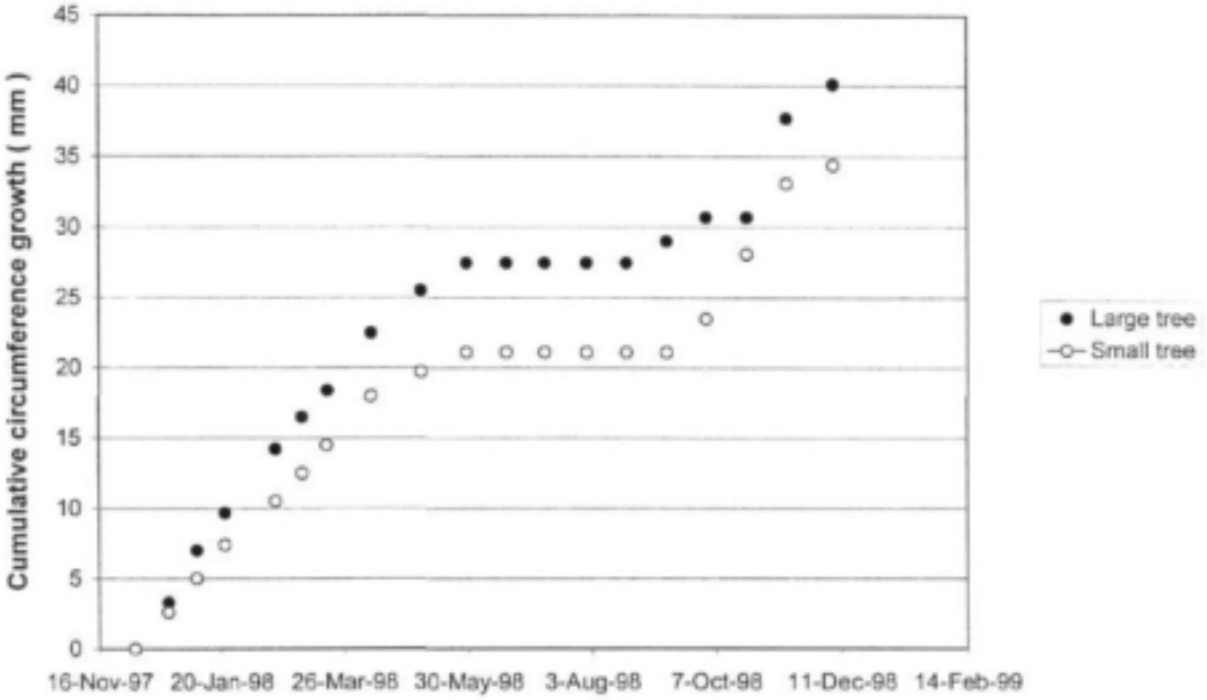

Figure 3.9 Circumference growth shown by dendrometers fitted to two sample *P. patula* trees at C41

Table 3.3 Summary of annual sap flow and annual volume growth recorded in sample trees at sites yielding good quality sap flow data.

Species	Compt	Tree age (yr)	Plantation	Tree size	Annual sap flow (m^3)	Annual volume growth (m^3)	m^3 water / m^3 wood
E. grandis	C1b	11	Shafton	Large	17.88	0.1534	116.56
E. grandis		11	Shafton	Small	9.71	0.0583	166.55
E. grandis	C28	7	Mt Desire	Large	11.43	0.0661	172.92
E. grandis		7	Mt Desire	Small	6.18	0.0276	223.91
E. grandis	B27a	11	Mt Desire	Large	12.37	0.0874	141.53
E. grandis		11	Mt Desire	Small	2.03	0.0116	175.00
E. grandis	A66	4	Mt Desire	Large	6.89	0.0168	410.12
E. grandis		4	Mt Desire	Small	4.09	0.0074	552.70
E. grandis	A46	7	Mt Desire	Large	5.61	0.0183	306.56
E. grandis		7	Mt Desire	Small	3.66	0.0088	415.91
P. patula	C52	9	DeMagtenburg	Large	12.20	0.0397	307.30
P. patula		9	DeMagtenburg	Small	3.28	0.0130	252.31
P. patula	C41	16	DeMagtenburg	Large	28.75	0.0976	294.57
P. patula		16	DeMagtenburg	Small	10.52	0.0678	155.16
P. patula	B15	8	Gilboa	Large	9.09	0.0594	153.03
P. patula		8	Gilboa	Small	3.65	0.0131	278.63
P. patula	C13c	14	Gilboa	Large	41.32	0.4918	84.02
P. patula		14	Gilboa	Small	15.58	0.1354	115.07

The trend in these data is shown in Figure 3.10, 3.11 and 3.12. There is no clear indication that species, relative tree size in a stand, or site accounts for much of the observed scatter in data points, but Figure 3.12 does suggest that the older trees exhibit greater growth increments and a higher WUE than the younger trees. This appears to contradict trends in WUE reported by Dye (2000b) for espacement trial data in KwaZulu-Natal. These data illustrated rotation-long trends in stem growth per 100 mm of rainfall, and showed that highest rainfall efficiency occurs at an early age (3-5 years). What is also shown, however, is that this trend is markedly disrupted by periods of drought that cause WUE to decline rapidly and recover slowly over

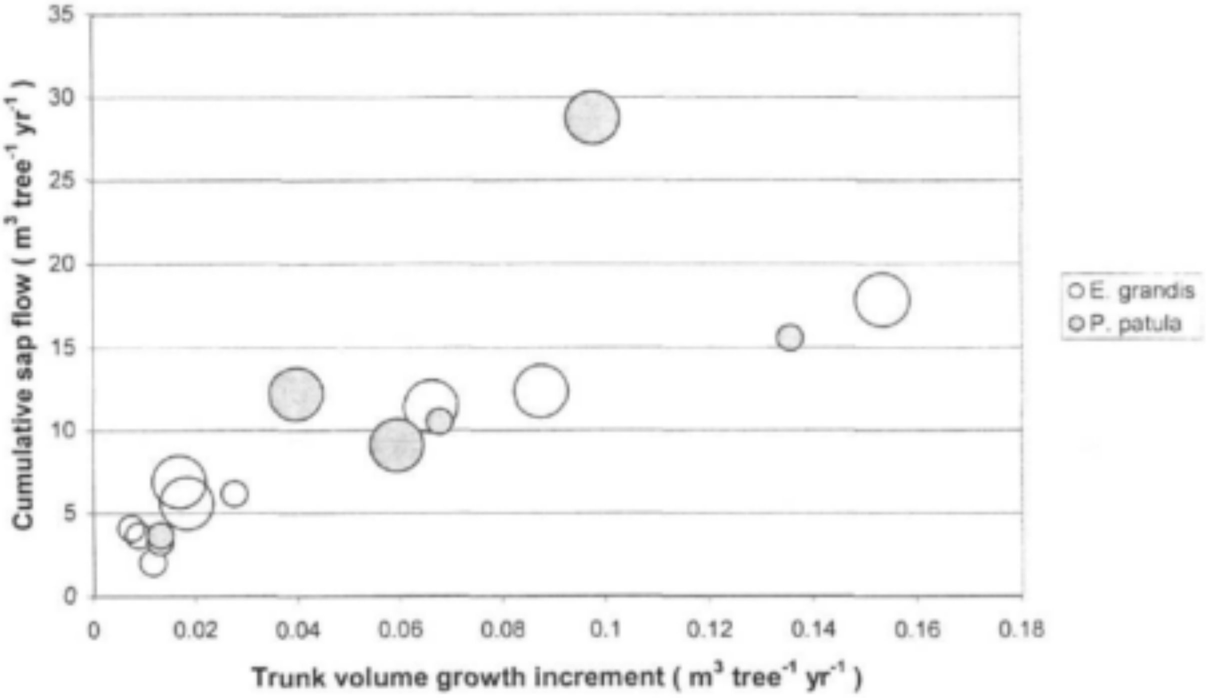

Figure 3.10 The relation between annual trunk volume growth increment and cumulative annual sap flow for the *E. grandis* and *P. patula* sample trees. Symbol size indicates the larger and smaller trees

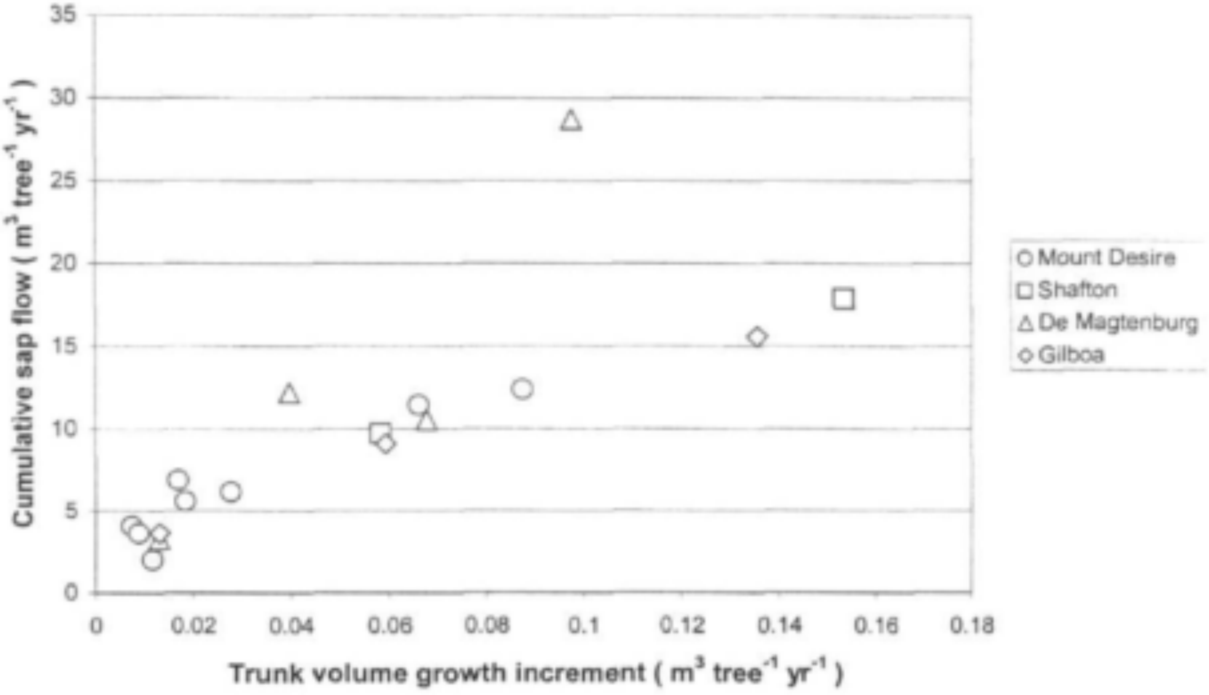

Figure 3.11 The relation between annual trunk volume growth increment and cumulative annual sap flow for the *E. grandis* and *P. patula* sample trees. Symbols identify the plantation in which the trees grew

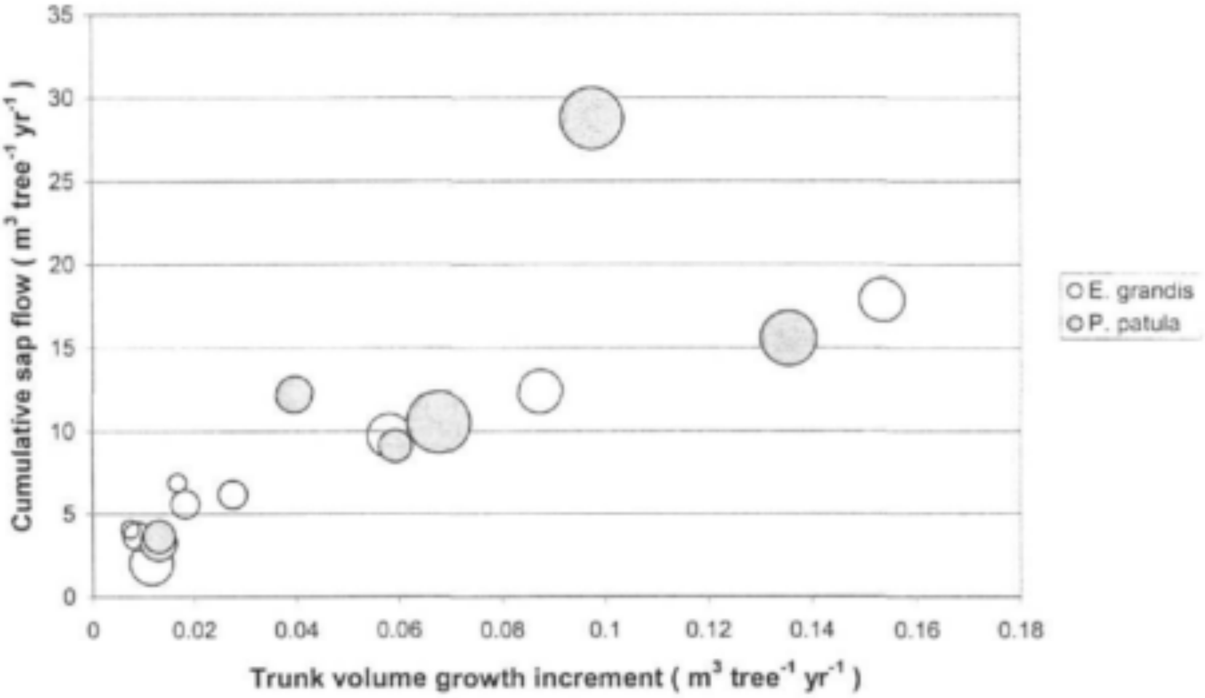

Figure 3.12 The relation between annual trunk volume growth increment and cumulative annual sap flow for the *E. grandis* and *P. patula* sample trees. Symbol size is proportional to tree age

several subsequent years. Furthermore, the whole-stand WUE estimate takes into account a degree of tree mortality. While the WUE of individual trees may increase with size and age, this may be masked by a significant decline in stand tree density.

The overall trend appears non-linear, with higher WUE displayed by the trees associated with higher annual growth increments. A tighter trend is demonstrated by *E. grandis* than by *P. patula*. A very large growth increment was recorded in the larger sample tree at C13c. This data point was excluded from the previous two figures, so that differences among the data sets would be more distinct. This data point supports the assumption of a non-linear trend. However, it must be treated with caution, since possible errors in estimating mean heat pulse velocities in such large trunks are high.

3.4 Comparison to other sources of data

The results of this study were pooled with additional annual WUE data reported for several independent studies of *Eucalyptus spp* and *P. patula*. The purpose was to validate the range of WUE shown in Figure 3.10, and suggest possible reasons for this variation. The additional data and their sources are listed in Appendix 1.

Figure 3.13 illustrates the overall trend shown by the combined set of data. The additional data points define a very similar band of WUE to that shown in Figure 3.10. The trend remains non-linear, with somewhat higher efficiency of water use shown by trees with greater annual volume increments. No species difference is apparent.

Three sources of information are further reviewed below:

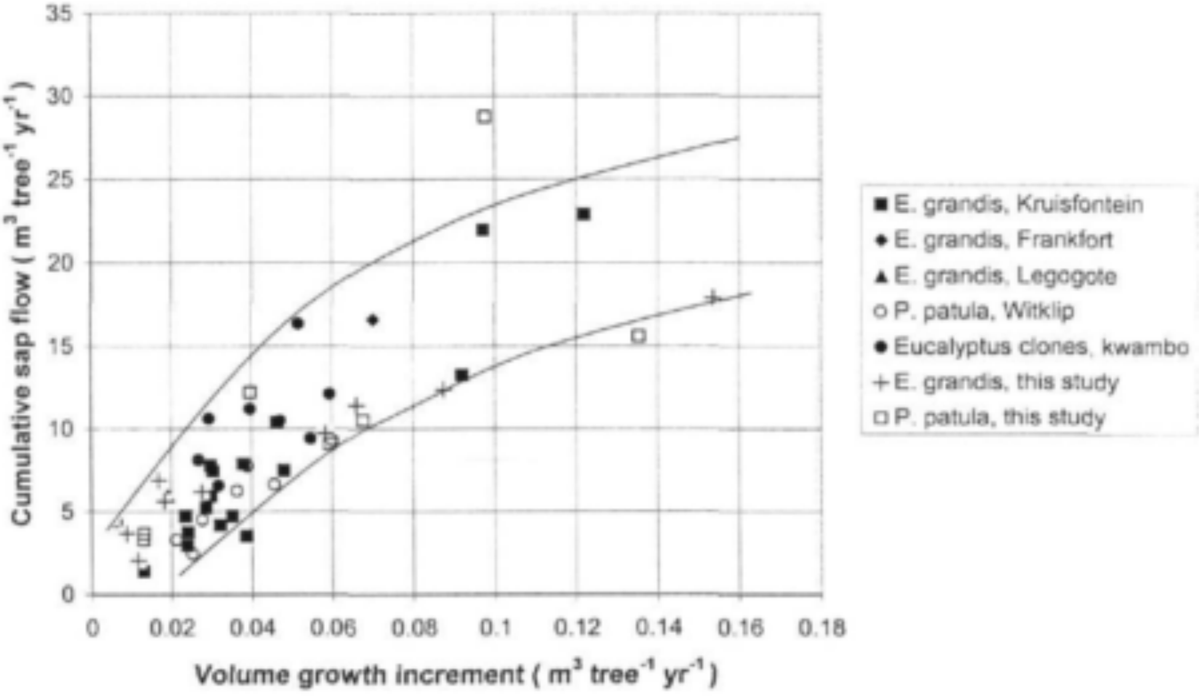

Figure 3.13 The relation between the annual trunk volume growth increment and the annual cumulative sap flow shown by all available WUE data

3.4.1 Clonal *Eucalyptus* study, Kwambonambi

One cause of the variability in WUE is particularly well illustrated by data applicable to the *E. grandis* "TAG5" clone in the clonal comparison study at Kwambonambi. Figure 3.14 shows the annual pattern of cumulative rainfall superimposed on the annual pattern of daily sap flow. The temporary revival of sap flow following episodes of winter rainfall, and the lower sap flow rates during the second summer of poor rainfall, is evidence of drought stress experienced by these trees. WUE (expressed as stem mass increment per mass of water transpired) calculated for the three clones monitored in this study showed a diminishing trend over the year, with especially low efficiency recorded towards the end (Figure 3.15). This trend was attributed to the summer drought causing unusually slow growth and low WUE during the second half of the measurement year (Dye *et al.*, 1997b). WUE calculated over the first six months was shown to be markedly higher than the comparable figure for the last six months. From this evidence, we conclude that drought stress is an important cause of the variation in WUE observed in Figure 3.13.

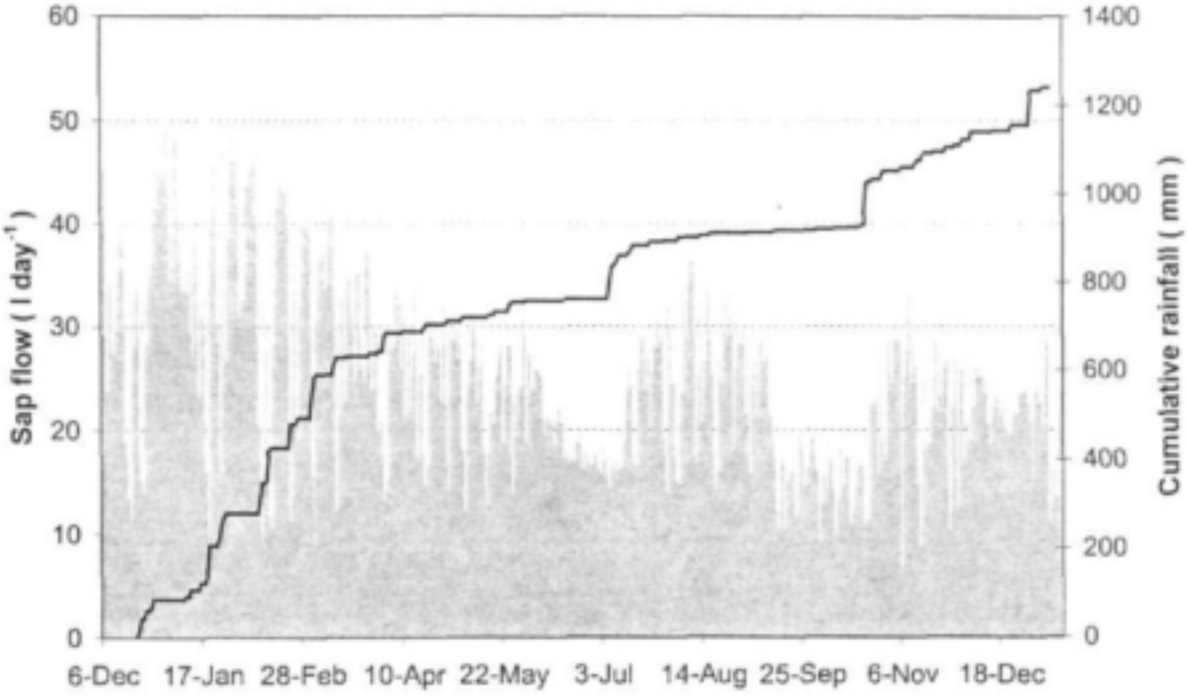

Figure 3.14 The annual pattern of mean daily sap flow recorded in three sample trees of a *Eucalyptus grandis* clone (TAG5) in the KwaMbonambi district. Cumulative rainfall over the same period is superimposed

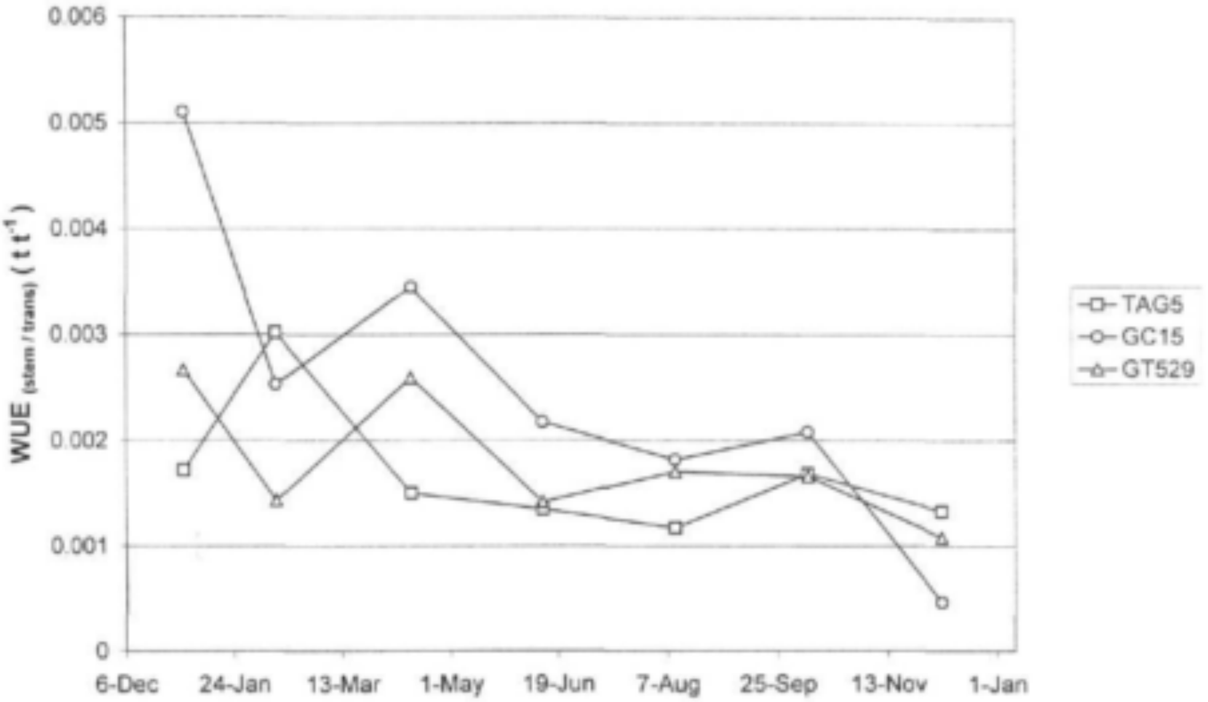

Figure 3.15 The trends in WUE (tonnes of stem per tonne of water transpired) shown by three *Eucalyptus* clones for the same period shown in Figure 3.14

There is a firm scientific basis for believing that WUE as we define it here (annual trunk volume increment per unit volume of water transpired) is higher in trees experiencing better growing conditions, than in those experiencing poorer growing conditions. In closed-canopy forests where soil water and nutrient supply do not significantly limit tree growth, carbon partitioning to roots, stem, branches and leaves can be relatively constant, leading to high correlations between stem growth and water use. Direct evidence of this correlation, and the influence of humidity on this relation, has been clearly demonstrated in stands of Willow (Lindroth and Cienciala, 1996; Lindroth *et al.*, 1994). There is much evidence, however, to indicate that trees experiencing stress can alter their carbon allocation strategy in favour of roots, especially the metabolically-active fine roots with a diameter of less than 2 mm. Fine root production is highly variable, and is variously estimated to range from 4 to 10 t ha^{-1} yr^{-1} by Cannell (1989), and from 1 to 12 t ha^{-1} yr^{-1} by Santantonio (1989). Although fine roots usually constitute less than 5% of total tree biomass, their high rate of turnover (estimated as 2 to 5 times per season by Cannell, 1989) masks the fact that they may account for a major proportion of net primary production, ranging from 5% in a fast growing pine plantation on a fertile site (Santantonio and Santantonio, 1987) to 68% in a mature sub-alpine forest (Grier *et al.*, 1981). Several studies have demonstrated that fine root turnover is considerably affected by the availability of nutrients and water. Estimates of the carbon balance of young *Pinus sylvestris* in central Sweden showed that 65 to 75% of annual photosynthetic production was allocated below ground in unfertilised soils, largely in the production of fine roots. Regular application of low-concentration liquid fertilizer during the growing season over five years reduced this to about 40% of the annual carbon income (Linder and Rook. 1983). Similar results from other forests (see reviews by Hermann, 1977; Santantonio *et al.*, 1977; Caldwell, 1979) have led to the conclusion that maximum above-ground biomass is achieved by plants that partition a minimum of their carbon below ground, especially to fine roots (Cannell, 1985). We hypothesize that the older and larger trees in this study that showed the highest annual growth increments were able, because of deep root systems and lower stand tree densities, to show a marginally higher WUE and carbon allocation to trunks than the smaller, younger trees.

3.4.2 Eucalyptus espacement trials, KwaZulu-Natal

A further check on the relation in Figure 3.13 was performed using annual rainfall and growth data recorded at three ICFR *E. grandis* espacement trials at Kwambonambi, Kia-Ora and Baynesfield, all in KwaZulu-Natal (Coetzee *et al.*, 1996; Coetzee and Naicker, 1998). A recent analysis showed that the trees at these sites differed markedly in their growth and efficiency of rainfall utilization (Dye, 2000b). We believed therefore that these trial results would permit a useful check on the range of WUE recorded in this study, especially as the estimate of annual water use was not based on sap flow measurement.

Annual growth increments (m^3 ha^{-1}) were calculated for the three replicate plots at each site that were planted with seedling trees at 792 and 1333 stems per hectare.

This is the range of tree density recorded in the vicinity of sample trees in the present study. These growth increments were divided by the number of live trees per hectare to calculate the mean volume growth increment per tree. The trees in these trials are believed to have used most of the annual rainfall (Dye, 2000b), due to the presence of closed canopies, rigorous weed control, flat topography and an absence of any sign of overland flow. We discounted 10% of annual rainfall to account for evaporation losses from canopy, litter and soil surface. Canopy rainfall interception has previously been reported to be approximately 4% of gross rainfall in a 4 year-old *E. grandis* stand with an LAI of 4 (Dye and Versfeld, 1992). The mean area occupied by a tree in each year was then used to estimate the volume of water transpired. Figure 3.16 shows a plot of annual volume increment versus the estimated annual transpiration (sap flow) for all plots. The band of WUE defined by the *E. grandis* trees sampled in the present study is superimposed, and illustrates that the espacement trial trees exhibit a very similar range of WUE. The tendency towards greater water use at low volume growth increments, and possibly lower water use at higher growth increments tracks a similar tendency in the *E. grandis* trees measured in this study (Figure 3.13). By comparison, the Kruisfontein data define a more linear trend. Possible reasons for these site differences are many, but would require further intensive investigation to clarify.

The espacement trial data illustrate a further important point. Volume growth of trees grown under short rotation varies greatly from year to year, and is not obviously related to tree age (Figure 3.17). This may explain why an age effect is not more clearly seen in the data. It also supports the notion that high annual growth increments and high WUE are associated with years of favourable weather conditions (especially the amount and distribution of rainfall), when above-ground allocation of carbon would be maximised.

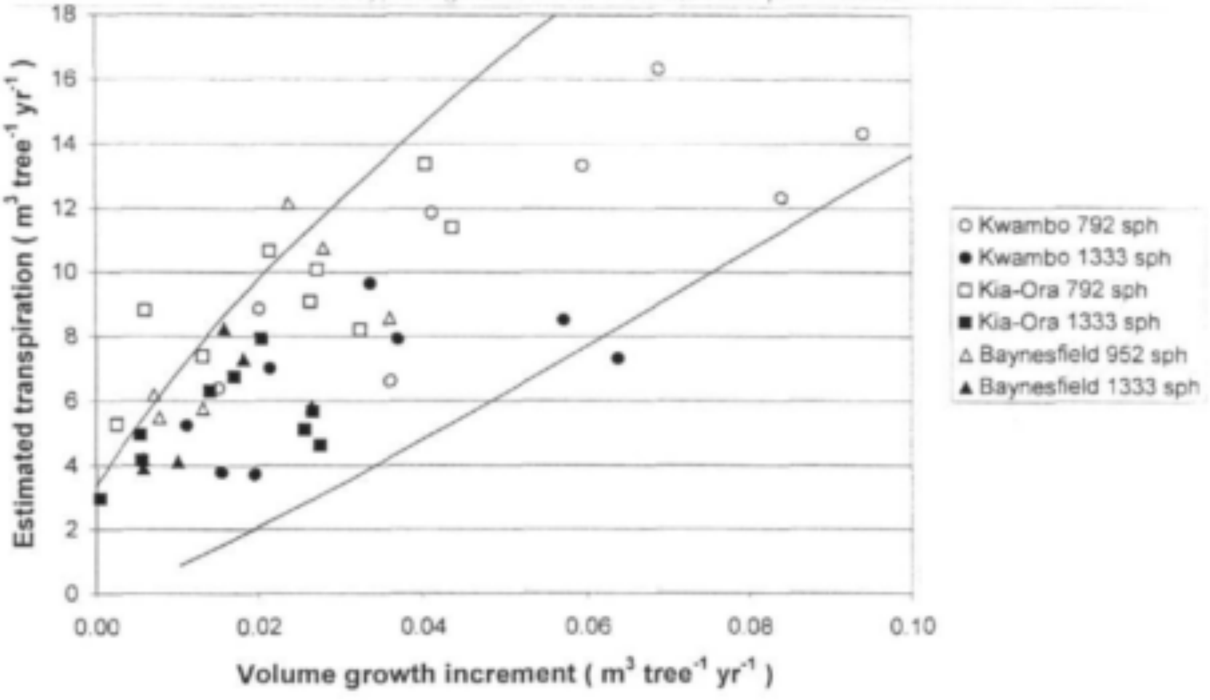

Figure 3.16 The relation between annual volume growth increment and estimated annual transpiration calculated for two tree densities at three espacement trials in KwaZulu-Natal. The superimposed lines indicate the range of data points recorded in the present study

Figure 3.16 suggests that trees grown at high density show greater efficiency of water use than trees grown at lower density. Trees in high density plots experience competitive stress, but the usual stress-response strategy of enhancing below-ground carbon allocation appears to be reversed by the need for greater height growth to access sunlight, and perhaps the high levels of root competition.

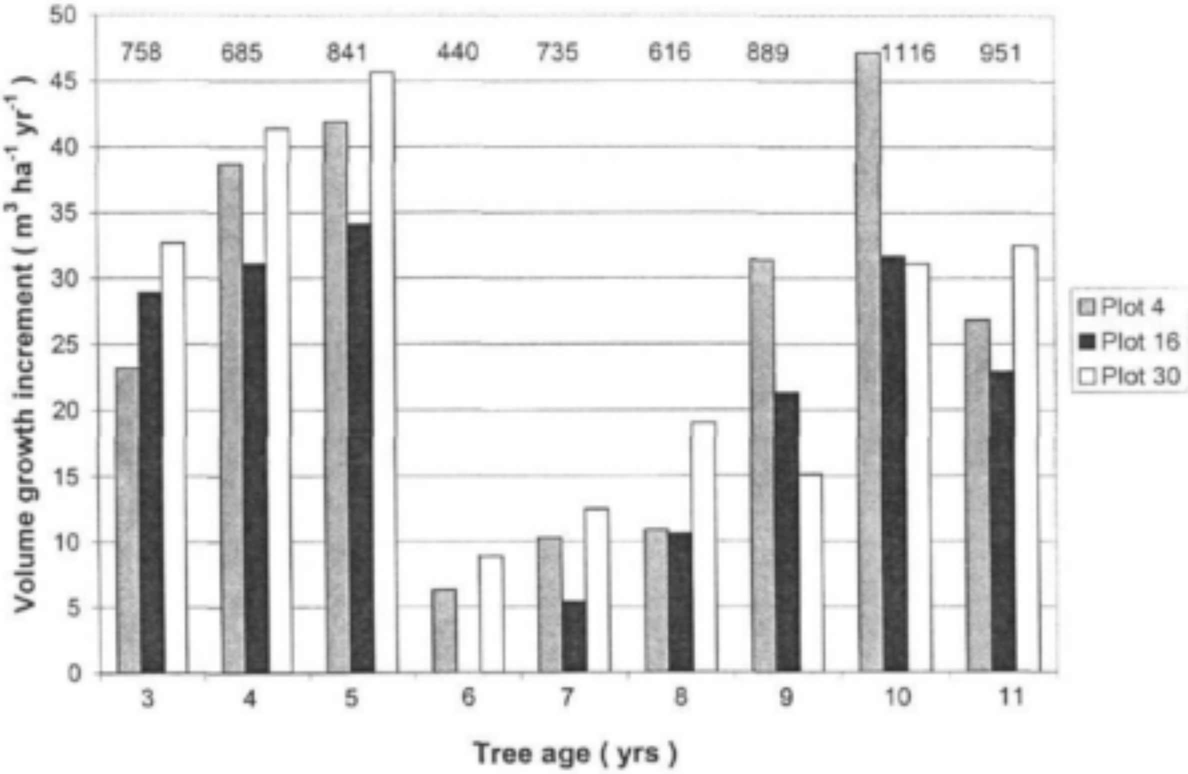

Figure 3.17 Annual volume growth increments recorded in replicate plots over a complete rotation at Kia-Ora, KwaMbonambi. Annual rainfall is illustrated at the top of the graph

3.4.3 Recent *Eucalyptus* data from Australia

Landsberg (1999a) has undertaken a recent and detailed analysis of the WUE of Australian *Eucalyptus* trees. Based on a review of Australian trial data and simulation results using the 3-PG forest growth and water use model, he demonstrated that climatic conditions may cause marked differences in WUE. Simulation results showed a slight increase over a rotation period under a high rainfall scenario, but this dropped significantly under a low rainfall scenario.

4. CONCLUSIONS AND RECOMMENDATIONS

This study has yielded firm evidence that annual WUE of *E. grandis* and *P. patula* is highly variable. Variation shown by the wider range of tree stands in this study is greater than suggested by the original Kruisfontein and Witklip data. The data suggest that WUE shows some correlation to the quality of growing conditions experienced by trees, with drought stress having a particularly marked effect of reducing WUE. Recent tree physiological research has demonstrated that there is an altered pattern of carbon allocation in stressed trees, resulting in a greater proportion of assimilates to roots at the expense of stem.

Acknowledgement of this variation in WUE, and the range exhibited by South African forest plantations, is vital for a balanced perspective of the efficiency of water use by forest plantations. This information is already being taken into account in a WRC project dealing with the economics of forest water use (Project no.1133).
Variable WUE should also be seen as a challenge to determine whether it can be exploited to improve the overall production and efficiency of water use in plantations. This could have particularly important benefits for forestry situated in marginally dry regions of the country. There is a growing trend towards plantation establishment by small-scale emergent growers in such areas (DWAF, 1997), and we believe that it is now timely to extend WUE research to investigate the scope for improving wood production and minimizing drought risk for this category of grower. It is appropriate to consider to what extent plantation WUE can be altered through selection of appropriate genotypes and perhaps management strategy. Research should be focussed on *Eucalyptus* species for two reasons. Firstly, they are the preferred species in areas of relatively low rainfall that are marginal for forestry and where a high WUE would be most beneficial. Secondly, much physiological diversity is known to exist among *Eucalyptus* hybrid clones that are already widely planted in South Africa. We believe that the scope for improving WUE through an appropriate tree breeding and selection process is considerable. The challenge will be to tease apart the genetic and environmental influences on tree WUE for a range of clones and plantation sites.

This study has revealed the need for a new methodology in forest WUE research. Long-term monitoring of sap flow by the heat pulse technique is fraught with risks. These have included malfunction or theft of equipment, corrosion of heat pulse probes by gum, unscheduled clearfelling of sample trees, and occasional uncertainty over the long-term development of wounded sapwood tissue following probe insertion. Sustaining high-quality measurements of sap flow over a full year has proved difficult and a number of sample trees had to be abandoned. We believe that further advances in our understanding of WUE will flow from the use of process-based models of forest growth and water use, which allow the separate influences of weather, stand characteristics and site conditions on carbon allocation patterns and transpiration rates to be assessed. Such models, when validated against appropriate short-term measurements of critical physiological parameters such as sap flow rates, leaf area index, canopy temperatures and growth rates, will greatly improve our understanding of the link between growth and water use. One such model (3-PG) shows much promise in this regard (Dye, 2000a), and is undergoing further testing in WRC project 1194.

5. DATA STORAGE

All relevant data files are copied onto CD disks, and lodged with the WRC and the senior author. A copy of the analysis programme developed for analyzing the heat pulse data is also included.

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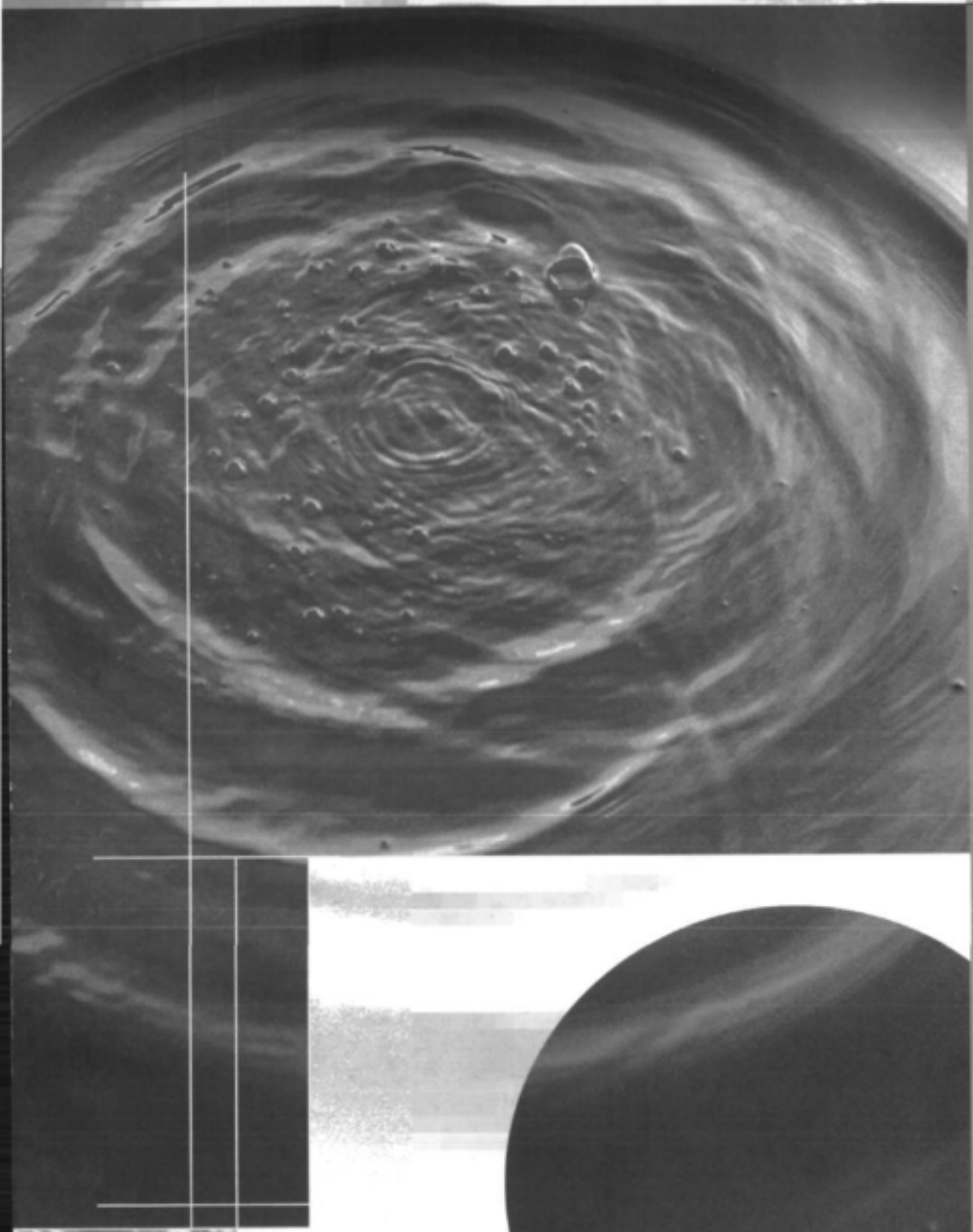
APPENDIX 1

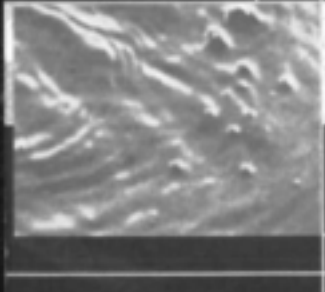
A summary of water use efficiency data recorded during previous studies at Kruisfontein[1] (White River), Kwambonambi[2] (Zululand), Frankfort Plantation[3] (Sabie), Legogote Plantation[3] (White River) and Witklip Plantation[4] (White River).

Kruisfontein	Species / clone	Sample tree	Annual sap flow (m^3)	Annual trunk volume growth (m^3)	m^3 water / m^3 wood
Kruisfontein	*E. grandis*	4	3.51	0.0387	91
Kruisfontein	*E. grandis*	5	3.74	0.0241	155
Kruisfontein	*E. grandis*	6	1.39	0.0130	107
Kruisfontein	*E. grandis*	8	22.90	0.1220	188
Kruisfontein	*E. grandis*	9	4.19	0.0321	130
Kruisfontein	*E. grandis*	10	7.48	0.0480	156
Kruisfontein	*E. grandis*	12	21.96	0.0970	226
Kruisfontein	*E. grandis*	13	4.71	0.0235	200
Kruisfontein	*E. grandis*	15	4.72	0.0351	134
Kruisfontein	*E. grandis*	19	7.76	0.0298	260
Kruisfontein	*E. grandis*	20	5.93	0.0299	198
Kruisfontein	*E. grandis*	21	7.44	0.0303	245
Kruisfontein	*E. grandis*	25	7.880	0.0379	208
Kruisfontein	*E. grandis*	26	2.93	0.0240	122
Kruisfontein	*E. grandis*	27	10.37	0.0463	224
Kruisfontein	*E. grandis*	28	13.26	0.0919	144
Kruisfontein	*E. grandis*	30	5.22	0.0286	56
Kwambonambi	GC15	1	10.62	0.0294	361
Kwambonambi	GC15	2	6.56	0.0317	207
Kwambonambi	GC15	3	8.12	0.0268	303
Kwambonambi	GT529	1	16.36	0.0516	317
Kwambonambi	GT529	2	12.11	0.0594	204
Kwambonambi	GT529	3	9.42	0.0546	172
Kwambonambi	TAG5	1	10.50	0.047	223
Kwambonambi	TAG5	2	7.79	0.0298	261

Kwambonambi	TAG5	3	11.22	0.0396	283
Sabie	*E. grandis*	Mean of 4	16.62	0.0703	236
White River	*E. grandis*	Mean of 4	5.94	0.0192	309
Witklip	*P. patula*	1	6.24	0.0363	172
Witklip	*P. patula*	2	4.49	0.0277	162
Witklip	*P. patula*	3	3.28	0.0212	155
Witklip	*P. patula*	4	2.43	0.0253	96
Witklip	*P. patula*	5	9.28	0.0602	154
Witklip	*P. patula*	6	6.62	0.0456	145
Witklip	*P. patula*	7	7.76	0.0389	199

1. Dye, 1996
2. Dye *et al.*, 1997a
3. Dye et al., 1997b
4. Olbrich *et al.*, 1996





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