Productivity and Water Use of Commercial Forestry Species and their Potential Impact on Surface Water Resources in Two Forestry Areas of KwaZulu-Natal, South Africa

by

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PREFACE

The research contained in this thesis was completed by the candidate while based in the Discipline of Agrometeorology, School of Agricultural, Earth and Environmental Sciences of the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Pietermaritzburg, South Africa. The research was financially supported by the Department of Water and Sanitation through Water Research Commission research project K5/ 2791.

The contents of this work have not been submitted in any form to another university and, except where the work of others is acknowledged in the text, the results reported are due to investigations by the candidate.

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DECLARATION 1: PLAGIARISM

I, Nkosinathi David Kaptein, declare that:

(i) the research reported in this thesis, except where otherwise indicated or acknowledged, is my original work;

(ii) this thesis has not been submitted in full or in part for any degree or examination to any other university;

(iii) this thesis does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons;

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a) their words have been re-written but the general information attributed to them has been referenced;

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(v) where I have used material for which publications followed, I have indicated in detail my role in the work;

(vi) this thesis is primarily a collection of material, prepared by myself, published as journal articles or presented as a poster and oral presentations at conferences. In some cases, additional material has been included;

(vii) this thesis does not contain text, graphics or tables copied and pasted from the Internet, unless specifically acknowledged, and the source being detailed in the thesis and in the References sections.

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DECLARATION 2: PUBLICATIONS

Details of contribution to publications that form part and include publications submitted and published, providing details of contribution by each author to the research and writing of each publication. The * indicates corresponding author. Some minor editorial differences may exist between the published or submitted papers and the thesis chapters.

Publication 1 (Chapter 2):

Kaptein ND*, Clulow AD. Toucher ML, Everson C, Dovey SB, Germishuizen I. 2023. Plantation water productivity (PWP_{WOOD}) and not water-use efficiency (WUE) as the measure of commercial plantation yield improvement: a review. *Southern Forests: a Journal of Forest Science*. Published.

Thes manuscript is a review, highlighting the benefits and importance of using the plantation water productivity (PWP_{WOOD}) as an alternative to water use efficiency (*WUE*) to determine productivity of commercial forestry genus. The PWP_{WOOD} successes from international studies are highlighted with practical practices that can be implemented by the South African commercial forestry industry to improve productivity. The review of relevant literature and content was conducted by ND Kaptein. The advice of the structure and content were provided by AD Clulow, ML Toucher, CS Everson, I Germishuizen and SB Dovey. This manuscript in totality was written by ND Kaptein and all results, tables and graphs were created by ND Kaptein, unless mentioned otherwise within the manuscript.

Publication 2 (Chapter 3):

Kaptein ND*, Clulow AD. Toucher ML, Everson C, Germishuizen I. 2023. Water use and potential hydrological implications by fast-growing nine-year-old *Eucalyptus grandis* x *Eucalyptus urophylla* hybrid in the northern Zululand, South Africa. *Water SA*. Published.

This paper analysed data collected at the KwaMbonambi study site in the northern Zululand coastal plains of South Africa. Tree water use and PWP_{WOOD} was measured and calculated, respectively. The automatic weather station data was sourced from Mondi KwaMbonambi nursery. The experiment was conceptualised by AD Clulow, ML Toucher and CS Everson. Literature review, data collection and data analysis were undertaken by ND Kaptein. This manuscript in totality was written by ND Kaptein and all results, tables and graphs were created by ND Kaptein, unless mentioned otherwise within the manuscript under guidance and advice of AD Clulow, ML Toucher, CS Everson and I Germishuizen.

Publication 3 (Chapter 4):

Kaptein ND*, Clulow AD. Toucher ML, Everson C, Dovey SB, Germishuizen I. 2023. Transpiration rates from mature *Eucalyptus grandis* x *Eucalyptus nitens* clonal hybrid and *Pinus elliottii* plantation near the Two Streams Research Catchment, South Africa. *Hydrological Earth Systems Science*. Published.

The data presented in this manuscript are based on measurements collected in field on tree water use paired with biomass measurements at two study sites near Two Streams research catchment. The PWP_{WOOD} was calculated from biomass and water use measurements. The experiment was conceptualised by AD Clulow, ML Toucher and CS Everson. ND Kaptein was actively involved in the collection and analysis of water use and PWP_{WOOD} dataset. The publication was entirely written by ND Kaptein under guidance and advice of AD Clulow, ML Toucher, CS Everson and I Germishuizen and all graphs, tables and figures were created by ND Kaptein, unless stated otherwise within the manuscript.

Publication 4 (Chapter 5):

Kaptein ND*, Clulow AD. Toucher ML, Everson C, Germishuizen I. 2023. Changes in energy balance and total evaporation with age, and between two commercial forestry genus in South Africa. *Journal of Hydrology*. Published.

The data presented in this manuscript are based on measurements collected in field at Two Streams research catchment. The energy balance and total evaporation data for this publication for periods, October 2007 to September 2008 and October 2012 to September 2013 were sourced from the Centre for Water Resources Research at the University of KwaZulu-Natal (through AD Clulow) and South African Environmental Observation Network (through ML Toucher). ND Kaptein was actively involved in the collection and analysis of water use and PWP_{WOOD} dataset for a period October 2019 to September 2020. The publication was entirely written by ND Kaptein under guidance and advice of AD Clulow, ML Toucher, CS Everson and I Germishuizen and all graphs, tables, figures were created by ND Kaptein, unless stated otherwise within the manuscript.

Publication 5 (Chapter 6):

Kaptein ND*, Toucher ML, Clulow AD, Everson C, Germishuizen I. 2023. The influence of different tree species and age on the water balance of a small commercial forestry catchment. *Journal of Hydrology: Regional studies*: Under review.

The data presented in this manuscript are based on measurements collected in field at Two Streams research catchment. The streamflow, total evaporation and rainfall data for this publication for periods, October 2008 to September 2009 and October 2012 to September 2013 were sourced from the Centre for Water Resources Research at the University of KwaZulu-Natal (through AD Clulow) and South African Environmental Observation Network (through ML Toucher). ND Kaptein was actively involved in the collection and analysis of total evaporation, streamflow and rainfall data for a period October 2020 to September 2021. The publication was entirely written by ND Kaptein under guidance and advice of AD Clulow, ML Toucher, CS Everson and I Germishuizen and all graphs, tables, results were created by ND Kaptein, unless stated otherwise within the manuscript.

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EXECUTIVE ABSTRACT

Water is a necessity for supporting life and development of a society and also provides many benefits such as different industrial products, transportation and can be used to generate power. In the 2030 Agenda for Sustainable Development, the United Nations Sustainable goal number six aims at protecting water resources so that they are available to all interested parties. Although there have been improvements in water resources sustainability, there are still challenges associated with proper management, protection and exploitation of water resources imposed by population growth, resulting in increased competition for water resources by different industries or water users. These challenges are exacerbated in South Africa, which is a water limited country, receiving rainfall of 495 mm per annum (approximately 50% below the world's average). The South African commercial forestry industry is subjected to the water competition challenges currently facing South Africa.

The role played by the commercial forestry industry in South Africa is valued and acknowledged through providing employment opportunities, contributing to agricultural GDP, decreasing the pressure on indigenous forest destruction and many other aesthetic benefits, which boosts the tourism industry. However, many studies around the world have associated the evergreen and tall commercial afforestation with high water usage compared to other vegetation types such as grasslands and shrubs. This has been ascribed to the capability of trees to root deeply and access water from deep water reserves, resulting in a reduction and even cessation of streamflow. Of the common commercial forestry genus planted in South Africa, the fast-growing *Eucalyptus* genus has been considered the highest water user, followed by pine and *Acacia*. The South African commercial forestry genus have been regulated by different environmental legislation, the most recent being the National Water Act No. 36 of 1998. This act regard commercial forest plantations as a streamflow reduction activity (SFRA), and these plantations are regulated using a water use licensing system.

The declaration of forest plantations as an SFRA was based on three commercial forestry genus, namely *Acacia mearnsii*, *Pinus patula* and *Eucalyptus grandis*. However, in the last 30 years, there have been changes in the genus planted by the commercial forestry industry. The *E. grandis* species has been replaced by *Eucalyptus* clonal hybrids and *Eucalyptus dunnii*, while *P. elliottii* has become an important pine planting option, creating a water use knowledge gap by genus and clonal hybrids currently planted by the commercial forestry industry. Considering

this water use knowledge gap, the overall aim of this research was to create knowledge and expand the understanding of tree water use by exotic forestry genus in two study areas: the Two Streams research catchment in the KwaZulu-Natal midlands and KwaMbonambi in the northern Zululand area of South Africa.

The Two Streams catchment has been an experimental site for the past 21 years, yielding valuable data on hydrological processes and water use by *Acacia mearnsii*. In 2018, *A. mearnsii* was harvested and catchment replanted with *E. dunnii*, with hydrological and water use measurements continued. This provided an opportunity to compare *A. mearnsii* and *E. dunni* water use in the early stages of growth with a matured *A. mearnsii*. The impact of *A. mearnsii* and *E.dunnii* on streamflow was quantified using groundwater level and streamflow measurements. Two additional study sites, with trees at the same stage of development, adjacent to the catchment, were identified, with one stand planted to *E. grandis* x *E. nitens* clonal hybrid (*GN*) and the other to *P. elliottii*, where water use measurements were quantified. The KwaMbonambi study site was planted to eight-year-old *E. grandis* x *E. urophylla* clonal hybrid (*GU*) at the start of the measurements. The water use measurements in each site were paired with biomass measurements to enable for the calculation of plantation water productivity (PWP_{WOOD}), defined as the maximum amount of biomass produced from a specific volume of total water used.

This research involved conducting a detailed literature review on PWP_{WOOD} as a tool to improve productivity in commercial forestry. Case studies in other countries indicated improvements in plantation productivity using PWP_{WOOD}, defined as the amount of utilisable wood produced from a given volume of water, instead of water use efficiency, defined as the tree biomass produced per unit of water used, were highlighted. Plantation management practices to enhanced water productivity that can be implemented by the commercial forestry industry in South Africa to improve PWP_{WOOD} are presented.

The state-of-the-art techniques for measuring transpiration (heat ratio method), total evaporation (eddy covariance and large aperture scintillometer) and quantifying the impact of commercial forestry on water resources were used. First, water use comparison between *E. grandis* x *E. nitens* clonal hybrid (*GN*) and *P. elliottii* at the Two Streams research catchment were conducted and the potential impact by each species on water resources was quantified. Second, total water use by previously planted *A. mearnsii* crop, the two-year-old *A. mearnsii* (total water use measurements were conducted when the crop was between the age 1.4 to 2.4 years old, and six-year-old *A. mearnsii* (total water use measurements were conducted when the crop was between 6.0 and 7.0 years old) was compared to a newly planted *E. dunnii* crop (total water use measurements were conducted when the crop was between the age 1.6 to 2.6 years old) to provide observation of a change in total water use and hydrology of a site over time. Third, water use by *GU* in KwaMbonambi, northern Zululand was measured and the potential impact of *GU* on groundwater resources was quantified. Fourth, the surface water balance for the Two Streams research catchment was calculated for the three-year-old *A. mearnsii* (trees were between 2.7 to 3.7 years in age), the seven-year-old *A. mearnsii* (trees were between 6.7 to 7.7 years in age) and the three-year-old *E. dunnii* (trees were between 2.6 to 3.6 years in age) to compare water balance over time and between species. The streamflow, total evaporation and interception loss were measured or modelled for each crop to understand the impact of each species on streamflow.

The Two Streams research catchment was found in previous studies to have water-use losses that exceed rainfall. This study found similar results, but the trees were not water stressed, with the exception of a *GN* study site where trees indicated signs of water stress. These long-term results suggested, with omission of the *GN* study site, that trees most likely sourced water in the soil water storage from previous wet years held deep in the soil profile or water from lateral flows from surrounding areas. Similar results were found on the fast-growing *GU* in KwaMbonambi. The total water balance of the catchment was found to be negative for all crops, with the total evaporation a main consumer of water in the catchment (consuming > 90%), while the total runoff water loss was about 4%.

Comparison of water use by *GN* and *P. elliottii* showed that, in the first year, *P. elliotti* water use significantly exceeded *GN* (mean daily water use: *P. elliottii* = 2.5 mm and *GN* = 1.9 mm), while water use was statistically similar in year two (mean daily water use: *P. elliottii* = 2.6 mm and *GN* = 2.1 mm). These results contrasted with findings from several previous long-term paired catchment studies, which indicated that *Eucalyptus* uses more water than pine and pose a significant negative impact on groundwater resources and the streamflow. However, the *GN* study site was found to be water stressed which may have influenced results from our study. The PWP_{WOOD}, calculated as a ratio of utilisable timber to transpiration, at the *GN* site was statistically greater than the *P. elliottii* site (mean: *GN* = 0.725 g wood kg^{-1} H_2O and *P. elliottii* = 0.59 g wood kg^{-1} H_2O), however, statistically lower than other similar studies (maximum =

3.1 g wood kg^{-1} H_2O), which was once again probably a result of soil water deficit at the study site. This relatively short-term study showed the different responses of the tree species to changes in season and available soil water with *GN* generally responding more rapidly. It also showed that in countries such as South Africa, where streamflow reduction by commercial forestry is modelled for water licensing purposes, soil water stress in the hydrological models must be able to constrain tree water-use. A recommendation is that these measurements are conducted over several forestry sites to include different soil and climatic conditions over a full crop rotation.

Total water use comparison between young *A. mearnsii* (two-year-old) versus young *E. dunnii* (two-year-old) versus matured *A. mearnsii* (six-year-old) at Two Streams catchment indicated that total water use by the two young crops was 12% greater than the matured crop. This finding was supported by literature, which suggests that the water use of young crops is generally higher, decreasing as the stand approaches maturity. The young *E. dunnii* PWP_{WOOD} (0.068 g wood kg^{-1} H_2O) was statistically greater than young *A. mearnsii* (0.018 g wood kg^{-1} H_2O), while the matured *A. mearnsii* PWP_{WOOD} (0.131 g wood kg^{-1} H_2O) was statistically greater than both the young crops. All three crops provided evidence that trees accessed soil water in areas that were not measured in the catchment, probably water stored deep in the soil profile from previous wet years. This suggests that afforesting the catchment have, to a certain extent, a negative impact of groundwater resources by using soil water stored deep in the soil profile to meet evaporative demands, therefore reducing water available for recharging the water table. A recommendation from this study is that hydrological measurements are continued at Two Streams catchment on the currently planted crop, the *E. dunnii*, for the full rotation to allow for comparison with *A. mearnsii* rotation.

The heat ratio technique indicated that the *GU* mean daily transpiration water use was 2.3 to 3.3 mm $tree^{-1}$ corroborating with previous water use studies conducted on *E. grandis* and *E. urophylla* in northern Zululand region. The PWP_{WOOD}, calculated from the ratio of utilisable timber to tree transpiration to, was higher (range: 1.4 to 1.74 g wood kg^{-1} H_2O) than other published studies (0.6 g wood kg^{-1} H_2O), which was attributed to a very high productivity potential of the study site. Trees did not show any signs of water stress, regardless of very low soil water content on the sites, inferring the possibility that *GU* trees were able to access water stored in the unsaturated zone to meet transpiration demands, with possible negative implications on groundwater reserves, reducing the water needed to recharge the water table, with possible long-term consequences on the streamflow.

The surface water balance of the catchment was negative for all the three cropping windows with a slightly greater margin for young crops. During the mature crop window period, the interception loss was the highest compared to young crop, which reduced effective precipitation, in turn contributing to the lowest measured streamflow. The negative surface water balance suggest that trees were accessing water external to the catchment, probably from the water stored deep in the soil profile from previous wet years. Further research using isotopes to trace the source of water used by the trees external to the catchment is suggested.

The Random Forests predictive model was used to determine the relationship between tree water use (evapourtranspiration and transpiration) for all study sites against micrometeorological variables (FAO reference evaporation for tall crop, rainfall, soil water content, vapour pressure deficit, relative humidity, air temperature, solar radiation, wind speed). The soil water content, vapour pressure deficit, solar radiation and FAO reference evaporation (tall crop) were found to be very important variables influencing water use on all our study sites, suggesting that these "easy to measure" variables can be modelled to estimate tree water use.

This thesis highlights the value that can be achieved from conducting direct water use measurements in commercial forest plantations. Before this study was conducted, there was a lack of water use information by clonal hybrids and genus currently planted by the commercial forestry industry in South Africa, which is now available in this thesis through the use of the "state of the art" measuring techniques. This thesis not only presents the first measurements of water use by *GU*, *GN* an *P. elliottii* in South Africa and first comparative water use by *P. elliotti* and *GN*, but is also one of the few studies that quantified the potential impact of *A. mearnsii* and *E. dunnii* on groundwater reserves in South Africa. The study provides decision makers, such as government officials with an opportunity to update policies using water use information from genus and hybrids currently planted by the South African commercial forestry industry. Data captured in this thesis will also be a useful resource in future modelling studies where water use could potentially be estimated from climatic variables beyond the Two Streams and KwaMbonambi study sites. This water use dataset provides invaluable data for validating remote sensing techniques. Finally, data from this study will form a good background for future water use studies by increasing sample dataset and the long-term measurements of water use will provide a robust understanding of water use by different species and their potential impact on water resources to accurately determine commercial forestry streamflow reduction activity.

Keywords: *Acacia mearnsii*, Surface water reserves, Eddy covariance technique, *Eucalyptus dunnii*, *E. grandis* x *E. nitens* clonal hybrid, *E. grandis* x *E. urophylla* clonal hybrid, Heat ratio technique, Plantation water productivity, Tree transpiration, Total evaporation,

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I would also like to acknowledge the Institute for Commercial Forestry Research (ICFR) and the entire staff for providing me with time to conduct the study and facilities and equipment to use in this study.

I am grateful to Mondi Forests for providing study sites and the automatic weather station data from KwaMbonambi nursery.

To the fellow students and staff at the University of KwaZulu-Natal, particularly at the Discipline of Agrometeorology and at the Centre for Water Resources Research, thank you for your assistance and support throughout the study period.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure **Page**

799 **LIST OF SYMBOLS**

α	Alpha
π	Pie (approximately 3.14, unitless)
A	Total ground area (m^2)
AE	Available energy ($W\ m^{-2}$)
c_p	Specific heat capacity for air at constant pressure ($J\ kg^{-1}\ K^{-1}$)
DBH	Diameter at breast height (cm)
D_M	Total dry matter accumulated by a tree (g)
D_q	Quadratic mean diameter (cm)
EB	Energy balance ($W\ m^{-2}$)
Es	Soil evaporation (mm)
ET	Total evaporation (mm)
ET_{EC}	Total evaporation (mm) measured using eddy covariance
ET_{LAS}	Total evaporation (mm) measured using large aperture scintillometer
ETo	FAO-56 reference evaporation (mm)
F	Ratio of variance of y- intercept to x-intercept
FAO-56 ETo	Food and Agricultural Organisation reference evaporation (mm)
G	Ground heat flux (Wm^{-2})
GDP	Gross domestic product (Rands)
h	Tree height (m)
H	Sensible heat flux ($W\ m^{-2}$)
HI	Harvest index ($g\ g^{-1}$)
I_l	Interception loss
I_s	Solar irradiance (Wm^{-2})
k	Thermal diffusivity of fresh wood (a nominal value of $2.5 \times 10^{-3}\ cm^2\ s^1$)
K_c	Crop factor
LTMAP	Long term mean annual precipitation (mm)
MAP	Mean annual precipitation (mm)
MAT	Mean annual temperature (mm)
LE	Latent heat flux ($W\ m^{-2}$)
$LSD_{5\%}$	Fischer's Least Significant Difference at 5% level of significance
ρ	Density of wood (kg m-3)
ρ_a	Density of dry air ($kg\ m^{-3}$),

P	Precipitation (mm)
PAW	Plant available water (kPa)
PWC	Profile water content
$PWC_{0.2}$	Profile water content at 0.2 m soil depth
$PWC_{0.4}$	Profile water content at 0.4 m soil depth
$PWC_{0.6}$	Profile water content at 0.6 m soil depth
P_{eff}	Effective rainfall (mm)
P_g	Gross precipitation (mm)
PWP	Plantation water productivity (g wood kg^{-1} water)
PWPWOOD	Plantation water productivity of commercial forestry (g wood kg^{-1} water)
Q	Streamflow (mm)
RH	Relative humidity (%)
RMSE	Root mean squared error
SE intercept	Standard error of an intercept
SE slope	Standard error of a regression line
spha	Stems per hectare
SWC	Soil water content (m^3 m^{-3})
R^2	Coefficient of determination
T	Transpiration (mm)
T_{air}	Temperature of air (°C)
TE	Transpiration efficiency (g of dry matter kg^{-1} water)
TE_{DM}	Transpiration efficiency of accumulated dry matter (g of dry matter kg^{-1} water)
T-Max	Maximum air temperature (°C)
T-Min	Minimum air temperature (°C)
v	Conical over bark volume (m^3)
V	Stand volume (m^{-3} ha)
Vh	Heat pulse velocity ($m.s^{-1}$)
vi	Productive volume of the *i*th tree (m^3)
VPD	vapour pressure deficit (kPa)
$V\rho$	Density of biomass (kg m^{-3})
w'	Vertical wind speed ($m.s^{-1}$)
WUE	Water use efficiency (g biomass kg^{-1} water)
x	Distance of each temperature probe from heater probe (0.6 cm)

LIST OF ABBREVIATIONS

Amear$_2$	Two-year-old *Acacia mearnsii* trees
Amear$_3$	Three-year-old *Acacia mearnsii* trees
Amear$_6$	Six-year-old *Acacia mearnsii* trees
Amear$_7$	Seven-year-old *Acacia mearnsii* trees
ANOVA	Analysis of variance
AWS	Automatic weather station
CV	Co-efficient of variation
CWRR	Centre for Water Resources Research
DEFF	Department of Environment, Forestry and Fisheries
EC	Eddy covariance
Edun$_2$	Two-year-old *Eucalyptus dunnii* trees
Edun$_3$	Three-year-old *Eucalyptus dunnii* trees
FAO	Food and Agricultural Organisation of United States
FSA	Forestry South Africa
GN	*Eucalyptus grandis* x *E. nitens* clonal hybrid
GU	*Eucalyptus grandis* x *E. urophylla* clonal hybrid
HPV	Heat pulse velocity
HRM	Heat ratio method
LAI	Leaf area index
LAS	Large aperture scintillometer
MDA	Mean Decrease Accuracy
MDG	Mean Decrease GINI
RF	Random Forests regression model
RMSE	Root mean square error
Rn	Net radiation
SAEON	South African Environmental Observation Network
SASA	South African Sugarcane Association
SASRI	South African Sugarcane Research Institute
SD	Standard deviation
SE intercept	Standard error of the intercept
SE slope	Standard error of a slope

SFRA	Streamflow reduction activity
TC	Thermocouple
UKZN	University of KwaZulu-Natal
WMO	World Meteorological Organisation
WRC	Water Research Commission
WS	Wind speed

CHAPTER 1: INTRODUCTION

1.1 Rationale for the research

1.1.1 Background

South Africa is generally regarded as a water limited country (Schulze and Lynch 2007) receiving a mean annual rainfall of approximately 495 mm, which is significantly lower than the world's average of 860 mm. As a result, there are mounting concerns regarding conflicting demands for water resources from different land uses. The commercial forestry industry faces similar water supply challenges, due to its high-water use compared to other vegetation types (Albaugh et al. 2013). There are more than four decades worth of research locally and internationally that investigated water use by commercial forestry genera and quantified the potential impact on water resources (Calder 1986, Dye 1996, Calder 1998, Dye et al. 2001, Whitehead and Beadle 2004, Scott and Prinsloo 2008),) with an overview of recent topics presented by Albaugh et al. (2013), Dye (2013), Dzikiti et al. (2013) and White et al. (2021).

1.1.2 Overview of commercial forestry in South Africa

Commercial plantation forests cover approximately 1 212 383 ha which is about 1% of South Africa's land area (Godsmark and Oberholzer 2019). This land area stretches from northern Limpopo, across the eastern seaboard of Mpumalanga, KwaZulu-Natal and Eastern Cape to the Western Cape (Figure 1.1). The majority of commercial plantations are spatially concentrated in KwaZulu-Natal and Mpumalanga, with relatively small areas in the Eastern Cape, Limpopo and Western Cape of 12%, 4% and 3.6%, respectively (Godsmark and Oberholzer 2019). As illustrated in Table 1.1, the top four most planted *Eucalyptus* species are *Eucalyptus dunnii*, *Eucalyptus grandis*, *Eucalyptus grandis* x *E. urophylla* and *Eucalyptus grandis* x *E. nitens*, while pine species are *P. patula*, *P. elliottii*, *P. elliottii* x *P. caribaea* clonal hybrid and *P. patula* x *P. tecunumannii* clonal hybrid. The significant portion of these forest plantations are positioned within catchments that play a significant role in supplying freshwater (Scott et al. 1999).

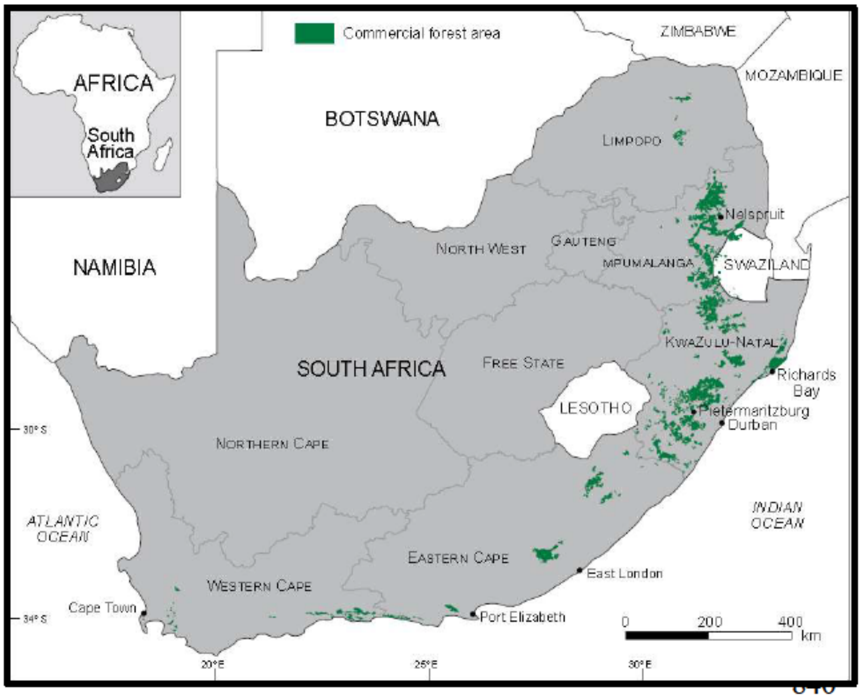


Figure 1.1: Distribution of commercial forestry in South Africa (Adopted form Xulu et al. 2019).

Table 1.1: The statistics of different commercial forestry genera and species most planted by the South African forestry industry (DAFF 2017).

Commercial forestry genera		Total area (ha^{-1})	
Pine		606 192	
Eucalypts		521 325	
Wattle		84 867	
Eucalyptus (ha^{-1})		Pine (ha^{-1})	
E. dunnii	125 659	*P. patula*	106 044
E. grandis	67 428	*P. elliottii*	54 232
E. grandis x *E. urophylla*	66 238	*P. elliottii* x *P. caribaea*	9 971
E.grandis x *E. nitens*	32 717	*P. patula* x *P. tecunumannii*	7 541
E. macarthurii	22 555	*P. taeda*	7197
E. nitens	18 720	*P. greggi*	2111
E. smithii	14 872	*P. radiata*	755
E. benthamii	11 360	*P. caribaea*	328
E. grandis x E. camaldulensis	7 463	*P. tecunumani*	177

1.1.3 Overview of the impact of commercial forestry on water resources

The availability of soil water is widely recognised as the most important environmental variable limiting tree productivity (Dye 1996). This creates a strong competition between water available for downstream water users and water available for forest production. Several South African studies (Scott et al. 1998, Gush et al. 2002, Scott and Prinsloo 2008) have proven that commercial forestry uses water more than other vegetation types (such as grasses, shrubs and indigenous forests) and negatively impact natural water resources such as streamflow and groundwater resources (Scott and Lesch 1997, Scott and Prinsloo 2008). The high-water use rate by commercial trees is attributed to fast growth rates, deep-rooting and tall and evergreen vegetation, which have replaced the dormant grasslands or shrubs (Dye and Versfeld 2007), resulting in very high total evaporation rates (Le Maitre et al. 2015), as well as deep rooting nature of commercial trees which enables them to access underground water during the dry season (van Dijk and Keenan 2007). In addition, the majority of South Africa's plantations forests are found near catchments that are used as freshwater sources which exacerbates the situation (Scott et al. 1999). For these reasons, the South African commercial forestry industry has been subjected to different forms of environmental legislations, the most recent being the National Water Act No. 36 of 1998 (RSA 1998). The act declares commercial forest plantation as a streamflow reduction activity (SFRA) and the planting of plantations is regulated through water use licensing systems.

1.2 Research question

Can existing micrometeorological techniques and hydrological processes be used to estimate water use of the new clonal hybrids and quantify the potential impact by these clonal hybrids on streamflow and groundwater reserves at Two Streams research catchment and KwaMbonambi, northern Zululand study sites?

1.3 Motivation for the study

The commercial forestry industry water-use and the impact on groundwater reserves is well document internationally and locally (Bosch and Hewlett 1982, Dye 1996, Gush et al. 2002, Bruijnzeel et al. 2005, Jackson et al. 2005, Dye and Versfeld 2007, Scott and Prinsloo 2008, Vanclay 2009, Bulcock at al. 2014, Gush et al. 2015, Mapeto et al. 2018). Most of this research in South Africa has been limited to few main commercial forestry species namely, *Eucalyptus grandis*, *Pinus patula* and *Acacia mearnsii*. Results from this research indicated that on average, an individual tree transpiration by a mature *E. grandis*, *P. patula* and *A. mearnsii* range from

50 L to 100 L, 15 L to 60 L and 10 L to 70 L $tree^{-1}$ day^{-1}, respectively. In addition to high water usage, commercial afforestation is known to negatively affect groundwater resources and reduce the flow of a stream. For example, in a study by Scott and Lesch (1997), afforesting the entire catchment with *E. grandis* and *P. patula* resulted to a reduction in streamflow during the third year of planting, and the stream stopped flowing in year number nine post planting (Scott and Lesch 1997), with streamflow returning five years after harvesting.

In addition, most measurements of tree water use in South Africa have been paired with productivity or biomass measurements to enable calculation of water use efficiency (WUE), defined as annual volume stem increment per unit volume of water transpired (Albaugh et al. 2013). Most studies in South Africa indicated that eucalypts are more water efficient than pine and wattle species (Le Roux et al. 1996, Dye et al. 1997, 2001, Whitehead and Beadle 2004), producing water use efficiency range of 0.0008 to 0.0123 m^3 of stemwood per m^3 of water transpired. A recent study, in central Chile by White et al. (2021), reported that *Eucalyptus globulus* was 50% more water use efficient than *Pinus radiata*. Though WUE has been used in many studies to determine biomass production per volume of water used, it has limitations. For example, non-productive water and the efficiency of transpiration is not accounted for (Bulcock et al. 2014), while total biomass production instead of marketable biomass is used in the calculation (White et al. 2014). The plantation water productivity of commercial forestry (PWP_{WOOD}) is considered a better alternative, defined as the maximum amount of wood produced from a given volume of water.

The declaration of commercial forestry as an SFRA in South Africa is based on three commercial forestry species, namely *Eucalyptus grandis*, *Pinus patula* and *Acacia mearnsii*, however, due to their susceptibility to pests and diseases, drought and poor pulping properties, the forestry industry is considering alternatives (Morris 2022). New genetically improved clonal hybrids and species have been produced by commercial forestry industry breeding programs, with better resistance to pests and diseases, drought and better pulping properties and meet the current market specifications. The *Eucalyptus dunnii* is currently the most planted *Eucalyptus* species in South Africa, while the clonal hybrid, *Eucalyptus grandis* x *E. nitens* (*GN*) is the fourth most planted hybrid by forest companies in warm temperate regions due to adaptability of this species to these conditions. In subtropical regions of Zululand north coast in South Africa, particularly the KwaMbonambi region, the *E. grandis* x *E. urophylla* (*GU*) clonal hybrid is the first choice by tree farmers as this hybrid is very adaptable to humid conditions. For pine species, *P. patula* is currently the most planted species in South Africa, however, this species is very susceptible to *F. circinatum* and *P. elliottii* is considered a better alternative.

The change in species preference has created a water use knowledge gap by species most planted by the commercial forestry industry. There is an urgent need to understand total water-use by *E. dunnii*, *GU*, *GN* and *P. elliottii* and the potential impact by each species on groundwater reserves and streamflow, hence the impact to downstream water users. This need has become more important with the proposed Genus exchange regulation in terms of National Water Act of 1998 (Gush 2016), outlining that any existing forest producer that intends to conduct genus exchange in their plantation, needs to apply for authorisation to implement the exchange. Furthermore, forest plantations should be enhanced to produce more marketable biomass volume per total water used. To our knowledge, there is no available literature or research study in commercial forest plantations that quantified PWP_{WOOD} of *GU*, *GN*, *P. elliottii*, *E. dunnii* and there is limited knowledge on *A. mearnsii*. The findings from this study will provide water use data by species currently planted by the South African forestry industry so that decision makers at government level can update the SFRA regulation.

1.4 Aims and objectives

The overall aim of the research in this thesis was to provide new knowledge and expand our understanding of tree water use and PWP_{WOOD} of exotic forestry species at Two Streams research catchment and KwaMbonambi, northern Zululand and also determine the impact of these species on groundwater resources and streamflow.

The objectives of the research were to:

- Review literature supporting PWP_{WOOD} as a better alternative to determining productivity of commercial forestry.
- Quantify water use by fast-growing *E. grandis* x *E. urophylla* clonal hybrid and its potential impact on water resources in sandy soils of KwaMbonambi, northern Zululand region.
- Compare water use by fast-growing *E. grandis* x *E. nitens* clonal hybrid and *P. elliottii* at the same stage of development near Two Streams research catchment.
- Improve our understanding of energy balance and total evaporation by young *E. dunnii* vs young *A. mearnsii* vs mature *A. mearnsii* plantations within the Two Streams research catchment.
- Compute the surface water balance of the three-year-old *A. mearnsii*, three-year-old *E. dunnii* and seven-year-old *A. mearnsii* at the Two Streams research catchment and

assess the potential impact of *A. mearnsii* and *E. dunnii* on the streamflow on the same catchment.

1.5 Research hypothesis

Previous research has shown that *Eucalyptus* genus (such as *Eucalyptus grandis*) generally use more water than *Pinus* genus (such as *Pinus patula*) (Scott and Lesch 1997, Dye et al. 2001, Albaugh et al. 2013). The deep rooting capability of commercial forest plantations enable these species to access water in underground water reserves, leading to streamflow reduction (van Dijk and Keenan 2007). In the past 30 years (Morris 2022), the breeding programs of the commercial forestry industry has produced genetically improved clonal hybrids with better characteristics such as pulping properties, high resistance to pests and diseases, more resistance to drought, high density and good stem form. From 1990s, *Eucalyptus* species has been extensively replaced by eucalypt clonal hybrids and *E. dunnii*, while of the *Pinus* species, *P. elliottii* has become an important pine planting option (Morris 2022). There is a knowledge gap on the water use by the species currently planted by the commercial forestry industry such as *E. dunnii*, *E. grandis* x *E. nitens*, *E. grandis* x *E. urophylla* and *P. elliottii*. A study was initiated to 1) review plantation water productivity (PWP_{WOOD}) as a determinant of productivity in commercial forest plantations 2) Quantify the water use by nine-year-old *E. grandis* x *E. urophylla* clonal hybrid in KwaMbonambi, Zululand coastal plains of South Africa 3) Measure and compare water use by eight-year-old *E. grandis* x *E. nitens* clonal hybrid and twenty-year-old *Pinus elliottii* (both species were at the same rotational age) at Two Streams research catchment in KwaZulu-Natal, South Africa 4) Compare total water use by two-year-old *E. dunnii* versus two-year-old *A. mearnsii* versus six-year-old *A. mearnsii* at the Two Streams research catchment in KwaZulu-Natal, South Africa and 5) Compute the catchment water balance for the three-year-old *A. mearnsii*, three-year-old *E. dunnii* and seven-year-old *A. mearnsii* and quantify the impact by these crops on the streamflow and the groundwater reserves at Two Streams research catchment.

This study hypothesises that:

i. The PWP_{WOOD} is a good determinant of commercial forest plantation productivity and a better alternative to water use efficiency, which is the currently used determinant of productivity by the commercial forestry industry.
ii. The nine-year-old *E. grandis* x *E. urophylla* water use is statistically lower than *Eucalyptus* species water use conducted in the KwaMbonambi and adjacent areas.

iii. Water use by the eight-year-old *E. grandis* x *E. nitens* clonal hybrid will be statistically greater than the twenty-year-old *Pinus elliottii* at Two Streams research catchment.

iv. The young crop total water use (two-year-old *E. dunnii* and two-year-old *A. mearnsii*) is hypothesised to be statistically greater than the matured crop (six-year-old *A. mearnsii*) total water use at the Two Streams research catchment.

v. The three crops (three-year-old *A. mearnsii*, three-year-old *E. dunnii* and seven-year-old *A. mearnsii*) will produce a negative catchment surface water balance and all crops will negatively impact the streamflow.

1.6 Outline of dissertation/thesis structure

An overview of the thesis is provided in Figure 1.2, showing the technique that was used to achieve the overall aim of the study. Each chapter begins with Figure 1.2 so that the chapter is placed in the context of the overall thesis, with the relevant part of the figure highlighted in grey. This thesis is written in a paper format, using a set of papers which are either intended for submission, submitted or published to a peer-reviewed journal, using the thesis format acceptable by the University of KwaZulu-Natal.

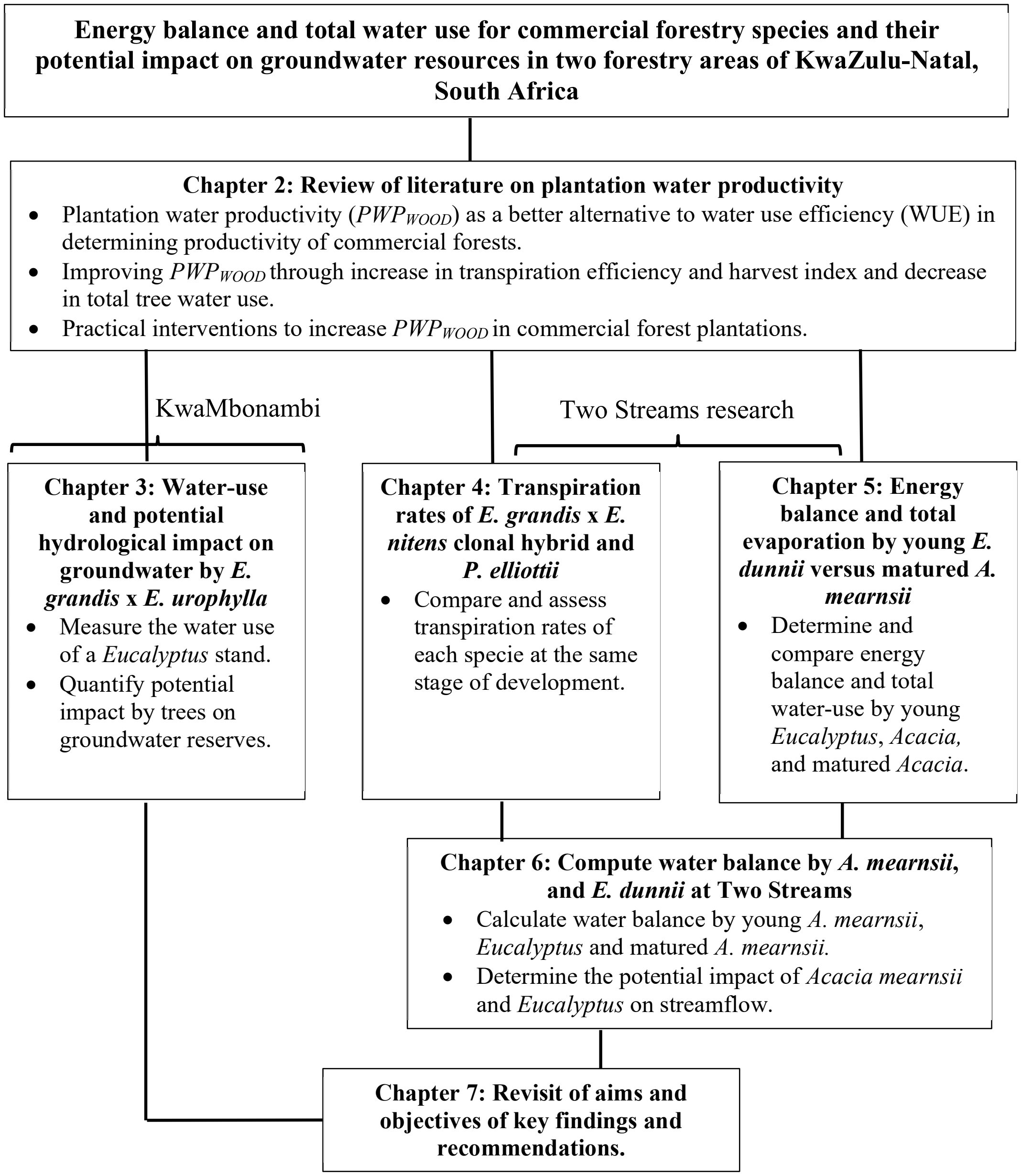


Figure 1.2 A conceptual framework of the research

Chapters 2 to 6 are written for publication, and each chapter includes a literature review, methodology used in data collection, research results, discussion, and conclusions. There is some overlap between chapters that is inevitable, particularly in the study area description and micrometeorological methods used to estimated tree water use. However, the focus of each chapter differs significantly, mainly due to the type of crop used in the study, soil and weather conditions. Once all the chapters are combined, they contribute towards improving the understanding of water use by commercial forestry species and their potential impact on groundwater resources and streamflow. The referencing style of each paper is aligned with a peer reviewed journal in which the manuscript was submitted, as per University of KwaZulu-Natal's thesis guideline. The outline for each chapter is described below:

Chapter 2 reviews the literature that outlines the importance of PWP_{WOOD}, defined as marketable biomass accumulation per unit of total water use by tree stand. This chapter highlights practical techniques that can be implemented by the commercial forestry industry in enhancing PWP_{WOOD}. The purpose of this chapter is to provide evidence that PWP_{WOOD} is a better alternative to water use efficiency, commonly used by the commercial forestry industry, in terms of producing more wood per unit of water used.

Chapter 3 is devoted to the expansion of water-use knowledge by the fast-growing *E. grandis* x *E. urophylla* clonal hybrid, popularly planted in humid northern Zululand regions of South Africa, through measurements of transpiration using sapflow techniques. In addition, the potential impact by deep-rooted trees on groundwater reserves was investigated.

Chapter 4 provides a comparison in water-use by fast-growing *E. grandis* x *E. nitens* clonal hydrid and *P. elliottii* at the same stage of development in warm temperate regions of South Africa, measured using the heat ratio method of measuring transpiration. In addition, the heat ratio method was calibrated using lysimeters to allow for the water use dataset to be corrected.

Chapter 5 provides insight into the differences in energy balance and total water-use by *E. dunnii* and *A. mearnsii* trees at Two Streams research catchment. Three measurement windows were identified where; i) *E. dunnii* tree were two years old ii) *A. mearnsii* trees were two years old and iii) *A. mearnsii* trees were six years old. Energy balance and total water use measurements were conducted using large aperture scintillometer (two-year-old *A. mearnsii*) and eddy covariance (two-year-old *E. dunnii* and six-year-old A. *mearnsii*), for a duration of one hydrological year. Comparison between energy balance and total water use was conducted over the three measurement windows.

Chapter 6 computes the surface water balance of the Two Streams research catchment when afforested with *A. mearnsii* and *E. dunnii*. Three measurement windows were identified where; i) *E. dunnii* trees were three years old ii) *A. mearnsii* trees were three years old and iii) *A.*

mearnsii trees were seven years old. The total evaporation, streamflow and rainfall data were sourced at CWRR for the three-year-old *A. mearnsii* and seven-year-old *A. mearnsii*, whereas direct measurements were conducted for *E. dunnii*. The potential impact by *A. mearnsii* and *E. dunnii* on streamflow was quantified.

The last chapter, Chapter 7, combines and synthesizes the research. The overall aim and objectives and research hypothesis of this research are revisited. The key findings, future research and limitations relating to different methods that were used to achieve the aims and objective of this research are also discussed.

1.7 References

Albaugh JM, Dye PJ, King JS. 2013: *Eucalyptus* and water use in South Africa. *International Journal of Forest Research* 11, 852540.

Bosch JM, Hewlett JD. 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. *Journal of Hydrology* 55: 3–23.

Bruijnzeel LA, Bonell M, Gilmour DA, Lamb D. 2005. Conclusion: forests, water and people in the humid tropics: an emerging view. In: Bonell M, Bruijnzeel LA (eds), Forests, water and people in the humid tropics: past, present and future hydrological research for integrated land and water management. Cambridge: Cambridge University Press. pp 906–925.

Bulcock HH, Gush MB, Jewitt GPW. 2014. A comparison of productive and non-productive green water-use efficiency of *Podocarpus henkelii* and *Pinus patula* in KwaZulu-Natal Midlands. *Southern Forests* 76(2): 75–84.

Calder IT.1986. A stochastic model of rainfall interception. *Journal of Hydrology* 89: 65–71.

Calder IR.1998. Water use by forests, limits and controls. *Tree Physiology* 18: 8-9.

DAFF (Department of Agriculture, Forestry and Fisheries). 2017. Report on commercial timber resources and primary roundwood processing in South Africa. Available at https://www.forestry.co.za/uploads/File/industry_info/statistical_data/new%20layout/Timber%20Statistics%20Report%20-%202016%20-%202017.pdf [accessed 15 June 2019].

Dye PJ. 1996. Response of *Eucalyptus grandis* trees to soil water deficits. *Tree Physiology* 16: 233–238.

Dye PJ, Poulter AG, Soko S, Maphanga D. 1997. *The determination of the relationship between transpiration rate and declining available water for Eucalyptus grandis*, Water Research Commission Report No. 441/1/97, ISBN 1868453057, Pretoria, South Africa, 103 pp., 1997.

Dye PJ, Vilakazi P, Gush M, Ndlela R, Royappen M. 2001. *Investigation of the feasibility of using trunk growth increments to estimate water use of Eucalyptus grandis and Pinus Patula plantation*. Water Research Commission Report No. 809/1/01, ISBN 1868458164, South Africa, 229 pp., 2001.

Dye PJ and Versfeld D. 2007. Managing the hydrological impacts of South African plantation forests: an overview. *Forest Ecology and Management* 251: 121-128.

Dye PJ. 2013. Review of changing perspectives on *Eucalyptus* water use in South Africa. *Forest Ecology and Management* 301: 51-57.

Dzikiti S, Schachtschneider K, Naiken V, Gush M, Le Maitre D. 2013. Comparison of water-use by alien invasive pine trees growing in riparian and non-riparian zones in the Western Cape Province, South Africa. *Forest Ecology and Management* 293: 92-102.

Godsmark R, Oberholzer F. 2019. South African forestry and forest products industry 2019. Available at https://www.forestry.co.za/uploads/File/industry_info/statistical_data/new%20layout/South%20African%20Forestry%20&%20Forest%20Products%20Industry%20-%202017.pdf [accessed 15 June 2019].

Gush M. 2016. Provision of expert opinion and advice in regard to proposed commercial forestry Genus Exchange regulations. CSIR REPORT FSA-1/2016.

Gush MB, Scott DF, Jewitt GPW, Schulze RE; Lumden T; Hallowes LA; Gorgens AHM. 2002. *Estimation of streamflow reduction resulting from commercial afforestation in South Africa*. WRC Report No. TT173/02. Pretoria: Water Research Commission.

Gush MB, Dye PJ, Naiken V, Geldenhuys CJ. 2015. Mixed species/mixed age Transkei Coastal Scarp Forest and Eucalyptus Plantation at Manubi. In: Gush, M.B. and Dye, P.J. (eds). 2015. *Water Use and Socio-Economic Benefit of the Biomass of Indigenous Trees*. WRC Report No.1876/2/15. Pretoria: Water Research Commission.

Jackson RB, Jobbágy EG, Avissar R, Roy SB, Barrett DJ, Cook CW, Farley KA, Le Maitre DC, McCarl BA, Murray BC. 2005. Trading water for carbon with biological carbon sequestration. *Science* 310: 1944–1947.

Le Roux D, Stock WD, Bond WJ, Maphanga D. 1996. Dry mass allocation, water use efficiency and δ13C in clones of *Eucalyptus grandis*, *E. grandis* x *E. camaldulensis* and *E. grandis* x *E. nitens* grown under two irrigation regimes. *Tree Physiology* 16: 497–502.

Mapeto T, Gush M, Louw J. 2018. Single-tree water use and water-use efficiencies of selected indigenous and introduced species in the Southern Cape region of South Africa. *Southern Forests* 80: 85–93.

Morris AR. 2022. Changing use of species and hybrids in South African forest plantations. *Southern Forests* 84(3): 1-13.

RSA (Republic of South Africa). 1998. National Water Act of the Republic of South Africa (No. 36 of 1998). *Government Gazette*, South Africa (19182).

Schulze RE, Lynch SD. 2007. *Monthly rainfall and its inter-annual variability*. In Schulze RE (ed.), South African atlas of climatology and agrohydrology, WRC Report no. 1489/1/06. Pretoria: Water Research Commission.

Scott DF, Lesch W. 1997. Streamflow responses to afforestation with *Eucalyptus grandis* and *Pinus patula* and to felling in the Mokobulaan experimental catchments, South Africa. *Journal Hydrology* 199: 360-377.

Scott DF, Le Maitre DC, Fairbanks DHK. 1998. Forestry and streamflow reductions in South Africa: a reference system for assessing extent and distribution. *Water SA* 24: 187–199.

Scott DF, Le Maitre DC, van Wyk E. 1999. *The effect of forestry on low flows: further studies on low flow in wet and dry cycles and in relation to catchments of increasing size*. CSIR Report No. ENV/S-C 99059. Pretoria: Council for Scientific and Industrial Research.

Scott DF. and Prinsloo FW. 2008. Longer-term effects of pine and eucalyptus plantations on streamflow. *Water Resources Research* 44: 1–8.

Vanclay JK. 2009. Managing water use from forest plantations. *Forest Ecology and Management* 257: 385–389.

van Dijk AI, Keenan RJ. 2007. Planted forests and water in perspective. *Forest Ecology and Management* 251: 1-9.

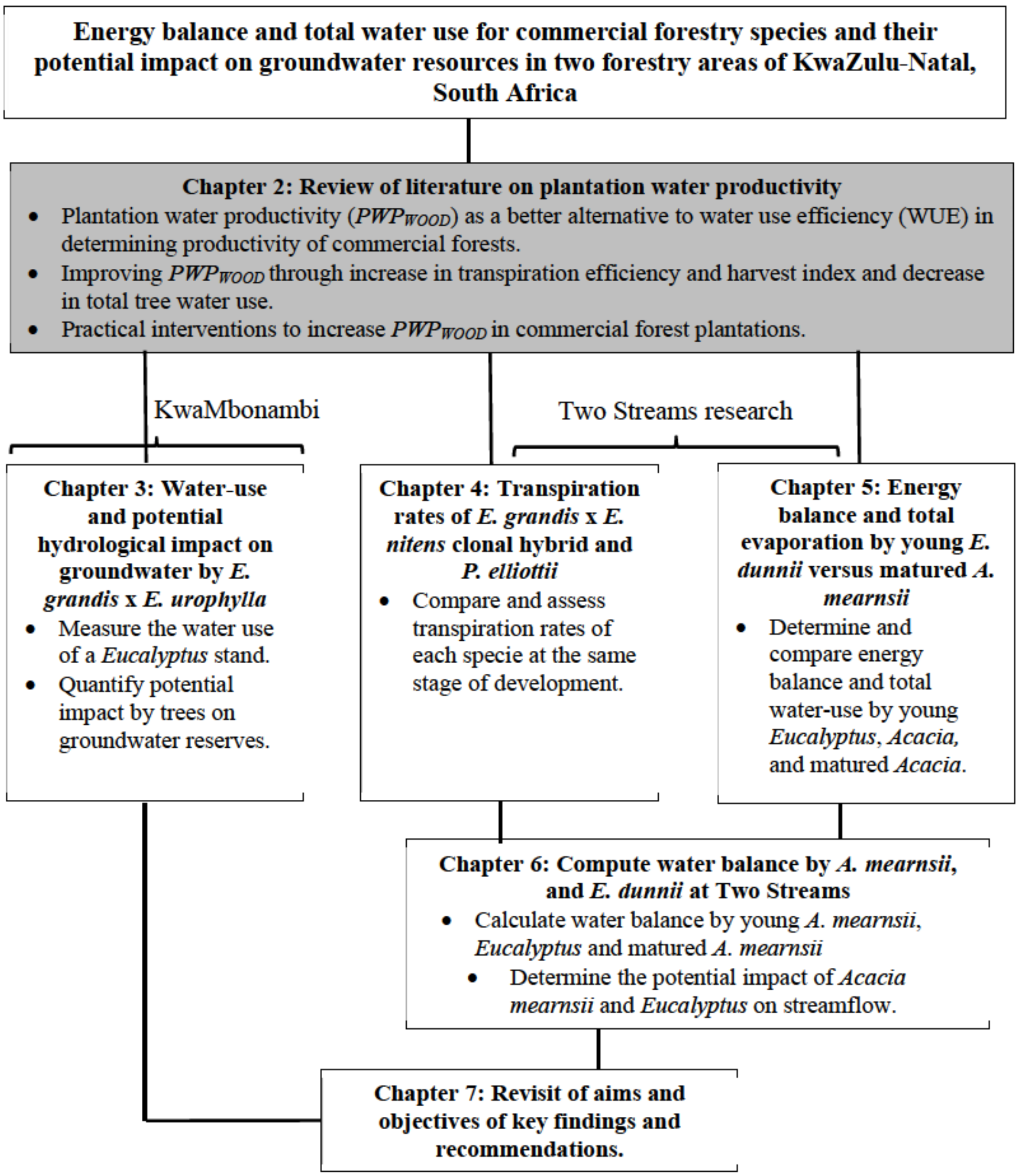
Whitehead D, Beadle CL. 2004. Physiological regulation of productivity and water use in *Eucalyptus*: a review. *Forest Ecology and Management* 193, 113-140.

White DA, Silberstein RP, Contreras FB, Quiroga JJ, Meason DF, Palma JHN, de Arellano PR. 2021. Growth, water use, and water use efficiency of *Eucalyptus globulus* and *Pinus radiata* plantations compared with natural stands of Roble-Hualo forest in the coastal mountains of central Chile. *Forest Ecology and Management* 501: 119675-119676.

White DA, McGrath JF, Ryan MG, Battaglia M, Mendham DS, Kinal J, Downes GM, Crombie DS, Hunt MA, 2014. Managing for water-use efficient wood production in *Eucalyptus globulus* plantations. *Forest Ecology and Management* 331: 272-280.

Xulu S, Gebreslasie MT, Peerbhay KY. 2019. Remote sensing of forest health and vitality: a South African perspective. *Southern Forests* 81(2): 91-102.

Lead into Chapter 2: Sets the scene and provides evidence locally and internationally of using plantation water productivity (*PWP_{WOOD}*) to enhance plantation yield of commercial forest plantations. The following literature review introduces the concept of *PWP_{WOOD}* as a better alternative to water use efficiency, and practical intervention that can be used by the commercial forestry industry to improve *PWP_{WOOD}* are provided. This chapter also provides fundamental background information which supports aims and objectives in subsequent chapters.



CHAPTER 2: PLANTATION WATER PRODUCTIVITY AS A MEASURE OF COMMERCIAL PLANTATION YIELD IMPROVEMENT: A REVIEW

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2.1 Abstract

Global demand for forest products is ever-increasing, creating competition for water between downstream water users and commercial forest producers. Tree production should, therefore, aim at the effective use of water, by producing maximum total dry stemwood with the least total evaporative losses. A ratio of accumulated biomass to transpiration (*T*) known as the water use efficiency (WUE) is a common technique used to determine productivity by the commercial forestry industry. This review argues that WUE does not account for total plantation water use (ET), transpiration efficiency of trees (*TE,* defined as the ratio of the volume of biomass produced per unit of water transpired by a leaf)) and the harvest index (HI, defined as a ratio of the percent of harvested wood mass to the total tree biomass, which is the most profitable component of a tree). We suggest using plantation water productivity of commercial plantation (PWP_{WOOD}), simply defined as a ratio of total dry stemwood per hectare (TE x HI) to ET. Improving PWP_{WOOD} requires that TE and HI are significantly increased through adequate supply of water and nutrient resources and cultural practices, while ET losses are kept to a minimum. Practical in-field interventions to improve TE and HI, while to a lesser extent reducing ET losses are discussed in detail and it is concluded that PWP_{WOOD} is a better alternative to WUE as shown by different case studies presented in this review.

Keywords: Effective water use, Evapotranspiration, Harvest index, Transpiration, Transpiration efficiency

2.2 Introduction

Global planted forest areas have increased in the last 26 years at an average rate of 2.5% per annum, reaching approximately 56 million ha (Payn et al. 2015). These plantations provide firewood, they are a source of renewable energy and many other environmental benefits (Bauhus et al. 2010, White et al. 2014). In many countries where exotic forests have been planted, the communities and governments have been concerned about the impact of these trees on natural resources such as water (Scott and Prinsloo 2008, Dye 2013, White et al. 2014). There is a high chance that these concerns may significantly increase in the future due to a rapid increase in wood demands as a result of population increase (estimated at 9 billion by 2050) and the implications of climate change (Hakamada et al. 2020). South Africa is one such country, which heavily depends on planting exotic timber species, particularly *Eucalyptus* and Pine to meet its wood demands, which contribute to the socio-economy and GDP of the country (Godsmark and Oberholzer 2017).

Most water-use experiments in South Africa (Le Roux et al. 1996, Dye et al. 2001) have included biomass measurements to enable the calculation of water use efficiency (WUE):

$$WUE = {}^{D_M}/_{T} \qquad (2.1)$$

where, D_M is the total dry matter accumulated by a tree (kg) and T is tree transpiration (kg H_2O). There is a consensus that improved WUE is synonymous with high plantation productivity (Dye et al. 2008). This paper raises the argument that the important determinant of plant yield improvement is the plantation water productivity (PWP) and not the WUE. The reasoning is that, 1) WUE only accounts for productive water use (the tree T) and not the non-productive water use (evaporative losses from the soil and tree canopy) (Bulcock et al. 2014), 2) WUE considers the total tree biomass (leaves, branches, roots etc), but stemwood is the most valuable component of a tree, and 3) The left-over harvest residues and fertilisation have a potential to improve T in a stand, through nutrient contribution and minimising soil evaporation, which are not factored in the WUE equation.

The PWP is defined as the maximum amount of utilisable wood produced from a given volume of water consumed by a tree (White et al. 2015). PWP targets effective use of water by a crop in conjunction with soil management practices such as plant nutrition. This technique was first proposed by Passioura (1977) and has since been successfully implemented in grain wheat farming (Passioura 2006) and commercial afforestation in Western Australia (White et al. 2014, 2015). Ongoing research efforts over recent decades by the agricultural industry (see Blum 2009 for a recent review) have seen doubled productivity using PWP. To avoid confusion with many other quantities labelled WUE and/ or PWP in literature, a term plantation water productivity of commercial forest plantations (PWP_{WOOD}) will be used in this study.

The commercial plantation wood yields (W, kg) can be expressed using (adapted from Passioura 1977):

$$W = T \times TE_{DM} \times HI \qquad (2.2)$$

where, TE_{DM} is the transpiration efficiency of accumulated dry matter (g of utilisable dry matter kg^{-1} H_2O), defined as WUE at the leaf level or a ratio of instantaneous CO_2 assimilation to plant T (Blum 2009), and HI is the partitioning of dry matter to harvestable stem wood (g of utilisable dry matter g^{-1} of total tree biomass). The W can be converted to wood volume (V, m^3) by dividing W with the specific gravity of wood. The specific gravity of wood is a measure of the amount of structural material a tree species allocates to support and strength (Williamson and Wiemann 2010). The total plantation water use (ET, mm) is the sum of T, total evaporation from the soil (Es, mm) and canopy and litter interception (C_I, mm) losses. Based on this information, the PWP_{WOOD} (g wood kg^{-1} H_20) can simply be calculated as:

$$\frac{Total\ dry\ stemwood}{Total\ plantation\ water\ use} \quad (2.3)$$

Equation 2.3 is further expressed in terms of the most important PWP_{WOOD} variables in Equation 2.4 as follows (Passioura 1977, White et al. 2014):

$$PWP_{wood} = \frac{T \times TE_{DM} \times HI}{T+Es+\ {}_{I}} \quad (2.4)$$

Equation 2.4 can be simplified to Equation 2.6

$$PWP_{wood} = \frac{TE_{DM} \times HI}{\frac{T}{T}+\frac{Es}{T}+\frac{C_I}{T}} \quad (2.5)$$

$$PWP_{wood} = \frac{TE_{DM}HI}{1+\left(\frac{E_{s}+C_I}{T}\right)} \quad (2.6)$$

The ratio of losses by $(Es + C_I)$ to T alters the denominator so that any fluxes other than T may produce efficiency reduction (White et al. 2021). The PWP_{WOOD} works best when paired with balanced soil nutrition. For example, key terms in equation 2.6, namely TE_{DM}, HI, $1 + \left(\frac{E_{s}+C_I}{T}\right)$ are all affected by the availability of soil nutrients. Application of fertiliser generally increases TE_{DM} of trees through high carboxylation and Rubisco regeneration (Warren et al. 2000) and high leaf area index (LAI), which result in increased solar radiation (*Is*) capture (Smethurst et al. 2003). In soil water limiting conditions, fertilised trees with high LAI may experience water stress that decreases TE_{DM} due to closure of stomata (Graciano et al. 2005), which in turn reduces the HI (Ryan et al. 2004). As a result, the interrelatedness and interdependence of soil water and nutrients on tree productivity cannot be overemphasised (Oren and Sherrif 1995). A variety of techniques can be used to enhance the management of nutrient and water supply to plantations, such as harvest residue retention, weed control, thinning and pruning and legume intercropping (Nambiar 1991).

Studies that investigate plantation productivity of commercial afforestation, with typical range values of 0.3 to 3.1 g wood kg^{-1} water (White et al. 2014, 2015), are of considerable importance, but they mainly focus on WUE. The objective of this review is to summarise current knowledge on (1) PWP_{WOOD} as a determinant of productivity in commercial forest plantations (2) the on-site practical interventions that can be implemented to improve PWP_{WOOD} in commercial forestry. The focus will be on the dominant commercial forestry genera in South Africa, namely *Eucalyptus* and *Pinus*, with reflection from international studies.

2.3 Materials and methods

2.3.1 Method

This study used a systematic review approach (Ham-Baloyi and Jordan 2015) that uses literature search techniques to select relevant studies that meet the topic in question. The goal of this review was to evaluate the extent of scientific consensus concerning the use of PWP_{WOOD} as a determinant of stem productivity with specific focus on soil water and nutrients. Improving commercial afforestation productivity may in turn address the issue of water competition between exotic plantations and downstream water users. A systematic literature search was conducted using key words and search terms. The sources of peer-reviewed publications and book chapters included Kopernio, ScienceDirect and Google databases. To broaden the scope of this study, grey literature was included such as scientific reports and dissertations. The following keyword combinations were used to retrieve relevant publications: plantation water productivity OR plant water productivity OR water use efficiency of commercial plantations OR impact of soil water and nutrients on plantation water productivity OR commercial forest harvest index OR transpiration efficiency in commercial forestry OR impact of total evaporation on forest productivity OR management interventions to enhance productivity in commercial forestry. As illustrated in Figure 2.1, the search identified 442 articles, which were narrowed down to 68 articles that made direct reference to PWP_{WOOD} (with specific reference to nutrients and water). The criteria used for selecting studies were as follows. First, they had to be restricted to commercial forest plantations (indigenous forests and other crops were used for comparison). Second, they had to make a direct reference to the impact of soil water and nutrients on PWP_{WOOD}.

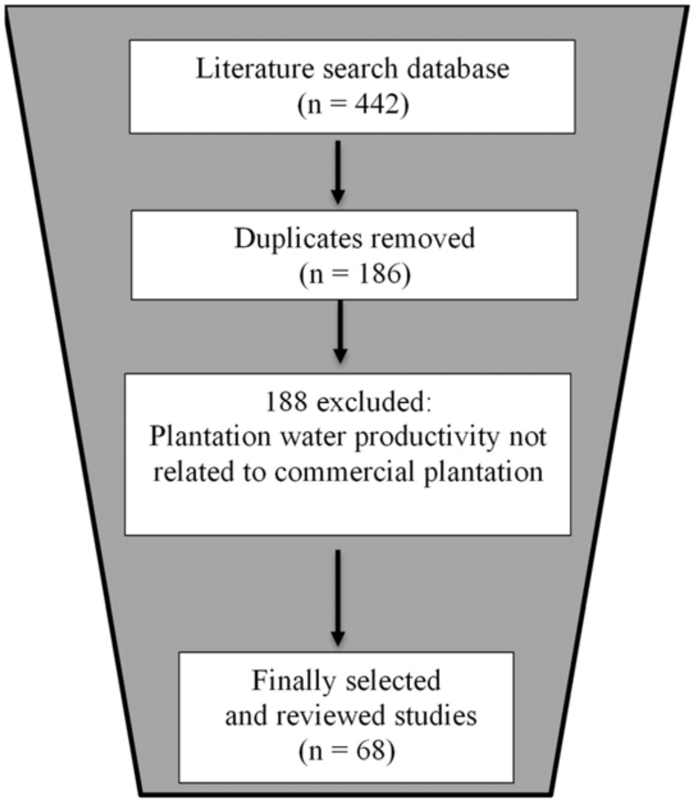

Figure 2.1: The schematic diagram showing the process followed in the literature search using various databases.

2.4 PWP_{WOOD} interplay with soil water and nutrient resources

Forest plantation productivity requires resources to be available in adequate quantities from the environment. These resources are converted to tree biomass via photosynthesis (Binkley et al. 2004). Woody biomass is the most important component to a tree farmer and constitutes 10 to 30% of the total tree biomass (Binkley et al. 2004). To manage PWP_{WOOD}, it is important to understand resources that are needed to drive the process of photosynthesis, and hence, tree productivity. These drivers are I_s (solar radiation), CO_2 in the air, air temperature (T_{air}), soil water and nutrients. At a given site, little can be done to optimise Is, CO_2 and T_{air} directly, such as row orientation (Campos et al. 2016). However, the availability of soil water content and nutrients can be adjusted easily, which will in turn increase tree leaf area resulting in more CO_2 and Is interception, therefore improving PWP_{WOOD} (Binkley et al. 2004, Stape et al. 2008). For example, in a study by Stape (2002) on a clonal *Eucalyptus* stand in Brazil, an increase in soil water content via irrigation increased gross primary production by 53%. Similarly, a *Eucalyptus* resource use efficiency study across a geographic gradient in Brazil found that productivity of *Eucalyptus* plantations increased with increasing rainfall (Stape et al. 2004). The aboveground net primary production increased by 2.3 Mg ha^{-1} $year^{-1}$ for each 100 mm increase in rainfall. However, both these studies could not separate the effects of water availability from other confounding factors such as soil nutrition, which are equally important.

White et al. (2014) reported a significant improvement in PWP_{WOOD} from 1.15 to 1.4 g of wood kg^{-1} H_2O due to the application of nitrogen (N) based fertilisers, which increased partitioning of dry matter (D_M) above ground, particularly the stemwood. A highly seasonal variation of PWP_{WOOD} from 0.3 to 3.1 g wood kg^{-1} H_2O was reported and attributed to progressive drying of soil. Ryan et al. (2004) concluded that an onset of water stress in a stand with adequate soil nutrients will result in an increased allocation of resources to belowground biomass in search for water, which will significantly impact stemwood productivity. In a comparative study (*Eucalyptus globulus* vs *Pinus radiata*) in central Chile (White et al. 2021), a PWP_{WOOD} of 3.8 and 1.2 g D_M kg^{-1} for *E. globulus* and *P. radiata* were reported, respectively. This suggested that *E. globulus* was an effective water user per D_M produced compared to *P. radiata.*
It is important to be cognisant of the interrelatedness and interdependence of soil water and nutrients as drivers of PWP_{WOOD} in commercial afforestation, suggesting that one variable becomes ineffective without the other. To improve PWP_{WOOD} in commercial afforestation, in - field cultural practices that influences both variables must be implemented.

2.5 Factors affecting commercial afforestation transpiration efficiency

Trees lose water into the atmosphere through the process of *T* when stomata open to acquire CO_2 for photosynthesis to take place. In turn, *T* results in the production of tree biomass (Sinclair 2012). The ratio of the volume of biomass produced per unit of water transpired by a leaf or the WUE at the leaf level is called transpiration efficiency (Condon et al. 2004, Blum 2009) mathematically expressed as:

$$TE = \frac{V\rho}{T} \qquad (2.7)$$

where, V is the volume of biomass produced per ground area (m^3 m^{-2}) and ρ is the density of biomass in kg m^{-3}. The *TE* is determined by the interplay between transient photosystem activity, concentration of substomatal cavity CO_2 and stomatal activity (Blum 2009). Seasonal

TE can also be estimated using carbon isotope discrimination measurement, also called delta (Blum 2009). For example, low delta correlates reasonably with high *TE* (Hall et al. 1994).

Increasing *TE* greater than $1 + \left(\frac{E_{S+C_I}}{T}\right)$ in equation 2.6, will result to a significant increase in PWP_{WOOD}. Transpiration efficiency has been reported to be highly influenced by silvicultural practices (such as thinning, pruning) and addition of resources (fertilisation and or irrigation), which has a potential to alter canopy conductance, leaf area, sapwood area and the water potential gradient between the soil and canopy, ultimately impacting tree productivity (Forrester et al. 2010, 2012, Hubbard et al. 2010). For example, thinning has been reported to positively influence *TE*, causing an increase in efficiency with which trees use water due to higher resources availability or acquisition (Stape et al. 2004, 2008). A study by Forrester et al (2012) on the effect of thinning and pruning on *TE* reported a 23 and 21% improvement of *TE* due to thinning and pruning, respectively. Thinning increased *TE* by improving the light penetration to lower tree canopy, while pruning removed the inefficient lower canopy foliage, thus increasing the efficiency of the foliage. Conversely, some studies have reported thinning and pruning to have negative impact on *TE*. For example, Macfarlane et al (2010) reported that thinning and pruning can lead to higher *Es*, soil temperatures and increased understory *T*. These conditions subject trees to high rates of *T* relative to V, reducing WUE, because of more open canopies leading to higher tree boundary layer conductance, making trees more sensitive to prevailing vapour pressure deficit.

Application of fertiliser and adequate plant available water often results in increases in LAI, which can result in high rates of *T* (Hubbard et al. 2010). The high rates of *T*, reduces plant available water, while high LAI increases C_I and increases self-shading within the canopy (Pinkard et al. 2007). A study by Stape et al (2008) showed that irrigation increased *TE* by approximately 28% in *E. grandis* and reported a positive correlation between *TE* with increased tree productivity. By contrast, Olbrich et al. (1993) demonstrated that during periods of limited water availability, *TE* increased. Similar findings were reported by Osorio et al. (1998) on the effects of water deficits on *TE* of *E. globulus* in Portugal, where a low watered treatment produced a higher *TE* compared to a well-watered treatment. This was attributed to stomatal closure, which reduced *T* and in doing so caused the tree to use water more effectively, resulting in an increase in tree biomass. In Northern China, Changhai et al (2010) reported that induced drought stress significantly increased *TE* by as much as 53%.

A study by Adamtey et al. (2010) on the effect of N enriched compost on *TE* under controlled irrigation, found that applying fast nutrient releasing fertilisers significantly increased *TE*. Application of potassium (K) on *E. grandis* increased *TE* for stem biomass production by 60% (Epron et al. 2012). In contrast, a study by Forrester et al. (2012) on *E. nitens* in South-east Australia reported that application of N did not increase *TE*, which was an indication that N application on its own did not improve *TE*.

The relationship between *TE*, cultural practices and water and nutrient resources is complex due to varying responses reported from different studies. The effectiveness of fertilisation can be influenced by soil water, another missing nutrient or weather factors. Similarly, the efficiency of cultural practices depends on site management practices and climatic conditions of a specific site.

2.6 Harvest index

Harvest index is defined as a ratio of the percent of harvested wood mass to the total tree biomass (including the below ground biomass) (White et al. 2014). The HI, also called the stemwood, is the most valuable component of a tree over the course of a rotation (Cannell and Willett 1976). Based on equation 2.6, to achieve the high PWP_{WOOD}, the HI needs to be significantly greater than $1 + \left(\frac{E_{S+C_I}}{T}\right)$. Breeding research has been successfully conducted to identify and select tree genotypes that convert a large proportion of photosynthates to HI (Mugnozza et al. 1996). Figure 2.2 presents several studies that quantified HI in commercial afforestation species in different countries. In commercial forestry, it has been reported that maximum HI is highly influenced by the availability of adequate soil water and nutrients in the vicinity of a tree throughout the crop rotation (Mugnozza et al. 1996). This can be enhanced by application of fertiliser and practicing cultural practices that minimise water loss from the soil surface such as retention of harvest residues. A lack of soil water and nutrients will cause a tree to allocate resources to belowground biomass (roots) to search for water and nutrients, which will impact negatively on the final harvest (Ryan et al. 2004). In pine species (ie. *P. sylvestris* L., *P. radiata*) the HI varies between 60 and 70% when computed as a ratio of stem biomass to total biomass (roots included) (White et al. 2021). In *E. globulus* plantations, Pereira et al. (1989) reported an HI increase of 30 to 60% in the first to third year, respectively. This increase was attributed to readily available water and nutrients due to irrigation and fertiliser application. Most studies that investigate HI in commercial plantations have neglected the belowground biomass because it is difficult to estimate (Friend et al. 1991). As a result, below ground biomass has been presumed to remain the same (Shepherd 1985), which is inaccurate as reported by Linder and Axelsson (1982).

There is a growing trend in the use of mechanised harvesting operations in South Africa as motor-manual harvesting operations carry a significant health and safety risks to operators (Christie 2006). During mechanical harvesting operation, stemwood can be subjected to damage by harvesting processes such as debarking and debranching (Connell 2003), resulting in low quality HI, thus reduced yields. Studies have reported mechanised harvesting damage on stemwood surface to be influenced by feed roller type, tree size and tree species (Nuutinen et al. 2010, Sveningsson 2011). Therefore, it is important for a tree farmer to adjust the mechanical harvester according to tree size, season, tree species and debarking or debranching equipment to minimise damage to the stemwood.

In conclusion, the HI is directly influenced by the presence of adequate soil water and nutrients in the vicinity of the crops. This can be achieved through fertilisation or cultural practices that minimises soil water loss. At harvesting, HI index can be reduced by mechanical harvesting technique damage, necessitating a thorough adjustment of the technique.

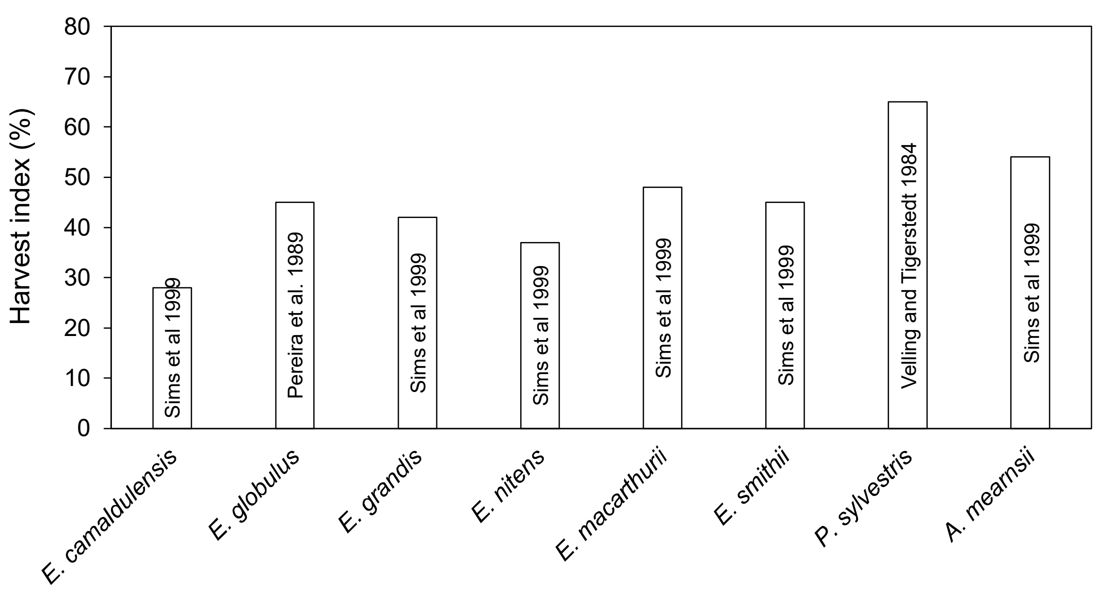

Figure 2.2: The harvest index for different *Eucalyptus*, pine and Acacia species.

2.7 Tree water losses

In a typical forest plantation, soil water can be lost through E_s, C_I, transpiration from understorey vegetation and T as influenced by atmospheric demands and climatic variables. As defined in Equation 2.6 soil water losses highly influence the PWP_{WOOD}.

2.7.1 Transpiration

There have been a considerable number of studies to estimate commercial forestry T in South Africa and internationally (Forrester et al. 2010, Hubbard et al. 2010, Dye et al. 2016, Hakamada et al. 2020) from a range of forestry species to understand the role played by tree transpiration in the water balance and tree productivity (Table 2.1). Exotic tree species T has been shown to increase sharply in the early stages of growth reaching a peak in the middle of the rotation, thereafter, declining as the stand matures (Delzon and Loustau 2005). A study by Forrester et al. (2010) on *E. globulus* in south-eastern Australia reported that T increased from 0.4 mm day^{-1} at two years of age to a peak of 1.6-1.9 mm day^{-1} at five- to seven years, before declining to 1.1 mm day^{-1} at eight years. This was associated with similar trends for LAI, sapwood area and annual increment in the above ground biomass. South African research has produced similar result patterns and mean daily T corroborates well with research from other countries (Dye 1996a, b).

Reflecting back to equation 2.6, the variable $1 + \left(\frac{E_{S+C_I}}{T}\right)$ indicates that T must be significantly increased to reduce the denominator of equation 2.6, which will in turn result to an increase in PWP_{WOOD}. For example, doubling T, while keeping all other variables constant increases PWP_{WOOD} by three folds. Tree T can be increased by supplying soil water and nutrients in adequate quantities. From South African forestry industry perspective, this can be achieved by 1) fertilisation at planting using the recommended fertiliser rates and fertiliser types as per laboratory analysis recommendations (Morris 2008) and 2) applying residue management practices that conserve soil water, since commercial afforestation in South African does not apply irrigation, such as retention of harvest residues after harvesting (e.g. windrowing, broadcasting or mulching and rolling). Retention of harvest residues will in turn minimise E_s.

Table 2.1: Selected transpiration rates (*T*, mm) for *Eucalyptus* and pine species in South Africa and in other countries. Mean daily *T* are shown or the daily T range.

Location	Species	Age (years)	*T* (mm)	Annual rainfall (mm)	Growing conditions	Source
Johannesburg, South Africa	*E. dunnii*	3	3.6	629	Plantation, grown in mine tailings	Dye et al. 2016
Johannesburg, South Africa	*E. grandis* x *camaldulensis*	4	4.4	795	Plantation, grown in mine tailings	Dye et al. 2016
Mount Desire, South Africa	*E. grandis*	7	7.8	800	Plantation	Dye et al. 2001
Mpumalanga, South Africa	*E. grandis*	9	2.0–4.0	1459	Access to groundwater	Dye 1996a Dye 1996b
Gilboa, South Africa	*P. patula*	8	4.6	850	Plantation	Dye et al. 2001
Demagtenburg, South Africa	*P. patula*	16	8.1	1125	Plantation	Dye et al. 2001
Wagga Wagga, New South Wales	*E. grandis*	5	4.3	570	Irrigated with effluent	Myers et al. 1998
Lisbon, Portugal	*E. globulus*	8	0.5–3.6	600	Plantation	David et al. 1997
Aracruz, Brazil	*E. grandis*	9	1.1–5.8	1396	Plantation	Soares and Almeida, 2001

2.7.2 Tree canopy interception and litter interception

It is well accepted that commercial forestry *ET* is larger than grasslands mainly due to the large amount of rainfall that is intercepted by the forest C_I (Calder 1986, Bulcock et al. 2012). This fraction of water does not reach the ground surface and therefore it is not available to the tree roots. Canopy and litter interception losses depends on precipitation characteristics and factors that affect *ET* such as T_{air}, wind speed, *Is* and relative humidity. Canopy and litter intercepted water has been found to evaporate at rates in excess of potential evaporation due to advection and low aerodynamic resistance of wet canopies (Bulcock et al. 2012). Two rainfall interception experiments undertaken in the Sabie area of Mpumalanga in South Africa (Dye 1993), reported C_I losses of 13 and 4.1% of gross rainfall for nine-year-old *P. patula* and two-year-old *E. grandis*, respectively. The results suggest that C_I depends on vegetative characteristics such as leaf shape, orientation, density or LAI and hydrophobicity of leaves and branches. A study by Bulcock et al. (2012) in KwaZulu Natal midlands of South Africa measured C_I in commercial forest plantations and showed that both play a very important role in the hydrological cycle, causing a reduction in gross precipitation by 24 to 33%. Canopy interception losses by five-year-old *Eucalyptus grandis*, five-year-old *Acacia mearnsii* and sixteen-year-old *Pinus patula* accounted for 14.9%, 27.7% and 21.4% of gross precipitation, respectively (Bulcock and Jewitt 2014). In comparison, it was found that litter interception resulted to 12.1% for *P. patula*, 8.5% for *E. grandis* and 6.6% for *A. mearnsii* losses of gross precipitation. These results are comparable to international studies. For example, Soares and Almeida et al. (2001) reported C_I losses of 11% in 9-year-old *E. grandis* in Brazil. The loss in C_I from *Eucalyptus* from studies in Israel, India and Australia produced a range from 10 to 34% of annual rainfall (Calder 1986), increasing with an increase in quantity of rainafall (Feller 2013). Canopy interception does not only reduce net precipitation, but is also a threshold process, meaning that a certain amount of precipitation is needed before subsequent processes such as infiltration and runoff may occur (Bulcock et al. 2012). This results in a delay in these processes, which may be in the order of days to weeks in cases where the next rainfall event is not large enough to exceed the canopy storage capacities. The research conducted shows that C_I losses reduce and delay hydrological processes, depending on the species planted.

The C_I is highly influenced by leaf area index, which is directly influenced by adequate supply of soil water and nutrients. Looking back at equation 2.6, maintaining adequate soil water and nutrients in the soil will positively influence the numerator (*TE* and *HI*), however, C_I will also increase which will negatively impact PWP_{WOOD}. Equation 2.6 indicates that doubling C_I, while all other variables are kept constant will decrease PWP_{WOOD} by a factor of 0.8 g wood kg^{-1} H_20.

2.8 Plantation management practices to enhance water productivity

Improving PWP_{WOOD} can be achieved in two ways; first, by significantly reducing ET lower than the associated W, second, by significantly increasing the W, while reducing ET. Little can be done on the former, while increasing W is a more feasible option from a plantation forestry operations perspective. The most practical interventions of increasing W to an extent greater than ET are discussed below.

2.8.1 Intensive silviculture

There are many examples where silvicultural practices such as competing vegetation control (Little et al. 2003), site preparation (Smith et al. 2001), fertilisation (du Toit et al. 2001), planting density (Bredenkamp 1987) and the planting stock quality (Zwolinski and Bayley 2001) have resulted in a significant increase in commercial plantation growth, hence improvement in plantation yield. The role of these plantation management practices has been associated with minimising environmental stresses and maximizing the use of resources to improve the final yield of a stand (Pallet and Sale 2002, du Toit et al. 2010).

2.8.1.1 Competing vegetation control

Competing vegetation management (also called weeds) has formed a vital part of forestry practices in around the world, including South Africa, and if conducted properly and timeously can result to yield improvements in forest plantations (Nambiar 1991, Wagner et al. 2006, Nambiar and Sands 2011). South African studies (Little and Rolando 2001, Little and van Staden 2003) have shown that vegetation management (using herbicides) is critical in terms of improving tree growth immediately after plantation establishment and up to the end of a rotation, with the exception of plantation forests grown at altitude above 1500 m a.s.l., where growth loses from competing vegetation has been reported to be rarely significant (Wagner et al. 2006). A South African study by Little et al (2003) investigated the impact of weedy versus weed free treatments on forest productivity in the KwaZulu-Natal, Zululand regions of South Africa. Results from this study showed that merchantable wood volume from weed free plots was 41% greater than weedy plots. Additional benefits achieved from keeping the plantation weed free were high wood fibre length and high wood density. In general, proper, and timely scheduling of vegetation management in *Eucalyptus* plantations have produced 29 to 122% improvement in stand volume when grown over a normal pulpwood rotation (Little 1999, Little et al. 2003). By comparison, pine plantations data (early to mid-rotation) suggest 10 to 100%

improvement in stem volume due to vegetation management (Kotze 2002, Rolando and Little 2004).

International studies from countries such as New Zealand, Australia, Brazil, Chile, Canada and USA found results similar to South African studies (Glover and Zutter 1993, Kimberly and Richardson 2004). For example, a study by Yildiz (2000) in the United States investigated the effects of vegetation control on commercially grown Douglas fir and results showed that a complete removal of vegetation in the first five years of tree growth improved stand volume by 454% relative to plots with no vegetative control. Similarly, a Brazilian study by de Toledo et al (2003) examined the effect of width of vegetation control band in *Eucalyptus grandis* x *E. urophylla* clonal hybrid (*GU*) and reported a 108% increase in *GU* stand volume due to competing vegetation control.

To achieved high yields in a commercial forest plantation, a recommendation for a forest producer is to develop a comprehensive competing vegetation control plan for the entire crop rotation with the intention of suppressing competing vegetation.

2.8.1.2 Fertilisation

The use of fertiliser to improve yields have been extensively researched and reviewed in South Africa (Herbert and Schonau 1989, 1990, Noble and Herbert 1991, Carlson et al. 2001, du Toit et al. 2001, du Toit and Drew 2003) due to its immediate alteration of site nutrient budgets. The current recommendation is that at planting, fertiliser is applied 10-20 cm from the plant and the fertiliser is buried under the surface (Herbert and Schonau 1989). This practice has been shown to significantly benefit the final yield, particularly on short rotation hardwood crops (Herbert and Schonau 1990, Herbert 1996), leading to the almost universal operational use of fertiliser at planting in South African forest plantations. A study by Davidson (1996) reported that residual effects of fertiliser applied at planting, contributed to tree growth throughout the stand rotation, a conclusion shared by Crous et al (2013) in a *P. patula* plantation in Usuthu, Swaziland.

Most documented responses indicated that *Eucalyptus* stand fertilisation at planting has a potential to increase timber volume on a matured stand by 20 to 90 m^3 ha^{-1}, with concurrent 15 to 30 kg m^{-3} in wood density (Carlson et al. 2001, du Toit at al. 2001, du Toit and Drew 2003). In softwood plantations, Herbert and Schönau (1989) reported a 58% tree productivity increase in *P. patula*, while Donald and Glen (1974) reported a 11.5% productivity improvement in *P. radiata* by the end of the first rotation after fertiliser application. Du Toit (2002) reported a 30 and 50 m^3 ha^{-1} increase in *Acacia mearnsii* productivity following the application of PK fertiliser at establishment.

2.8.1.3 Harvest residue management

Harvesting operation may leave as much as 51 tons ha^{-1} of harvest residues on a site (Dovey 2015) which constitute mainly forest litter, tree branches, treetops and low-quality wood. In Southern Africa, burning or removal of harvest residues is the most used residue management technique to enable site management ease, reduce fire risk and minimise nutrient immobilisation (Norris 1993, Smith et al. 2005). Many international studies have shown a significant reduction in stand productivity due to removal of harvest residues in countries such as North America (Scott and Dean, 2006), Brazil (Goncalves et al. 2007), Republic of Congo (Nzila et al. 2004), Australia (O'Connel et al. 2004) and China (Xu et al. 2004). In a study by Goncalves et al (2007) comparing *E. grandis* productivity under different residues management practices, complete removal of harvest residues caused productivity reduction of 30% (equivalent to 52 t ha^{-1}) in comparison to plots where harvest residues were not removed. Similar results were reported on other studies comparing removal and retention of harvest residues treatments (O'Connel et al. 2004, Nzila et al. 2004). In a Brazilian study by Rocha (2016), burning of harvest residues significantly increased wood volumes in the first stand rotation, however, wood volumes decreased to levels of harvest residues removal in the second rotation, which was 40% less than harvest residue retention.

In southern Africa, a study by du Toit et al. (2004) in Karkloof, South Africa found that the only removal of harvest residue had a significant negative effect on tree productivity, while burning and retention of harvest residues had the best growth response. Mavimbela et al. (2018) on *P. patula* in Swaziland indicated that a complete removal of harvest residues resulted in 9 and 33% loss in tree productivity in the second and third rotation, respectively.

The retention of harvest residues in the soil has been associated with many benefits such as: 1) reduction of extreme soil surface temperatures (Goncalves et al. 2000), 2) increase microbial activity of the soil (Wu et al. 2011), 3) protection of soil against erosion (Bertoni and Lombardi Neto 2008), 4) increase nutrient mineralisation (Fernandez et al. 2009) and 5) reduced water loss through soil evaporation (Matthews 2005). Each of these benefits have been reported to positively influence commercial forest plantation productivity (Rocha et al. 2016).

2.8.2 Planting density

The choice of planting in South Africa is highly dependent on the requirement of the market (Norris 2000). For example, pulpwood where the main aim is to produce high fibre, a planting density that is high is a better option (ie. 1667 tree ha^{-1}), while a low planting density is used for sawlog. Higher density of planting has been associated with higher total biomass, increased mean annual increment, decreased time to attain mean annual increment, however, with decreased total biomass per tree (Crous et al. 2019). According to Stape et al (2001), there is no one optimum spacing, however, a spacing between 1200 and 1500 trees ha^{-1}, produced very little changes in final tree productivity. A South African study by Smith et al (2007) on the effects of initial stand density on tree growth and yield found that on highly productive sites, a stocking rate of between 1200 and 1500 trees ha^{-1} produced the maximum growth and yield (24% greater than 1111 tree per ha^{-1}), which can be achieved by commercially using a stand density of 1667 trees ha^{-1}. Crous et al (2019) compared trees planted at 1111 (low density) versus 1667 trees ha^{-1} (high density) in KwaZulu Natal midlands of South Africa and found that high density trees had 10.4% and 6% greater basal area and utilisable volume than low density trees, respectively. In a tree spacing experiments of *E. grandis* (Smith et al. 2005) within temperate regions of South Africa, an increase in productivity of between 2 to 7 m^3 ha^{-1} $year^{-1}$ was recorded close to rotation end when trees were planted at density of 1667 trees ha^{-1} compared to 1111 trees per ha^{-1}.

For commercial forest plantations that are mechanically harvested, it is critical to be mindful that mechanised harvesting operations productivity improves with an increase in the average tree volume (Ramantswana et al. 2013). Therefore, it is crucial to balance between planting density, harvesting costs and the mean tree size, as the density of planting that produces the high tree volume might not be the most financially viable option (Crous et al. 2019).

2.8.3 Site-species matching

Plantation forest areas in South Africa cover a wide range of areas which subject them to a wide variation in soil types, rainfall and temperatures (Morris 2008). It is primarily for this reason of site diversity, that species suitable for a specific site is selected for the with an intention of managing risks associated with a failure of crop due to drought, hail and snow, pests and diseases and frost (Swain and Gardner 2004). The site-species matching in commercial forestry species has been well researched and summarised in South Africa (Clarke et al. 1997, Gardner 2007, Swain and Gardner 2004, Nichols et al 2010, Gardner et al. 2018) providing clear evidence that selecting a best species for a specific site results in improved tree productivity and ultimately crop yields. In a South African study by Gardner et al (2018) in warm temperate areas of KwaZulu-Natal, the basal area for *E. dunnii*, considered to be best suited to these climatic conditions, was 42 to 62% greater than alternative species (*E. grandis* and *E. benthamii*). Under similar conditions, a study by Crous et al. (2019) reported a 10% higher survival, 6.4% greater basal area and 18.9% greater production in volume per ha by the first-choice species (*E. dunnii*) relative to a species that was an alternative (*E. grandis*, *E. smithii* and *E. macarthurii*). In New Zealand, a study by Sims et al (1999) investigated the effect of site-species matching of nine *Eucalyptus* species and found that correctly matching species to site conditions produced a 15 to 20-fold increase in final yields.

In subtropical regions of South Africa, *E. grandis* is being replaced with *GU*, while in warm temperate regions, the *E. dunnii* is the species of choice (Morris 2022). These changes have been associated with statistically significant improvements in crop yields of 2 to 47% depending on the species and the site conditions (Morris 2008). In cool, temperate regions, the *E. nitens* and *E. macarthurii* are the two species of choice (Morris 2022). A comparative paired study measuring *E. nitens* and *E. macurthurii* on 23 locations (comparable sites) found that *E. nitens* is the most productive species, while *E. macarthurii* was found to be the most tolerant to frost (Morris 2008).

In addition, matching the species to a site assists in pest management, as trees that are physiologically stressed are more likely to be attacked by pathogens and pests (Nambiar and Harwood 2014) leading to productivity decline.

2.8.4 Quality of the planting stock and planting practices

High rate of seedling survival and early growth may be achieved by using planting stock of high quality integrated with planting practices that minimise the stresses associated with planting (South et al. 1993, Menzies et al. 2001, Mason 2001). A combination of poor-quality seedlings, poor handling, poor transportation and poor planting systems have been ascribed to reduce seedling survival and uniformity and translated to about 5% reduction in mean annual increment by the end of the rotation (Mead 2005). A South African study on *P. radiata*, using medium quality seedlings (South et al. 2001), produced an extra 20 m^3 ha^{-1} (equivalent to 22%) stand volume at 7 years of age, relative to poor quality seedlings. Similar responses have been reported by other studies (South et al. 1993), concluding that high quality planting stock plus good planting practices would produce 40-50% volume gain over a short-term, decreasing to 10% over long-term.

2.8.5 Tree improvement

Tree improvement is central to increasing plantation productivity per unit land area of commercial forestry species and have been implemented with success in many parts of the world, including Australia (Hamilton et al. 2008), Portugal (Borralho et al. 1992), Chile (Arnold et al. 1991) and South Africa (Boreham and Pallet 2009, Swain et al. 2015, Crous et al. 2019). Typical gain for first- and second-generation breeding programs for most commercial forestry species are 10 to 20% and 20 to 30%, respectively (Nambiar 1996, Martin and Shiver 2002). A study by Verryn et al (2007) predicted an average tree volume improvement of 27% of the second generation of *E. grandis* over the unimproved breeding material. A recent study by Crous et al (2019) in KwaZulu-Natal midlands of South Africa found that material that is improved genetically had a 4.5% higher utilisable wood volume than unimproved material. Overall, South African studies indicated that 5–20% productivity improvement can be achieved from a single generation of breeding (Boreham and Pallet 2009, Crous et al. 2019).

2.8.6 Yield improvement from combined effects of silviculture and genetic changes

To maximise yields in forest plantations, genetically improved trees must be planted at optimum sites, at the correct planting density and managed through good husbandry after planting. Research studies that measured a combination impact of practices of silviculture, choice of a species and improvements in genetics indicated that these benefits could improve productivity by 65% (range: 27 to 131%) (Boreham and Pallet 2009, Morris 2008, Crous et al. 2019). The impact of combined effects of silvicultural practices, stocking and genetics were demonstrated by Boreham and Pallet (2009) in a series of operation gain trials established across five sites within the temperate areas of KwaZulu-Natal in South Africa. A baseline (indicated as control or the first vertical bar in Figure 2.3) consisted of genetically unimproved material, established at a planting density of 1111 trees ha^{-1}, and consisted of very low silvicultural practices (no fertilisation and less weeding) across all five trials. The mean baseline control value was 25.3 m^3 ha^{-1} $year^{-1}$. Productivity improvement associated with genetic material, resulted in productivity gains of 8% across all five sites (Figure 2.3), indicated by a grey light-coloured vertical bar). Improvements in silviculture or stocking ranged from 13-14%, while a combination produced productivity gains of 34% (Figure 2.3). An overall productivity improvement of 46% was achieved when all silvicultural factors were combined.

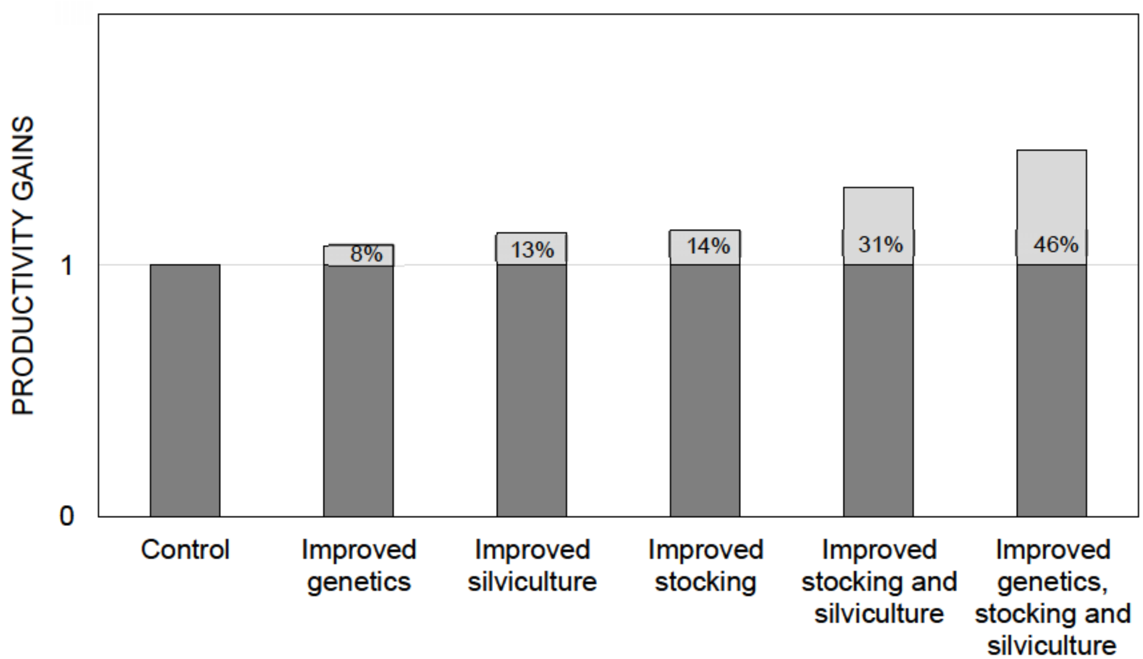

Figure 2.3: Middle of the rotation yield gains as influenced by tree improvements (genetics), intensive silviculture, stocking, a combination of stocking and intensive culture and genetics plus stocking plus intensive silviculture. Reproduced from Boreham and Pallet (2009).

2.8.7 Application of plantation water productivity

Commercial forest plantations are grown in compartments with varying levels of productivity, broadly categorised as highly productive sites (up to 58 m^3 ha^{-1} $year^{-1}$) and low productive sites (as low as 18 m^3 ha^{-1} $year^{-1}$) (Smith et al. 2006). Productivity of low productive sites is usually hampered by nutrient shortages, soil water shortages, poor matching of species to sites and low seedling survival post planting. In low productive sites, PWP_{WOOD} can be implemented inorder to improve plantation productivity, through plantation management practices highlighted in section 2.8 above. For example, 1) harvest residues can be retained after clearfelling, which is rarely done in commercial forests because they hamper site management ease, inorder to improve the soil water content of the soil (by minimising soil evaporation) and improve soil nutrients availability over time due to decomposition of harvest residues 2) Chemical fertilisers can be applied to correct for nutrient deficiencies where economically feasible 3) species suitable for conditions of a respective site implemented to minimise tree mortality and low growth rates. Implementing these practices will reduce the evapourtranspiration of the site, and increase the transpiration efficiency, thereby improving the PWP_{WOOD}.

2.9 Conclusions

In this review we provided the reasoning behind our suggestion of considering PWP_{WOOD} (equation 2.6), simply calculated as total dry stemwood (*TE* x *HI*) divided by total plantation water use (*ET*), as a better alternative to WUE. Literature suggests that improving PWP_{WOOD} requires a significant increase in *TE* and *HI*, which can be achieved through provision of resources (water and nutrients) and cultural practices. However, *ET* should be reduced through practices such as retention of harvest residues on site. We provide case studies in South Africa and in other countries where these interventions have been implemented with positive results. Management practices that can be implemented in-field by the commercial forestry industry to increase dry stemwood and to a lesser extent reduce *ET* losses, to increase PWP_{WOOD} were discussed showing that there are many aspects to increasing PWP_{WOOD} and management aspects to consider. In conclusion, PWP_{WOOD} is a better alternative to WUE and a transition to PWP_{WOOD} has many benefits.

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2.11 References

Adamtey N, Cofi O, Ofosu-Budu KG, Ofosu-Anim J, Laryea KB, Forster D. 2010. Effect of N-enriched co-compost on transpiration efficiency and water use efficiency of maize (*Zea Mays L*.) under controlled irrigation. *Agricultural Water Management 97*: 995-1005.

Arnold R, Carmona JC, Balocchi C. 1991. Clonal propagation program for *Eucalyptus globulus* in Chile. *Bosque* 12: 3-9.

Bauhus J. van der Meer P, Kanninen M. 2010. Ecosystem Goods and Services form Plantation Forests. Earthscan, London, UK.

Bertoni J, Lombardi Neto F. 2008. Conservation of the soil. *Icone Sao Polo* 12: 12-20.

Binkley D, Stape JL, Ryan MG. 2004. Thinking about efficiency of resource use in forests. *Forest Ecology and Management* 193: 5-16.

Blum A. 2009. Effective use of water (EUW) and not water-use efficiency (WUE) is the target of crop yield improvement under drought stress. *Field Crops Research* 112: 119–123.

Boreham GR, Pallett RN. 2009. The influence of tree improvement and cultural practices on the productivity of *Eucalyptus* plantations in temperate South Africa. *Southern Forests* 71: 85–9.

Borralho NMG, Cotterill PP, Kanowski PJ. 1992. Genetic parameters and gains expected from selection for dry weight in *Eucalyptus globulus spp*. globulus in Portugal. *Forest Science* 38: 80-94.

Bredenkamp BV. 1987. Effects of spacing and age on growth of *Eucalyptus grandis* on a dry Zululand site. *South African Forestry Journal* 115: 47–49.

Bulcock HH, Gush MB, Jewitt GPW. 2014. A comparison of productive and non-productive green water-use efficiency of *Podocarpus henkelii* and *Pinus patula* in KwaZulu-Natal Midlands. *Southern Forests* 76(2): 75–84.

Bulcock HH, Gush MB, Jewitt GPW. 2012. Field data collection and analysis of canopy and litter interception in commercial forest plantations in KwaZulu-Natal Midlands, South Africa. *Hydrological Earth Systems Sciences* 16: 3717-3728.

Calder IT.1986. A stochastic model of rainfall interception. *Journal of Hydrology* 89: 65–71.

Campos I, Neale CMU, Calera A. 2016. Is row orientation a determinant factor for radiation interception in row vineyards? *Australian Journal of Grape and Wine Research* 23(1): 77-86.

Carlson CA, Allan R, Soko S. 2001. Responses of *Eucalyptus* species to fertiliser applications made at planting on granite parent material in the Mpumalanga and Northern provinces of South Africa. *South African Forestry Journal* 191: 29-37.

Cannell, MGR, and Willett SC. 1976. Shoot growth phenology, dry matter distribution and root:shoot ratios of provenances of *Populus trichocarpa*, *Picea sitchensis* and *Pinus contorta* growing in Scotland. *Silvae Genetics* 25: 49–59.

Changhai S, Baodi D, Yunzhou Q, Yuxin L, Lei S, Mengyu L, Haipei L. 2010. Physiological regulation of high transpiration efficiency in winter wheat under drought conditions. *Plant Soil Environment* 56: 340-347.

Clarke CRE, Clegg PA and Galloway GA. 1997. Measurement of productivity in trials of E. grandis hybrid clones at two sites. In: Proceedings of the IUFRO conference on silviculture and management of eucalypts, Salvador, Brazil, 24–29 August 1997, vol. 1. Embrapa–Centro Nacional de Pesquisa de Florestas, Colombo, Brazil. pp 259–263.

Condon AG, Richards RA, Rebetzke GJ, Farquhar GD. 2004. Breeding for high water-use efficiency. *Journal of Experimental Botany* 55: 2447-2460.

Connell MJ. 2003. Log presentation: log damage arising from mechanical harvesting or processing. Forestry and Forest Products Report no. PN02.1309. [Melbourne]: Forest and Wood Products Research and Development Corporation.

Crous JW, Morris AR, Scholes MC. 2013. Effects of residual phosphorus and potassium fertiliser on organic matter and soil nutrients on *Pinus patula* plantation. Australian Forestry 3: 200-208.

Crous JW, Sale G, Naidoo T. 2019. The influence of species, tree improvement and cultural practices on rotation-end fibre production of *Eucalyptus* pulpwood plantations in South Africa. *Southern Forest: a journal of Forest Science* 81: 307-317.

David TS, Ferreira MI, David JS, Pereira JS. 1997. Transpiration from mature *Eucalyptus globulus* plantation in Portugal during a spring-summer period of progressively higher water deficit. *Oecologia* 110: 153-159.

Davidson J. 1996. Off site and out of sight! 1996. How bad cultural practices are offsetting genetic gains in forestry. In: Dieters MJ, Matheson AC, Nikles DG, Harwood CE, Walker SM. Proceedings of QFRI-IUFRO Conference on tree improvement for sustainable Tropical Forestry. Caloundra. Australia. pp. 288-294.

Delzon S, Loustau D. 2005. Age-related decline in stand water use: sap flow and transpiration in a pine forest chronosequence. *Agricultural and Forest Meteorology* 129: 105-119.

de Toledo REB, Victoria FR, Bezutte AJ, Pitellii RA, Da Costa AA, Do Valle CF, Alvarenga SF. 2003. Períodos de controle de Brachiaria sp e seus reflexos na produtividade de Eucalyptus grandis. *Scientia Forestalis* 63: 221-232.

Donald DGM, Glen LM. 1974. The response of *Pinus radiata and Pinus pinaster* to N, P and K fertilizers applied at planting. *South African Forestry Journal 91:* 19–28.

Dovey SB. 2015. Nitrogen mineralisation in a clonal *Eucalyptus* plantation on sandy soil after clearfelling and residue burning. *Indian Forester* 141 (4): 411-421.

du Toit B, Arbuthnot A, Oscroft D, Job RA. 2001. The effects of remedial fertilizer treatments on growth and pulp properties of *Eucalyptus grandis* stands established on infertile soils of the Zululand coastal plains. *South African Forestry Journal* 192: 9–18.

du Toit B. 2002. Wattle nutrition. In: Dunlop R, McLennan WL. Black Wattle: The South African research experience. Institute for Commercial Forestry Research, Pietermaritzburg, South Africa.

du Toit B, Drew D. 2003. Effects of fertilising four eucalypt hybrid stands at planting on wood density, screened pulp yield and fibre production. *ICFR Bulletin No. 22/2003*. Institute for Commercial Forestry Research. Pietermaritzburg, South Africa.

du Toit B, Dovey SB, Fuller GF, Job RA. 2004. Effects of harvesting and site management on nutrient pools and stand growth in a South African eucalypt plantation. In: Nambiar EKS, Ranger J, Tiarks A, Toma T (eds), Site management and productivity in tropical plantation forests: proceedings of the workshops in Congo (July 2001) and China (February 2003). Bogor: Center for International Forestry Research. pp 31–43.

du Toit B, Smith CW, Little KM, Boreham G and Pallett RN. 2010. Intensive, site-specific silviculture: Manipulating resource availability at establishment for improved stand productivity. A review of South African research. *Forest Ecology and Management* 259: 1836–1845.

Dye PJ. 1993. Development of generalized models of rainfall interception by *Eucalyptus grandis* and *Pinus patula* plantations. Report FOR-DEA 623, Department of Water Affairs and Forestry, Pretoria, South Africa.

Dye PJ. 1996a. Climate, forest and streamflow relationships in South African afforested catchments. *The Commonwealth Forestry Review* 22: 31–38.

Dye PJ. 1996b. Response of Eucalyptus grandis trees to soil water deficits. *Tree Physiology* 16: 233–238.

Dye P, Vilakazi P, Gush M, Ndlela R, Royappen M. 2001. Investigation of the feasibility of using trunk growth increments to estimate water use of *Eucalyptus grandis* and *Pinus patula* plantation. WRC Report No. 809/1/01. Pretoria: Water Research Commission.

Dye PJ, Gush MB, Everson CS, Jarmain C, Clulow A, Mengistu M, Geldenhuys CJ, Wise R, Scholes RJ, Archibald S, Savage MJ. 2008. Water use in relation to biomass of indigenous tree species in woodland, forest and/or plantation conditions. WRC Report No. TT361/08. Pretoria: Water Research Commission

Dye PJ. 2013. Review of changing perspectives on *Eucalyptus* water use in South 482 Africa. *Forest Ecology and Management* 301: 51-57.

Dye PJ, Clulow AD, Prinsloo E, Naiken V, Weiersbye I. 2016. The annual pattern of sap flow in two *Eucalyptus* species established in the vicinity of gold-mine tailings dams in central South Africa. *Southern Forests: a Journal of Forest Sience* 78: 307–313

Epron D, Laclau J-P, Almeida JCR, Gonçalves JLM, Ponton S, Sette CRJR, Delgado-Rojas JS, Bouillet J-P, Nouvellon Y. 2012. Do changes in carbon allocation account for the growth response to potassium and sodium applications in tropical *Eucalyptus* plantations? *Tree Physiology* 31: 1–13.

Fernandez C, Vega JA, Bara S, Beloso C, Alonso M, Fonturbel T. 2009. Nitrogen mineralisation after clearcutting and residue management in a second rotation *E. globulus Labill*. Stand in Galicia (NW Spain). *Annals of Forest Science* 66: 1-7.

Ferraz SF, Rodrigues CB, Garcia LG, Alvares CA, Lima W. 2019. Effects of Eucalyptus plantations on streamflow in Brazil: moving beyond the water use debate. Forest Ecology and Management 453: 117571.

Forrester DI, Theiveyanathan S, Collopy JJ, Marcar NE. 2010. Enhanced water use efficiency in a mixed *Eucalyptus globulus* and *Acacia mearnsii* plantation. *Forest Ecology and Management* 259: 1761–1770.

Forrester DI, Collopy JJ, Beadle CL, Warren CR, Baker TG. 2012. Effect of thinning, pruning and nitrogen fertiliser application on transpiration, photosynthesis and water-use efficiency in a young *Eucalyptus nitens* plantation. *Forest Ecology and Management* 266: 286–300.

Godsmark R, Oberholzer F. 2017. South African forestry and forest products industry 2017. Available at https://www.forestry.co.za/uploads/File/industry_info/statistical_data/new%20layout/South%20African%20Forestry%20&%20Forest%20Products%20Industry%20-%202017.pdf [accessed 15 June 2019].

Goncalves JM, Stape JL, Benedettii V, Fessel VAG, Gava JL. 2000. Reflections of minimal and intensive soil cultivation in its fertility and tree nutrition. Piracicaba. IPEF

Gonçalves JM, Wichert MCP, Gava JL, Masetto AV, Arthur JC, Serrano MIP, Mello SLM. 2007. Soil fertility and growth of *Eucalyptus grandis* in Brazil under different residue management practices. *Southern Hemisphere Forestry Journal* 69: 95–102.

Graciano C, Guiamet JJ, Goya JF. 2005. Impact of nitrogen and phosphorus fertilization on drought responses in *Eucalyptus grandis* seedlings. *Forest Ecology and Management* 212, 40–49.

Feller MC. 2013. Water balances in *Eucalyptus regnans*, *E. obliqua*, and *Pinus radiata* forests in Victoria. *Australian Forestry* 44: 153-161.

Friend AL, Scarascia-Mugnozza GE, Isebrands JG, Heilman PE. 1991. Quantification of two-year-old hybrid poplar root systems: morphology, biomass and 14C distribution. *Tree Physiology* 8: 109–119.

Gardner RAW. 2007. Investigating the environmental adaptability of promising sub-tropical and cold-tolerant eucalypt species in the warm temperate climate zone of KwaZulu-Natal, South Africa. *Southern Hemisphere Forestry Journal* 69: 27–38.

Gardner RAW, Little KM, Kanzler A, Naidoo T. 2018. Alternative eucalypts for commercial pulpwood production at moderately dry sites in the warm temperate zone of KwaZulu-Natal, South Africa. *Southern Forests* 80: 115–129.

Glover GR, Zutter BR. 1993. Loblolly pine and mixed hardwood stand dynamics for 27 years following chemical, mechanical and manual site preparation. *Canadian Journal of Forest Research* 23: 1-12.

Hakamada RE, Hubbard RM, Stape JL, Lima W, Moreira G, Ferraz. 2020. Stocking effects on seasonal tree transpiration and ecosystem water balance in a fast-growing *Eucalyptus* plantation in Brazil. *Forest Ecology and Management* 466: 118149-118149.

Hall AE, Richards RA, Condon AG, Wright GC, Farquhar GD. 1994. Carbon isotope discrimination and plant breeding. *Plant Breeding Reviews* 12: 81-113.

Ham-Baloyi W, Jordan P. 2015. Systematic review as a research method in post graduate nursing education. *Health SA Gesondheid* 21: 120-125.

Hamilton M, Joyce K, Williams D, Dutkowski G, Potts B. 2008. Achievements in forest tree improvement in Australia and New Zealand 9. Genetic improvement of *Eucalyptus nitens* in Australia. Australian Forestry 71: 82-93.

Herbert MA, Schönau APG. 1989. Fertilising commercial forest species in southern Africa: Research progress and problems (part 1). *South African Forestry Journal 151:* 58–70.

Herbert MA, Schonau APG. 1990. Fertilising commercial forest species in Southern Africa: research progress and problems (part 2). *South African Forestry Journal* 152: 34-42.

Herbert MA. 1996. Fertilisers and eucalypt plantations in South Africa. In: Attiwill PM, Adams MA (Eds). Nutrition of eucalypts. CSIRO, Australia, pp 303-325.

Hubbard RM, Stape J, Ryan MG, Almeida AC, Rojas J. 2010. Effects of irrigation on water use and water use efficiency in two fast growing *Eucalyptus* plantations. *Forest Ecology and Management* 259: 1714–1721.

Kimberly MO, Richardson B. 2004. Importance of seasonal growth patterns in modelling interactions between radiata pines and some common weed species. *Canadian Journal of Forest Research* 43: 184-194.

Kotze H. 2002. *P. patula–S. megaphylla* competition trial at Frankfort. SAFCOL Document, Weed/104/001/00/807. Safcol Research, Sabie, South Africa.

Le Maitre DC, Gush MB, Dzikiti S. 2015. Impatcs of invading alien plant species on water flows at stand and catchment scales. *AOB Plants* 7: 13-21.

Le Roux D, Stock WD, Bond WJ, Maphanga D. 1996. Dry mass allocation, water use efficiency and δ13C in clones of Eucalyptus grandis, *E. grandis* x *E. camaldulensis* and *E. grandis* x *E. nitens* grown under two irrigation regimes. *Tree Physiology* 16: 497–502.

Linder S, Axelsson B. 1982. Changes in carbon uptake and allocation patterns as a result of irrigation and fertilization in a young *Pinus sylvestris* stand. In Carbon uptake and allocation in sub-alpine ecosystems as a key to management. Edited by R.M. Waring. Oregon State University, Corvallis. pp. 38–44.

Little K. 1999. The influence of vegetation control on the growth and pulping properties of a *Eucalyptus grandis* × *camaldulensis* hybrid clone. PhD thesis, University of Natal, South Africa.

Little KM, Rolando CA. 2001. The impact of vegetation control on the establishment of pine at four sites in the summer rainfall region of South Africa. *South African Forestry Journal* 192: 31 – 40.

Little KM, Rolando CA. 2002. Post establishment vegetation control in a *Eucalyptus grandis* x *E. camaldulensis* stand: research note. *Southern African Forestry Journal* 193: 25-31.

Little KM, van Staden J, Clarke GPY. 2003. The relationship between vegetation management and the wood and pulping properties of a *Eucalyptus* hybrid clone. *Annals of Forest Science* 60: 673–680.

Little KM, van Staden J. 2003. Interspecific competition affects early growth of a *Eucalyptus grandis* × *E. camaldulensis* hybrid clone in Zululand. *South Africa Southern African Journal* 69: 505–513.

Martin SW, Shiver BD. 2002. Impacts of vegetation control, genetic improvement and their interaction on Loblolly pine growth in the Southern United States-age 12 results. *Southern Journal of Applied Forestry* 26: 37-42.

Mason EG. 2001. A model of the juvenile growth of *Pinus radiata D*. Don: adding the effect of seedling quality. *New Forests* 22: 133-158.

Matthews S. 2005, The water vapour conductance of *Eucalyptus* litter layers. *Agricultural Forest Meteorology* 135: 73-81.

Mavimbela L, Crous JW, Morris AR, Chirwa PW. 2018. The importance of harvest residue and fertiliser on productivity of *Pinus patula* across various sites in their first, second and third rotations, at Usutu Swaziland. *New Zealand Journal of Forestry Science* 48: 5

Mead JM. 2005. Opportunities for improving plantation productivity. How much? How quickly? How realistic? *Biomass and Bioenergy* 28: 249-266.

Menzies MI, Holden DG, Klomp BK. 2001. Recent trends in nursery practice in New Zealand. *New Forests* 22: 3-17.

Morris AR. 2008. Realising the benefit of research in eucalypt plantation management. *Southern Forests* 70: 119–129.

Morris AR. 2022. Changing use of species and hybrids in South African forest plantations. *Southern Forests: a journal of forest science* 84(3): 1-13.

Mugnozza GE, Ceulemans R, Hellman PE, Isebrands JG, Stettler RF, Hinckley. 1996. Production physiology and morphology of Populus species and their hybrids grown under short rotation. II. Biomass components and harvest index of hybrid and parental species clones. *Canadian Journal of Forest Research* 27: 285-294.

Myers BJ, Benyon RG, Theiveyanathan S, Criddle RS, Smith CJ, Falkiner RA. 1998. Response of effluent-irrigated *Eucalyptus grandis* and *Pinus radiata* to salinity and vapour pressure deficits. *Tree Physiology* 18: 565-573.

Nambiar EKS. 1991. Management of forests under nutrient and water stress. *Water Air Soil Pollution* 54: 209-230.

Nambiar EKS. 1996. Sustained productivity of forests is a continuing challenge to soil science. *Soil Science Society of America Journal* 60: 1629-1642.

Nambiar EKS, Sands R. 2011. Competition for water and nutrients in forests. *Canadian Journal of Forest Research* 23: 1955-1968.

Nichols JD, Geoff R, Smith B, Grant J, Glencross K. 2010.Subtropical eucalypt plantations in eastern Australia. *Australian Forestry* 73: 53-62.

Noble AD, Herbert MA. 1991. Influence of soil organic matter content on the responsiveness of E. grandis to Nitrogen fertiliser. *South African Forestry Journal* 1: 23-27.

Norris CH. 1993. Slash management. *ICFR Bulletin Series no. 15/1993*. Institute for Commercial Forestry Research. Pietermaritzburg, South Africa.

Norris CH. 2000. Silviculture regime: eucalypts. In: Owen DL (eds) South African forestry handbook, vol. 1 4th edn. Southern African Institute of Forestry, Pretoria. pp 121-123.

Nuutinen Y, Väätäinen K, Asikainen A, Prinz R, Heinonen J. 2010. Operational efficiency and damage to sawlogs by feed rollers of the harvester head. *Silva Fennica* 44: 121–139.

Nzila JD, Deleporte P, Bouillet JP, Laclau JP, Ranger J. 2004. Effects of slash management on tree growth and nutrient cycling in second-rotation Eucalyptus replanted sites in the Congo. In: Nambiar EKS, Ranger J, Tiarks A, Toma T (eds), Site management and productivity in tropical plantation forests: Proceedings of the workshops in Congo (July

2001) and China (February 2003). Bogor: Center for International Forestry Research. pp 15–30.

O'Connell AM, Grove TS, Mendham DS, Rance SJ. 2004. Impact of harvest residues management on soil nitrogen dynamics in *Eucalyptus globulus* plantations in south western Australia. *Soil Biology and Biochemistry* 36: 39-48.

Olbrich BW, Le Roux D, Poulter AGW, Bond J, Stock WD. 1993. Variation in water use efficiency and δ 13C levels in *Eucalyptus grandis* clones. *Journal of Hydrology* 150: 615–633.

Oren R, Sheriff DW. 1995. Water and nutrient acquisition by roots and canopies: In: Smith WK, Hinckley TM (eds), Resource physiology of conifers: acquisitions, allocation and utilisation. Cambridge: Academic Press. pp 39–74.

Osorio J, Osorio ML, Chaves MM, Pereira JS. 1998. Effects of water deficits on 13C discrimination and transpiration efficiency of *Eucalyptus globulus* clones. *Australian Journal of Plant Physiology* 25 (6): 645-653.

Passioura JB. 1977. Grain Yield, Harvest Index and Water Use of Wheat. *Journal of the Australian Institute of Agricultural Science* 22: 117–120.

Passioura JB. 2006. Increasing crop productivity when water is scarce—from breeding to field management. *Agricultural Water Management* 80: 176–196.

Payn T, Carnus JM, Freer-Smith P, Kimberley M, Kollert W, Liu S, Orazio C, Rodriguez L, Silva LN, Wingfield MJ. 2015. Changes in planted forests and future global implications. *Forest Ecology and Management* 352: 57–67.

Pereira JS, Linder S, Araujo MC, Pereira H, Ericsson T, Borralho N, Leal LC. 1989. Optimization of biomass production in *Eucalyptus globulus* plantations—a case study. In Biomass production by fast-growing trees. Edited by J.S. Pereira and J.J. Landsberg. Kluwer Academic Publ., Dordrecht, Netherlands. pp.101–121.

Pinkard EA, Battaglia M, Mohammed CL. 2007. Defoliation and nitrogen effects on photosynthesis and growth of *Eucalyptus globulus*. *Tree Physiology* 27: 1053-1063.

Ramantswana M, McEwan A, Steenkamp J. 2013. A comparison between excavator-based harvester productivity in coppiced and planted *Eucalyptus grandis* compartments in KwaZulu-Natal, South Africa. *Southern Forests* 75: 239–246.

Rocha JHT, Goncalves JLD, Gava JL, Godinho TD, Melo EASC, Bazani JH, Hubner A, Arthur JC, Wichert MP. 2016. Forest residue maintenance increased the wood productivity of a *Eucalyptus* plantation over two short rotations. *Forest Ecology and Management* 379: 1–10.

Ryan M, Binkley D, Fownes J, Giardina C, Senock R. 2004. An experimental test of the causes of forest growth decline with stand age. *Ecological Monograms* 74: 393– 414.

Scott DF, Prinsloo FW. 2008. Longer-term effects of pine and *Eucalyptus* plantations on streamflow. *Water Resources Research* 44: 1–8.

Scott DA, Dean TJ. 2006. Energy trade-offs between intensive biomass utilisation, site productivity loss, and ameliorative treatments in loblolly pine plantations. *Biomass Bioenergy* 30: 1001-1010.

Shepherd KR. 1985. Carbon balance partitioning and yield of forest crops. In Research for forest management. Edited by J.J. Landsberg and W. Parsons. Commonwealth Scientific and Industrial Research Organization, Canberra. pp285

Sims REH, Senelwa K, Maiava T, Bullock BT. 1999. *Eucalyptus* species for biomass energy in New Zealand—Part I: growth screening trials at 2rst harvest. *Biomass and Bioenergy* 16:199 –205.

Sinclair TR. 2012. Is transpiration efficiency a viable plant trait in breeding crop improvement? *Functional Plant Biology* 39 (5): 359-365.

Smethurst PJ, Baillie C, Cherry M, Holz G. 2003. Fertilizer effects on LAI and growth of four *Eucalyptus nitens* plantations. *Forest Ecology and Management* 176: 531–542.

Smith CW, Little KM and Norris CH. 2001. The effect of land preparation at re-establishment on the productivity of fast-growing hardwoods in South Africa. *Australian Forestry* 64: 165–174.

Smith CW, du Toit B. 2005. The effect of harvesting operations, slash management and fertilisation on the growth of a *Eucalyptus* clonal hybrid on a sandy soil in Zululand, South Africa. *Southern African Forestry Journal* 203: 15–26.

Smith CW, Gardner RAW, Pallett RN, Swain T, Du Plessis M, Kunz RP. 2005. A site evaluation for site: species matching in the summer rainfall regions of southern Africa. *ICFR Bulletin Series 04/2005*. Pietermaritzburg: Institute for Commercial Forestry Research.

Smith CW, Kassier H, Morley T. 2006. The effect of initial stand density on the growth and yield of selected Eucalyptus grandis clonal hybrids in Zululand. *ICFR Bulletin Series 04/2006*. Pietermaritzburg: Institute for Commercial Forestry Research

Smith CW, Morley T, Kassier H. 2007. The effect of initial stand density on the growth and yield of selected cold-tolerant eucalypts. *ICFR Bulletin Series 13/2007*. Pietermaritzburg: Institute for Commercial Forestry Research.

Soares JV, Almeida AC. 2001. Modelling the water balance and soil water fluxes in a fast-growing *Eucalyptus* plantation in Brazil. *Journal of Hydrology* 253: 130–147.

South DB, Mitchell RJ, Zutter BR, Balneaves JM, Barber BL, Zwolinski JB. 1993. Integration of nursery practices and vegetation management: economic and biological potential for improving regeneration. *Canadian Journal of Forest Research* 23: 2083-2092.

South DB, Zwolinski JB, Kotze H. 2001. Early growth responses from weed control and planting larger stock of *Pinus radiata* are greater than that obtained from mechanical soil cultivation. *New Forests* 22: 199-211.

Stape JL, Goncalves JLM, Goncalves AN. 2001. Relationship between nursery practices and field performance for *Eucalyptus* plantations in Brazil. *New Forests* 22: 19-41.

Stape JL. 2002. Production ecology of clonal *Eucalyptus* plantations in north-eastern Brazil. Ph.D. dissertation, Colorado State University, Ft. Collins.

Stape JL, Binkley D, Ryan MG, Gomes ADN. 2004. Water use, water limitation, and water use efficiency in a *Eucalyptus* plantation. *Bosque* 25, 35-41.

Stape JL, Binkley D, Ryan MG. 2008. Production and carbon allocation in a clonal E*ucalyptus* plantation with water and nutrient. *Forest Ecology and Management* 255 (3-4): 920-930.

Sveningsson L. 2011. Dubbskador på Alvestakubb [Stud damages on Alvestakubb]. MFor thesis, Swedish University of Agricultural Sciences, Sweden.

Swain TL, Gardner RAW. 2004. Cold tolerant *Eucalypts* in South Africa-growth information for informed site-species matching. *Southern African Forestry Journal* 202: 25-36.

Verryn SD, Snedden CL, Eatwell KA. 2007. A comparison of deterministically predicted genetic gains with those realised in a South African *Eucalyptus grandis* breeding program. *Southern Forests* 71: 141–146.

Wagner RG, Little KM, Richardson B, McNabb K. 2006. The role of vegetation management for enhancing productivity of the world's forests. *Forestry* 79: 57-79.

Warren CR, Adams MA, Chen Z. 2000. Is photosynthesis related to concentrations of nitrogen and Rubisco in leaves of Australian native plants? *Australian Journal of Plant Physiology* 27: 407–416.

White DA, McGrath JF, Ryan MG, Battaglia M, Mendham DS, Kinal J, Downes GM, Crombie DS, Hunt MA, 2014. Managing for water-use efficient wood production in Eucalyptus globulus plantations. *Forest Ecology and Management* 331: 272-280.

White DA, Beadle CL, Worledge D, Honeysett JL. 2015. Wood production per evapotranspiration was increased by irrigation in plantations of *Eucalyptus globulus* and *E. nitens*. *New Forests* 47: 303-317.

White DA, Silberstein RP, Contreras FB, Quiroga JJ, Meason DF, Palma JHN, de Arellano PR. 2021. Growth, water use, and water use efficiency of *Eucalyptus globulus* and *Pinus radiata* plantations compared with natural stands of Roble-Hualo forest in the coastal mountains of central Chile. *Forest Ecology and Management* 501: 119675-119676.

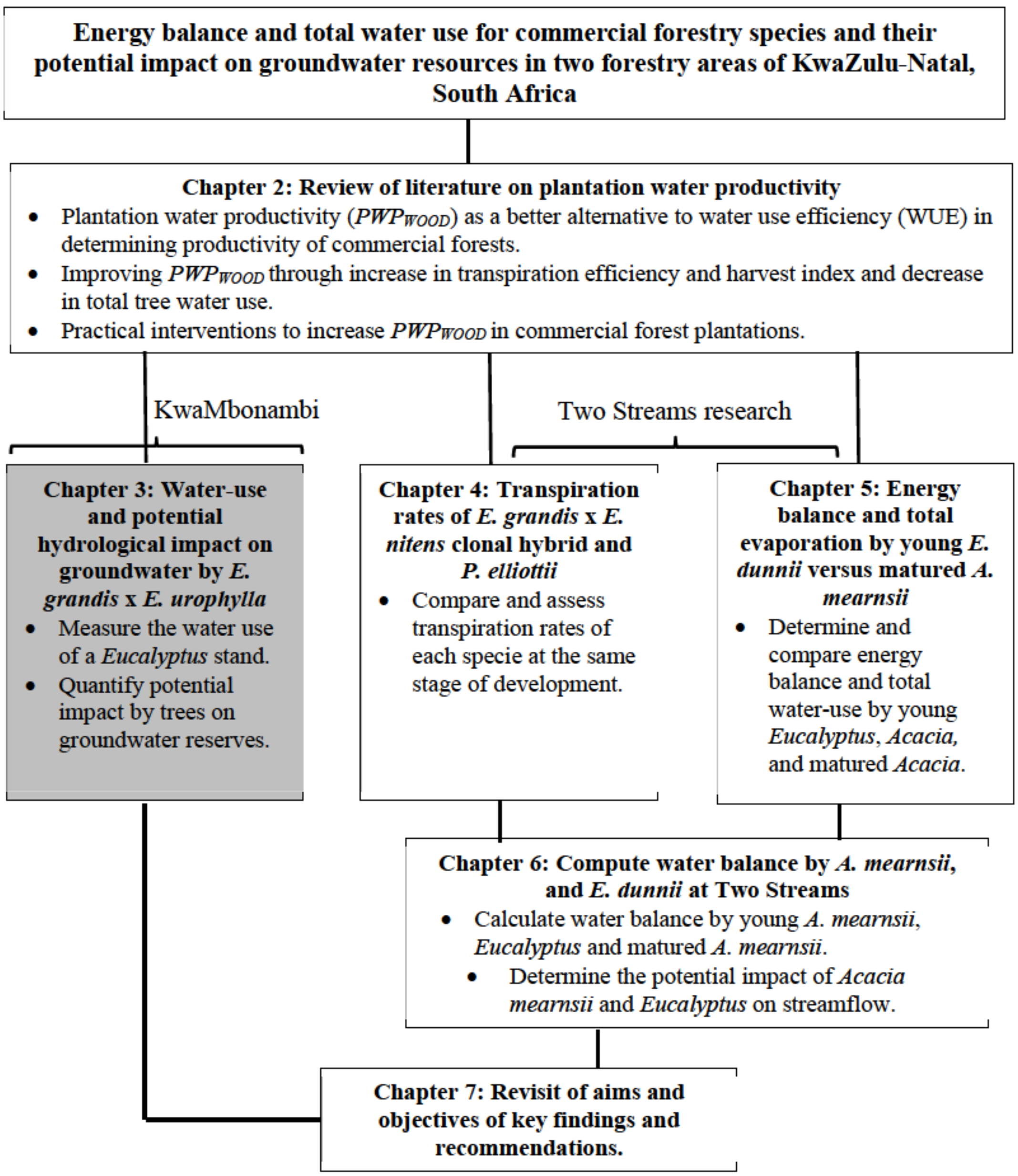
Wolliamson GB, Wiemann MC. 2010. Measuring wood specific gravity … Correctly. *American Journal of Botany* 97(3): 519-524.

Xu DP, Yang ZJ, Zhang NN. 2004. Effects of site management on tree growth and soil properties of a second-rotation plantation of Eucalyptus urophylla in Guangdong Province, China. In: Nambiar EKS, Ranger J, Tiarks A, Toma T (eds), Site management and productivity in tropical plantation forests. Proceedings of the workshops in Congo (July 2001) and China (February 2003). Bogor: Center for International Forestry Research. pp 45–60.

Yildiz O. 2000. Ecosystem effects of vegetation removal in coastal Oregon Douglas-fir experimental plantation: impacts on establishment and long-term growth of *Pinus radiata* plantations. PhD thesis, Oregon State University, USA.

Zwolinski J and Bayley AD (2001) Research on planting stock and forest regeneration in South Africa. *New Forests* 22: 59–76.

Lead into Chapter 3: While previous *Eucalyptus* tree water use studies in humid northern Zululand of KwaZulu-Natal have made a significant contribution on stand water use and hydrological implications over the years, none have measured water use by fast growing *Eucalyptus grandis* x *E. urophylla* clonal hybrid (*GU*), which is the most planted *Eucalyptus* species by the commercial forestry industry in this region. Consequently, the objective of chapter 3 was to expand water use knowledge by *GU*, calculate PWP_{WOOD} of *GU* and quantify *GU* potential impact on groundwater resources in KwaMbonambi, northern Zululand, South Africa.



CHAPTER 3: WATER USE AND POTENTIAL HYDROLOGICAL IMPLICATIONS OF FAST-GROWING NINE-YEAR OLD *EUCALYPTUS GRANDIS* X *EUCALYPTUS UROPHYLLA* HYBRID IN THE NORTHERN ZULULAND, SOUTH AFRICA

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3.1 Abstract

Measuring tree sapflow at a scale of a forest stand is vital in providing a better understanding of the hydrological impact that *Eucalyptus* may cause on soil water resources. In this study, we measured the sapflow of four, nine-year-old, *Eucalyptus grandis* x *Eucalyptus urophylla* clonal hybrid (*GU*) trees in the commercial forestry area of northern KwaZulu-Natal, on the north-east coast of South Africa. Sapflow was measured using the heat ratio method of the heat pulse velocity technique over two consecutive hydrological years (2019/ 20 and 2020/ 21) and up-scaled to a stand level transpiration. Measurements of leaf area index (LAI), quadratic mean diameter, calculated as the square root of the sum of squared mean diameters and soil water content (*SWC*) were conducted over the same period using an LAI 2200 plant canopy analyser, manual dendrometers and CS616 sensors, respectively. Results showed that the sapflow followed a seasonal pattern, with mean daily sapflow of 2.3 mm tree^{-1} day^{-1} (range: 0.18 to 4.55 mm tree^{-1} day^{-1}) and 3.3 mm tree^{-1} day^{-1} (range: 0.06 to 6.6 mm tree^{-1} day^{-1}) for 2019/ 20 and 2020/ 21 years, respectively, corroborating with previous studies in KwaMbonambi. The annual *GU* sapflow was higher than international studies under similar conditions, regardless of the low soil water content measured in the study site, but within the same sapflow range as *Eucalyptus* genotypes in KwaMbonambi area. The plantation water productivity, which was calculated as a ratio of stand volume to tree sapflow, was higher than other published studies which was attributed to a very high productive potential of the study site. The simple linear regression between sapflow and growth variables was weak (R^2: 0.20 to 0.30). Multiple regression using the Random Forests predictive model indicated that FAO reference evaporation, solar radiation and *SWC* (measured at 0.6 m depth) were the most important predictors of sapflow. There is a high possibility that our *GU* tree rooting system extracted water in the unsaturated zone during the dry season to meet transpiration demands, resulting to a reduction in water available to recharge the water table. Due to short-term results in this study, the impact of *GU* on groundwater resources could not be quantified, however, previous long-term paired catchment studies in South Africa concluded that *Eucalyptus* caused a negative impact on groundwater resulting to streamflow reduction. Further research is suggested with long-term measurements of sapflow, total evaporation, soil water storage and an isotope study to partition the sources of water use by the *GU* trees to confirm the use of unsaturated zone water.

Keywords: Heat pulse velocity, Ground water reserves, Plantation water productivity, Sapflow

3.2 Introduction

Eucalyptus plantations in many countries have been a subject of criticism due to their high-water use compared to indigenous forests and grasslands (Morris et al. 2004, Scott and Prinsloo 2008, Vanclay 2009) and other negative environmental impacts (Scott et al. 1999). The impact is more severe in semi-arid countries such as South Africa (Schulze and Lynch 2007, Dye 2013). Commercial forest plantations in South Africa are generally restricted to high rainfall areas (> 800 mm) (Albaugh et al. 2013). The potential evaporation from these areas typically ranges from 1100 to 1200 mm per annum, which is significantly greater than precipitation (Dye and Versfeld 2007, Albaugh et al. 2013). Trees have been reported to survive in these areas due to their deep rooting system enabling them to access deep water reserves, especially during drier months (van Dijk and Keenan 2007). Kimber (1974) reported that eucalypts may develop a dimorphic root structure to increase chances of accessing water in the soil surface as well as in deep soil layers.

Some studies have provided evidence that well-managed *Eucalyptus* plantations provide more benefits that negative impacts to the environment (Casson 1997), for example commercial forests improve soil infiltration (van Dijk and Keeenan 2007), significantly reduce surface runoff (soil erosion) and minimise soil evaporation from forest compartments (Wichert et al. 2018). However, studies in South Africa (Dye 1996), India (Calder 1992) and southern China (Morris et al. 2004) showed that with limited water resources, the management and location of *Eucalyptus* trees must be carefully considered to minimise water competition with other water users.

Expansion of the knowledge of *Eucalyptus* water use (particularly the genetically improved clonal hybrids produced by forest breeding programs) is vital to understand the impact these species have on the environment and to plan strategies near the important catchments where the production of wood plays a pivotal role in the economy. Research in several countries, including South Africa (Dye 1996, Dye et al. 2016), Australia (Myers et al. 1996), Brazil (Hubbard et al. 2010, Smethurst et al. 2015, Hakamada et al. 2020) and central Chile (White et al. 2021) has increased our understanding of *Eucalyptus* water use, but there are limited studies that have investigated the water use of clonal hybrids in subtropical regions of South Africa such as northern KwaZulu-Natal in South Africa.

In 2019, the South African Department of Environment, Forestry and Fisheries (DEFF) reported that the subtropical regions (northern KwaZulu-Natal coast, South Africa) were planted to 66 803 ha of *Eucalyptus* plantations, which account for 5.6% of total commercial forestry areas in South Africa, and play a crucial role in the economy of this region (DSSA 2019). The most planted forest species in this region is *Eucalyptus grandis* x *Eucalyptus urophylla* clonal hybrid (*GU*) due to its high tolerance to fungal diseases such as *Crysoporthe austroafricana* and *Coniothyrium spp* which are prevalent in the humid coastal belt of KwaZulu-Natal (Swain et al. 2003). Soils in this area are deep, extremely well drained and have a low water holding capacity (due to their low clay content) (Hartemink and Hutting 2005). There have been concerns that the high-water using eucalypts may contribute to reduction in underground water reserves (Dye 1997) in this area. The only tree water use study previously conducted in the region investigated *E. grandis* (Dye 1997, Everson et al. 2019) and *E. grandis* x *E. camaldulensis* clonal hybrid (Dye et al. 2004) and to our knowledge, there has been no previous work on water use by *GU*. This study reports daily and annual water use (referred to as sapflow in this study) by nine-year-old *GU* stand in KwaMbonambi, northern KwaZulu-Natal, South Africa. In addition, the relationship between sapflow and micrometeorological variables was established to enable the estimation of sapflow from easy to measure micrometeorological data.

3.3 Materials and methods

3.3.1 Study site

The site was located in the Zululand coastal plains, (KwaMbonambi, northern KwaZulu-Natal, South Africa, Figure 3.1) 25 km north of Richards Bay (28°36’03.05”S 32°11’18.00”E) with extensive areas of sandy structureless albic arenosols (Fey and Hughes 2010). Measurements were initiated at the end of September 2019 in a 5-ha stand of a nine-year-old *GU* at the Mondi KwaMbonambi nursery. The coastal areas in the KwaMbonambi region were previously converted from a mosaic of indigenous lowland coastal forest and grassland to commercial forestry (Fey and Hughes 2010). Soils in this area are very deep (> 30 m), free draining aeolian sands with organic carbon content less than 1% (Dovey et al. 2011). The climatic and soil characteristics of the site were typical of subtropical humid conditions as detailed in Table 3.1. The *GU* trees were planted in October of 2011 with a spacing of 3 m x 2 m (1667 trees ha^{-1}) using clonal cuttings. The study site was subjected to standard afforestation practices such as pruning and thinning and weeding pre-canopy closure.

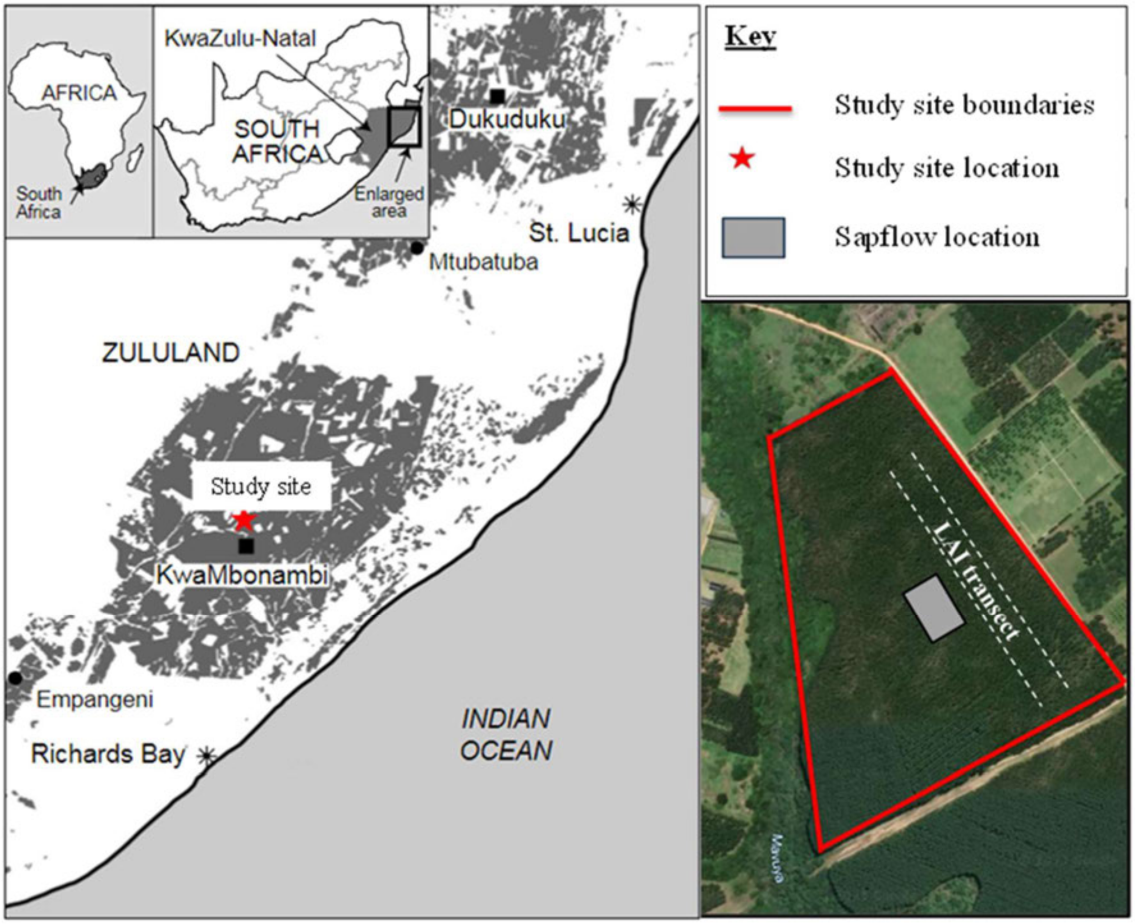

Figure 3.1: Location of KwaMbonambi study site in the north-eastern area of KwaZulu-Natal. Grey areas indicate the distribution of commercial forestry areas. The Google Earth Pro extract (bottom right) provides aerial view of the study site planted with *Eucalyptus grandis* x *E. urophylla*, showing the placement of the sapflow measuring equipment and the transect used to measure the leaf area index (LAI).

Table 3.1: Characteristics of the Kwambonambi study site.

Characteristics	***E. grandis* x *E. urophylla* site**
Soil texture	Sandy soil
Bulk density (g. cm^3)	0.88
Mean annual precipitation (mm)	1260
Mean annual temperature (°C)	21.9
Altitude (m)	24

*South African Taxonomic System

3.3.2 Environmental monitoring

Weather data were sourced from the open access Mondi KwaMbonambi automatic weather station (AWS) (28°36'1"S 32°10'53"E) located about 500 m from the study site (Mondi Forest Operations, 2022) with all sensor measurements at a height of 2 m above the ground surface except the raingauge which was at 1.2 m. Hourly and daily data of air temperature (T_{air}, ºC) (HMP 60, Vaisala Inc., Helsinki, Finland), relative humidity (RH, %) (HMP 60, Vaisala Inc., Helsinki, Finland), solar radiation (I_s, MJ m^{-2}) (Kipp and Zonen, CMP3), wind speed (WS, $m.s^{-1}$), (model 03003, R.M. Young, Traverse City, Michigan, USA), rainfall (mm) (TE525, Texas Electronics Inc., Dallas, Tx, USA), calculated Vapour Pressure Deficit (VPD) (using T_{air} and RH measurements according to Savage et al. 1997) and FAO reference evaporation (mm) (FAO ETo) were downloaded online at: https://sasri.sasa.org.za/rtwd/524/index.html.

3.3.3 Transpiration flux measurements

Four representative trees were selected within the tree stand of the study site based on diameter stratification. This was achieved by measuring 48 tree diameters at breast height (DBH, 1.3 m) using a diameter tape and stratifying the measured trees according to four size classes; small, medium, medium large and large.

A heat pulse velocity system (HPV) of the heat ratio technique (Burgess et al. 2001) was used to estimate sapflow at various depths across the sapwood of each selected tree for the 2019/ 20 hydrological year (October 2019 to September 2020) and 2020/ 21 hydrological year (October 2020 to September 2021). The HPV system consisted of a line heater probe (40 mm long and of 0.18 cm outside diameter brass tubing) with enclosed constantan filament that provides a heat source for 0.5 s when powered and a pair of type T copper-constantan thermocouples to measure the heat ratio (Supplementary Figure 3.1). Prior to probe installation, thickness of the bark was measured, and suitable sensor insertion depth was identified using an increment borer and Methyl Orange staining. The thermocouples and heater probes were inserted in holes which were made using a drill and a drill guide to ensure that holes were drilled with the correct spacing and parallel alignment. A heater probe was installed in the central hole and thermocouples installed in each of the holes up (upstream) and down (downstream) from the heater probe relative to the sapflow direction. Probes were installed at various depths (Table 3.2) within each tree. Hourly measurements were executed and recorded on a datalogger (CR1000, Campbell Scientific Inc., Logan, Utah, USA), which was powered by a single 55-amp hour lead acid deep cycle battery. Thermocouples were connected to a multiplexer (AM 16/32, Campbell Scientific Inc.), which were in turn connected to the datalogger to allow for

32 thermocouple measurements at various sapwood depths across the four instrumented trees (Supplementary Figure 3.2). Measurements were conducted at different sapwood depths due to radial differences in sapflow at different depth in the sapwood (Nadezhdina et al. 2002, Ford et al. 2004). Data were remotely downloaded using a GSM modem (Maestro Wireless Solutions Ltd. Hong Kong, China). The hourly measurement sequence included measuring each thermocouple ten times for accurate initial temperatures. Following a heat pulse, the downstream and upstream temperatures were measured approximately 40-times between 60 and 100s. Thereafter, sapflow (Vh, cm hr^{-1}) was calculated using (Burgess et al. 2001),

$$V_h = \frac{k}{x} \ln\left(\frac{V_1}{V_2}\right) 3600 \tag{3.1}$$

where, k is a thermal diffusivity of fresh wood (a nominal value of 2.5 x 10^{-3} cm^2 s^1, Marshall 1958), x is the distance of each temperature probe from heater probe (0.6 cm), and V_1 and V_2 are temperature increases in upstream and downstream probe (°C) at equidistant points from the heater probe.

Table 3.2: Detailed description of four trees selected for instrumentation with heat pulse velocity technique in KwaMbonambi study area.

Tree no	Overbark diameter (cm)	Bark thickness (cm)	Probe depth (mm)			
Tree 1	10.3	0.7	0.8	1.5	2.5	3.5
Tree 2	19.8	1.2	0.8	1.5	2.5	3.5
Tree 3	16.2	1.1	0.8	1.5	2.5	3.5
Tree 4	15.1	0.9	0.8	1.5	2.5	3.5

3.3.3.1 Corrections

A slight probe misalignment may occur during the drilling process even when a drill guide is used. This was assessed by checking for inconsistencies in the zero flux values in periods where sapflow was expected to be zero, such as over pre-dawn, during rainfall events, or in high RH and low *SWC* conditions. The sapflow values during these times may be adjusted to zero and an offset may be calculated from an average of these values and applied to the whole dataset. It is important to note that values less than zero (negative values) can be measured in deep rooted trees such as *Eucalyptus* due to hydraulic redistribution (Scholz et al. 2002), however these values have been reported to be negligible. For probes used in this study, the offset was < 5% of the midday sapflow rates.

Wounding or non-sap conducting area around the thermocouples was accounted for using wound correction coefficients described by Burgess et al. (2001). Thereafter, sap velocities were calculated accounting for moisture fraction and wood density as described by Burgess et al. (2001). Finally, sap velocities were up-scaled (L day^{-1} and mm day^{-1}) by summing products of sap velocity and cross-sectional area for individual stems. The sapflow rates were then up scaled from sample trees to the entire forest stand using sapflow distribution in DBH classes method as described in detail by Cermak et al (2004).

3.3.4 Soil water content

Soil water content (*SWC*, m^3 m^{-3}) was measured in the upper 0.60 cm of the soil profile (0.2-, 0.4- and 0.6-m depth) using CS616 soil water content measuring sensors (Campbell Scientific Inc.) (Supplementary Figure 3.4). The CS616 *SWC* sensor consists of two 30 cm long stainless-steel rods that uses the time domain reflectometer method to measure the *SWC*. The sensor circuitry generates an electromagnetic pulse, of which an elapsed pulse travel time and reflection are measured and then used to calculate the *SWC*. The CS616 *SWC* sensors were placed adjacent to the HPV system, with a single sensor per depth and each sensor interpreted separately. Previous *Eucalyptus* root studies (Christina et al. 2016) indicated that majority of large and fine roots are located in the top 0.6 m of the soil profile, hence *SWC* measurements in this study were conducted in the top 0.6 m of the soil profile. The *SWC* measurements ran concurrently with the sap-flow measurements and were recorded on the CR1000 datalogger.

3.3.5 Growth measurements

Measurements of DBH (cm) were conducted for a period of 24 months (measurements conducted once every two months, producing 12 measurement points) using manual dendrometer bands (D1, UMS, Muchin, Germany) permanently attached to a tree, with an accuracy of 0.1 mm (Supplementary Figure 3.3). Dendrometer bands were installed in the middle of September 2019 on 48 trees and data collected for 12 months (once every two months). The quadratic mean diameter (D_q, cm) was calculated for 48 trees using (Curtis and Marshall 2000):

$$Dq = \sqrt{\frac{(\sum(DBH)^2)}{n}} \quad (3.2)$$

Tree heights (h, cm) for the 48 trees were measured at the same time as DBH measurements, using a hypsometer (Vertex Laser VL402, Haglof, Sweden).

The conical overbark volume (v, m^3) for each month was calculated using equation 3.3 (White et al. 2014)

$$v = \left(\frac{\pi}{12}\right)\left(\frac{Dq}{100}\left(\frac{h}{h-1.3}\right)\right)^2 h \quad (3.3)$$

where, h is the tree height. The stand volume (V, m^3 ha^{-1}) was calculated using:

$$V = \frac{10\ 000}{A}\sum_{i=1}^{n} vi \quad (3.4)$$

where vi was the productive volume of the ith tree, A was the total area (m^2) of the plot where measurements were conducted, n is the total number of trees within a plot and 10 000 represents one hectare (equivalent to 10 000 m^2).

LAI was measured once every two months using an LAI-2200 Plant Canopy Analyzer (Licor Inc., Lincoln, New York, USA) from August 2019 to August 2021. Measurements were conducted on a transect that was identified in the middle of the study site.

3.3.6 Plantation water productivity (PWP_{WOOD})

The annual plantation water productivity (PWP_{WOOD}), expressed in g wood kg^{-1} of water was calculated for *GU* as a ratio of *V* to *T* for 2019/ 20 (October 2019 to September 2020) and 2020/ 21 (October 2020 to September 2021) hydrological years.

3.3.7 Statistical analysis

The statistical analysis was performed using the R version 3.6.1 statistical computing software (R Development Core team 2008). Variables were transformed as appropriate to meet the assumptions of normality. The analysis was conducted using two approaches, first, a simple linear regression model was used to establish a relationship between sapflow and growth parameters (D_q, tree heights and LAI), where the overall F-statistic was significant ($p < 0.05$), treatment means were compared using Fischer's Least Significant Difference at the 5% level of significance ($LSD_{5\%}$). The second approach applied the Random Forests (RF) regression algorithm (Breiman 2001) in R statistical computing where sapflow was made a response variable and meteorological data (T_{air}, RH, I_s, WS, rainfall, FAO ETo, VPD and *SWC*), predictor variables. This machine learning approach doesn't make the assumptions of linear regression and performs well when the relationship among the response variable and independent variables are complex and non- linear. The RF regression model was optimised in terms of the parameters ntree (number of trees built by the model) and mtry (number of variable predictors used at each node split using the Caret package (Kuhn, 2008). The RF regression was evaluated using the R^2 metric and the contribution of each variable to the model accuracy was determined by developing a variable importance plot. The variable importance was calculated from the out-ot-bag (OOB) samples. Using a bootstrap sample with replacement, two thirds of the original dataset used to train individual trees in the ensemble, whereas the remaining one third of a sample is used for determining ranked variable importance, providing a measure of accuracy (Breiman, 2001). In this study, the two thirds of the dataset for each measurement period were used for calibrating and validating the model, while the one third was used for testing the model. The variable importance plot was assessed using the mean decrease accuracy (MDA) coefficient measures (Breiman et al., 1984). The MDA is calculated during the OOB sample computation phase. The values of a particular variable are randomly permuted on the OOB sample, enabling the new classification to be determined from the modified sample. For more details on how MDA is quantified refer to Cutler et al (2007) and Aria et al (2021). The difference between the rate of misclassification for the modified sample and the original sample is used as a measure of the variable importance. Each predictor variable was scored based on the MDA for the *GU* measurement period (October 2019 to September 2021).

3.4 Results

3.4.1 Weather data

Solar irradiance followed the diurnal and seasonal trends expected of the northern KwaZulu-Natal area with the same pattern for both measurement years (Figure 3.2). The maximum daily I_s on clear days in winter was approximately 14 MJ m^{-2} day^{-1}, while in summer, 31.5 MJ m^{-2} day^{-1} for 2019/ 20 and 30.6 MJ m^{-2} day^{-1} for 2020/ 21 was measured. In both years, there were noticeably more cloudy days during summer months with cloud dominating until later morning on many days. Maximum daily T_{air} in summer for both years was 38.8 °C, which is an indication of warm summer months. Minimum daily T_{air} in summer was as high as 24°C decreasing to 2.7

and -0.1°C in the winters of 2019/ 20 and 2020/ 21, respectively. Daily mean VPD was not as seasonal as T_{air} and I_s, although it tended to be slightly higher in summer and slightly lower in winter. The average VPD for 2019/ 20 was 0.73 vs. 0.62 kPa in 2020/ 21, reaching maximum values in summer of 2.69 and 1.79 kPa for 2019/ 20 and 2020/ 21, respectively. Rainfall occurred throughout the year with the majority (60%) falling in the summer period (October to March) (Figure 3.2). Total measured rainfall in 2019/ 20 was 1104.4 mm, whereas 2020/ 21 experienced 28% more rainfall (1532.8 mm). By comparison, FAO ETo totals calculated using hourly AWS data and the FAO56 method (Allen et al. 1998) amounted to 1213.4 and 1128.0 mm for 2019/ 20 and 2020/ 21, respectively, following seasonal trends (Table 3.3). Monthly average WS were variable (range: 1.3 to 10.7 m. s^{-1}) over the two years with maximum WS reaching 39.4 m. s^{-1} in February 2021.

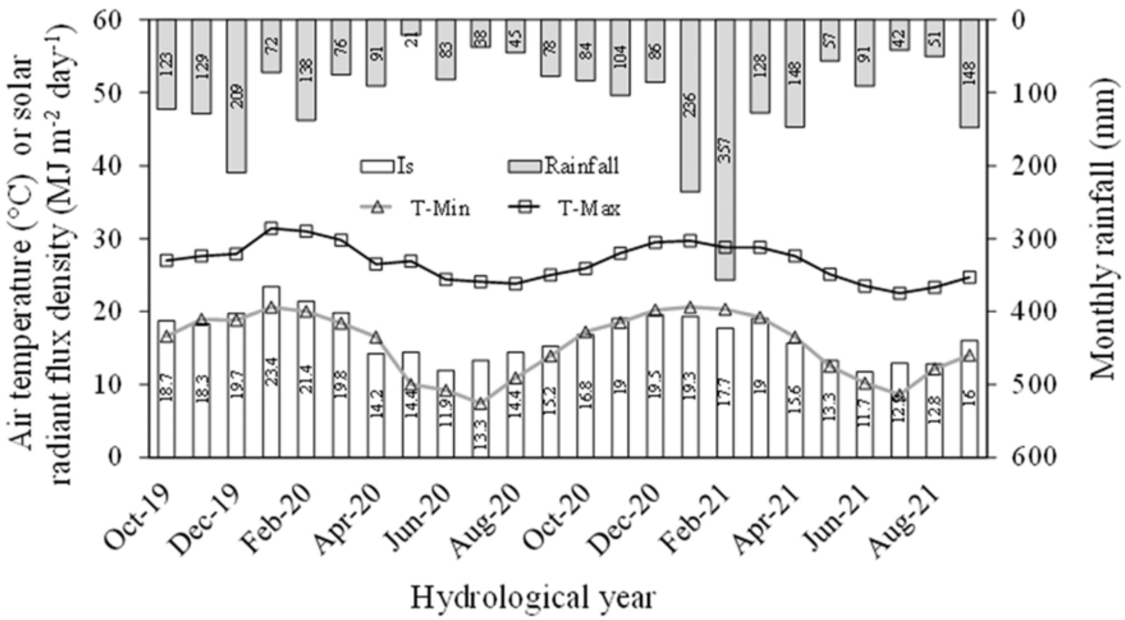

Figure 3.2: Monthly values of mean daily maximum (T-Max) and minimum (T-Min) air temperatures (°C), mean daily radiant flux density (MJ m^{-2} day $^{-1}$) and corresponding total monthly rainfall (mm) measured near KwaMbonambi from October 2019 to September 2021.

Table 3.3: Monthly FAO-56 reference total evaporation (FAO ETo) totals (mm) calculated from hourly automatic weather station data near *Eucalyptus grandis* x *Eucalyptus urophylla* clonal hybrid in KwaMbonambi over two consecutive hydrological years; 2019/ 20 (October 2019 to September 2020) and 2020/ 21 (October 2020 to September 2021).

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	Jul	Aug	Sep	Totals
2019/'20	120	117	129	162	134	123	77	66	54	62	79	91	**1213.4**
2020/'21	113	123	135	134	103	114	84	60	45	56	69	92	**1128.0**

3.4.2 Soil water content

All *SWC* sensors responded to rainfall events, except when precipitation was small (< 3 mm) (Figure 3.3). The *SWC* was generally low on the site, between 4 and 16% (Figure 3.3), indicating low water retention properties by the sandy soils. Post a rainfall event, the *SWC* for all three probes increased rapidly and decreased rapidly during the subsequent period of no rainfall as the water drained quickly through the soil.

Eucalyptus trees are known to have a very deep rooting system and are capable of accessing soil water in deeper soil water reserves (Christina et al. 2016). A study by Dye (1996) in the Mpumalanga province of South Africa reported that *Eucalyptus grandis* trees abstracted water down to 8 m below the soil surface. Soils in our study site was reported to be very deep (> 30 m) and free draining. There is, therefore, a high possibility that tree roots in this study accessed soil water stored deep in the soil profile from previous wet years.

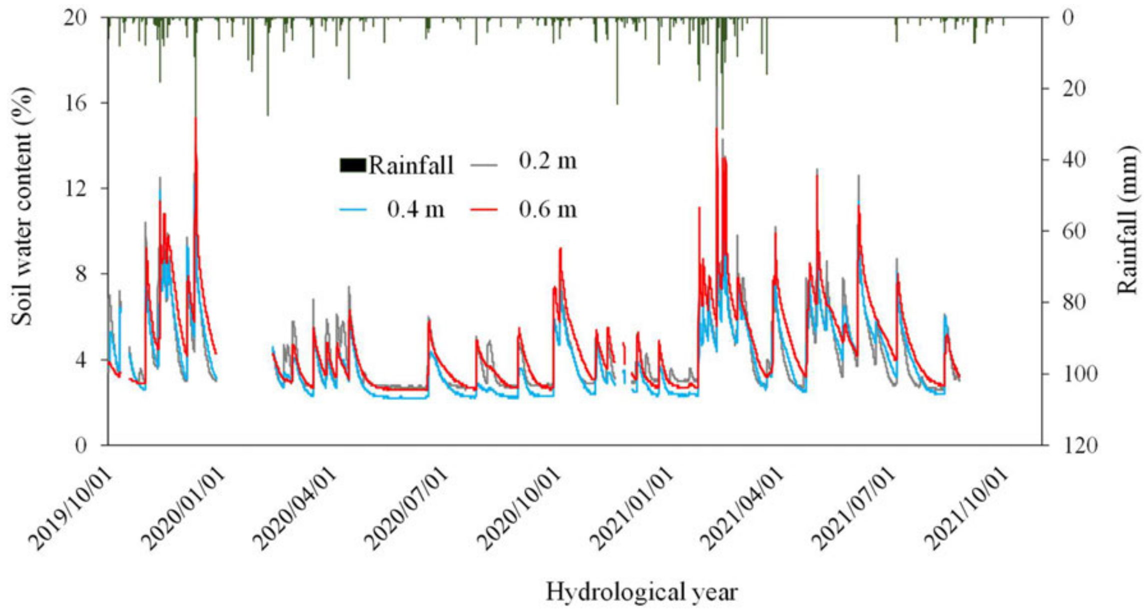

Figure 3.3: The mean daily soil water content (%) measured at different soil depths (0.2 m, 0.4 m and 0.6 m) with corresponding rainfall over a duration of October 2019 to September 2021. Missing data typically occurred due to instrument failure or power interruption.

3.4.3 Sapflow

The sapflow rates followed typically diurnal trends for both measuring years (Figure 3.4). Mean daily sapflow values in summer (October to March) of 2019/ 20 and 2020/ 21 were 2.7 mm tree^{-1} day^{-1} (15.5 L tree^{-1} day^{-1}) and 3.3 mm tree^{-1} day^{-1} (19.7 L tree^{-1} day^{-1}), respectively. Daily peak summer sapflow of 6.5 mm tree^{-1} day^{-1} (38.3 L tree^{-1} day^{-1}) in 2019/ 20 increasing to 6.8 mm tree^{-1} day^{-1} (41 L tree^{-1} day^{-1}) in 2020/ 21 were measured in the middle of October for both years, which coincided with high values of I_s and T_{air}. During the winter months (May to August), sapflow measurements were between 0.6–1.6 mm tree^{-1} day^{-1} (3.6–9.0 L tree^{-1} day^{-1}) in 2019/ 20, while 2020/ 21 experienced 2.4–3.1 mm tree^{-1} day^{-1} (14.2–18.5 L tree^{-1} day^{-1}). As expected, trees with large overbark diameter produced more sapflow than small diameter trees.

The differences in seasonal patterns of sapflow are best illustrated using daily accumulated sapflow over each year as presented in Figure 3.5. Rainfall varied from one year to the next with the 2020/ 21 having almost 26% more rain than 2019/ 20. FAO ETo responded to the higher rainfall in the 2020/ 21 by being 85 mm lower and likely a result of slightly less solar irradiance due to cloud or decreased VPD due to the wetter conditions. The sapflow responded to the increased rainfall in the 2020/ 21, increasing by 242 mm or nearly 20%. This indicated that the trees were water limited in the first year and that when more water became available, the trees were able to use it.

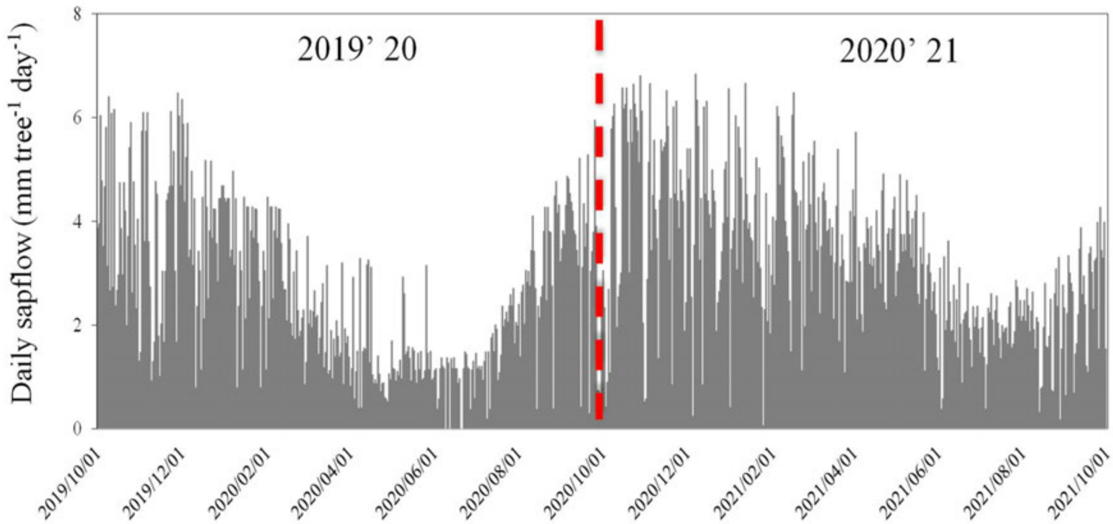

Figure 3.4: Daily sapflow volumes (mm tree^{-1} day^{-1}) measured using the heat ratio method of heat pulse velocity technique on a nine-year-old *Eucalyptus grandis* x *Eucalyptus urophylla* clonal hybrid over 2019/ 20 (October 2019 to September 2020) and 2020/ 21 (October 2020 to September 2021) hydrological years. Red line separates the hydrological measurement years.

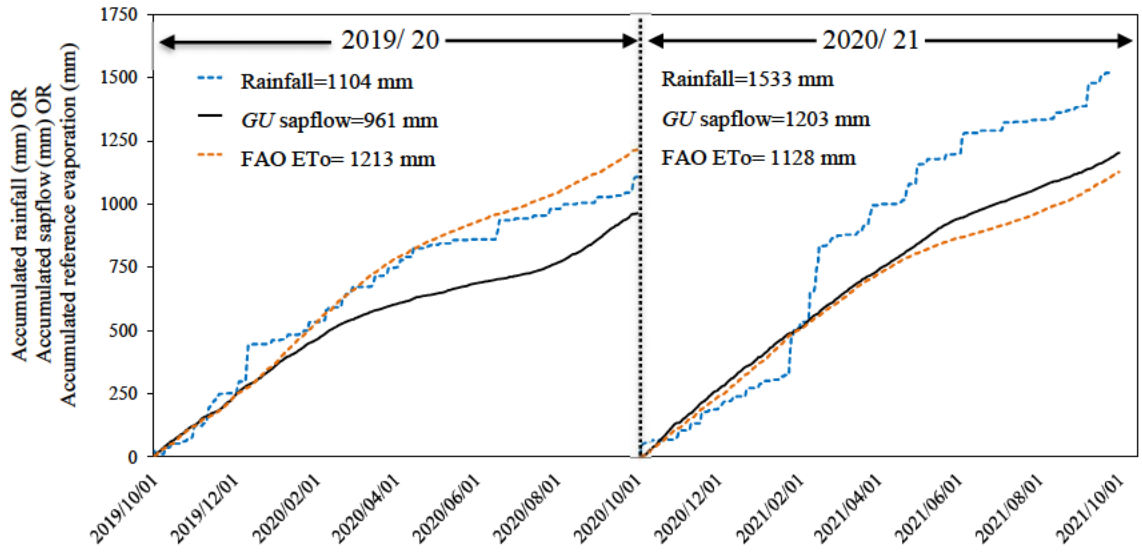

Figure 3.5: The accumulated sapflow (mm), rainfall (mm) and FAO reference evaporation (ETo, mm) for 2019/ 20 (October 2019 to September 2020) and 2020/ 21 (October 2020 to September 2021) hydrological year.

The simple regression on monthly sapflow were considered with growth parameters (D_q, h and LAI) and it was found that these were poor, with coefficient of determination ranging from 0.21 to 0.30 (data not shown). The results of the RF multiple regression predictive model rated FAO ETo as the most important predictor of sapflow (Figure 3.6). Meteorological variables, I_s, *SWC* at 0.6 m, T_{air} and WS in a descending order of importance were also determined to be very important. By comparison, RH and rainfall were the least important variables in a model. Overall, the model showed that sapflow is influenced by micrometeorological variables at different degrees of influence.

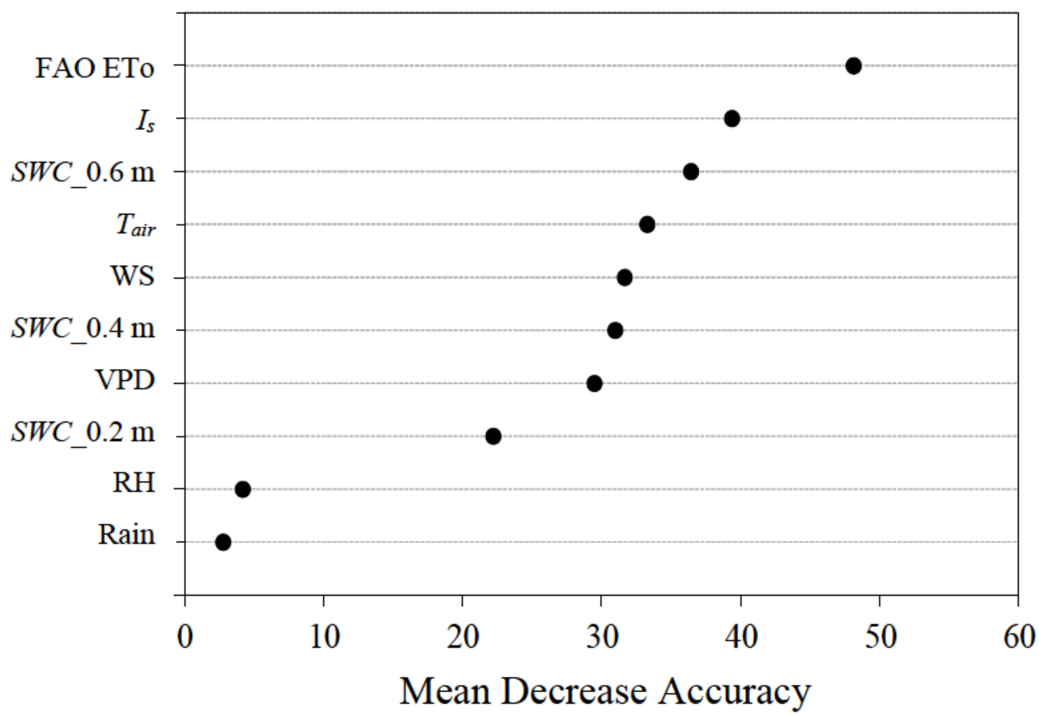

Figure 3.6: Variable importance plot from the random forest model for FAO reference evaporation (FAO ETo), solar radiation (I_s), air temperature (T_{air}), vapor pressure deficit (VPD), wind speed (WS), relative humidity (RH), soil water content (*SWC*) at a soil depth of 0.2-, 0.4- and 0.6 m. Mean Decrease Accuracy is a measure of how much the model error increases when a particularly variable is randomly permuted. The high MDA indicates that a variable is a good predictor.

3.4.4 Tree growth

The *GU* DBH increased continuously over the measurement period (Figure 3.7a), with significant differences ($p < 0.05$) in the annual diameter increment between the two years (mean: 2019/ 20 = 0.82 cm and 2020/ 21 = 0.67). There was a very low growth increment (D_q and tree heights) between November 2020 and January 2021 (Figure 3.7a and 3.7b), which was probably caused by very low *SWC*, which was less than 5% during this period. Tree heights were statistically similar ($p > 0.05$) for both years, with monthly growth increment of approximately 0.25 m (Figure 3.7b).

The LAI showed seasonal patterns (Figure 3.8) with peak LAI measured during the high rainfall months (October to December), while the low LAI was measured in the dry season (May to

September). During the dry season, *GU* trees were observed to drop leaves in response to soil water deficit, causing a decrease in LAI.

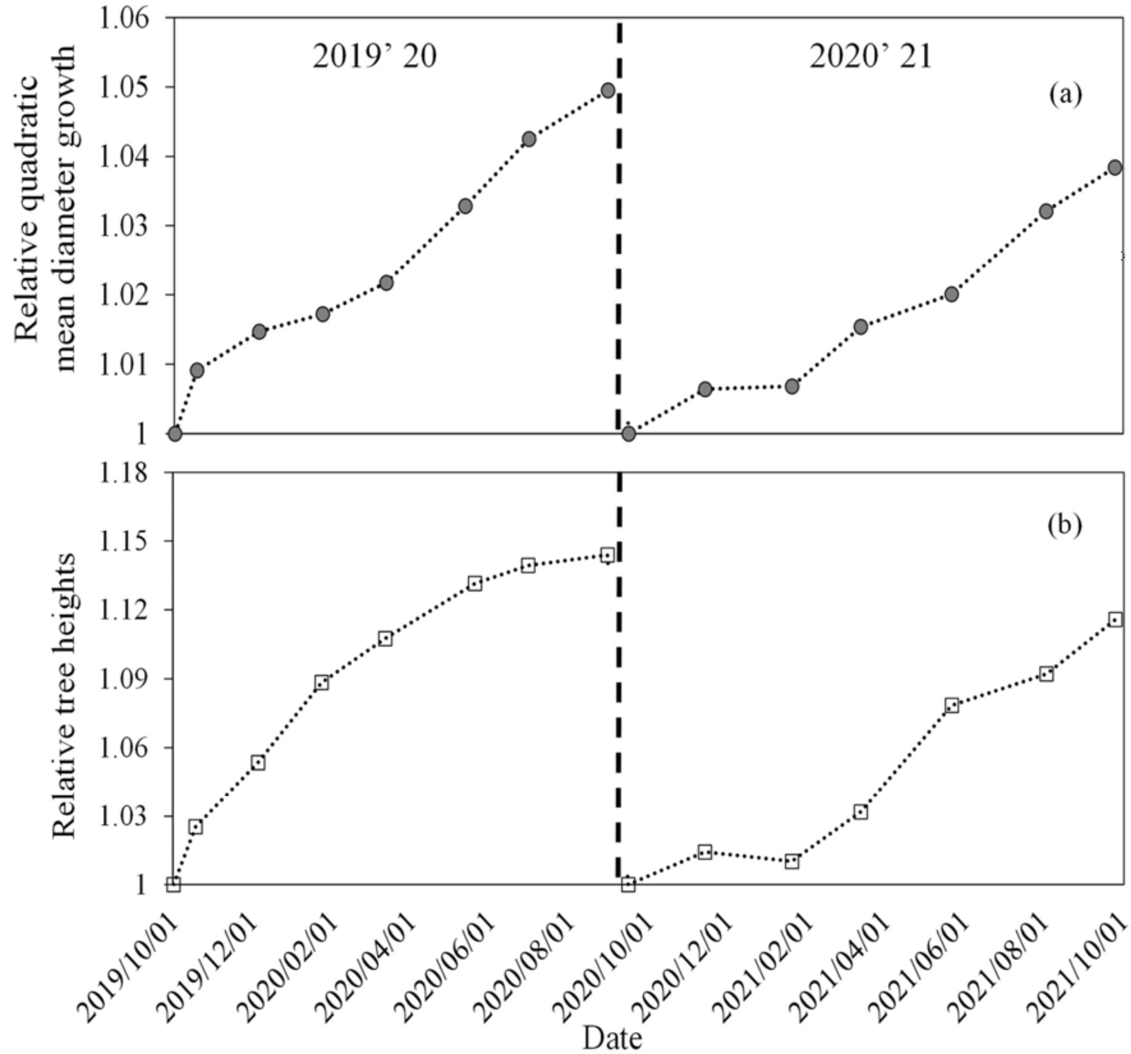

Figure 3.7: (a) Relative quadratic mean diameters (calculated as a ratio of monthly diameters relative to initial diameter measurement, unitless) measured using manual dendrometers bands and (b) Relative tree heights (calculated as a ratio of monthly tree heights relative to initial tree height measurement, unitless) measured using a hypsometer for a nine-year-old *Eucalyptus grandis* x *Eucalyptus urophylla* clonal hybrid in KwaMbonambi over two consecutive years, 2019/ 20 (October 2019 to September 2020) and 2020/ 21 (October 2020 to September 2021). Each point represents an average of 48 trees.

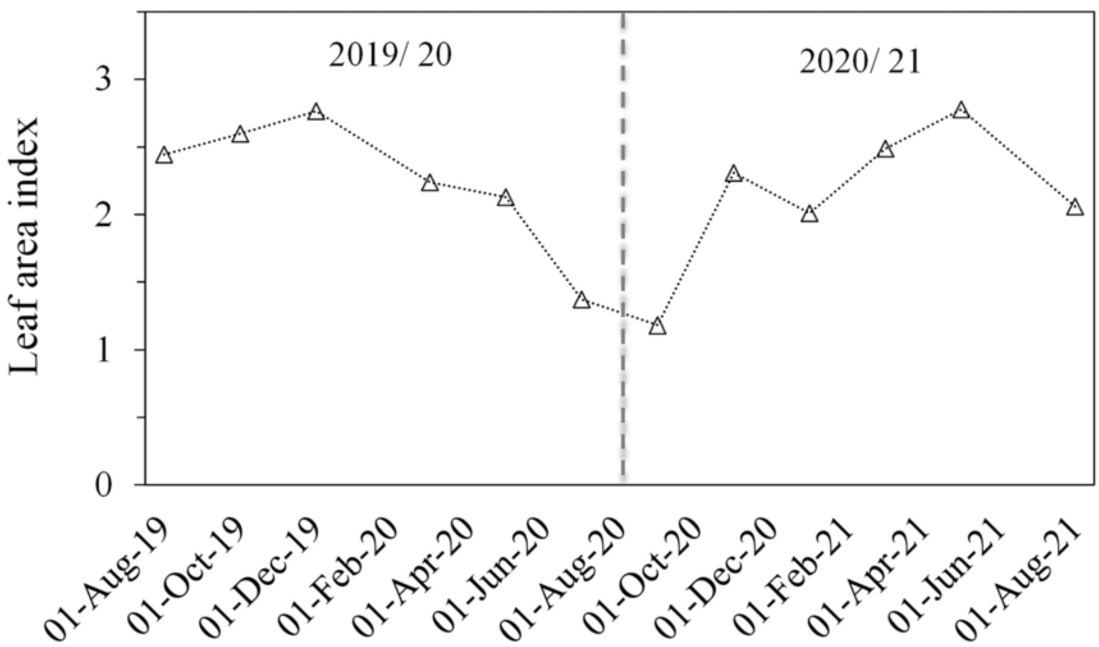

Figure 3.8: A leaf area index of *Eucalyptus grandis* x *Eucalyptus urophylla* clonal hybrid measured in KwaMbonambi, Zululand from August 2019 to August 2021.

3.4.5 Plantation water productivity

The mean annual $GU\ PWP_{WOOD}$ was 1.74 g wood kg^{-1} water in 2019/ 20 decreasing by 17% in 2020/ 21 to 1.43 wood kg^{-1} water. This decrease was attributed to T in 2020/ 21 that was significantly ($p < 0.05$) greater than 2019/ 20 (2019/ 20=961 mm vs 2020/21=1203 mm).

3.5 Discussion

3.5.1 Weather

The Zululand area is well-known to experience variable MAP (periods of extended drought conditions and periods of high rainfall), with some years receiving as little as 427 and as much as 1689 mm (Scott-Shaw et al. 2016). The meteorological data during the study period, however, was representative of the Zululand area and rainfall was within the long-term mean annual precipitation (LTMAP = 926 mm) of the KwaMbonambi area (Schulze and Lynch 2007). The measurements of 1104.4 mm and 1532.8 mm were in the middle to upper range in MAP, respectively. Air temperature, RH, I_s and WS were all as expected with no unusual weather conditions over the study period.

3.5.2 Sapflow

3.5.2.1 Daily sapflow

The mean sapflow for the instrumented *GU* increased from 2.7 mm tree^{-1} day^{-1} (15.5 L tree^{-1}) in 2019/ 20 to 3.3 mm tree^{-1} day^{-1} (19.7 L tree^{-1} day^{-1}) in 2020/ 21, reaching a peak of 6.5 mm tree^{-1} day^{-1} (38 L tree^{-1} day^{-1}) and 6.8 mm tree^{-1} day^{-1} (48 L tree^{-1} day^{-1}) for 2019/ 20 and 2020/ 21 years, respectively. These results are corroborated by other studies of *Eucalyptus* species of a similar age in the northern Zululand region of South Africa. A study by Dye et al. (1997) in KwaMbonambi on eight-year-old *E. grandis* measured a sapflow range of 15 – 34 L tree^{-1} day^{-1} on less productive sites, increasing to 30 – 64 L tree^{-1} day^{-1} on highly productive sites. Everson et al. (2019) reported summer mean sapflow of 18.04 L tree^{-1} day^{-1} decreasing to 7.76 L tree^{-1} day^{-1} in winter season for *E. grandis* in the Maputaland coastal belt. In southern China, a study by Morris et al. (2004) on *E. urophylla* established on sandy soils of sedimentary origin, measured a mean sapflow of 13.9 L tree^{-1} day^{-1} with peak of 49 L tree^{-1} day^{-1}. A comparison of results from our study with local (adjacent to our study site, Dye et al. 1997) and international studies conducted under similar conditions (Almeida et al. 2007) suggest that the sapflow of the genetically improved *GU* is statistically similar to genotypes (*E. grandis* or *E. urophylla*).

3.5.2.2 Annual sapflow

The annual *T* rates in our study were much higher than *T* measurements across other regions of the world (Table 3.4), however, within the same range of *Eucalyptus* clones *T* measured by Dye et al (1997) in the KwaMbonambi area of South Africa. There was a surplus in the water balance between inputs (water supply by precipitation) and *T* losses of 143 mm (13% of rainfall) and 330 mm (22% of rainfall) in 2019/ 20 and 2020/ 21, respectively. In this surplus, water losses from soil evaporation and C_I were not included, since they were not measured in this study. Measurements of *SWC* in the top 0.6 m of the soil profile indicated that *SWC* was very low, particularly in winter (a peak of 7.5% in 2019/ 20 and 13% in 2020/ 21) indicating that the sandy soils (closer to the surface) were dry and had poor water holding capabilities. However, *GU* trees did not show any visible signs of water stress throughout the monitoring period. This is a strong indication that *GU* trees accessed soil water elsewhere, either than at the soil surface. *Eucalyptus* trees are known to develop a dimorphic roots structure (deep tap root and superficial lateral roots), to increase the chances of accessing water near the soil surface as well as in deep soil layers (Jacobs 1955, Kimber et al. 1974) and even the water table. However, penetration may be restricted by soil or regolith layers (Ngubo et al. 2022). *Eucalyptus* tap root has been reported to reach the depths of 28 m (Dye 1996) and even greater than 60 m was observed in one recorded case (Stone and Kalisz 1991).

In our study, the depth to water table was not physically measured, however, there was a borehole nearby (approximately 300 meters from our study site), where depth to groundwater was measured at 28 m during installation in year 2016. A study by Calder et al (1997) in southern India reported an average root extension of approximately 2.5 m per year in *E. camaldulensis*. Based on a constant annual root depth growth rate of 2.5 m in 9 years, which was highly possible in deep free draining Zululand sandy soils, roots for our *GU* trees would approximately be 22 m deep during the study period. Given the maximum reported capillary fringe of 0.5 m in sandy soils (Shen et al. 2013), direct groundwater uptake by our *GU* tree roots would be possible up to 22.5 m deep. Using the depth to water table for borehole next to our study area as a reference, there is a high possibility that the unconfined and semi-confined aquifers were too deep for roots of our *GU* crop. Evidence of a lack of contact with groundwater was corroborated with a significant decrease in *T*, DBH and LAI of our *GU* crop during the dry season and increased during the wet season when significant rainfalls return. With the *SWC* very low at the soil surface and the water table too deep for access by *GU* trees, the only available water that could be extracted by trees is water that occur within the unsaturated zone or the perched aquifers. These findings suggest that, to some extent, the *GU* trees have a significant impact on groundwater levels by extracting water from within the unsaturated zone to meet *T* demands, thereby reducing water available for recharging the aquifer. Similar results were reported by Kok (1976) and most recently by Ngubo et al (2022) where groundwater recharge was reduced after afforestation due to water extraction through increased *T* from unsaturated zone.

3.5.2.3 Relationship between sapflow and micrometeorological variables

Sapflow in *Eucalyptus* has been described to have a strong relationship with atmospheric micrometeorological conditions (Lundblad and Lindroth 2002) and readily available water in the rooting area (Oren and Pataki 2001). In our study, Random Forest variable importance measures indicated that FAO ETo, I_s, *SWC* (measured at a depth of 0.6 m) and T_{air} were the most influential variables in the model. Similar results have been documented in other *Eucalyptus* studies (Taylor et al. 2001, Ouyang et al. 2017, Perez et al. 2021). For example, Ouyang et al (2017) reported a very good relationship between T and VPD ($R^2 > 0.80$). Perez et al (2021) concluded that climatic variables are a good predictor of stand *T*. However, it is important to note that these relationships are complex as they are dependent on tree species, genera, age and physiology (Zweifel et al. 2005). Though I_s was found to be the second most important meteorological variable influencing sapflow by the RF model, and FAO ETo the first, it is important to be cognisant that FAO ETo calculation includes I_s, meaning that I_s played a significant role in FAO ETo calculation. However, a study by Calder (1998) indicated that total evaporation in evergreen forests, unlike shorter vegetation which is highly influenced by the supply of I_s, is highly influenced by advection energy greater than I_s. This suggests that I_s on its own can not be used to estimated total evaporation in commercial forests.

The LAI responded to rainfall and *SWC*, where LAI increased in the wet season and decreased in the dry season. A visual observation of a leaf drop by *GU* in this study has been reported as an adaptive mechanism to soil water deficit by certain *Eucalyptus* species (Saadaoui et al. 2017). Trees with larger DBH produced significantly greater sapflow than the smaller diameter trees, which is attributed to larger sap conducting area than the small trees. Similar results were reported by Otto et al. (2014) in a Brazil *Eucalyptus* Potential Productivity study where larger trees did not only transpire more than smaller trees, but they produced more wood per unit of water used. This may be an indication of significant variability between the trees in the *GU* stands and suggests that monitoring of such variability would be useful in terms of assessing variability of wood productivity.

Table 3.4: The annual transpiration (T) and annual total evaporation (ET) of *Eucalyptus* species in experiments conducted in different parts of the world. A hyphen (–) indicates that data was not shown.

Study	Tree age (years)	Location	Species	Annual rainfall (mm)	Annual T (mm)
Our study	9	South Africa, KwaMbonambi	*E. grandis x E. urophylla*	1104 and 1533	961 and 1203
Dye et al. (1997)	7	South Africa, KwaMbonambi	*E. grandis clones*	1107	601, 608, 740, 777, 1412, 1423
Almeida et al. (2007)	8	Brazil	*E. grandis*	1147	885
Lane et al. (2004)	9	China	*E. urophylla*	1525–2226	498–548
Engel et al. (2005)	10	Argentine	*E. camaldulensis*	803	348–817
Macfarlane et al. (2010)	6-12	Australia	*E. marginata*	1135–1235	231–505
Silveira et al. (2016)	8	Uruguay	*E. globulus*	792–2523	–

3.5.3 Potential implication of GU on water resources

Forest plantation water-use studies and their potential impact on water resources are complex and require comprehensive long-term measurements of total water balance parameters to be conclusive. Our results indicated that *GU* tree roots most likely did not access groundwater resources, as roots were shallow, however, tree *T* continued in the dry season regardless of very low *SWC*. This suggested that *GU* trees most likely accessed water stored in unsaturated zone. There are several long-term paired catchment studies conducted in South Africa (van Lill et al., 1980; Smith and Scott, 1992; Scott and Lesch, 1997; Scott and Smith, 1997; Scott et al., 2000) that quantified the impact of commercial forest plantation on water resources, particularly the ground water and streamflow. A study by Scott and Lesch (1997) on the streamflow response to afforestation with *E. grandis* and *P. patula* in Mokobulaan experimental catchment in South Africa indicated that eucalypts cause a faster reduction in streamflow (90–100%) compared to afforestation with pines (40–60%). These results were verified in a study conducted by Scott et al (2000) where peak reductions in streamflow were reported between 5 and 10 years after establishing eucalypts, and between 10 and 20 years after planting pines, with the size of the reduction driven by soil water availability. Another South African study by Smith and Scott (1992), investigated the impact of pine and eucalypts on low flows in various paired catchments located in various regions of South Africa (Westfalia Estate, Cathedral Peak, Jonkershoek, Mokobulaan). Results from this study showed that afforestation have a significant effect on low flow on all paired catchments (low flows reduced by up to 100% in certain cases), with eucalypts having a severe impact compared to pine. Afforestation with commercial forest plantation over successive rotations have been shown to deplete soil water reserves within the perched aquifers or soil water stored in unsaturated zone (Dye et al. 1997, Ngubo et al. 2022). Evidence of this was shown in a paired catchment experiment by Scott and Lesch (1997) where eucalypts were clearfelled at 16 years of age, but full perennial streamflow returned five years later. The delay in streamflow recovery was attributed to eucalypts desiccating the deep-water reserves, which had to be restored before the stream could return to a normal flow.

The above-mentioned studies from South African long-term paired catchments concluded with solid evidence that commercial forest plantations, particularly *Eucalyptus*, pose a severe negative impact on groundwater resources and ultimately streamflow. Although, results from our study indicated that our *GU* trees most likely impacted groundwater resources indirectly, the extent of the impact can not be quantified without long-term measurements of at least one crop rotation. Due to climate variability in plantation forest areas, long-term studies under non-stressed and stressed conditions are needed in this region to quantify the total water balance (total evaporation, surface runoff, soil water storage and how water partitioning responds to climate change and afforestation over time). In addition, using the data from the satellite is suggested for future research to allow for estimation of *T* over a large spatial scale.

3.5.4 Plantation water productivity

The annual PWP_{WOOD} calculated in our study of 1.74 and 1.43 wood kg^{-1} water for 2019/ 20 and 2020/ 21, respectively, was categorised as productive (based on a typical PWP_{WOOD} typical range values of 0.3 to 3.1 g wood kg^{-1} water, White et al. (2014, 2015)). There are few studies that have quantified PWP_{WOOD} in South Africa and internationally with which to compare these results. However, Forrester et al. (2010) calculated PWP_{WOOD} of approximately 0.6 g wood kg^{-1} water in Australia on a 14-year-old *Eucalyptus globulus*. The PWP_{WOOD} values in our study corroborated with unmanaged coppice values (range: 0.2 to 3.1 g wood kg^{-1} water) reported by

Hubbard et al (2010) and Drake et al (2012), managed coppice (White et al. 2014) and irrigated *E. globulus* (White et al. 2015), but higher than managed dryland commercial forest plantation. High PWP_{WOOD} values in our study were not surprising as soils in northern Zululand regions has been reported to have a very high growth potential (Dye et al. 2004) and the rainfall is high in comparison with other areas where eucalypts are planted. In addition, a study by Dovey et al (2011) adjacent to our study site reported that atmospheric nutrient deposition (compounds primarily from industrial pollution, biomass burning, lightning and coastal wind-blown sea-spray or mist) may provide trees with adequate nutrients, which may have influenced high PWP_{WOOD} in our study.

3.6 Conclusion

This study has quantified the seasonal variation of water use by a nine-year-old *GU* plantation in a remote study site in KwaMbonambi, northern region of KwaZulu-Natal, using the most advanced sapflow measuring technique, the HPV. Previous studies have shown that measuring water use using the HPV provides reliable and continuous measurements but requires routine maintenance. In our study, annual water use by *GU* was higher than international studies conducted under similar conditions, but within the range of water use studies conducted in the KwaMbonambi area. Though these results well represented the northern regions of northern Zululand, it is recommended that water use measurements are replicated to other adjacent sites on different clonal hybrids to improve confidence limits of our water use results. There is a high possibility that our *GU* tree rooting system accessed water stored in unsaturated zone during the dry season to maintain *T*, as roots were most likely shallow to access the water table. Using water from unsaturated zone to maintain *T* will negatively impact groundwater resources, as this water is used for recharging the water table. However, to quantify the impact of *GU* on groundwater reserves requires long-term measurements of total tree water use and depth to groundwater. Due to short-term nature of measurements in this study, the impact of *GU* on groundwater can not be quantified, but previous long-term paired catchment studies in South Africa showed conclusive evidence that commercial afforestation has a negative impact on groundwater and ultimately the streamflow, particularly *Eucalyptus* plantations.

The model developed in this study indicated that FAO ETo, I_s and *SWC* can be used as good predictors of stand *T* in commercial forest stand. This model will form a good background for future modelling studies where a difficult water use measurement can be estimated from an "easy to measure" weather variables.

A conclusion from this study is that 1) water use by *GU* is not different from other genotypes, based on results from local (adjacent to study sites) 2) The nine-year-old *GU*, has a potential to use water stored in unsaturated zone to meet *T* demands in the dry season, thereby reducing soil water needed to recharge the water table 3) the *GU* in this study had high PWP_{WOOD} than in other studies which was probably influenced by high production potential of our study site. Further long-term measurements of total evaporation and isotope research is suggested on the study site to quantify from where *GU* trees are sourcing their water.

3.7 Acknowledgements

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3.8 References

Albaugh JM, Dye PJ, King JS. 2013. *Eucalyptus* and water use in South Africa. *International Journal of Forestry Research* 2013: 1–8.

Allen RG, Pereira LS, Raes D, Smith M. 1998. *Crop Evapotranspiration: guidelines for Computing Crop Water Requirements*. FAO Irrigation and Drainage Paper no. 56. Rome: Food and Agriculture Organization of the United Nations.

Allen RG, Pereira LS, Howell TA, Jensen ME. 2011. Evaporation information reporting: I. factors governing measurement accuracy. *Agricultural Water Manage*ment 98: 899–920.

Almeida AC, Soares JV, Landsberg JJ, Rezende GD. 2007. Growth and water balance of *Eucalyptus grandis* hybrid plantations in Brazil during a rotation for pulp production. *Forest Ecology and Management* 251: 10-21.

Aria M, Cuccurullo C, Gnasso A. 2021. A comparison among interpretative proposals for Random. *Machine Learning Applications* 6: 1000094.

Benyon RG, Doody TM. 2015. Comparison of interception, forest floor evaporation and transpiration in *Pinus* and *Eucalyptus globulus* plantations. *Hydrological processes* 29: 1173-1187.

Borin M, Milani M, Salvato M, Toscano A. 2011. Evaluation of *Phragmites australis* (*Cav*) *Trin*. Evapotranspiration in northern and southern Italy. *Ecological Engineering* 37: 721-728.

Breiman L. 2001. Random forests. *Machine Learning* 45: 15–32

Bulcock HH, Jewitt GPW. 2012a. Field data collection and analysis of canopy and litter interception in commercial forest plantations in the KwaZulu-Natal Midlands, South Africa. *Hydrological Earth Systems Science* 16: 3717-3728.

Bulcock HH, Jewitt GPW. 2012b. Modelling canopy and litter interception in commercial forest plantations in South Africa using the Variable Storage Gash model and idealised drying curves. *Hydrological Earth Systems Science* 16: 4693-4705.

Burgess SSO, Adams M, Turner NC, Beverly CR, Ong CK, Khan AAH, Bleby TM. 2001. An improved heat pulse method to measure low and reverse rates of sap flow in woody plants. *Tree Physiology* 21: 1157–1157.

Calder IR, Hall RL, Adlard PG. 1992. *Growth and water use of forest plantations*. Chichester: John Wiley and Sons.

Calder IR, Rosier PTW, Prasanna KT, Parameswarappa S. 1997. Eucalyptus water use greater than rainfall input – possible explanation from southern India. *Hydrological Earth Systems Science* 1: 249-256.

Calder IR.1998. Water use by forests, limits and controls. *Tree Physiology* 18: 8-9.

Cannell M GR. 1999. Environmental impacts of forest monocultures: water use, wildlife conservation, and carbon storage. *New Forest*s 17: 239–262.

Casson, A. 1997. *The controversy surrounding eucalypts in social forestry programs of Asia*. Economics Division Working Paper 97/1. Canberra: National Centre for Development Studies.

Cermak JN, Kucera J, Nadezhdina N. 2004. Sapflow measurements with some thermodynamic methods, flow integration within trees and scaling up from sample trees to entire forest stands. *Trees* 18(5): 529-546.

Christina M, Nouvellon Y, Laclau JP, Stape JL, Bouillet JP, Lambais GR, Le Maire G. 2016. Importance of deep-water uptake in tropical eucalypt forest. Functional Ecology 31: 509-519.

Curtis RO, Marshall DD. 2000. Technical Note: Why Quadratic Mean Diameter? *Western Journal of Applied Forestry* 15 (3): 137-139.

Cutler DR, Edwards TC, Beard KH, Cutler A, Hess KT, Gibson J, Lawler JJ. 2007. Random Forests for classification in ecology. *Ecology* 88: 2783-2792.

Delzon S, Loustau D. 2005. Age-related decline in stand water use: sapflow and transpiration in a pine forest chronosequence. *Agricultural and Forest Meteorology* 129: 105-119.

Dovey SB, du Toit B, de Clercq W. 2011. Nutrient fluxes in rainfall, throughfall and stemflow in Eucalyptus stands on the Zululand coastal plain, South Africa. *Southern Forests: a journal of Forest Science* 73: 193–206.

Drake PL, Mendham DS, White DA, Ogden GN, Dell B. 2012. Water-use and water-use efficiency of coppice and seedling *Eucalyptus globulus* Labill.: a comparison of stand water balance components. *Plant and Soil* 350: 221–235.

DSSA (Department of Statistics South Africa). 2019. *Forestry, logging and related services industry, 2019*. Stats SA Report No. 12-00-00. Pretoria: Statistics South Africa.

Dye PJ. 1996. Response of *Eucalyptus grandis* trees to soil water deficits. *Tree Physiology* 16, 233–238.

Dye PJ, Soko S, Maphanga D. 1997. *Intra-annual variation in water-use efficiency of three clones in kwaMbonambi, Zululand*. CSIR Report ENV/P/C 97048. Pretoria: Council for Scientific and Industrial Research.

Dye PJ, Jacobs S, Drew D. 2004. Verification of 3-PG growth and water-use predictions in twelve *Eucalyptus* plantation stands in Zululand, South Africa. *Forest Ecology and Management* 193, 197–218.

Dye PJ and Versfeld D. 2007. Managing the hydrological impatcs of South African plantation forests: an overview. *Forest Ecology and Management* 251: 121-128.

Dye PJ. 2013. A review of changing perspectives on *Eucalyptus* water-use in South Africa. *Forest Ecology and Management* 301: 51-57.

Dye PJ, Clulow AD, Prinsloo E, Naiken V, Weiersbye I. 2016. The annual pattern of sap flow in two *Eucalyptus* species established in the vicinity of gold-mine tailings dams in central South Africa. *Southern Forests: a journal of Forest Science* 78 (4): 307-313.

Engel V, Jobbágy EG, Stieglitz M, Williams M, Jackson RB. 2005. Hydrological consequences of *Eucalyptus* afforestation in the Argentine Pampas. *Water Resources Research*, 41: 10409-10423.

Everson CS, Scott-Shaw BC, Kelbe BE, Starke A, Pearton T, Geldenhuys C, Vather T, Maguire M. 2019. *Quantifying the water use of dominant land uses in the Maputaland coastal plain,* WRC Report no. K5/ 2554. Pretoria: Water Research Commission.

Fey M, Hughes J. 2010. *Soils of South Africa*. Cape Town: Cambridge University Press.

Ford CD, McGuire MA, Mitchell RJ, Teskey RO. 2004. Assessing variation in the radial profile of sap flux density in Pinus species and its effect on daily water use. *Tree Physiology* 24(3): 241-249.

Forrester DI, Collopy JJ, Morris JD. 2010. Transpiration along an age series of Eucalyptus globulus plantations in south-eastern Australia. *Forest Ecology and Management*, 259(9): 1754–1760.

Hakamada RE, Hubbard RM, Stape JL, Lima W, Moreira G, Ferraz. 2020. Stocking effects on seasonal tree transpiration and ecosystem water balance in a fast-growing *Eucalyptus* plantation in Brazil. *Forest Ecology and Management* 466: 118149-118149.

Hartemink AE, Hutting J. 2005. Sandy soils in Southern and Eastern Africa: extent, properties and management. In: Proceedings of the Management of tropical sandy soils for sustainable agriculture: a holistic approach for sustainable development of problem soils in the tropics, 27 November – 2 December 2000, Asia, Khon Kaen, Thailand: Food and Agricultural Office.

Hubbard RM, Stape J, Ryan MG, Almeida AC, Rojas J. 2010. Effects of irrigation on water use and water use efficiency in two fast growing *Eucalyptus* plantations. *Forest Ecology and Management* 259: 1714-1721.

Jacobs MR. 1955. *Growth habits of the Eucalyptus*. Canberra: Commonwealth 543 Government Printer.

Kimber PC. 1974. *The root system of jarrah (Eucalyptus marginata)*. FDWA Research Paper no. 10. Perth: Forests Department of Western Australia.

Kok TS. 1976. Die geohidrologie van die Bloemendalbasboompiaas, distrik Pietermaritzburg, Natal. Department of Water and Forestry Report GH 2924. Pretoria: Department of Water and Forestry.Kostner B, Falge E, Tenhenen JD. 2002. Age-related effects on leaf area/sapwood area relationships, canopy transpiration and carbon gain of Norway spruce stands (*Picea abies*) in the Fichtelgebirge, Germany. *Tree Physiology* 22: 567-574.

Kuhn M. 2008. Building predictive models in R using the caret package. *Journal of Statistical software* 28 (5): 1-26.

Lane PN, Morris J, Zhang N, Zhou G, Xu D P. 2004. Water balance of tropical eucalypt plantations in south-eastern China. *Agricultural and Forest Meteorology* 124: 253–267.

Lundblad M, Lindroth A. 2002. Stand transpiration and sapflow density in relation to weather, soil moisture and stand characteristics. *Basic and Applied Ecology* 3: 229-243.

Macfarlane C, Bond C, White DA, Grigg AH. 2010. Transpiration and hydraulic traits of old and regrowth eucalypt forest in southwestern Australia. *Forest Ecology and Management* 260: 96–105.

Maier CA, Albaugh TJ, Cook RI, Hall K, McInnin D, Johnsen KH, Johnson J, Rubilar RA, Vose JM. 2017. Comparative water use in short-rotation *Eucalyptus benthamii* and *Pinus* *taeda* trees in the Southern United States. *Forest Ecology and Management* 397: 126-138.

Marshall DC. 1958. Measurement of sap flow in conifers by heat transport. *Plant Physiology*. 33: 385-396.

Momolli DR, Schumacher MV, Viera M, Ludvichak AA, Guimaraes CC, de Souza HP. 2019. Incident precipitation partitioning: throughfall, stemflow and canopy interception in *Eucalyptus Dunnii* stand. *Journal of Agricultural Science* 11: 372-380.

Mondi Forest Operations, 2022. Online automatic water data. Available at https://sasri.sasa.org.za/rtwd/524/index.html [accessed 14 May 2022].

Morris JIM, Ningnan Z, Zengjiang Y, Collopy J, Daping X. 2004. Water use by fast growing *Eucalyptus urophylla* plantations in Southern China. *Tree Physiology* 24: 1035-1044.

Myers BJ, Theiveyanathan S, O'Brien NDO, Bond WJ. 1996. Growth and water use of *Eucalyptus grandis* and *Pinus radiata* plantations irrigated with effluent. *Tree physiology* 16: 211-219.

Nadezhdina N, Nadezhdin V, Ferreira MI, Pitacco A. 2007. Variability with xylem depth in sap flow in trunks and branches of mature olive trees. *Tree Physiology* 27(1):105-113.

Ngubo CZ, Demlie M, Lorentz S. 2022. Investigation of hydrological processes and the impacts of Acacia mearnsii plantations on groundwater in secondary aquifers: Case study at the two-streams research catchment, South Africa. *Journal of Hydrology*: *Regional Studies* 40: 101018.

O'Grady AP, Eamus D, Hutley LB. 1999. Transpiration increases during the dry season: patterns of tree water use in eucalypt open-forests of northern Australia. *Tree Physiol*ogy 19, 591–597.

Oren R, Pataki D. 2001. Transpiration in response to variation in microclimate and soil moisture in southeastern deciduous forests. *Oecologia* 127: 549-559.

Otto MS, Hubbard RM, Binkley D, Stape JL. 2014. Dominant clonal *Eucalyptus grandis* x *urophylla* trees use water more efficiently. *Forest Ecology and Management* 328: 117-121.

Ouyang L, Zhao P, Zhou G, Zhu L, Huang Y, Zhao X, Ni G. 2017. Stand-scale transpiration of a *Eucalyptus urophylla* x *Eucalyptus grandis* plantation and its potential hydrological implication. *Ecohydrology* 11: 1-10.

Pereira LS, Paredes P, Hunsaker DJ, Urrea RL, Shad ZM. 2021. Standard single and basal crop coefficients for field crops. Updates and advances to the FAO 56 crop water requirements method. *Agricultural Water Management* 243: 106466.

Perez C, Frangi J, Teson N, Arturi M. 2021. Transpiration rates, climate and soil water balance of Eucalyptus grandis afforestation on temperate grassland in ne Argentina. *Journal of Sustainable Forestry* 40: 607-621.

R Development Core Team. 2008. R: a language and environment for statistical computing. Vienna: R Foundation for Statistical Computing. Available at http://www.R-project.org [accessed 21 January 2023].

Saadaoui E, Yahia KB, Dhahri S, Jamaa MLB, Khouja ML. 2017. An overview of adaptive responses to drought stress in *Eucalyptus spp*. *Forestry Studies* 67: 86-96.

Schulze RE, Lynch SD. 2007. Monthly rainfall and its inter-annual variability. In Schulze RE (ed.), *South African atlas of climatology and agrohydrology,* WRC Report no. 1489/1/06. Pretoria: Water Research Commission.

Scholz FG, Bucci SJ, Goldstein G, Meinzer FC, Franco AC. 2002. Hydraulic redistribution of soil water by neotropical savanna trees. Tree Physiology 22: 603-612.

Scott DF, Lesch W. 1997. Streamflow responses to afforestation with *Eucalyptus grandis* and *Pinus patula* and to felling in the Mokobulaan experimental catchments, South Africa. *Journal Hydrology* 199: 360-377.

Scott DF, Smith RE. 1997. Preliminary empirical models to predict reductions in annual and low flows resulting from afforestation. Water SA 23: 135-140.

Scott DF, Le Maitre DC, van Wyk E. 1999. *The effects of forestry on low flows: further studies on low flow in wet and dry cycles and in relation to catchemnts of increasing size*. CSIR Report no. ENV/S-C 99059. Pretoria: Council for Scientific and Industrial Research.

Scott DF, Prinsloo FW, Moses G, Mehlomakulu M, Simmers DA. 2000. *A re-analysis of the South African catchment afforestation experimental data*. Water Research Commission Report No. 810/1/00. Pretoria: Water Research Commission.

Scott DF, Prinsloo FW. 2008. Longer-term effects of pine and eucalyptus plantations on streamflow. *Water Resources Research* 44: 1–8.

Scott-Shaw BC, Everson CS, Geldenhuys CJ, Starke A, Atsame-Edda A, Schutte SR, Mupemba M. 2016. *Rehabilitation of alien invaded riparian zones and catchments using indigenous trees: an assessment of indigenous tree water-use volume 1*. WRC Report no. 2081/1/16. Pretoria: Water Research Commission.

Shen R, Pennell KG, Suuberg EM. 2013. Influence of soi moisture on soil gas vapor concentration for vapor intrusion. Environmental Engineering Science 30: 628-637.

Silveira L, Gamazo P, Alonso J, Martínez L. 2016. Effects of afforestation on groundwater recharge and water budgets in the western region of Uruguay. *Hydrological Processes* 30: 3596–3608.

Smethurst PJ, Almeida AC, Loos RA. 2015. Stream flow unaffected by *Eucalyptus* plantation harvesting implicates water use by the native forest streamside reserve. *Journal of Hydrology: Regional Studies* 3: 187-198.

Smith RE, Scott DF. 1992. The effects of afforestation on low flows in various regions of South Africa, *Water SA* 18: 185-194.

Soares JV, Almeida AC. 2001. Modelling the water balance of soil water fluxes in a fast-growing *Eucalyptus* plantation in Brazil. *Journal of Hydrology* 253: 130-147.

Stone EL, Kalisz PJ. 1991. On the maximum extent of tree roots. *Forest Ecology and Management* 46: 59-102.

Sudmeyer RA, Speijers J, Nicholas BD. 2004. Root distribution of Pinus pinaster, P. radiater, *Eucalyptus globulus* and E. kochii and associated soil chemistry in agricultural land adjacent to tree lines. *Tree Physiology* 24: 1333-1346.

Swain T, Gardner RAW. 2003. Cold tolerant eucalypt species (CTE's): A summary of information for site species matching and optimum growth. *ICFR Technical Note 03*. Pietermaritzburg, South Africa: Institute for Commercial Forestry Research.

Taylor PJ, Nuberg KI, Hatton TJ. 2001. Enhanced transpiration in response to wind effects at the edge of a blue gum (*Eucalyptus globulus*) plantation. *Tree Physiology* 21: 403-408.

Tyree MT, Sperry JS. 1988. Do woody plants operate near the point of catastrophic xylem dysfunction caused by dynamic water stress? *Plant physiology* 88(3): 574-580.

Vanclay JK. 2009. Managing water use from forest plantations. *Forest Ecology and Management* 257: 385-389.

Van Dijk AI, Keenan RJ. 2007. Planted forests and water in perspective. *Forest Ecology and Management* 251: 1-9.

Van Lill WS, Kruger FJ, Van Wyk DB. 1980. The effect of afforestation with *Eucalyptus grandis* Hill ex Maiden and *Pinus patula* Schlecht. et. Cham. on streamflow from experimental catchments at Mokobulaan, Transvaal, Journal of Hydrology 48: 107-118.

White DA, McGrath JF, Ryan MG, Battaglia M, Mendham DS, Kinal J, Downes GM, Crombie DS, Hunt ME. 2014. Managing for water-use efficient wood production in Eucalyptus globulus plantations. Forest Ecology and Management 331: 272-280.

White DA, Beadle CL, Worledge D, Honeysett JL. 2015. Wood production per evapotranspiration was increased by irrigation in plantations of *Eucalyptus globulus* and *E. nitens*. New Forests 47: 303–317.

White DA, McGrath JF, Ryan MG, Battaglia M, Mendham DS, Kinal J, Downes GM, Crombie DS, Hunt MA. 2014. Managing for water-use efficient wood production in *Eucalyptus globulus* plantations. *Forest Ecology and Management* 331:272–280.

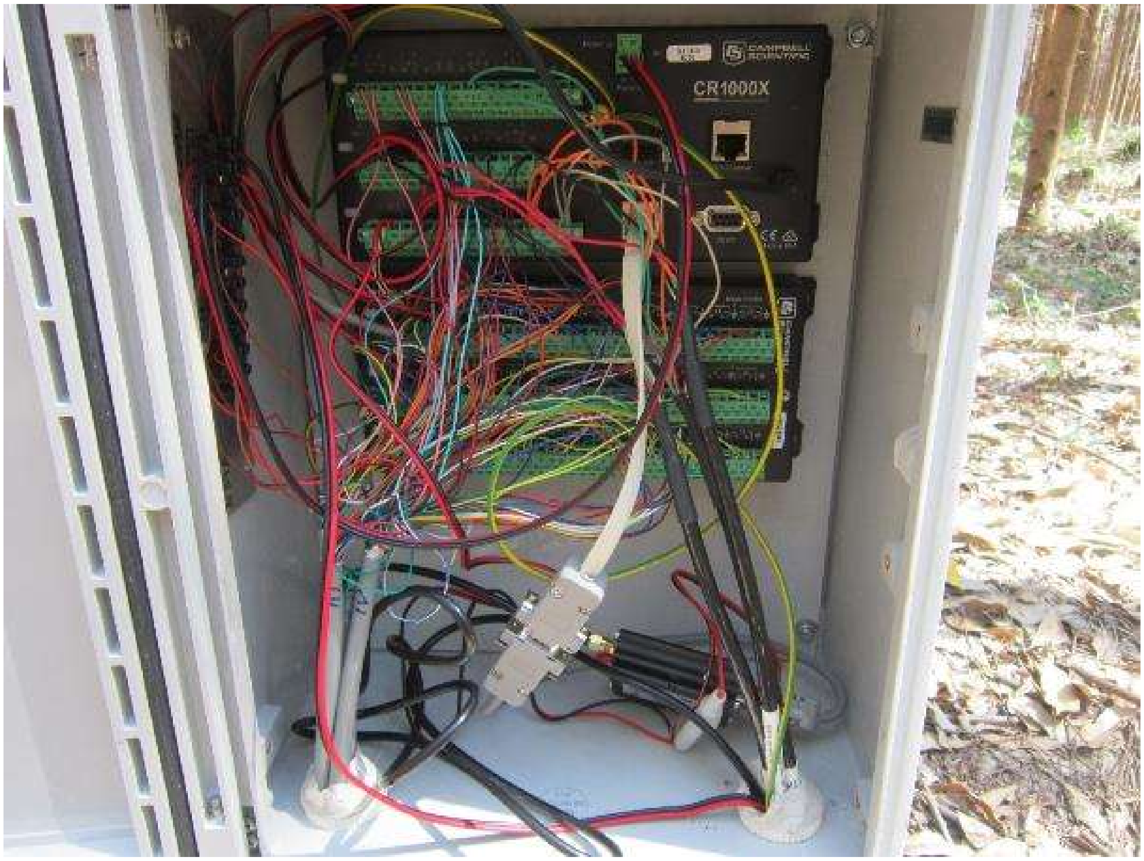
White DA, Silberstein RP, Contreras FB, Quiroga JJ, Meason DF, Palma JHN, de Arellano PR. 2021. Growth, water use, and water use efficiency of *Eucalyptus globulus* and *Pinus radiata* plantations compared with natural stands of Roble-Hualo forest in the coastal mountains of central Chile. *Forest Ecology and Management* 501: 119675-119676.

Wichert MCP, Alvares CA, Junior JCAJ, Stape JL. 2018. Site preparation, initial growth and soil erosion in *Eucalyptus grandis* plantations on steep terrain. *Scientia Forestalis* 46: 17-30.

Zweifel R, Zimmermann L, Newbery DM. 2005. Modelling tree water deficit from microclimate: an approach to quantifying drought stress. *Tree Physiology* 25: 147-156.

3.9 Supplementary material

Supplementary Figure 3.1: The insulated heat ratio technique installed on a *Eucalyptus grandis* x *E. urophylla* clonal hybrid tree, while the inset picture indicates heat ratio probes on a tree before insulation in the KwaMbonambi study site.

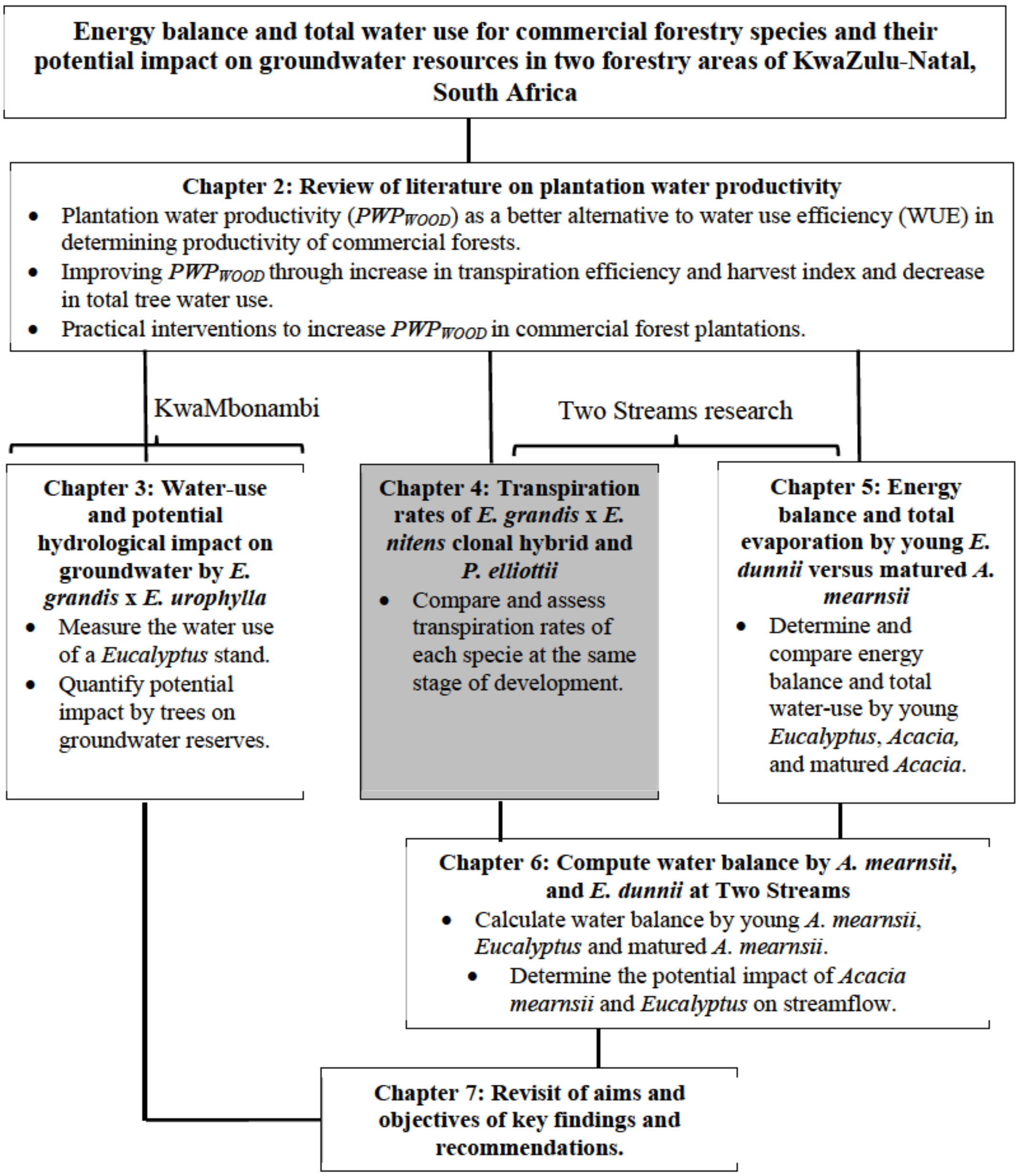


Supplementary Figure 3.2: The main control box used to operate the heat ratio technique which consist of a CR1000 datalogger, a multiplexer and a cellphone modem used for communication in the KwaMbonambi study site.

Supplementary Figure 3.3: The dendrometer band installed on a *Eucalyptus grandis* x *E. urophylla* clonal hybrid tree in the KwaMbonambi study site.

Supplementary Figure 3.4: A CS616 soil water content sensor used to measure soil water content at different depths (200 mm, 400 mm and 600 mm) under the *Eucalyptus grandis* x *E. urophylla* clonal hybrid in the KwaMbonambi study site.

Lead into Chapter 4: The use of heat ratio technique from previous chapter was extended to two study sites next to Two Streams research catchment to further expand water use knowledge by fast-growing *Eucalyptus grandis* x *E. nitens* (*GN*) *and Pinus elliottii* in warm temperate regions of KwaZulu-Natal, South Africa. Therefore, the objective of chapter 4 was to provide comparative water use between *GN* and *P. elliottii*, the first comparative study between the two genera in South Africa, calculate PWP_{WOOD} by *GN* and *P. elliottii* and to quantify the potential impact on groundwater resources.



CHAPTER 4: TRANSPIRATION RATES FROM MATURE *EUCALYPTUS GRANDIS* X *E. NITENS* CLONAL HYBRID AND *PINUS ELLIOTTII* PLANTATION NEAR THE TWO STREAMS RESEARCH CATCHMENT, SOUTH AFRICA

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* Referencing style conforms to format of Hydrology and Earth System Sciences.

4.1 Abstract

Pine plantations are the dominant species currently planted within the South African commercial forestry industry. Improvements in bioeconomy markets for dissolving wood pulp products have seen an expansion in fast-growing *Eucalyptus* plantations due to their higher productivity rates and better pulping properties than pine. This has raised concerns regarding the expansion of *Eucalyptus* plantations and how they will affect water resources as they have been reported to have higher water-use (quantified using transpiration rates) than pine. We measured transpiration rates (mm year^{-1}), diameter at breast height (quantified as quadratic mean diameter, *Dq*, m) and leaf area index of an eight-year-old *Eucalyptus grandis* x *Eucalyptus nitens* clonal hybrid (*GN*) and a twenty-year-old *Pinus elliottii*. Transpiration rates were measured for two consecutive hydrological years (2019/ 20 and 2020/ 21) using a heat ratio sap-flow method, calibrated against a lysimeter. In the 2019/ 20 year, annual transpiration for *P. elliottii* exceeded *GN* by 28%, while for the 2020/ 21 hydrological year, there was no significant difference between the transpiration of the two species, despite a 17 and 21% greater leaf area index for *P. elliottii* than *GN* in 2019/ 20 and 2020/ 21 measurement years, respectively. Quadratic mean diameter increments were statistically similar ($p > 0.05$) in 2019/ 20, whereas the 2020/ 21 year produced significant differences ($p < 0.05$). Tree transpiration is known to be influenced by climatic variables; therefore, a Random Forest regression model was used to test the level of influence between tree transpiration and climatic parameters. The soil water content, solar radiation and vapour pressure deficit were found to highly influence transpiration, suggesting these variables can be used in future water-use modelling studies. The profile water content recharge was influenced by rainfall events. After rainfall and soil profile water recharge, there was a rapid depletion of soil water by the *GN* trees, while the soil profile was depleted more gradually at the *P. elliottii* site. As a result, trees at the *GN* site appeared to be water stressed (reduced stem diameters and transpiration), suggesting that there was limited access to alternative water source (such as groundwater). The *GN* PWP_{WOOD} was lower than other *Eucalyptus* studies in South Africa and internationally, suggesting that productivity of eucalypts can be limited by water stress in forest plantations. The study concluded that previous long-term paired catchment studies indicate that eucalypts use more water than pine, however, periods of soil water stress and reduced transpiration observed in this study must be accommodated in hydrological models. Long-term total soil water balance studies are recommended in the same region to understand the long-term impact of commercial plantations on water resources.

Keywords: Heat pulse velocity, Plantation water productivity, Sapflow, Water use

4.2 Introduction

The expansion of new areas of commercial afforestation in South Africa have generally slowed in recent years in favour of the composition of existing plantations changing. This decrease has been attributed to political, environmental and climate change influences (Nambiar, 2019). Pine plantations are still the dominant species in South Africa occupying approximately 49.6% of total commercial forest plantation areas (Forestry South Africa, 2020). These plantations are mainly grown for sawlog (74.7%) and coarse-fibre pulpwood (24.9%). Over the years, there has been an improvement in the bioeconomy market for dissolving wood pulp products such as short fine-fibre pulp. Fast-growing *Eucalyptus* species are now being considered an alternative to pine due to their superior fibre and pulping properties (Dougherty and Wright, 2012), short rotation (8-12 years) and high productivity rates (Albaugh et al., 2013). *Eucalyptus* plantation productivity can be as high as 35 m^3 ha^{-1} $year^{-1}$ on highly productive sites compared to 25-27 m^3 ha^{-1} $year^{-1}$ of pine (Fox et al., 2007). As a result, over the past 10 years, the areas planted to pine in South Africa have decreased by 2% while *Eucalyptus* increased by 10% (Forestry South Africa, 2020). There are now plans to replace as many as 300 000 ha of pine with *Eucalyptus* over the next 20 years (Forestry South Africa, 2020).

The potential for an increase in planting *Eucalyptus* species in South Africa may present several environmental considerations including a potential impact to biodiversity (Callaham et al., 2013) and high rates of transpiration and total evaporation (Stanturf et al., 2013). There is a wide body of knowledge indicating that *Eucalyptus* species transpiration is greater than pine (Scott and Lesch, 1997; Albaugh et al., 2013) and can reduce off-site water yield (Calder, 2002). Given the imminent increase in *Eucalyptus* plantations in the near future, it is vital to understand water-use by pine and *Eucalyptus*. A *Eucalyptus grandis* versus *Pinus patula* comparison by Scott and Lesch (1997) on very deep soils, found that *E. grandis* used up to 100 mm more water per year than *P. patula* using streamflow measurements. In contrast, White et al. (2021), reported no annual differences between T of *E. globulus* and *P. radiata* in central Chile.

Pinus elliottii and *E. grandis* x *Eucalyptus nitens* clonal hybrid (*GN*) are the second and fourth most planted species in South Africa, respectively. There is no existing literature that quantifies transpiration by these two species in South Africa and there are mixed reports in international literature. The objective of this study was therefore to measure transpiration (as an indicator of tree water-use) of *GN* and *P. elliottii* plantations and the impact posed by each species on plantation water yield. In South Africa, forest companies harvest trees at an age aimed at maximising profit, with *Eucalyptus* species (grown for pulp) rotation generally ranging from 7 to 10 years, whereas pine (grown for sawlog) is usually 18 to 24 years (Forestry South Africa, 2020). Using an average rotation of 8.5 years for *Eucalyptus* and 21 years for pine, transpiration measurements in our study were conducted on a 8-year-old *GN* (approximately 94% into the rotation) and 20-year-old *P. elliottii* (approximately 95% into the rotation) and both species were therefore presumed to be in the same stage of development (same rotational age).

4.3 Materials and methods

4.3.1 Description of study area

The study area was located on the Mistley Canema estate (29°12'19.78°S, 30°39'3.78°E) in the KwaZulu-Natal midlands of South Africa, which is about 70 km north-east of Pietermaritzburg (Fig. 4.1). The area is generally hilly with rolling landscapes and a high percentage of arable land (Everson et al., 2014). It is dominated by forb-rich, tall, sour *Themeda triandra* grasslands of which only a few patches remain due to invasion of native *Aristida junciformis*. Soils in this area are highly leached with apedal and plinthic soil forms, mostly derived from shales (Ecca group). The area experiences mist which could significantly contribute to overall precipitation (Mucina and Rutherford, 2006). The study site weather classification according to Koppen-Geiger climate classification (Peel et al., 2007) falls within the Cwa bioclimatic zone characterised by dry, cold winters and warm and wet summer months.

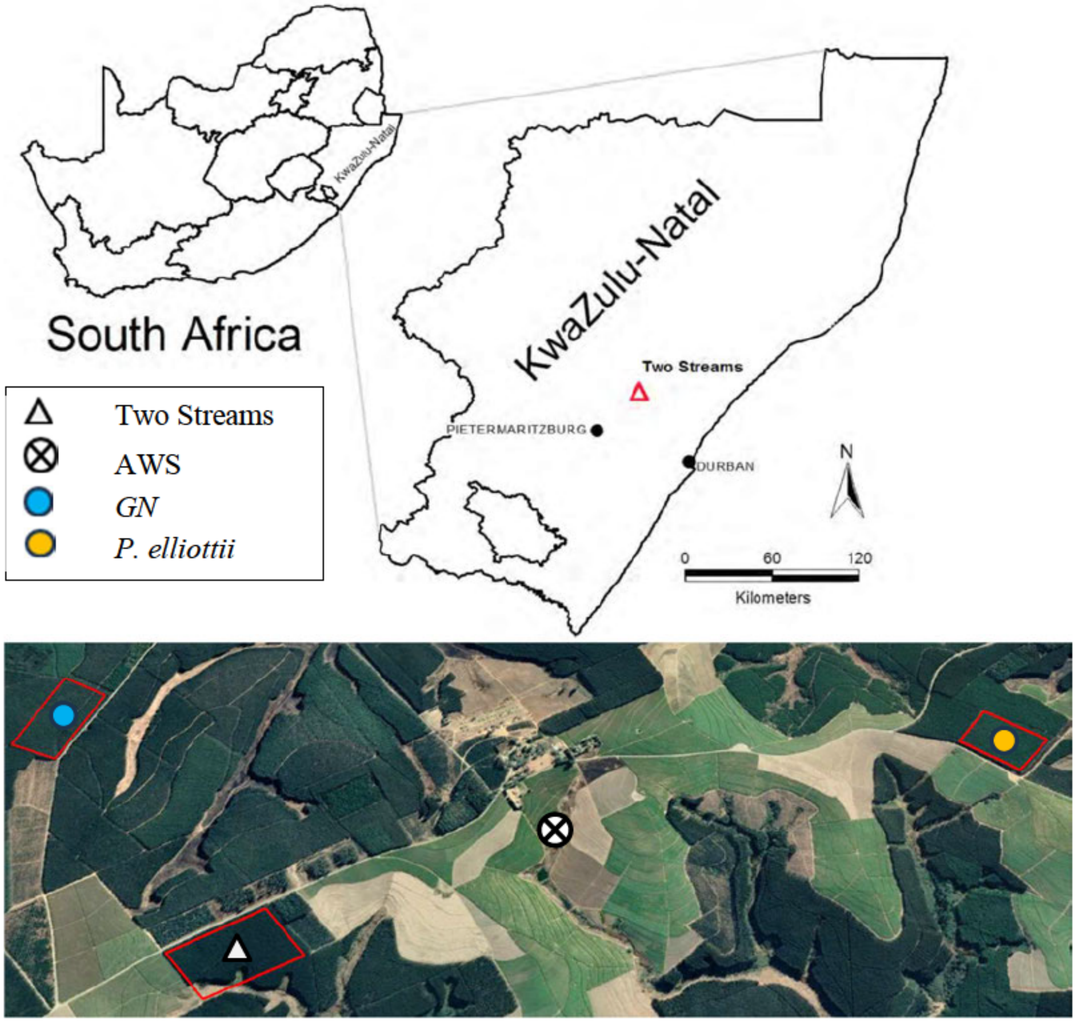


Figure 4.1. Location of the study area next to Two Streams Research Catchment. The Google Earth Pro extract (above) provides location of the two study sites, *E. grandis* x *E. nitens* (*GN*), *Pinus elliottii* and the automatic weather station (© Google Maps 2022). Red lines indicate the boundaries of the compartment for each study site. Dark green vegetation indicates commercial forest plantations and light green vegetation is the sugarcane fields.

4.3.2 Site description

The study sites were located adjacent to the Two Stream Research Catchment used in previous (Clulow et al., 2011; Everson et al., 2014) forestry research (Fig. 4.1). Study site 1 was situated on the north-western side of the catchment (1.6 km away) and planted to *GN* in August of 2013.

Study site 2 (3.5 km away from the catchment) was established in August 2001 and planted to *Pinus elliottii.* Soil characteristics from the Two Streams research catchment, which is adjacent to our study sites, is presented in Table 4.2 to show a general soil characteristics picture. Research by Clulow et al. (2011) and Everson et al. (2014) at Two Streams Research Catchment classified the soil profile to be as deep as 13 m (Table 4.2) and below that consists of a weathered bedrock (saprolite) and fractured basement rock. The soil form was classified as Hutton (Soil Classification Working Group, 1991). Study sites were 4 km away from each other with the automatic weather station located approximately equidistant between the two sites. Both *GN* and *P. elliottii* were planted at a spacing of 2 x 3 m (1667 trees ha^{-1}). The *GN* trees were established using cuttings, while for *P. elliottii*, seedlings were used. Both study sites were subjected to standard afforestation practices such as pruning and thinning, weeding prior to canopy closure and slash removal every 5^{th} row to minimise fire risk.

Table 4.1: The general characteristics of the two study sites at Mistley Canema. The abbreviations MAP and MAT denotes mean annual precipitation and mean annual temperature, respectively (Clulow et al. 2011, Everson et al. 2014)

	Study sites	
Characteristics	***P. elliottii***	***GN***
Lithology	Arenite	Arenite
Soil texture	Sandy loam	Sandy clay
Bulk density ($g.cm^3$)	1.33	1.17
Altitude	884	976
Climate	Warm temperate	Warm temperate
MAP (mm)	800 – 1200	800 – 1200
MAT (°C)	17	17

Table 4.2: A general description of substrate (soil and geology) characteristics based on characterisation conducted at the Two Streams research catchment, which is adjacent to our study site (sourced from Clulow et al. 2014).

Horizons	Approximate depth (m)
Orthic A	0 – 0.25 m
Red apedal B	0.26 – 13 m
Saprolite	14 – 20 m
Grey fine-grained shale	21 – 40 m
Grey fractured basement granite	41 – 80 m

4.3.3 Environmental monitoring

An automatic weather station (AWS) was installed on a flat uniform grassland area in the middle of the two study sites to provide supporting meteorological measurements. Measurements of air temperature (T_{air}, °C) (HMP 60, Vaisala Inc., Helsinki, Finland), the relative humidity (*RH*, %) (HMP60, Vaisala Inc., Helsinki, Finland), the wind speed (m s^{-1}) and direction (degrees) (Model 03003, R.M. Young, Traverse City, Michigan, USA), the solar radiation (I_s, MJ m^{-2} day^{-1}) (Kipp and Zonen CMP3) and rainfall (mm day^{-1}) (TE525, Texas Electronics Inc., Dallas, Tx, USA) were conducted every 10 s and output hourly. The sensors were installed according to recommendations of the World Meteorological Organisation (WMO, 2010) with the rain gauge orifice at 1.2 m and the remaining sensors at 2 m above the ground surface. The CR1000 datalogger (Campbell Scientific Inc., Logan, Utah, USA) recorded data every 6-min and was programmed to calculate the Vapour Pressure Deficit (VPD, kPa) using T_{air} and *RH* measurements according to Savage et al. (1997).

4.3.4 Transpiration flux measurements

Four representative trees were selected within each study site based on diameter stratification. This was achieved by measuring 48 tree diameters at breast height (DBH, 1.3 m) using a diameter tape and stratifying the measured trees according to four size classes; small, medium, medium large and large.

The heat ratio method of a heat pulse velocity system (HPV) (Burgess et al., 2001) was used to estimate sap-flow at various depths across the sap-wood of each selected tree for the 2019/ 20

(October 2019 to October 2020) and 2020/ 21 hydrological years (October 2020 to October 2021). The HPV system consisted of a line heater probe (4 cm long and of 0.18 cm outside diameter brass tubing) with enclosed constantan filament that provides a heat source for 0.5 s when powered and a pair of type T copper-constantan thermocouples to measure the heat ratio. For *Pinus elliottii* trees, slightly longer heater probes (6 cm) were used due to the xylem being situated deeper. Prior to probe installation, thickness of the bark was measured, and suitable sensor insertion depth was identified using an increment borer and Methyl Orange staining. The thermocouples and heater probes were inserted in holes, which were made using a drill and a drill guide to ensure that holes were drilled with the correct spacing and parallel alignment. A heater probe was installed in the central hole and thermocouples installed in each of the holes up (upstream) and down (downstream) from the heater probe relative to the sap-flow direction. Probes were installed at various depths (Table 4.3) within a tree. Hourly measurements were executed and recorded using a CR1000 datalogger (Campbell Scientific Inc.) powered by a single 55-amp hour lead acid deep cycle battery. Thermocouples were connected to an AM 16/32B multiplexer (Campbell Scientific Inc.), which was in turn connected to a datalogger (CR1000, Campbell Scientific Inc.) to allow for 32 measurements at various sap-wood depths across the four instrumented trees. Data were remotely downloaded using a GSM modem (Maestro Wireless Solutions Ltd. Hong Kong, China)

Hourly measurements started by measuring each thermocouple ten times for accurate initial temperatures. Following a heat pulse, the downstream and upstream temperatures were measured 40 times between 60 and 100s. Thereafter, heat pulse velocity (V_h, cm hr^{-1}) was calculated using (Burgess et al., 2001),

$$V_h = \frac{k}{x}\ln\left(\frac{V_1}{V_2}\right)3600 \qquad (4.1)$$

Where k is a thermal diffusivity of fresh wood (a nominal value of 2.5 x 10^{-3} cm^{2} s^{1}), x is the distance of each temperature probe (0.6 cm) from heater probe (cm), and V_1 and V_2 are temperature increases in upstream and downstream probe (°C) at equidistant points.

A slight probe misalignment may occur during the drilling process even when a drill guide is used. This was assessed by checking for inconsistencies in the zero flux values in periods where sap-flow was expected to be zero, such as over pre-dawn, during rainfall events, or in high *RH* and low soil water content (*SWC*) conditions. The sap-flow values during these times were adjusted to zero and an offset calculated from an average of these values and applied to the whole dataset. It is important to note that values less than zero (negative values) can be measured in deep rooted trees such as *Eucalyptus* due to hydraulic redistribution (Scholz et al. 2002), however these values have been reported to be negligible. For probes used in this study, the offset was < 5% of the midday sap-flow rates.

Wounding or non-sap conducting area around the thermocouples was accounted for using wound correction coefficients described by Burgess et al. (2001). Thereafter, sap velocities were calculated accounting for moisture fraction and wood density as described by Burgess et al. (2001). Finally, sap velocities were converted to T rates (mm day^{-1}) by summing products of sap velocity and cross-sectional sapwood area for individual stems. The sapflow rates were then up-scaled from sample trees to the entire forest stand using sapflow distribution in DBH classes method as described in detail by Cermak et al (2004) using:

$$Sapflow\ rates = ((T_1 \times 23\%) + (T_2 \times 24\%) + (T_3 \times 24\%) + (T_4 \times 29\%) \qquad (4.2)$$

where, T_1, T_2, T_3 and T_4, is tree 1, tree 2, tree 3 and tree 4, respectively. Different percentages represent a tree contribution to a stand.

Table 4.3: Detailed description of trees monitored on *Pinus elliottii* and *E. grandis* x *E. nitens* clonal hybrid (*GN*) study sites.

Trees	Overbark diameter (cm)		Bark (cm)		Sap-wood depth (cm)		Probe depth under bark surface (cm)	
	P. elliotti	*GN*	*P. elliotti*	*GN*	*P. elliotti*	*GN*	*P. elliotti*	*GN*
Tree 1	10.7	10.5	2.2	0.7	4.88	2.55	1	1
Tree 2	15.9	11.4	2.4	0.8	7.2	2.8	2	1.5
Tree 3	18.2	12.5	2.4	0.8	8.3	3.0	3	2.5
Tree 4	22.4	14.2	2.5	0.9	10.2	3.9	4	3.5

4.3.5 Soil water content and profile water content

At both sites hourly *SWC* was measured in the upper 0.60 m of the soil profile (0.20 m, 0.40 m and 0.60 m depth) using CS616 soil water measuring sensors (Campbell Scientific Inc.). The CS616 *SWC* sensor consists of two 30 cm long stainless-steel rods that uses the time domain reflectometer method to measure the *SWC*. The sensor circuitry generates an electromagnetic pulse, of which an elapsed pulse travel time and reflection are measured and then used to calculate the *SWC*. Research conducted at Two Streams Catchment (Clulow et al., 2011; Everson et al., 2014) reported that the majority of large and fine roots were located in the top 0.06 m to 0.4 m of the soil profile, hence *SWC* measurements were conducted in the top 0.6 m of the soil profile in our study. The *SWC* measurements ran concurrently with the sap-flow measurements and were recorded on a datalogger (CR1000, Campbell Scientific Inc.). The profile water content at 0.6 m soil depth ($PWC_{0.6}$) was estimated from the *SWC* measurements using:

$$PWC_{0.6} = \left(\frac{SWC_{0.2}\times 0.2)+(SWC_{0.4}\times 0.2)+(SWC_{0.6}\times 0.2}{1000}\right)\times 100 \qquad (4.3)$$

where, $SWC_{0.2}$, $SWC_{0.4}$, $SWC_{0.6}$ was the soil water content measured at 0.2 m, 0.4 m and 0.6 m, respectively.

4.3.6 Heat ratio technique calibration

The HPV method is an internationally recognised and reliable technique for measuring individual tree *T* in uniform stands (Hatton and Wu, 1995; Meiresonne et al., 1995; Crosbie et al., 2007). There are however difficulties, bringing uncertainty to the accuracy of the absolute sap-flow results, such as the anisotropic sap-wood properties (Vandegehuchte et al., 2012), radial patterns of the sap-flow (Cermák and Nadezhdina, 1998), tree symmetry (Vertessy et al., 1997) and changes in spatial patterns of *T* (Traver et al., 2010). Some studies have indicated that the technique underestimates sap-flow in *Eucalyptus* by as much as 45% (Maier et al., 2017; Fuchs et al., 2017), whereas pine may be overestimated by as much as 49% (Dye et al., 1996b). This necessitated a calibration experiment to validate the field measurements.

The calibration experiment was conducted in an open area at the Institute for Commercial Forestry Research nursery, located at the University of KwaZulu-Natal, Pietermaritzburg for a period of 30 days as illustrated in Figure 4.2. Two-year-old *GN* and four-year-old *Pinus elliottii* trees grown in 25-L plastic containers (diameter=36 cm, height = 42 cm) filled with vermiculite were sourced from Mondi Mountain Home Estate nursery (Hilton, South Africa). The containers had holes at the base (to allow for drainage) and were placed on a rubber mat with slots to prevent root contact with soil and to allow water to drain away from the container. Twenty-four hours before starting the experiment, both trees were well watered, and each container was insulated using plastic at the tree base to prevent soil evaporation and induce water loss solely through *T*. Tree diameters at the start of an experiment were 0.044 and 0.036 m for *GN* an *P. elliottii*, respectively. Each tree was instrumented with HPV sensors to measure hourly sap-flow (as discussed in section 4.3.4) and summed up over 24 hours to make up daily tree *T* (L day^{-1}). Concurrently, each soil container was weighed in the morning and afternoon, using a lysimeter (resolution=0.001g, placed on a flat concrete surface to ensure it remains level during the experiment) to determine daily changes in container weight (kg, where 1 kg was assumed to be equivalent to 1 L) as a measure of *T*. This process was repeated for five days to get a calibration over a range of plant available water values, whereafter trees were again well-watered (achieved by removing insulation plastic) and allowed to drain completely before restarting measurements. Sapwood area and wounding was accounted for according to Burgess et al. (2001) to derive daily *T*. A simple regression was conducted between daily *T* and daily change in tree mass.

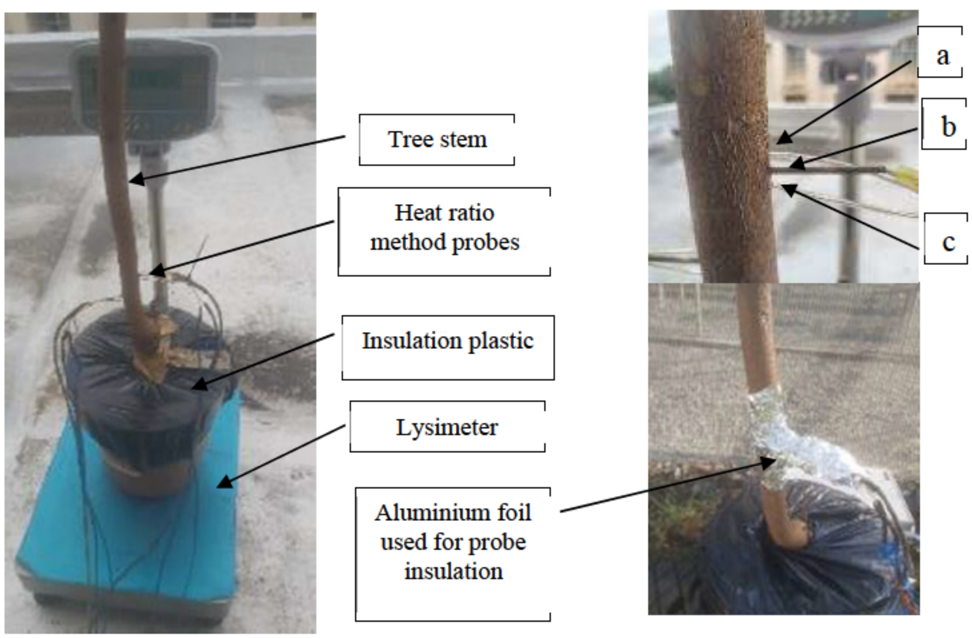


Figure 4.2. An illustration of a calibration experiment setup showing a tree installed with the heat ratio probes, placed on a lysimeter. Insert: a= downstream probe, b= heater probe, c= upstream probe with aluminium foil used for insulation.

4.3.7 Growth measurements

Measurements of DBH were conducted monthly using manual dendrometer bands (D1, UMS, Muchin, Germany) permanently attached to a tree, with an accuracy of 0.1 mm. Dendrometer bands were installed at beginning of October 2019 on 48 trees including the four HPV instrumented trees and data were manually collected for 21 months. The quadratic mean diameter (D_q) was calculated for 48 trees using (Curtis and Marshall, 2000):

$$Dq = \sqrt{\frac{(\sum(DBH)^2}{n}} \quad (4.4)$$

where; *d* is the DBH (m) of an individual tree and n is the total number of trees. Tree heights for the 48 trees were measured simultaneously using a hypsometer (Vertex Laser VL402, Haglof, Sweden).

The conical over bark wood volume (v, m^3) for each month was calculated using equation 4.5 (White et al. 2014):

$$v = \left(\frac{\pi}{12}\right)\left(\frac{Dq}{100}\left(\frac{h}{h-1.3}\right)\right)^2 h \quad (4.5)$$

where, h is the tree height. The stand volume (V, m^3 ha^{-1}) was calculated using:

$$V = \frac{10\,000}{A}\sum_{i=1}^{n} vi \quad (4.6)$$

where vi was the productive volume of the *i*th tree, *A* was the total area (m^2) of the plot where measurements were conducted, n is the total number of trees within a plot and 10 000 represents one hectare (equivalent to 10 000 m^2).

Monthly measurements of leaf area index (LAI) were conducted using a LAI-2200 Plant Canopy Analyzer (Licor Inc., Lincoln, New York, USA) on a transect that was identified through the middle of each study site from October 2019 to October 2021.

4.3.8 Plantation water productivity (PWP_{WOOD})

The annual plantation water productivity (PWP_{WOOD}), expressed in g wood kg^{-1} of water was calculated for *GN* and *P. elliottii* as a ratio of *V* to ET for 2019/ 20 (October 2019 to September 2020) and 2020/ 21 (October 2020 to September 2021). The Es and I were estimated from rainfall using published studies from similar age *Eucalyptus* and *Pinus* studies under relatively similar environmental conditions.

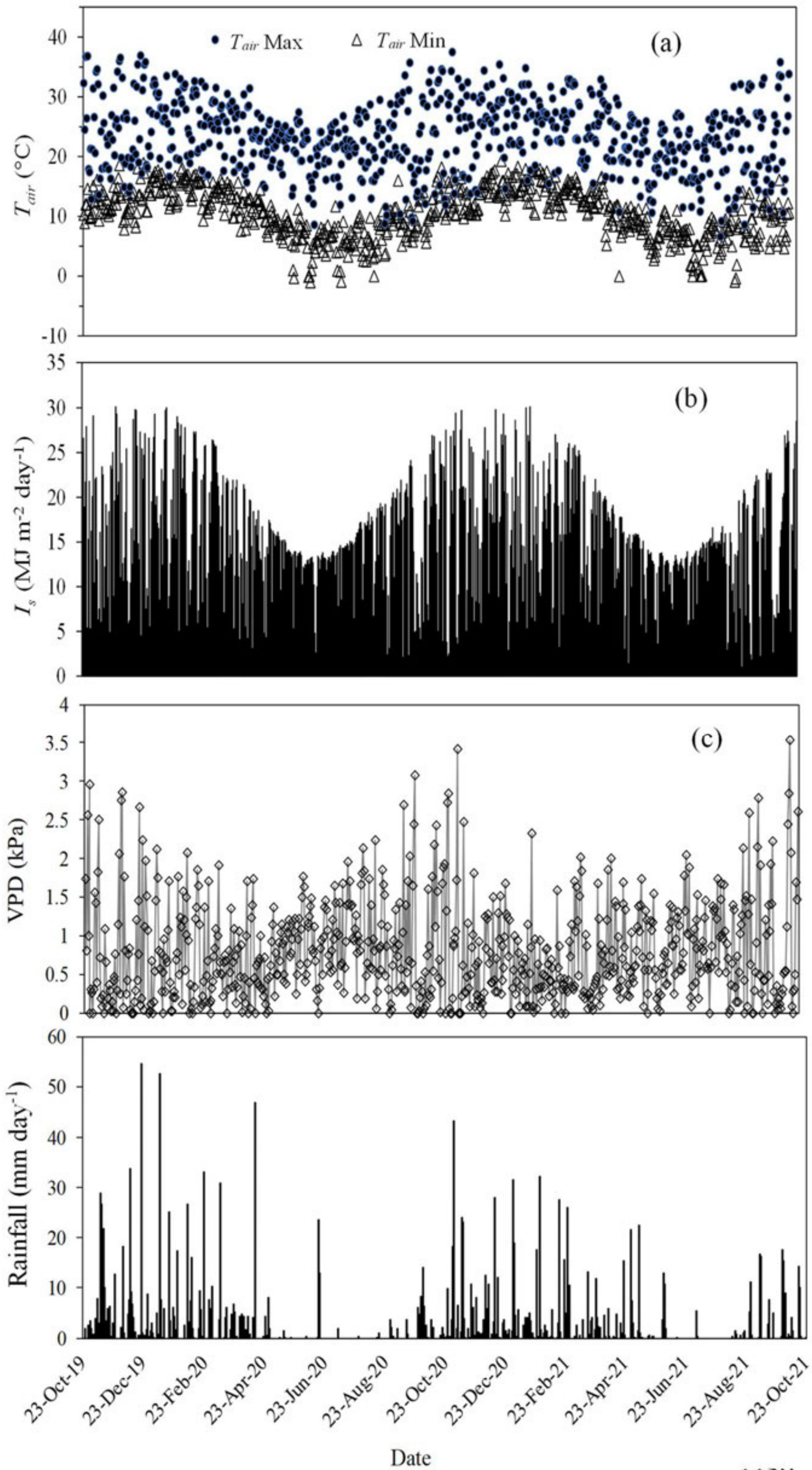
4.3.9 Statistical analysis

Analysis variance (ANOVA) was used to analyse species differences in stand characteristics (transpiration, D_q, tree heights and leaf area index) using the R version 3.6.1 statistical package. Variables were transformed as appropriate to meet the assumptions of normality. Where the overall F-statistic was significant ($p < 0.05$), treatment means were compared using Fischer's Least Significant Difference at the 5% level of significance ($LSD_{5\%}$). Statistical parameters that were used included the regression co-efficient (R^2), root mean square error (RMSE), standard error of a regression slope (SE slope), standard error of the intercept (SE intercept) and a ratio of variance of y-intercept to x-intercept (F). In addition, Random Forests (RF) regression algorithm (Breiman, 2001) in R statistical computing software (R Development Core team, 2008) was used to rank climatic variables that influence transpiration, where transpiration was made a response variable and meteorological data (Is, VPD, *SWC*, T_{air}, rainfall, wind speed and RH) as predictor variables. This machine learning approach does not make the assumptions of linear regression and performs well when the relationship among the response variable and independent variables are complex and non- linear. The RF regression model was optimised in terms of the parameters ntree (number of trees built by the model) and mtry (number of variable predictors used at each node split using the Caret package (Kuhn, 2008). The RF regression was evaluated using the R^2 metric and the contribution of each variable to the model accuracy was determined by developing a variable importance plot. The variable importance was calculated from the out-ot-bag (OOB) samples. Using a bootstrap sample with replacement, two thirds of the original dataset are used to train individual trees in the ensemble, whereas the remaining one third of a sample is used for determining ranked variable importance, providing a measure of accuracy (Breiman, 2001). In this study, the two thirds of the dataset for each measurement period were used for calibrating and validating the model, while the one third was used for testing the model. The variable importance plot was assessed using the mean decrease accuracy (MDA) coefficient measures (Breiman et al., 1984). The MDA is calculated during the OOB sample computation phase. The values of a particular variable are randomly permuted on the OOB sample, enabling the new classification to be determined from the modified sample. For more details on how MDA is quantified refer to Cutler et al (2007) and Aria et al (2021). The difference between the rate of misclassification for the modified sample and the original sample is used as a measure of the variable importance. Each predictor variable was scored based on the MDA for *GN* and *P. elliottii* measurement period.

4.4 Results

4.4.1 Automatic weather station

The minimum and maximum daily T_{air} were typical of the 30-year average of Mistley Canema. Maximum recorded T_{air} was 36.5 and 37.5°C for 2019/ 20 and 2020/ 21 hydrological years, respectively. There were several days where T_{air} were below freezing between May and July for both measurement years (Fig. 4.3a). Rainfall between 01 October 2019 and 30 September 2020 amounted to 857 mm and 825 mm for 01 October 2020 to September 2021. Majority of this rainfall (70%) fell during summer months (November to March) for both years (Fig. 4.3d). By comparison, potential evaporation totals calculated using hourly AWS data and the FAO56 method (Allen et al., 1998) amounted to 1100 mm and 1056 mm for 2019/ 20 and 2020/ 21 hydrological years, respectively. Daily maximum VPD was 3.08 kPa for 2019/ 20 increasing to 3.53 kPa for 2020/ 21 year during hot summer months (Fig. 4.3c). Monthly average wind speed ranged from 2.2 to 7.7 m s^{-1} over the two hydrological years with maximum wind speeds up to 37 m s^{-1} in August/ September. The *RH* reached 100% during the night, decreasing to as low as 20% during the day on hot summer months. Average I_s for 2019/ 20 and 2020/ 21 hydrological years was 15.5 and 16 MJ m^{-2} day^{-1}, respectively, while both years experienced a maximum I_s of 30 MJ m^{-2} day^{-1} in summer (Fig. 4.3b).



T_{air} Max
T_{air} Min
(a)
T_{air} (°C)
(b)
I_s (MJ m^{-2} day^{-1})
(c)
VPD (kPa)
Rainfall (mm day^{-1})
23-Oct-19
23-Dec-19
23-Feb-20
23-Apr-20
23-Jun-20
23-Aug-20
23-Oct-20
23-Dec-20
23-Feb-21
23-Apr-21
23-Jun-21
23-Aug-21
23-Oct-21
Date

3339

Figure 4.3: (a) the daily minimum (T-Min) and maximum (T-Max) air temperature (°C) (b) daily total solar irradiance (MJ m^{-2} day^{-1}) (c) daily mean vapour pressure deficit (VPD, kPa) and (d) total daily rainfall (mm) for a duration October 2019 to October 2021.

4.4.2 Soil profile water content

The $PWC_{0.6}$ was very responsive to rainfall events (Fig. 4.4 and Fig. 7a) on both study sites. The peak $PWC_{0.6}$ for the *GN* site during the wet season was 227 mm and 198 mm day^{-1} in 2019/ 20 and 2020/ 21 hydrological years, respectively. By comparison, the maximum measured $PWC_{0.6}$ in the *P. elliottii* site was 128 mm day^{-1} in 2019/ 20 and 125 mm day^{-1} in 2020/ 21. The $PWC_{0.6}$ at both study sites did not significantly respond to rainfall events below 5 mm hr^{-1}, except during consecutive rainfall events. After a significant rainfall event, the $PWC_{0.6}$ for the *GN* site was depleted rapidly, within hours (Fig. 4.4 and Fig. 4.7a), which contrasts with the *P. elliottii* site, where $PWC_{0.6}$ was depleted more gradually, lasting for a few days after the rainfall event. The swift depletion of plant available water at the *GN* site, resulted in the site experiencing extended periods of low-profile water content. During the dry season, the $PWC_{0.6}$ was maintained at approximately 50 and 60 mm day^{-1} for *P. elliottii* and *GN* (Fig. 4.7b), respectively, except when significant rainfall events occurred.

Commercial forest plantations are known to have a very deep rooting system and are able to access soil water in deeper soil water reserves (Christina et al. 2016). A study adjacent to our study site (Everson et al. 2014) reported that *Acacia mearnsii* tree roots were as deep as 8 m into the soil profile. Similar results were reported by Dye (1996) in the Mpumalanga province of South Africa, where *Eucalyptus grandis* trees abstracted water down to 8 m below the soil surface. The deep soil profile with the presence of weathered bedrock (saprolite) in our study site suggests that trees were capable of rooting as deep as 20 m into the soil profile and were probably restricted by the bedrock (grey fine-grained shale). However, Hasenmueller et al. (2017) indicated that shale may consist of fractures where tree roots may grow through. There is, therefore, a high possibility that tree roots in this study accessed soil water stored deep in the soil profile from previous wet years.

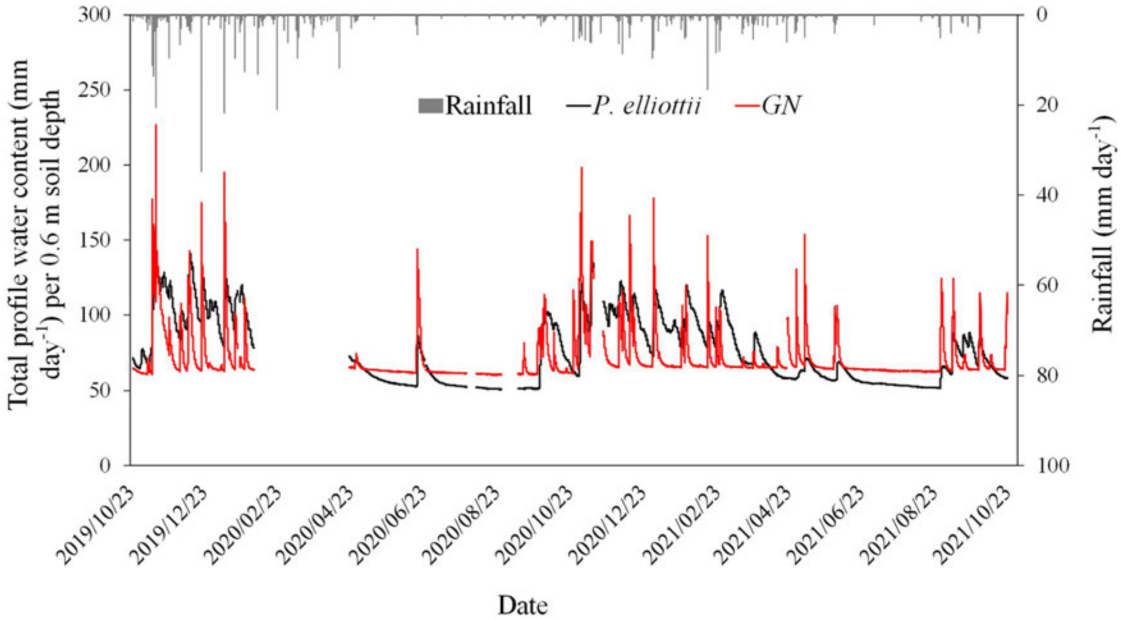


Figure 4.4: The total profile water content (mm day^{-1}) measured in the top 0.6 m of the soil profile in the *Pinus elliottii* and *Eucalyptus grandis* x *E. nitens* clonal hybrid sites in response to rainfall events (mm day^{-1}) during the period October 2019 to October 2021. A gap in the graph indicates a missing data.

4.4.3 Heat ratio calibration

The HPV system slightly overestimated *T* (in the case of the *GN*) and underestimated *T* (in the case of the *P. elliotii*) when compared to the lysimeter system. A simple regression between the two systems produced a good linear relationship (*GN*: R^2=0.73, *P. elliottii*: R^2=0.76) for both tree species (Fig. 4.5a and 4.5b), with a RMSE of 0.57 and 0.36 L tree $^{-1}$ day^{-1} for the *GN* and *P. elliottii*, respectively. This relationship was used to correct the *T* results for both tree species:

$$GN = 1.17x - 0.011 \quad (4.6)$$

$$P.\ elliottii = 0.81x + 0.11 \quad (4.7)$$

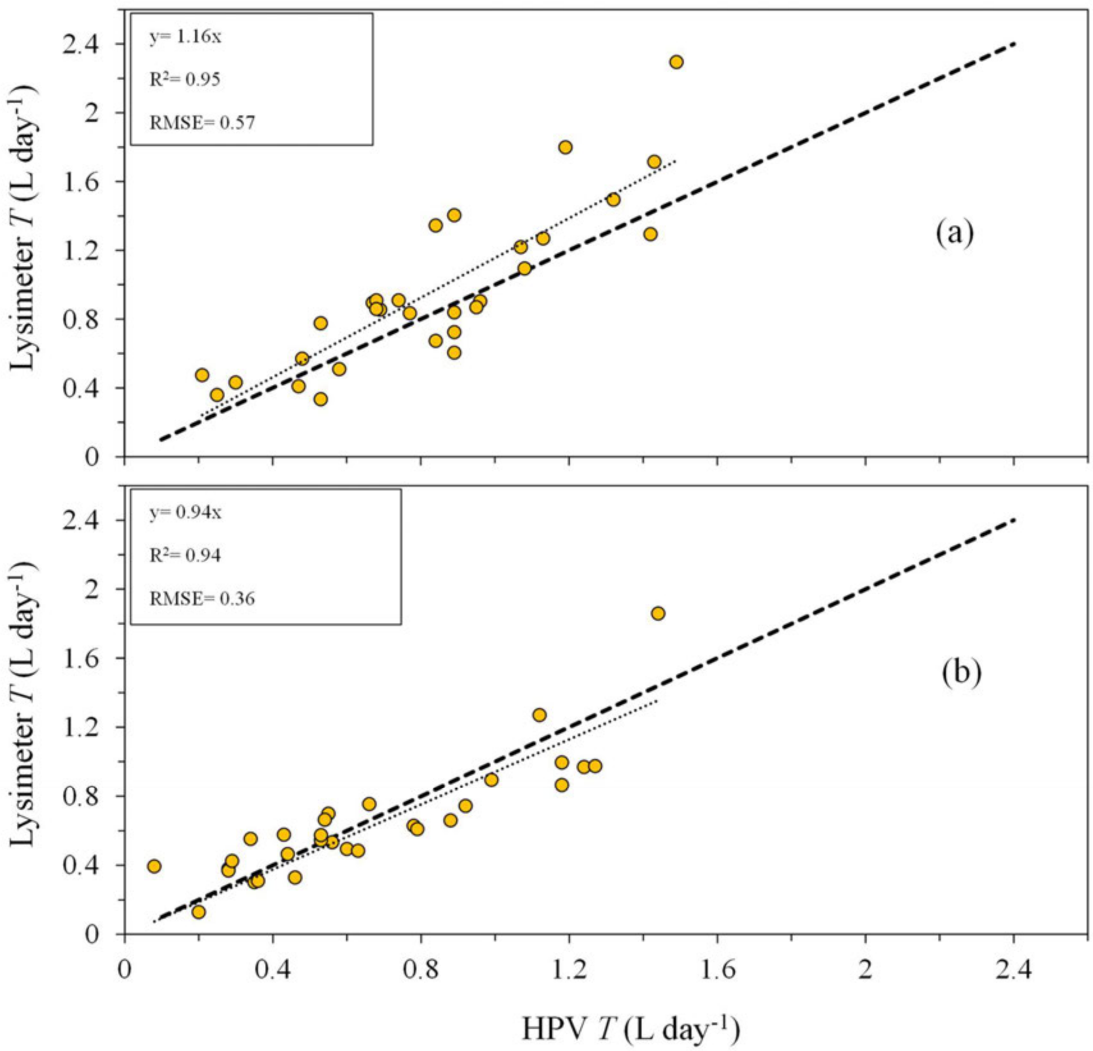


Figure 4.5: Relationship between daily transpiration (*T*) measured using a heat ratio technique (HPV, L day^{-1}) and the *T* measured using a lysimeter (through a change in mass, L day^{-1}) for (a) two-year-old *Eucalyptus grandis* x *Eucalyptus nitens* clonal hybrid and (b) three-year-old *Pinus elliottii*. The equation of the regression line, regression coefficient (R^2), root mean square error (RMSE), standard error of the regression slope (SE slope) and coefficient of variation (CV) for each species is presented. The dashed line is the 1:1 line.

4.4.4 Transpiration rates

The T followed typical seasonal and diurnal pattern for both sites in both 2019/ 20 and 2020/ 21 hydrological years (Fig. 6). *Pinus elliottii* had significantly ($p < 0.01$) higher mean daily *T* compared to *GN* (Fig. 4.6) except for the winter of 2021 (May to August) where *GN* was statistically (p=0.012) greater. Mean daily *T* values in summer of 2019/ 20 for *Pinus elliottii* and *GN* were 2.5 and 1.9 mm tree^{-1} day^{-1}, respectively. By comparison, summer mean *T* values of 2020/ 21 were 2.6 mm tree^{-1} day-1 for *P. elliottii* and 2.1 mm tree^{-1} day^{-1} for *GN* ($p < 0.05$). After a significant rainfall event (~5 mm hr^{-1}), *T* for *GN* momentarily exceeded *P. elliottii* for a few days, thereafter, falling below *P. elliottii* again. The maximum *T* for *GN* was 5.2 mm tree^{-1} day^{-1} and 3.8 mm tree^{-1} day^{-1} for 2019/ 20 and 2020/ 21 measurement year, respectively, versus 5.6 mm tree^{-1} day^{-1} for *P. elliottii* in both seasons. During 2019/ 20, *GN* reached peak *T* rates early in summer (late December 2019) compared to *P. elliottii*, where peak *T* rates were measured in late January to early February of 2020 (Fig. 4.6). However, maximum *T* rates were reached mid-January for the 2020/ 21 measurement year by both crops, which coincided with high I_s, T_{air} and VPD. During winter months (June to July) of both the 2019/ 20 and 2020/ 21 hydrological years no *T* could be detected by probes on *GN* trees on several days, despite clear weather conditions. This corresponded with low $PWC_{0.6}$ (approximately 60 mm day^{-1} per 0.6 m soil depth). By comparison, *T* could be measured in *P. elliottii* trees where the $PWC_{0.6}$ was low (~ 50 mm day^{-1} per 0.6 m soil depth), although at very low *T* rates (~0.33 mm tree^{-1} day^{-1}). Following rainfall, the *P. elliottii* response to PAW lagged behind the *GN* trees. While *GN T* increased almost immediately, *P. elliottii T* only responded a few days later (Fig. 4.8). The slow recovery in *P. elliotti* was most likely caused by low hydraulic resistance, since the xylem anatomy of pine consists of narrow tracheids. Another cause could be refill-capacitance, where the xylem pressure drops when transpiration increases, allowing sufficient time lag for stomata to open and close (Zeppel et al., 2004; McCulloh et al., 2014).

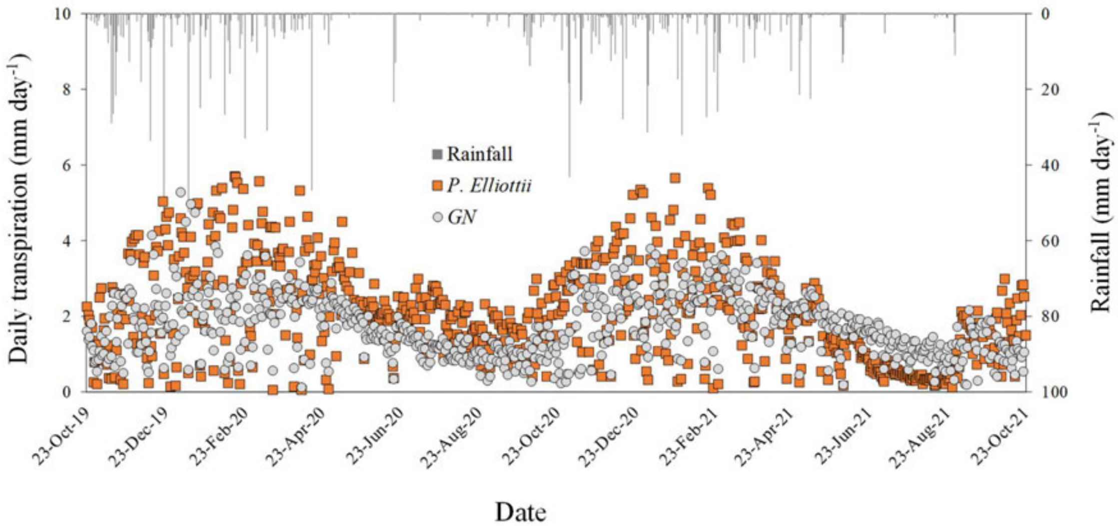


Figure 4.6: Mean daily transpiration (*T*, mm tree^{-1} day^{-1}) and corresponding rainfall in an 8-year-old *E. grandis* x *E. nitens* clonal hybrid (*GN*) and 20-year old *P. elliottii* trees for a duration October 2019 to October 2021. Each point is a mean of four trees.

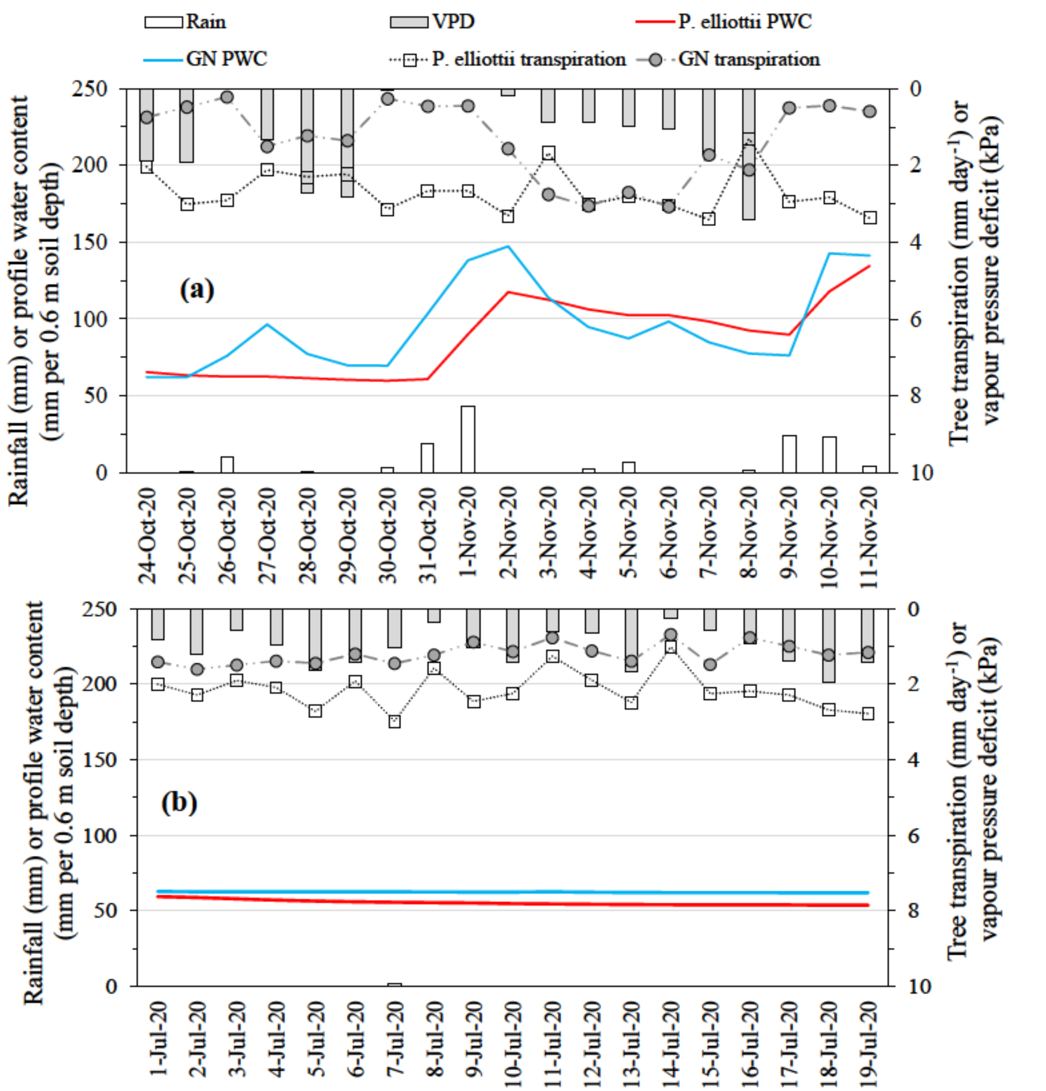


Figure 4.7: A daily tree transpiration (mm) of *P. elliottii* and *Eucalyptus grandis* x *E. nitens* clonal hybrid (*GN*) with corresponding daily rainfall (mm day^{-1}), daily vapour pressure deficit (kPa) and daily profile water content (*PWC*, mm per 0.6 m soil depth) over (a) the summer season (24 October to 11 November 2020, the wet season) and (b) the winter season (01 July to 19 July 2020, the dry season).

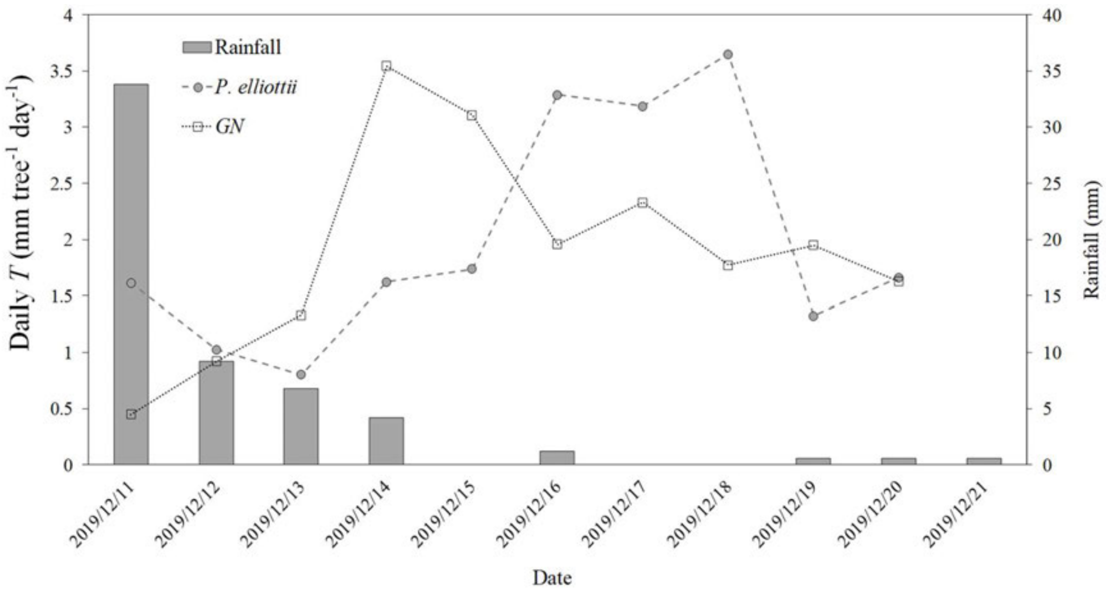


Figure 4.8: Ten-day daily transpiration (*T*, mm tree^{-1} day^{-1}) for 20-year-old *P. elliottii* and 8-year-old *Eucalyptus grandis* x *Eucalyptus nitens* clonal hybrid (*GN*) with corresponding rainfall (mm) showing *T* response by each species to rainfall.

The differences in seasonal patterns of transpiration are illustrated using daily accumulated transpiration (Fig. 4.9). Over the 2019/ 20 measurement year, the total accumulated daily transpiration for *P. elliottii* was 30% greater than *GN*. The total accumulated transpiration rate of *P.elliottii* was also higher in 2020/ 21 but statistically similar ($p > 0.05$). Total annual transpiration rates for *GN* were slightly higher in 2020/ 21 than 2019/ 20 measurement years (6%), while *P. elliottii* transpiration rates reduced by 19% over the same period (Fig. 4.9). The accumulated rainfall was 18 and 20% greater than transpiration for *P. elliottii* and *GN*, respectively, while the accumulated potential evaporation exceeded rainfall by 22% in both seasons.

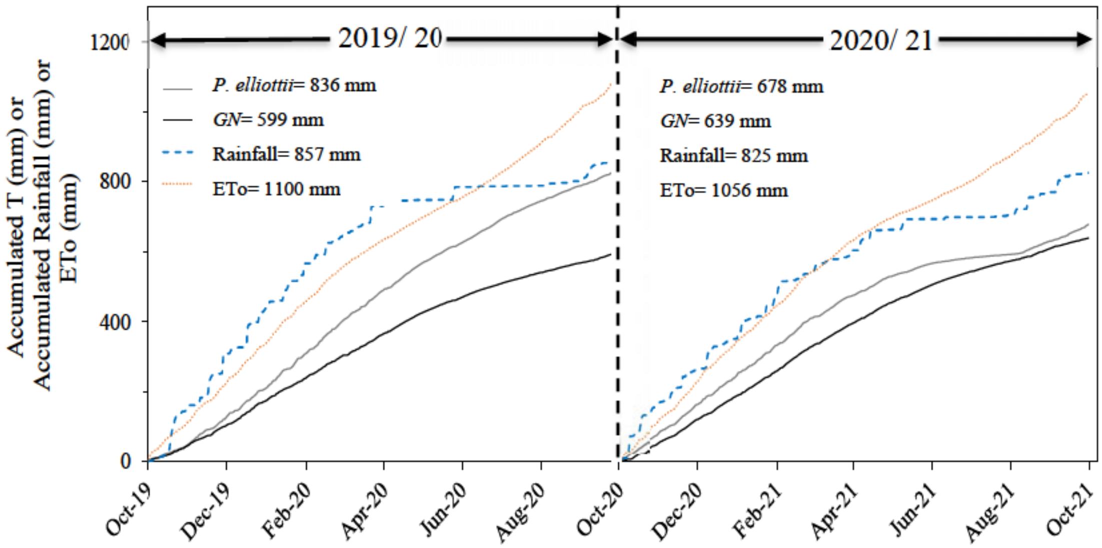


Figure 4.9: The accumulated transpiration (*T*, mm), rainfall (mm) and FAO reference evaporation (ETo, mm) for 2019/ 20 (Oct 2019 to Oct 2020) and 2020/ 21 (Oct 2020 to Oct 2021).

4.4.5 Influence of climatic variables on tree transpiration

The RF model performed well in ranking climatic variables influencing transpiration for both species, producing an overall coefficient of determination (R^2) of 0.91 and 0.85 for *GN* and *P. elliottii*, respectively. The overall root mean square error was 0.58 mm for *GN* and 0.9 mm for *P. elliottii*, indicating a very good predictive power. The RF predictive model rated *SWC* measured at 40 cm depth and *SWC* measured at 60 cm depth as the most important influencers of transpiration for *GN* and *P. elliottii*, respectively (Fig. 4.10). Climatic variables, I_s, VPD and T_{air} in descending order of importance were also scored as important in *GN*, whereas in *P. elliottii*, soil water content measured at 40 cm, VPD and I_s were found to be important variables (Fig. 4.10). Rainfall was found to be the least important variable in a model in *P. elliottii*, while wind speed was not a good influencer of transpiration in *GN*. The model indicated that transpiration is influenced by micrometeorological variables at varying levels of influence.

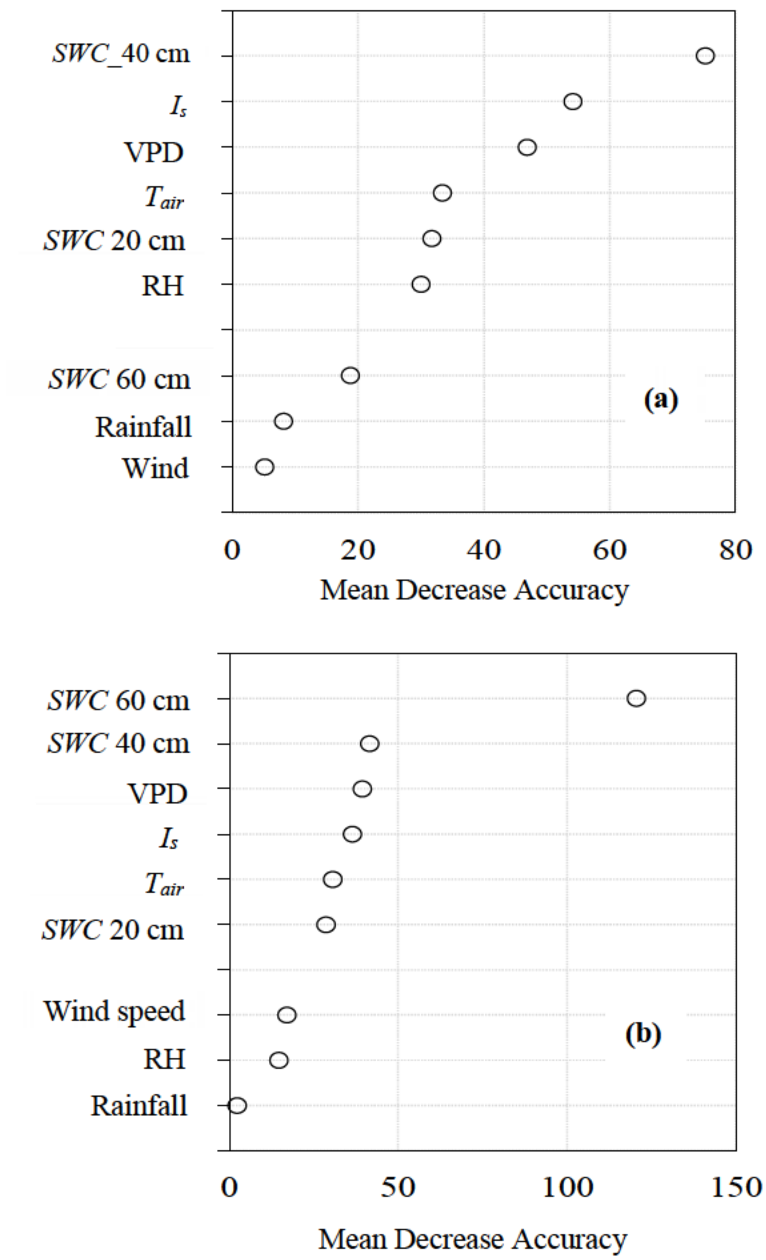


Figure 4.10: Variable importance plots of (a) *Eucalyptus grandis* x *E. nitens* (*GN*) and (b) *Pinus elliottii* from the random forest regression model using solar radiation (Is), vapor pressure deficit (VPD), air temperature (T_{air}), relative humidity (RH), wind speed, rainfall and soil water content measured at 20 cm depth (*SWC* 20 cm), 40 cm depth (*SWC* 40 cm) and 60 cm depth (*SWC* 60cm). Mean Decrease Accuracy is a measure of how much the model error increases when a particularly variable is randomly permuted.

4.4.6 Tree growth

At the beginning of the study, *P. elliottii* trees were larger in diameter than *GN*. There was a seasonal pattern in D_q increment by both species (Fig. 4.11), with no significant ($p > 0.05$) differences in 2019/ 20, while 2020/ 21 produced significantly ($p < 0.05$) greater growth increment in *P. elliottii* than *GN*. Interestingly, a negative growth increment was measured during the winter of 2019/ 20 for *GN*, which was probably caused by low $PWC_{0.6}$.

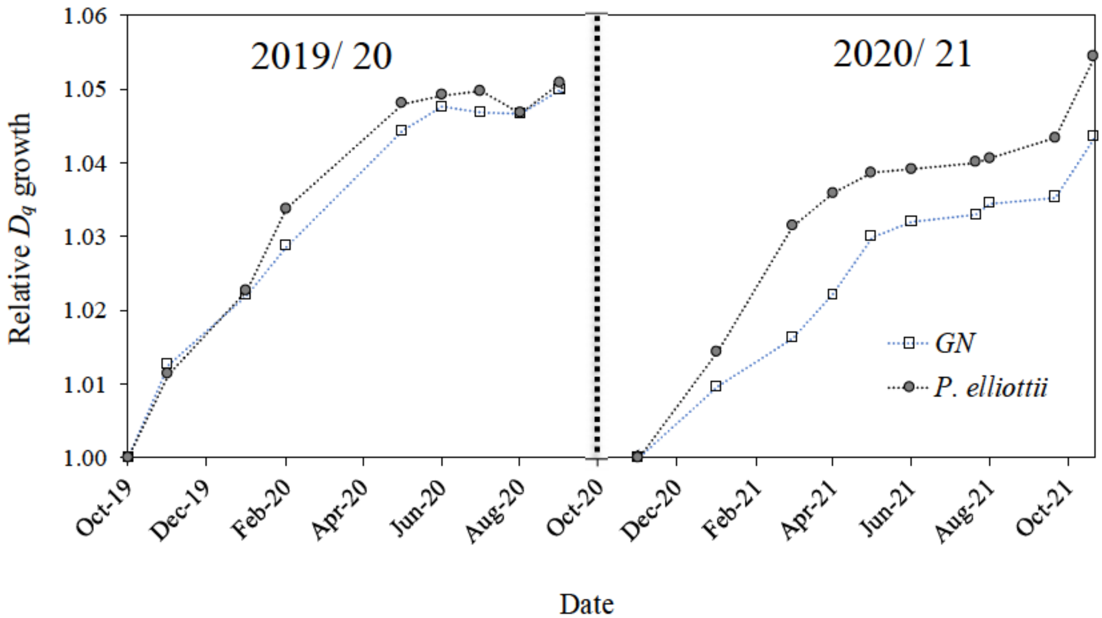


Figure 4.11: Relative quadratic mean diameters (D_q, normalised) measured using manual dendrometers bands for *Eucalyptus grandis* x *E. nitens* (*GN*) and *Pinus elliottii*. Measurements were conducted for hydrological years, 2019/ 20 (October 2019 to October 2020) and 2020/ 21 (October 2020 to October 2021) and the vertical dotted line separates the hydrological years. Each point represents an average of 48 trees for each species.

4.4.7 Leaf area index

The mean summer LAI for *P. elliottii* was 17% greater than *GN* (*P. elliottii*=2.5 vs *GN*=2.05, $p < 0.05$) in 2019/ 20 increasing to 21% (*P. elliottii*=3.1 vs *GN*=2.4, $p < 0.05$) in 2020/ 21. Winter LAI decreased to 1.76 and 1.31 for *P. elliottii* and *GN*, respectively (Fig. 4.12). Total monthly *T* was linearly related to monthly LAI of both *P. elliottii* and *GN* (Fig. 4.13), with statistical differences in the regression ($p < 0.05$). However, there was a greater RMSE, SE intercept and

SE slope in *P. elliotti* than in *GN*, indicating that the regression line in the *GN* fits the data better than *P. elliottii*, and *GN* has more precise prediction from leaf area index than *P. elliottii*.

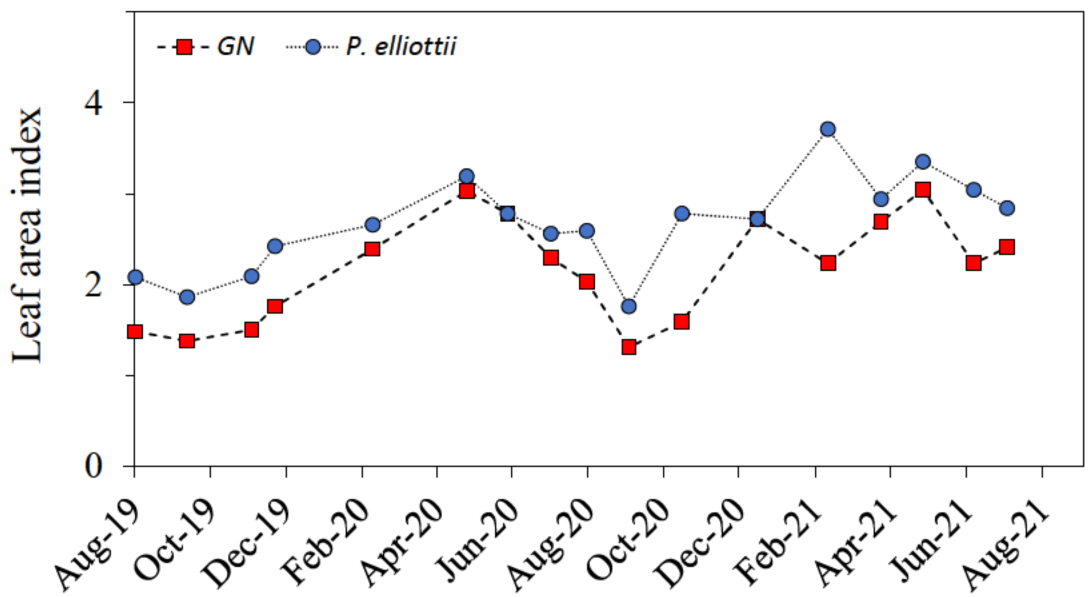


Figure 4.12: A leaf area index (LAI) of *Eucalyptus grandis* x *Eucalyptus nitens* clonal hybrid (*GN*) and *Pinus elliottii* measured near Two Streams research catchment from August 2019 to July 2021.

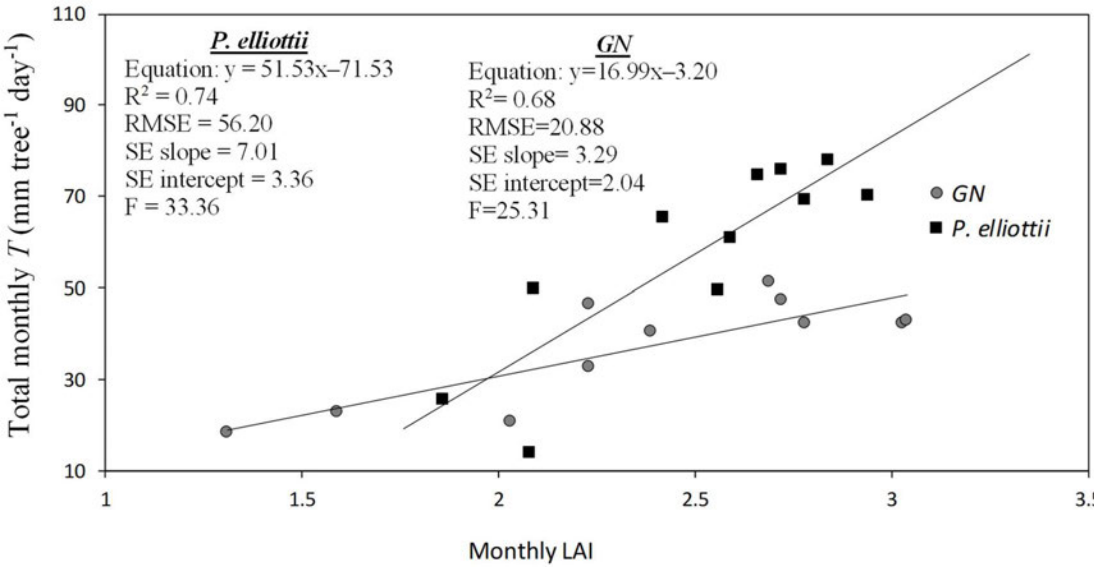


Figure 4.13: A linear relationship between total monthly transpiration (*T*, mm tree^{-1} day^{-1}) and monthly measured leaf area index (LAI) for *E. grandis* x *E. nitens* clonal hybrid (*GN*) and *P. elliottii*. The equation of the regression line, regression coefficient (R^2), root mean square error (RMSE), the standard error of the regression slope (SE slope), the standard error of the y- intercept (SE intercept) and the ratio of variance (F) for each specie is presented.

4.4.8 Plantation water productivity

The *GN* crop produced statistically ($p < 0.05$) greater annual PWP_{WOOD} than *P. elliottii* in 2019/ 20 (Table 4.4), despite the water stress conditions experienced at the *GN* site. However, in 2020/ 21, PWP_{WOOD} between species was statistically ($p > 0.05$) similar for both crops. In 2020/ 21, there was a 15% and 8% decrease in PWP_{WOOD} of *GN* and *P. elliottii*, respectively.

Table 4.4: Comparison of plantation water productivity (*PWP_{WOOD}*, g wood kg^{-1} water) of *Eucalyptus grandis* x *E. nitens* clonal hybrid (*GN*) and *Pinus elliottii* for 2019/ 20 (September 2019 to October 2020) and 2020/ 21 (September 2020 to October 2021). Different subscripts denote significant differences at $p < 0.05$.

	GN (g wood kg^{-1} H_2O)	*P. elliottii* (g wood kg^{-1} H_2O)
2019/ 20	0.78^{a}	0.61^{b}
2020/ 21	0.67^{a}	0.57^{a}
Average	**0.72**	**0.59**

4.5 Discussion

4.5.1 Daily transpiration

The *P. elliottii* mean daily *T* exceeded *GN* by about 24% over the 2019/ 20 and by 19% in 2020/ 21 measurement years, mainly influenced by *SWC*, VPD and I_s. Differences in *T* between *GN* and *P. elliottii* could be attributed to the following reasons: 1) trees at the *GN* site were water stressed and evidence of water stress was observed through shrinking of tree stem diameters during winter, zero rates of *T* on some days during winter months and a significant decrease in LAI over winter. This suggests that trees were unable to access soil water stored from previous wet years held deep in the soil profile or the *GN* trees had already accessed and depleted the stored soil water before the study period. *Eucalyptus T* has been shown to increase sharply in the early stages of growth, reaching a peak in the middle of the rotation, thereafter, declining as the stand matures (Delzon and Loustau 2005) and, sap-wood for *P. elliottii* was nearly twice the sap-wood area of *GN* due to the different tree structures. The *GN* mean *T* range of 0.9–5.2 mm tree^{-1} day^{-1} and 0.5–3.8 mm tree^{-1} day^{-1} for 2019/ 20 and 2020/ 21, respectively, measured in this study agreed with *Eucalyptus* studies in relatively low rainfall areas with trees of the same age. For example, a study by Forrester et al. (2010) on seven-year-old *E. globulus* in Australia measured a *T* range of 0.4–1.9 mm tree^{-1} day^{-1} (MAP=708 mm). David et al. (1997) measured daily *T* of 0.5–3.64 mm tree^{-1} day^{-1} at a *E. globulus* site in Portugal with a MAP of 600 mm. A South African study by Dye et al. (1996a) on nine-year-old *E. grandis* in Mpumalanga, South Africa measured *T* of 2.0–7.5 mm tree^{-1} day^{-1} with the potential to exceed 8.0 mm day^{-1} under high VPD (Dye et al., 2013), however, this study was conducted in a high rainfall area (MAP=1459), with almost double the MAP of the current study. For *P. elliottii*, peak *T* of 5.6 mm tree^{-1} day^{-1} in this study agreed with other studies, such as Hatton and Vertessy

(1990) who measured a maximum *T* of 5 mm tree^{-1} day^{-1} in *P. radiata* in new South Wales, Australia.

During summer *GN T* peaked earlier than the *P. elliottii* (more distinct in 2019/ 20) and then decreased swiftly, so that it was less than the *P. elliottii T* in the late summer to early autumn. In addition, the *GN T* increased sharply after the rainfall events and thereafter decreased as $PWC_{0.6}$ was rapidly depleted, while *P. elliottii* responded more gradually. This suggests that *GN* trees have a different growth and water use strategy to *P. elliottii,* that involves using available water rapidly. A similar observation was reported by White et al. (2021) from *E. globulus* in central Chile. This implies that *GN* trees compete for water and use it more rapidly when it becomes available, and this strategy can expose them to extreme water stress if soil water deficit conditions persist as reported by Mitchell et al. (2013). *P. elliottii* had a greater *T* at stem sizes similar to the *GN* (ie. D_q for smallest *P. elliottii* tree versus D_q for largest *GN* tree). This may be attributed to a markedly smaller heartwood in *P. elliottii* than *GN*. However, it should be noted that pine trees consist of several latewood rings in which no sap movement occurs (Dye et al., 2001). Diurnal changes in *T* typically lagged behind VPD, creating a pattern of hysteresis, where at similar VPD, *T* was greater in the morning than in the afternoon for *GN*. Studies by O'Grady et al. (1999) and Maier et al. (2017) attributed this to low soil hydraulic conductivity or the use of stored stem water for *T* in the first portion of the day. Further analysis in our study indicated that *GN T* was significantly influenced by VPD only in summer, suggesting that soil water deficit may have affected soil water uptake to a greater extent in the dry season (winter).

4.5.2 Annual transpiration

On an annual basis, *P. elliottii* trees transpired 28% more water (836 mm) than *GN* (599 mm) in 2019/ 20, while the 2020/ 21 saw no significant differences between the two species (*P. elliottii*=678 mm year^{-1} vs. *GN*=639 mm year^{-1}). The low rates of *T* in winter months (May to August) of 2021 on the *P. elliotti* site (Fig. 6), were caused by low *SWC*, which resulted in similar annual *T* rates in 2020/ 21 by both species. Other studies of pine (Moran et al., 2017; Samuelson et al., 2019) reported that the first reaction by pine species to a decrease in *SWC* is a significant reduction in stomatal aperture, causing a decrease or cessation of *T*. By comparison, *GN* indicated a different response, where *T* continued (even when *SWC* was marginally limiting) to a point where it was below detection by our HPV system and this trait makes eucalypts vulnerable during extended or severe drought periods. South African studies (Dye et al. 1996 and Eksteen et al. 2013) using *E. grandis* crop showed that trees utilised *SWC* till permanent wilting point, which seems to be well beyond the -1500 kPa typically cited in literature for many plants (Santra et al., 2018). An international study by White et al., (1999) found similar results in *E. nitens* in western Australia. The wood of angiosperm species (eucalypts) has been shown to have more complex anatomy compared to gymnosperms (pine), with sapwood comprising of an axial system composed of vessels for water transport (a dense concentration of fibres for support and varying amounts of parenchyma for storing carbohydrates) (Barotto et al. 2016). In addition, angiosperms consist of other cell types with intermediate anatomy and functions between vessels and fibres, such as tracheids and fibre-tracheids (Barotto et al. 2016). As a results, the function of tracheids in angiosperms is to improve vessel communication thereby increasing xylem connectivity. By comparison, gymnosperms sapwood consists of a series of growth rings with tracheids that increase in diameter as the tree grows (Benito et al., 2017). The differences in sapwood anatomy between angiosperms and gymnosperms suggests that angiosperms have a more coordinated water transport process compared to gymnosperms. As a result, gymnosperms are generally more resistant to drought induced cavitation compared to angiosperms (Maherali and DeLucia 2000; Benito et al. 2017; Barotto et al. 2016). This is mostly likely the reason why *GN* trees in our study were subjected to more water stress than *P. elliottii.*

There are contrasting results in some annual comparative studies of *T* between *Eucalyptus* and *Pinus* species. In an eight-year-old *E. benthamii* vs *P. taeda* comparative water use study in the United States (Maier et al., 2017), annual *T* of 1077 and 733 mm year^{-1} for *E. benthamii* and *P. taeda*, respectively, were measured. In a South African study (tree water use estimated using water balance), *Eucalyptus grandis* used 100 mm more water per year than *Pinus patula* (Scott and Lesch, 1997). Notwithstanding these findings, another study in southeastern Australia, Benyon and Doody (2015) found no significant differences between annual water use (only *T* was measured) between *E. globulus* and *P. radiata*, with or without access to groundwater. A most recent study by White et al. (2022) using meta-analysis of published evapotranspiration estimates found no significant differences in water use between *Eucalyptus* and *Pinus* genera. The annual *T* rates for our study were relatively lower than the above-mentioned studies (2019/ 20: *GN*=599 mm, *P. elliottii*=836 mm; 2020/ 21: *GN*=639 mm, *P. elliottii*=678 mm) which was most likely influenced by low rainfall (rainfall: 2019/ 20: 857 mm; 2020/ 21: 825 mm).

Like other studies (Whitehead and Beadle, 2004; Samuelson et al., 2008), a strong correlation between *T* and LAI was observed in this study, with *P. elliottii* having a greater *T* rate than *GN* at a similar LAI. This good correlation may present a modelling opportunity to estimate *T* using site measurements of LAI or remote sensing estimates of LAI.

4.5.3 Response of tree transpiration to climatic variables

Conventional micrometeorological techniques of estimating transpiration (such as heat pulse velocity) in commercial forest plantations are not easy to conduct due to the remote and inaccessible nature of forest plantations, vulnerability of instrumentation to damage by animals and a threat posed by extreme weather events. In addition, this instrumentation is very expensive, require technical skills to use and provide measurements on few trees within a stand. An improved technique for estimating transpiration from easy to measure variables would be an advantage. There are many external regulators that have been described to have a strong relationship with transpiration, which includes readily available soil water in the rooting area (Oren and Pataki, 2001), the atmospheric micrometeorological conditions (Lundblad and Lindroth, 2002) and aerodynamic resistance (Hall, 2002). However, these relationships are complex, because exotic trees can have several internal mechanisms, which can vary between species, tree age and tree physiology (Zweifel et al., 2005). Nevertheless, in most actively growing tree species, there is a consensus that certain meteorological variables can highly influence transpiration (Albaugh et al., 2013).

Results from regression analysis using RF showed that *SWC*, VPD and I_s have a significant influence on transpiration, in a decreasing order of importance for both species. These results were expected as other studies have shown that tree transpiration is influenced by *SWC* (Dye, 1996; Maier et al., 2017), VPD (Dye and Olbrich, 1993, Scott and Lesch, 1997; Campion et al., 2004, Albaugh et al., 2013) and I_s (Zeppel et al., 2004; Albaugh et al., 2013). For example, in South African studies by Dye (1996a) and Dye et al (2004), *E. grandis* daily water-use exceeded 90 litres day^{-1} (equivalent to 7 mm day^{-1}) on hot dry days in the middle of summer (when *SWC* was not limiting), and then declined during the dry season as temperatures decrease and the photoperiod shortened. Rainfall was found to be a weak influencer of tree transpiration, which could be linked to high rate of rainfall interception reported in commercial forests of 14.9% for *Eucalyptus* and 21.4% for pine of gross precipitation (Bulcock and Jewitt, 2012). These results suggest that certain climatic variables can be used as an input in commercial forest plantation models to improve estimation of tree water-use.

4.5.4 Implications for the catchment water yield

Forest plantation water-use studies and their potential impact on water resources are complex and require comprehensive long-term measurements of total water balance parameters to be conclusive. Our results indicated that *P. elliottii* water-use was significantly greater than *GN* in 2019/ 20, while 2020/ 21 water-use patterns were statistically similar. These year-on-year differences have been attributed to low *SWC* and plant stress reducing the accumulated *GN* transpiration. However, this result is in contrast with most of the long-term studies which indicate *GN* to use more water than *P. elliottii*. It is clear that the implications over a full rotation or over several rotations cannot be quantified from such short-term studies. In particular, lags that occur in hydrology between rainfall, changes in groundwater and streamflow have been reported to exceed the time period of this study and will be poorly captured. There are several long-term paired catchment studies conducted in South Africa (van Lill et al., 1980; Smith and Scott, 1992; Scott and Lesch, 1997; Scott and Smith, 1997; Scott et al., 2000) that compared water-use between pine and *Eucalyptus* and quantified the impact of these species on water resources, particularly the streamflow. A study by Scott and Lesch (1997) on the streamflow response to afforestation with *E. grandis* and *P. patula* in Mokobulaan experimental catchment in South Africa indicated that eucalypts cause a faster reduction in streamflow (90–100%) compared to afforestation with pines (40–60%). These results were verified in a study conducted by Scott et al (2000) where peak reductions in streamflow were reported between 5 and 10 years after establishing eucalypts, and between 10 and 20 years after planting pines, with the size of the reduction driven by soil water availability. Another South African study by Smith and Scott (1992), investigated the impact of pine and eucalypts on low flows in various paired catchments located in various regions of South Africa (Westfalia Estate, Cathedral Peak, Jonkershoek, Mokobulaan). Results from this study showed that afforestation have a significant effect on low flow on all paired catchments (low flows reduced by up to 100% in certain cases), with eucalypts having a severe impact compared to pine. Results from our *GN* study site indicated that the site was likely water stressed, suggesting that trees were probably unable to access soil water stored from previous wet years held deep in the soil profile. Afforestation with commercial forest plantations over successive rotations have been shown to deplete soil water reserves within the profile, leading to increased soil water deficit (Dye et al., 1997) and ultimately reduction in streamflow. Evidence of this was shown in a paired catchment experiment by Scott and Lesch (1997) where eucalypts were clear-felled at 16 years of age, but full perennial streamflow returned five years later. The delay in streamflow recovery was attributed to eucalypts desiccating the deep-water reserves, which had to be restored before the stream could return to a normal flow.

All of the above-mentioned South African long-term paired catchment studies suggest that commercial forest plantations, particularly *Eucalyptus*, pose a severe negative impact on water yield. Results from our study indicated that *P. elliottii* used more water than *GN* over the first year of measurement due to limited soil water availability and a conclusive impact on water reserves cannot be quantified without long-term measurements of at least one crop rotation. This relatively short-term study did however show that commercial forest plantations may deplete soil water stored within the soil profile during dry period, resulting in potential streamflow reduction over a long term. Due to climate variability in plantation forest areas, long-term studies under non-stressed and stressed conditions are needed in this region to quantify the total water balance (total evaporation, surface runoff, soil water storage and how water partitioning responds to climate change and afforestation over time).

4.5.5 Plantation water productivity

The *GN* PWP_{WOOD} in this study was lower than other similar age *Eucalyptus* studies (Forrester et al. 2010, Drake et al. 2012, White et al. 2014, Hakamada et al. 2020). This was mostly likely due to soil water deficit experienced at this site. For example, White et al. (2014) measured a maximum PWP_{WOOD} of 3.1 g wood kg^{-1} water in *Eucalyptus globulus* in south-western Australia. In general, trees in drier sites have a higher root area to LAI ratio, and a very deep fine root system as a strategy to avoid negative effects of drought. This suggests that more biomass (PWP_{WOOD}) is produced belowground than aboveground (Laclau et al. 2013, Hamer et al. 2016, Pinheiro et al. 2016, Christina et al. 2018). There is a high possibility that low aboveground PWP_{WOOD} was a result of trees producing more PWP_{WOOD} belowground, to counter the effects of drought. Despite the water stress conditions experienced at the *GN* site, PWP_{WOOD} for *GN* was statistically ($p < 0.05$) greater than *P. elliottii* in 2019/ 20 and these results are not unique to this study. In a *E. globulus* and *P. radiata* comparative study in coastal mountains of central Chile, *E. globulus* produced significantly greater PWP_{WOOD} (3.5 g wood kg^{-1} water) compared to *P. radiata* (2.1 g wood kg^{-1} water). Results from our study suggest that *GN* will need less land and water, even under water stressed forestry stands, than *P. elliottii* to produce the same quantity of wood.

4.6 Conclusion

This paper presents a water-use study by *GN* and *P. elliottii* near the Two Streams Research Catchment in the KwaZulu-Natal midlands of South Africa, quantified using the heat ratio method (HRM). A calibration of the method was conducted and is recommended for this technique to achieve improved accuracy. Annual water-use results indicated that *P. elliottii* used 28% more water than *GN* in the first measurement year (2019/ 20), while there were no significant differences in tree transpiration in the second year of measurement (2020/ 21). These findings contrast with most long-term paired catchment studies in South Africa and internationally, which reported that *Eucalyptus* species are heavy water users compared to pine and both species cause negative impacts on the water yield. This relatively short-term study showed the different responses of the tree species to changes in season and available soil water with *GN* generally responding more rapidly. It also showed that in countries such as South Africa, where streamflow reduction by commercial forestry is modelled for water licensing purposes, soil water stress in the hydrological models must be able to constrain tree water-use. The *GN* PWP_{WOOD} was lower than other *Eucalyptus* studies in South Africa and internationally, suggesting that productivity of eucalypts can be limited by water stress in forest plantations. Long-term research is suggested to quantify the total water balance (total evaporation, surface runoff, soil water storage and how water partitioning responds to climate change and afforestation over time), so that the impact of species (such as *GN* and *P. elliottii*) on water yield can be determined. A good relationship between tree transpiration and meteorological variables suggests that "easy to measure" weather variables can be incorporated in future water-use modelling studies to estimate a difficult to derive tree transpiration.

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4.8 References

Albaugh, J. M., Dye, P. J., King, J. S. 2013: *Eucalyptus* and water use in South Africa. Int. J. For. Res., 11, 852540, http://doi:10.1155/2013/852540, 2013.

Allen, R. G., Pereira, L. S., Raes, D., and Smith, M.: Crop evapo-transpiration: Guidelines for computing crop water requirements, FAO Irrigation and Drainage Paper 56, Food and Agriculture Organization of the United Nations, Rome, Italy, 1998.

Aria, M., Cuccurullo, C, Gnasso, A.: A comparison among interpretative proposals for Random Forests, Mach. Learn. Appl, 6,1000094, https://doi.org/10.1016/j.mlwa.2021.100094. 2021.

Benyon, R. G, Doody, T. M.: Comparison of interception, forest floor evaporation and transpiration in *Pinus radiata* and *Eucalyptus globulus* plantations, Hydrol. Process*.,* 29, 1173-1187, https://doi.org/10.1002/hyp.10237, 2014.

Barotto, A. J., Fernandez, M. E., Gyenge, J., Meyra, A., Martinez-Meier, A., Monteoliva, S.: First insights into the functional role of vasicentric tracheids and parenchyma in Eucalyptus species with solitary vessels: do they contribute to xylem efficiency or safety? Tree Physiol., 12, 1485-1497, https://doi.org/10.1093/treephys/tpw072, 2016

Benito, D. M., Anchukaitis, K. J., Evans, M. N., Rio, M. D., Beeckman, H. Canellas, I.: Effects of drought on xylem anatomy and water-use efficiency of two co-occuring pine species. Forests, 8, 332, https://doi.org/10.3390/f8090332, 2017.

Breiman, L.: Random forests. Mach. Learn., 45, 15–32, 2001.

Bulcock, H. H, Jewitt, G. P. W.: Field data collection and analysis of canopy and litter interception in commercial forest plantations in KwaZulu-Natal midlands, South Africa, Hydrol. Earth Syst. Sci, 16, 3717-3728, https://doi.org/10.5194/hess-16-3717-2012, 2012.

Bulcock, H. H., Gush, M. B., Jewitt, G. P. W.: A comparison of productive and non-productive green water-use efficiency of *Podocarpus henkelii* and *Pinus patula* in KwaZulu-Natal Midlands. Southern Forests, 76, 75–84, https://doi.org/10.2989/20702620.2014.915451, 2014.

Burgess, S. S. O., Adams, M. A., Turner, N. C., Beverly, C. R., Ong, C. K., Khan, A. A. H., and Bleby, T. M.: An improved heat pulse method to measure low and reverse rates of sap flow in woody plants, Tree Physiol., 21, 589–598, http://dx.doi.org/10.1093/treephys/21.9.589, 2001.

Curtis, R. O, Marshall, D, D: Why Quadratic Mean Diameter? Pac. Res. Stat., Olympia, Technical Note, 13799., 2000.

Calder, I. R: *Eucalyptus*, water and the environment, In: *Eucalyptus*, edited by: Coppen, J. J. W., Taylor and Francis, Wales, London, 16-23, 2002.

Callaham, M. A., Stanturf, J. A., Hammond, W., Rockwood, D. L., Wenk, E. S., O'Brien, J. J.: Survey to evaluate escape of eucalyptus spp. seedlings from plantations in south eastern USA, Int. J. Forest. Res., 13, http://dx.doi.org/10.1155/2013/946374, 2013.

Campion, M., Dye, P. J., Scholes, M. C.: Modelling maximum canopy conductance and transpiration in Eucalyptus grandis stand not subjected to soil water deficit, South Afri. For. J., 202, 3-11, http://dx.doi.org/10.1080/20702620.2004.10431784, 2004.

Canadell, J., Jackson, R. B., Ehleringer, J. B., Mooney, H. A, Sala, O. E., Schulze, E. D.: Maximum rooting depth of vegetation types at the global scale, Oecologia, 108, 583–595, https://doi.org/10.1007/bf00329030, 1996.

Cannell, M. G. R.: Environmental impacts of forest monocultures: water use, wildlife conservation, and carbon storage. New Forest, 17, 239–262, http://10.1007/978-94-017-2689-4_17, 1999.

Cermák, J. and Nadezhdina, N.: Sapwood as the scaling parameter- defining according to xylem water content or radial pattern of sap flow?, Ann. For. Sci., 55, 509–521, https://doi.org/10.1051/forest:19980501, 1998.

Christina, M., Nouvellon, Y., Laclau, J. P., Stape, J. L., Bouillet, J. P., Lambais, G. R., Le Maire, G.: Importance of deep-water uptake in tropical eucalypt forest, Funct. Ecol., 31, 509-519, https://doi.org/10.1111/1365-2435.12727, 2016.

Clulow, A. D., Everson, C. S., Gush, M. B.: The long-term impact of *Acacia mearnsii* trees on evaporation, streamflow and groundwater resources, Water Research Commission Report TT 505/11, ISBN 9781431200203, South Africa, 104 pp., 2011.

Crosbie, R., Wilson, B., Hughes, J., and McCulloch, C.: The upscaling of transpiration from individual trees to areal transpiration in tree belts, Plant Soil, 297, 223–232, https://doi.org/10.1007/s11104-007-9337-y, 2007.

Cutler, D. R., Edwards, T. C., Beard, K. H., Cutler, A., Hess, K. T., Gibson, J., Lawler, J. J.: Random Forests for classification in ecology, Ecol., 88, 2783-2792, https://doi.org/10.1890/07-0539.1. 2007.

David, T. S., Ferreira, M. I., David, J. S., Pereira, J. S.: Transpiration from mature *Eucalyptus globulus* plantation in Portugal during a spring -summer period of progressively high-water deficit, Oecologia, 110, 153-159, https://doi.org/10.1007/PL00008812, 1997.

Dougherty, D., Wright, J.: Silviculture and economic evaluation of eucalypt plantations in the Southern US, BioResources, 7, 1994–2001, http://dx.doi.org/10.15376/biores.7.2.1994-2001, 2012.

Dye, P. J., Olbrich, B. W.: Estimating transpiration from 6-year-old Eucalyptus grandis trees: development of a canopy conductance model and comparison with independent sap flux measurements, Plant Cell Environ., 16, 45-53, https://doi.org/10.1111/j.1365-3040.1993.tb00843.x, 2012.

Dye, P. J.: Response of *Eucalyptus grandis* trees to soil water deficits, Tree Physiol., 16, 233–238, http://doi: 10.1093/treephys/16.1-2.233, 1996a.

Dye, P. J., Soko, S., Poulter, A. G.: Evaluation of the heat pulse velocity method for measuring sap flow in *Pinus Patula*, J. Exp. Bot., 47, 975–981, https://doi.org/10.1093/jxb/47.7.975, 1996b.

Dye, P. J, Poulter, A. G., Soko, S., Maphanga, D.: The determination of the relationship between transpiration rate and declining available water for *Eucalyptus grandis*, Water Research Commission Report No. 441/1/97, ISBN 1868453057, Pretoria, South Africa, 103 pp., 1997.

Dye, P. J., Vilakazi, P., Gush, M., Ndlela, R., Royappen, M.: 2001. Investigation of the feasibility of using trunk growth increments to estimate water use of *Eucalyptus grandis* and *Pinus Patula* plantation. Water Research Commission Report No. 809/1/01, ISBN 1868458164, South Africa, 229 pp., 2001.

Dye, P. J., Jacobs, S., Drew, D.: Verification of 3-PG growth and water-use predictions in twelve *Eucalyptus* plantation stands in Zululand, South Africa, For. Ecol. Manage., 193, 197–218, http://dx.doi.org/10.1016/j.foreco.2004.01.030, 2004.

Dye, P. J.: A review of changing perspectives on *Eucalyptus* water-use in South Africa, For. Ecol. Manage., 301, 51-57, http://dx.doi.org/10.1016/j.foreco.2012.08.027, 2013.

Eksteen, A. B., Grzeskowiak, V., Jones, N. B., Pammenter, N. W.: Stomatal characteristics of *Eucalyptus grandis* clonal hybrids in response to water stress, South. For., 75, 105-111, https://doi.org/10.2989/20702620.2013.804310, 2013.

Everson, C. S., Clulow, A. D., Becker, M., Watson, A., Ngubo, C., Bulcock, H., Mengistu, M., Lorentz, S., Demlie, M.: The long-term impact of *Acacia mearnsii* trees on evaporation, streamflow, low flows and ground water resources. Phase II: Understanding the controlling environmental variables and soil water processes over a full crop rotation, Water Research Commission Report K5/2022, ISBN 9781431205165, South Africa, 155 pp., 2014.

Forrester, D. I., Collopy, J. J., Morris, J. D.: Transpiration along an age series of Eucalyptus globulus plantation in southeastern Australia, For. Ecol. Manage., 259, 1754-1760, https://doi.org/10.1016/j.foreco.2009.04.023, 2010.

Fox, T. R., Jokela, E. J., Allen, H. L.: The development of pine plantation silviculture in the southern United States, J. Forest. 105, 337–347, https://doi.org/10.1093/jof/105.7.337, 2007.

Forestry South Africa: Report on commercial timber resources and primary roundwood processing in South Africa, URL: https://www.forestrysouthafrica.co.za/wp-content/uploads/2023/06/TimberStats-2018_19.pdf, [last accessed: 05 July 2023], 2020.

Fuchs, S., Leuschner, C., Link, R., Coners, H., Schuldt, B.: Calibration and comparison of thermal dissipation, heat ratio and heat field deformation sap flow probes for diffuse-porous trees, Agric. For. Meteo., 244-245, 151-161, https://doi.org/10.1016/j.agrformet.2017.04.003, 2017.

Hall, R. L.: Aerodynamic resistance of coppiced poplar, Agric. For. Meteorol., 114, 83-102, https://doi.org/10.1078/1439-1791-00099, 2002.

Hasenmueller, A. A., Gu, X., Weitzman, J. N., Adams, T. S., Stinchcomb, G. E., Eissenstat, D. M., Drohan, P. J., Brantley, S. L., Kaye, J. P.: Weathering of rockto regolith: The activity of deep roots in bedrock fractures, Geoderma, 300, 11-31, https://doi.org/10.1016/j.geoderma.2017.03.020, 2017.

Hatton, T. J, Vertessy, R. A.: Transpiration of plantation *Pinus radiata* estimated by the heat pulse method and the Bowen ratio, Hydrol. Processes, 4, 289-298, https://doi.org/10.1002/hyp.3360040309, 1990.

Hatton, T. J. and Wu, H.-I.: Scaling theory to extrapolate individual tree water use to stand water use, Hydrol. Proc., 9, 527–540, https://doi.org/10.1002/hyp.3360090505, 1995.

Kuhn, M.: Building predictive models in R using the caret package. J. Stat. Softw., 28 (5), 1-26, https://doi.org/10.18637/jss.v028.i05, 2008.

Lundblad, M., Lindroth, A.: Stand transpiration and sapflow density in relation to weather, soil moisture and stand characteristics, Basic Appl. Ecol., 3, 229-243, https://doi.org/10.1078/1439-1791-00099, 2002.

Maherali, H., DeLucia, E. H.: Xylem conductivity and vulnerability to cavitation of ponderosa pine growing in contrasting climates. Tree Physiol., 20, 859-867, 2000.

Maier, C. A, Albaugh, T. J, Cook, R. I, Hall, K., McInnin, D., Johnsen, K. H., Johnson, J., Rubilar, R.A., Vose, J. M.: Comparative water use in short-rotation *Eucalyptus benthamii* and *Pinus taeda* trees in the Southern United States, For. Ecol. Manage, 397, 126-138, https://doi.org/10.1016/j.foreco.2017.04.038, 2017.

McCulloh, K. A., Johnson, D. M., Meinzer, F. C., Woodruff, D. R.: The dynamic pipeline: hydraulic capacitance and xylem hydraulic safety in four tall conifer species. Plant Cell Environ., 37, 1171-1183, https://doi.org/10.1111/pce.12225, 2014.

Medhurst, J. L., Beadle, C. L.: Sapwood hydraulic conductivity and leaf area sapwood area relationship following a thinning of a Eucalyptus nitens plantation. Plant Cell Environ., 25, 1011-1019, https://doi.org/10.1046/j.1365-3040.2002.00880.x., 2002.

Meiresonne, L., Nadezhdin, N., Cermák, J., Van Slycken, J., and ˇ Ceulemans, R.: Measured sap flow and simulated transpiration from a poplar stand in Flanders (Belgium), Agr. For. Meteorol., 96, 165–179, https://doi.org/10.1016/S0168-1923(99)00066-0, 1999.

Mitchell, P. J., O’Grady, A. P., Tissue, D. T., White, D. A., Ottenschlaeger, M. L., Pinkard, E. A.: Drought response strategies define the relative contributions of hydraulic dysfunction and carbohydrate depletion during tree mortality. New Phytol., 197, 862–872, https://doi.org/10.1111/nph.12064, 2013.

Moran, E., Lauder, J., Musser, C., Stathos, A., Shu M.: The genetics of drought tolerance in conifers, New. Phytol., 216, 1034-1048, https://doi.org/10.1111/nph.14774, 2017.

Morris, J. D., Collopy, J. J.: Water use and salt accumulation by *Eucalyptus camaldulensis* and *Casuarina cunninghamiana* on a site with shallow saline groundwater, Agric. Water Manag., 39, 205–227, https://doi.org/10.1016/S0378-3774(98)00079-1, 1999.

Mucina, L., Rutherford, M. C.: The Vegetation of South Africa, Lesotho and Swaziland, Strelitzia 19, South African National Biodiversity Institute, Pretoria, South Africa, 2006.

Nambiar, E. K. S.: Tamm Review: Re-imagining forestry and wood business: pathway to rural development, poverty alleviation and climate change mitigation in the tropics, For. Ecol. Manage., 448, 160–173, https://doi.org/10.1016/j.foreco.2019.06.014, 2019.

O'Grady, A. P., Eamus, D., Hutley, L. B.: Transpiration increases during the dry season: patterns of tree water use in eucalypt open-forests of northern Australia, Tree Physiol., 19, 591-597, https://doi:10.1093/treephys/19.9.591, 1999.

Oren, R., Pataki, D.: Transpiration in response to variation in microclimate and soil moisture in southeastern deciduous forests, Oecologia 127, 549-559, https://doi.org/10.1007/s004420000622, 2001.

Peel, M. C., Finlayson, B. L., McMahon, T. A.: Updated world map of the Koppen-Geiger climate classification, Hydrol. Earth Syst. Sci., 11, 1633-1644, https://doi.org/10.5194/hess-11-1633-2007, 2007.

R Development Core Team: R: a language and environment for statistical computing, Vienna: R Foundation for Statistical Computing, URL: http://www.R-project.org [accessed 02 August 2023], 2008.

Samuelson, L. J., Farris, M. G., Stokes, T. A., Coleman, M. D.: Fertilization but not irrigation influences hydraulic traits in plantation-grown loblolly pine, For. Ecol. Manage., 255, 3331–3339, https://doi.org/10.1016/j.foreco.2008.02.014, 2008.

Samuelson, L. J., Stokes, T. A., Ramirez, M. R., Mendonca, C. C.: Drought tolerance of a *Pinus palustris* plantation, For. Ecol. Manage., 451, Article 117557, https://doi.org/10.1016/j.foreco.2019.117557, 2019.

Santra, P., Kumar, M., Kumawat, R. N., Painuli, D., K., Hati, K. M., Heuvelink, G. B. M., Batjes, N. H.: Pedotransfer functions to estimate soil water content at field capacity and permanent wilting point in hot Arid Western India, J. Earth Syst. Sci., 127, 439–448, https://doi.org/10.1007/s12040-018-0937-0, 2018.

Savage, M. J., Everson, C. S., and Metelerkamp, B. R.: Evaporation measurement above vegetated surfaces using micrometeorological techniques, Water Research Commission Report No. 349/1/97, ISBN 1-86845 363 4, Water Research Commission, Pretoria, South Africa, 248 pp., 1997.

Scholz, F. G., Bucci, S. J., Goldstein, G., Meinzer, F. C., Franco, A. C: Hydraulic redistribution of soil water by neotropical savanna trees. Tree Physiol., 22, 603-612, 2002.

Scott, D. F., Lesch, W.: Streamflow responses to afforestation with *Eucalyptus grandis* and *Pinus patula* and to felling in the Mokobulaan experimental catchments, South Africa, J. Hydrol., 199, 360–377, https://doi.org/10.1016/S0022-1694(96)03336-7, 1997.

Scott, D. F., Smith, R. E.: Preliminary empirical models to predict reductions in annual and lo flows resulting from afforestation, Water SA, 23, 135-140, 1997.

Scott, D. F., Prinsloo, F. W., Moses, G., Mehlomakulu, M., Simmers, D. A.: A re-analysis of the South African catchment afforestation experimental data, Water Research Commission Report No. 810/1/00, ISBN 1868456722, Water Research Commission, Pretoria, South Africa, 122 pp., 2000.

Smith, R. E., Scott, D. F.: The effects of afforestation on low flows in various regions of South Africa, Water SA, 18, http://dx.doi.org/10.1007/978-1-4612-0919-5_13, 1992.

Soares, J. V., Almeida, A. C.: Modeling the water balance and soil water fluxes in a fast-growing *Eucalyptus* plantation in Brazil. J. Hydrol., 253, 130–147, https://doi.org/10.1016/S0022-1694(01)00477-2, 2001.

Soil Classification Working Group: Soil classification: a taxonomic system for South Africa, Department of Agriculture Report No. 15, Pretoria, South Africa, 257 pp., 1991.

Stanturf, J. A., Vance, E. D., Fox, T. R., Kirst, M.: *Eucalyptus* beyond its native range: Environmental issues in exotic bioenergy plantations, Int. J. For. Res. 16, https://doi.org/10.1155/2013/463030, 2013.

Sun, G., Noormets. A., Gavazz, M. J.: Energy and water balance of two contrasting loblolly pine plantations on the lower coastal plain of North Carolina, USA, For. Ecol. Manage., 259, 1299–1310, https://doi.org/10.1016/j.foreco.2009.09.016, 2010.

Traver, E., Ewers, B. E., Mackay, D. S., and Loranty, M. M.: Tree transpiration varies spatially in response to atmospheric but not edaphic conditions, Funct. Ecol., 24, 273–282, https://www.jstor.org/stable/40603043, 2010.

Vandegehuchte, M. W. and Steppe, K.: Use of the correct heat conduction–convection equation as basis for heat-pulse sap flow methods in anisotropic wood, J. Exp. Bot., 63, 2833–2839, https://doi.org/10.1093/jxb/ers041, 2012.

Van Lill, W. S., Kruger, F. J., Van Wyk, D. B.: The effect of afforestation with *Eucalyptus grandis* Hill ex Maiden and *Pinus patula* Schlecht. et. Cham. on streamflow from experimental catchments at Mokobulaan, Transvaal, J. Hydrol., 48, 107-118, https://doi.org/10.1016/0022-1694(80)90069-4, 1980.

Vertessy, R. A., Hatton, T. J., Reece, P., O'Sullivan, S. K., and Benyon, R. G.: Estimating stand water use of large mountain ash trees and validation of the sap flow measurement technique, Tree Physiol., 17, 747–756, https://doi.org/10.1093/treephys/17.12.747, 1997.

White, D. A., Beadle, C. L., Sands, P. J., Worledge, D., Honeysett, J. L.: Quantifying the effect of cumulative water stress on stomatal conductance of *Eucalyptus globulus* and *Eucalyptus nitens*: a phenomenological approach, Aust. For., 26, 17-27, http://dx.doi.org/10.1071/PP98023, 1999.

White, D. A., McGrath, J. F., Ryan, M. G., Battaglia, M., Mendham, D. S., Kinal, J., Downes, G. M., Crombie, D. S., Hunt, M. E.: Managing for water-use efficient wood production in *Eucalyptus globulus* plantations, For. Ecol. Manage., 331, 272-280, https://doi.org/10.1016/j.foreco.2014.08.020, 2014.

White, D. A., Silberstein, R. P., Contreras, F. B., Quiroga, J. J., Meason, D. F., Palma, J. H. N., de Arellano, P. R.: Growth, water use, and water use efficiency of *Eucalyptus* globulus and *Pinus radiata* plantations compared with natural stands of Roble-Hualo Forest in the coastal mountains of central Chile, For. Ecol. Manage., 501, 119675-119676, https://doi.org/10.1016/j.foreco.2021.119676, 2021.

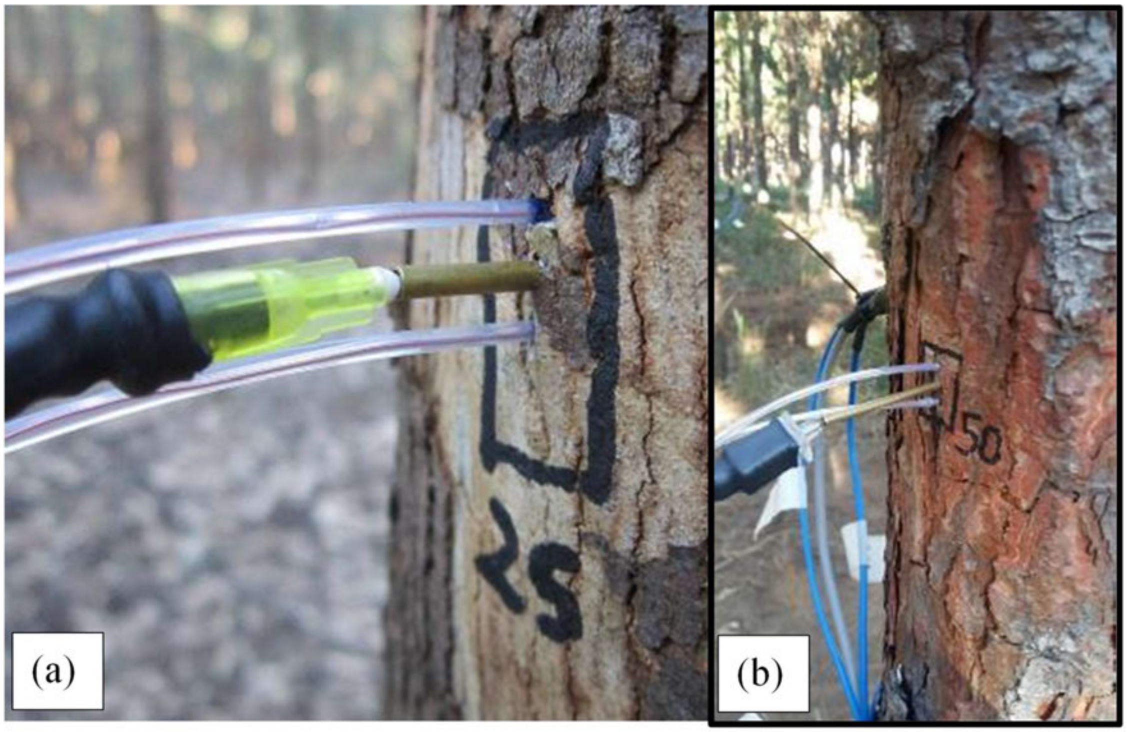
White, D. A., Ren, S., Mendham, D. S., Contreras, F. B, Silberstein, R. P., Meason, D., Iroume, A., de Arellano, P. R.: Is the reputation of *Eucalyptus* plantations for using more water than *Pinus* plantations justified? Hydrol. Earth Syst. Sci., 26, 5357-5371, https://doi.org/10.5194/hess-26-5357-2022, 2022.

Whitehead, D., Beadle, C. L.: Physiological regulation of productivity and water use in Eucalyptus: a review. For. Ecol. Manage., 193, 113-140, https://doi.org/10.1016/j.foreco.2004.01.026, 2004.

WMO: Guide to Meteorological Instruments and Methods of Observation, World Meteorological Observation Report No.8, Geneva, Switzerland, 716 pp., 2010.

Zeppel, M. J. B, Murray, B. R., Barton, C., Eamus, D.: Seasonal responses of xylem sap velocity to VPD and solar radiation during drought in a stand of native tree in temperate Australia. Australia Funct. Plant Biol., 31, 461-471, https://doi.org/10.1071/FP03220., 2004.

Zweifel, R., Zimmermann, L., Newberry, D. M.: Modelling tree water deficit from microclimate: an approach to quantifying drought stress, Tree Physiol., 25,147-156, https://doi.org/10.1093/treephys/25.2.147, 2005.

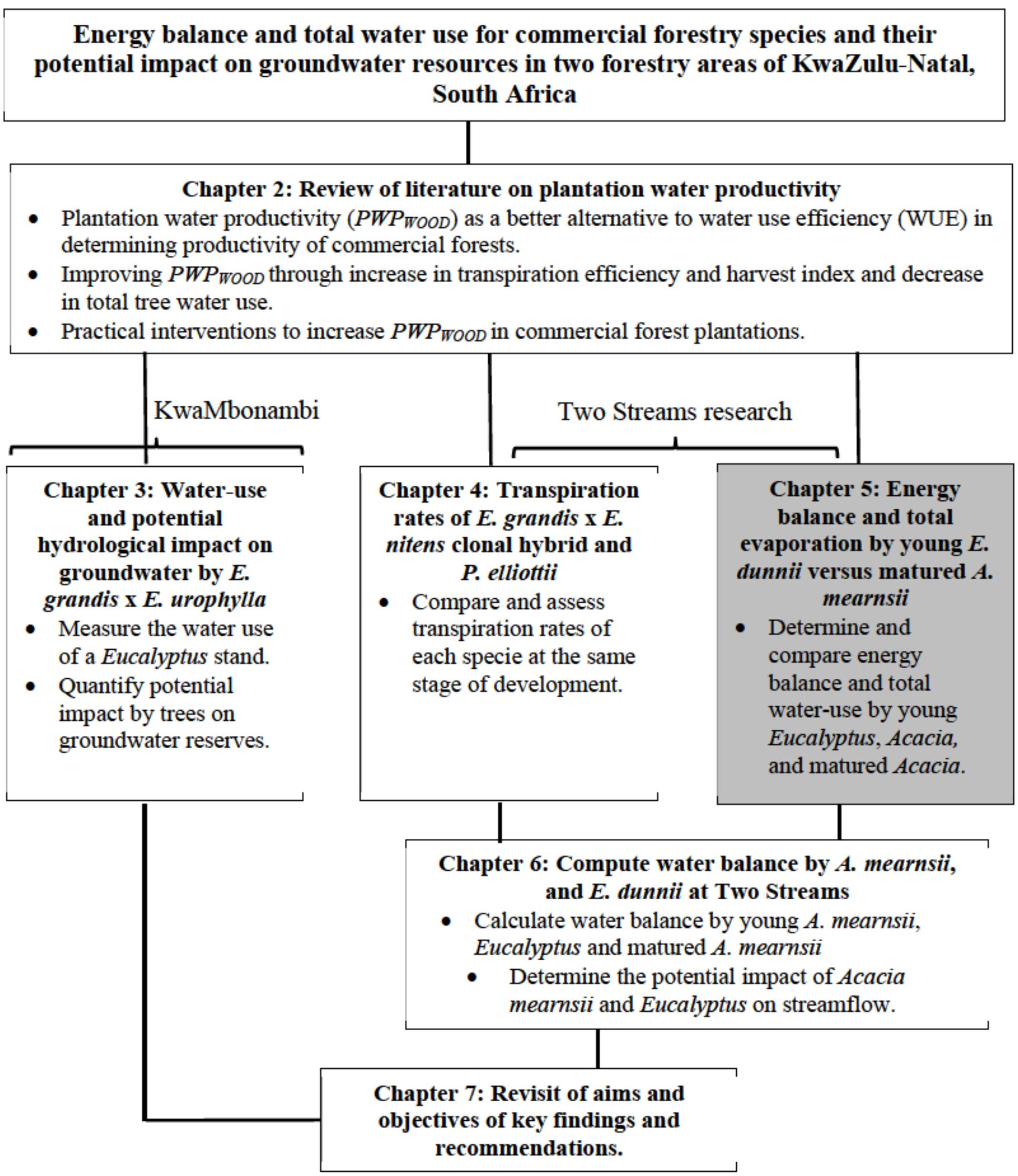


4.9 Supplementary information

Supplementary Figure 4.1: The heat ratio technique probes installed on (a) a *Eucalyptus grandis* x *E. nitens* clonal hybrid tree and (b) *Pinus elliottii* near Two Streams research catchment study site.

Supplementary Figure 4.2: A wood sample collected using an increment borer to differentiate between tree bark, tree softwood and tree heartwood to determine probe insertion depth.

Lead into Chapter 5: Hydrological processes and water use has been monitored at the Two Streams research catchment over the past two decades. After harvesting of *A. mearnsii*, a genus exchange was proposed with subsequent replanting of the catchment with *E. dunnii*. This provided an opportunity to measure total water use by the young *E. dunnii* crop and compare with the previous crop (*A. mearnsii*) at various stages of development. Therefore, the objective of this study was to compare the energy balance, total water use and plantation water productivity (PWP_{WOOD}) of three periods of measurement including two-year-old *A. mearnsii*, two-year-old *E. dunnii* and six-year-old *A. mearnsii* to quantify the potential impact of tree age and species on water resources.



CHAPTER 5: CHANGES IN ENERGY BALANCE AND TOTAL EVAPORATION WITH AGE, AND BETWEEN TWO COMMERCIAL FORESTRY SPECIES IN SOUTH AFRICA

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5.1 Abstract

Expansion of the area planted to eucalypts has been observed in the last two decades due to an improvement in markets for products from this tree species. This has raised concerns over the management of freshwater resources as other species are replaced by *Eucalyptus*, which has been shown to use more water than other commercial forestry species. The energy balance (EB) and total evaporation (ET) over *Acacia mearnsii* was previously monitored at the Two Streams research catchment, and the site harvested in 2018 with subsequent re-planting of *E. dunnii*. This presented an opportunity to measure the two-year-old *E. dunnii* ($Edun_2$) EB and ET for comparison on the same site with the previously planted *A. mearnsii* with results from two-year-old *A. mearnsii* ($Amear_2$) and six-year-old *A. mearnsii* ($Amear_6$) crops. ET and EB measurements on $Amear_2$ were obtained using a large aperture scintillometer, while eddy covariance was used for $Amear_6$ and $Edun_2$. Measurements were conducted in October 2007 to September 2008, October 2012 to September 2013 and October 2019 to September 2020 for $Amear_2$, $Amear_6$ and $Edun_2$. The leaf area index (LAI) was measured using a LAI 2200 plant canopy analyser for all crops. The annual plantation water productivity (PWP_{WOOD}) was calculated as a ratio of productive stand volume to ET for $Amear_2$, $Amear_6$ and $Edun_2$. The $Edun_2$ and $Amear_2$ annual ET was statistically ($p > 0.05$) similar, while ET of the younger crops ($Amear_2$ and $Edun_2$) was 12% greater than $Amear_6$. High ET in $Edun_2$ was caused by high LAI while $Amear_2$ was caused by high transpiration per unit leaf area in young trees than in mature trees. Climatic variables, in particular solar radiation as well as FAO reference evaporation (FAO ETo), which is derived from climatic variables and dominated by solar radiation, were good predictors of ET. Monthly crop factors were derived from FAO ETo and ET for all three crops, providing a convenient and transferable method of estimating tree water-use from meteorological data. The $Edun_2$ PWP_{WOOD} was greater than $Amear_2$, while $Amear_6$ was greater than both the young crops. This study provides insight into the total water-use by different species at different stages of growth at the same site. It is recommended that catchment water balance measurements be continued on the current *E. dunnii* crop for the full crop rotation to assess the long-term impact of *E. dunnii* on streamflow.

Keywords: Crop factor, Eddy covariance, Energy balance closure, Heat pulse velocity, Water use

5.2 Introduction

South Africa is currently faced with several water resources problems common to other semi-arid countries (Gush et al. 2019). These challenges include water shortages due to an increase in human population, economic growth and climate change (Midgley and Lotze 2011). As a result, there is a growing conflict from different land uses for water resources. The commercial forestry industry is also subjected to water challenges currently facing South Africa, with *Eucalyptus* species considered a high-water user (Gush et al. 2002, Scott and Prinsloo 2008). *Eucalyptus* is planted worldwide and has rapidly increased over the past two decades to more than 19 million ha (Iglesias and Wilstermann 2009), playing a vital role as a timber source globally (Ouyang et al. 2017). In South Africa, *Eucalyptus* plantations comprises 43% of the total commercial forestry area, with *Eucalyptus dunnii* (34%) being the most planted specie

(Godsmark and Oberholzer 2018). Eucalypts are mainly grown for dissolving wood pulp products such as high-quality short fine-fibre pulp which is in high demand by the expanding bioeconomy market.

Acacia mearnsii is an equally important plantation species in South Africa, mainly grown for bark tannin and wood chips export to Brazil (Griffin et al. 2011). The current area planted to *A. meansii* in South Africa amounts to 110 000 ha (6.8 % of total commercial forestry) of which the high wood density and pulp yield offers an economic advantage for pulp production and long-distance transport capability (Muneri 1997).

Over the past 10 years, areas planted to eucalypts have increased by 10%, while areas planted to *A. mearnsii* have decreased by 21%, owing to the developing bioeconomy markets for dissolving woodpulp (Forestry South Africa 2018). These markets prefer *Eucalyptus* plantations (Hinchee et al. 2010) over other forest species (such as *A. mearnsii*) due to their high productivity (>35 m^3 ha^{-1} $year^{-1}$), high rates of growth, good properties of wood, and a provision of benefits to the environment such as sequestering carbon (Forrester et al. 2010, Ouyang et al. 2017). As a result, there has been an increase in genus exchange from other forestry species (*A. mearnsii* and *Pinus*) to *Eucalyptus* (Forestry South Africa 2018). There are now plans to exchange as many as 300 000 ha of wattle and pine plantations with *Eucalyptus* over the next 20 years (Forestry South Africa, 2018). However, concerns are mounting over the imminent increase in area planted to *Eucalyptus*, as many local and international studies (Scott and Lesch 1997, Jackson et al. 2005, Vanclay 2009, Almeida et al. 2010, Buckley et al. 2012, Forrester et al. 2010) conclusively reported that these plantations consume more water than other commercial forestry species and grasslands. For example, studies by Silberstein et al. (2001) and White et al. (2014) linked higher total evaporation (ET) rates by eucalypts with potentially low recharge and slow rehabilitation of local water resources. An Australian study by Forrester et al. (2010) found that *E. globulus* ET exceeded *A. mearnsii* by 39%. Though eucalypts were found to be excessive water consumers by many studies, that likely deplete water resources, results from other studies are inconclusive and sometimes even contradictory (Lane et al. 2004, Jackson et al. 2005, Smethurst et al. 2015). An example is the most recent study by White et al. (2021) in central Chile where *Eucalyptus globulus* ET was statistically similar to *Pinus radiata* and both species had 10% greater ET than the native natural forests. Based on these results, a conclusion was drawn that exchanging a genus from *P. radiata* to *E. globulus* will likely not cause severe negative implications on water resources.

Despite a large body of knowledge on *Eucalyptus* and *A. mearnsii* water-use worldwide, very few studies have compared water-use by *A. mearnsii* (at different stages of development) with young *E. dunnii* in the same study area. An improved understanding of water-use by commercially planted exotic species at different stages of growth will allow for a better estimation of commercial tree regional-scale total water use. A unique opportunity was presented at the Two Streams research catchment, which has been used as an experimental catchment for over two decades to measure energy fluxes and ET over *A. mearnsii* (Clulow et al. 2011, Everson et al. 2014). Post clearing of *A. mearnsii* (February 2018), a change in genus was proposed with subsequent planting of *E. dunnii* in March 2018, with ET measurements commencing in September 2019. Total water-use and energy flux data over the *A. mearnsii* and *E. dunnii* plantations were used to accomplish the following objectives:

1. Compare *A. mearnsii* seasonal energy balance and total evaporation at two-years-old and six-years-old.
2. Compare the seasonal energy balance and total evaporation of a two-year-old *A. mearnsii* against a two-year-old *E. dunnii* from a previous rotation planted on the same site.
3. Investigate the controlling climatic variables and their influence on total evaporation for two-year-old *E. dunnii* vs two-year-old *A. mearnsii* vs six-year-old *A. mearnsii*

5.3 Study area

5.3.1 The climate and location of Two Stream research catchment

The catchment location is at the Mistley Canema (29°12'19.78°S, 30°39'3.78°E) in the Seven Oaks Area, northeast of Pietermaritzburg in the KwaZulu-Natal province of South Africa (Figure 5.1). The catchment is in a part of the midlands mist-belt grassland Bioregion, mostly dominated by forb-rich, tall, sour *Thermeda triandra* of which few patches remain due to *Aristida junciformis* invasion (Everson et al. 2014). The catchment size is approximately one km^2 with hilly topography and rolling landscapes that dips towards the southeast, resulting in the northwest to southeast surface drainage. Climatically, the catchment experiences rainy, hot and humid summers, whereas winter season is dry and cold as detailed in Table 5.1. The catchment consists of a very deep soil profile (13 m deep) underlined by a weathered bedrock (saprolite) and fractured basement rock (Clulow et al. 2011 and Everson et al. 2014).

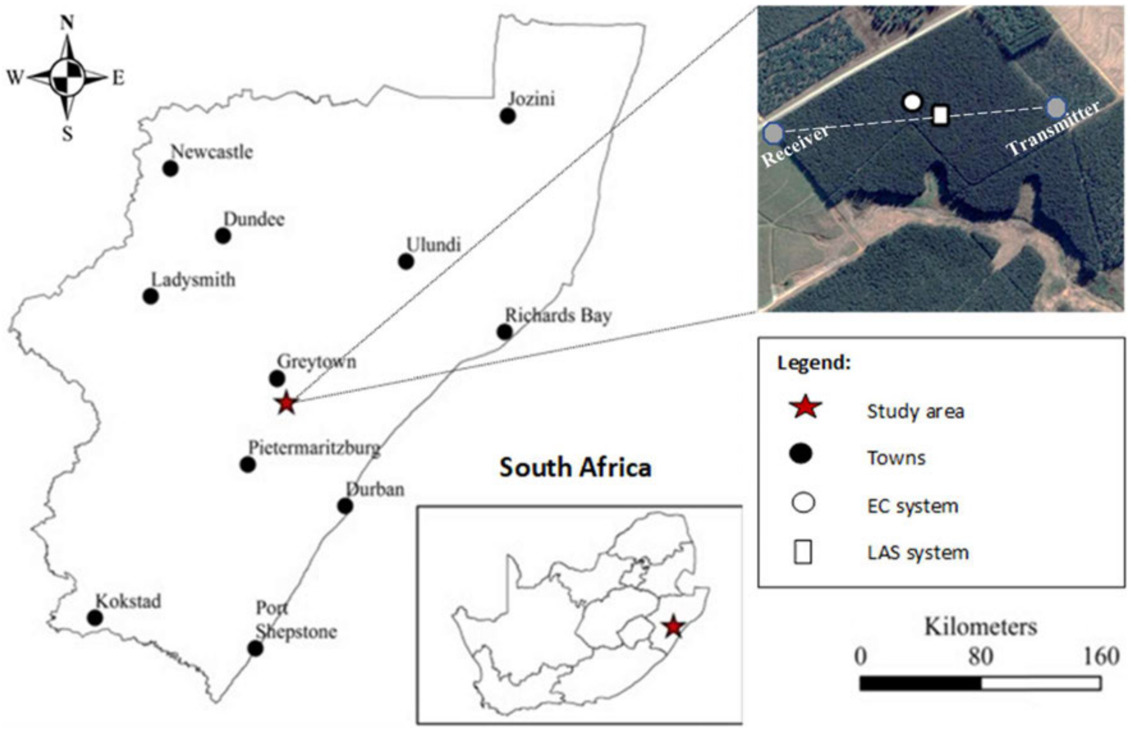

Figure 5.1: Location of the study area at Two Streams Research Catchment. The Google Earth extract (top right) provides aerial view of the catchment (© Google Maps 2022) and the measurement sensor placement. The LAI, EC and LAS are leaf area index, eddy covariance and large aperture scintillometer, respectively.

Table 5.1: The general characteristics of the Two Streams Research catchment. The abbreviations MAP and MAT denotes mean annual precipitation and mean annual temperature, respectively (Clulow et al. 2011, Everson et al. 2014).

Characteristics	**Two Streams Research site**
Minimum MAT (ºC)	4.5
Maximum MAT (ºC)	31.7
MAP (mm)	778
Climate	Warm subtropical
Altitude (meters above sea level)	1060 – 1110
Bulk density (g. cm^3)	1.25
Soil texture	Sandy clay
Lithology	Shale
Soil form	Red sands and yellow apedal

5.3.2 Study site

The site was previously planted to *A. mearnsii* for a period of 12 years (March 2006 to February 2018), where Clulow et al. (2011) and Everson et al. (2014) measured energy balance (EB) and ET using a large aperture scintillometer (ET_{LAS}) and eddy covariance techniques (ET_{EC}). *A. mearnsii* trees were harvested in February of 2018 and site subjected to burning of harvest residues for site management ease and replanted to a different genus (*E. dunnii*) in March 2018 using seedlings at a tree spacing of 2 m x 3 m (1667 trees ha^{-1}). For a newly planted *E. dunnii* crop, ET measurements were conducted when trees were 1.6 years old (October 2019). Trees were subjected to standard afforestation practices such as pruning and thinning, weeding pre-canopy closure and forest litter removal every 5th row to minimise fire risk. The catchment has a north-west orientation, with a slope of approximately 20%. A lattice mast (24 m tall) constructed in the middle of the plantation to provide a solid point for the installation of different measurement sensors (Supplementary Figure 5.1).

5.4 Material and methods

The detailed materials used in measuring energy fluxes, ET, T, weather data and ancillary measurements on *A. mearnsii* crop can be found in Clulow et al (2011) and Everson et al (2014).

The focus in this study will be on measurements conducted on the *E. dunnii* crop, after a change of genus.

5.4.1 Micrometeorological measurements

An automatic weather station was installed on a flat uniform grassland area adjacent to the study site to provide supporting meteorological measurements (Supplementary Figure 5.2). Measurements of air temperature (T_{air}) (HMP 60, Vaisala Inc., Helsinki, Finland), relative humidity (RH) (HMP60, Vaisala Inc., Helsinki, Finland), wind speed (WS) and direction (Model 03003, R.M. Young, Traverse City, Michigan, USA), solar radiation (I_s) (Kipp and Zonen CMP3) and rainfall (TE525, Texas Electronics Inc., Dallas, Tx, USA) were conducted every 10 s. The sensors were installed according to recommendations of the World Meteorological Organisation (WMO, 2008) with rain gauge orifice at 1.2 m and the remaining sensors at 2 m above the ground surface. The sensor outputs were recorded on a CR1000 datalogger (Campbell Scientific Inc., Logan, Utah, USA) at 30 min intervals. The datalogger was programmed to calculate the Vapour Pressure Deficit (VPD) using T_{air} and RH measurements according to Savage et al. (1997).

5.4.2 Energy balance and flux measurements

The energy balance equation is an indirect method to calculate ET by quantifying and partitioning the energy at the Earth's surface. This equation is presented as:

$$R_n = H + LE + G + C_s + LE_{adv} + H_{adv} \quad (5.1)$$

where, R_n is the net irradiance, H is the sensible heat flux, C is the latent heat flux, G is the ground heat flux, C_s is the canopy-stored heat, LE_{adv} is the LE_{adv} advection and H_{adv} is the H advection. Units for all terms are in W m^{-2}. Equation 5.1 can be presented as shortened energy balance by neglecting the terms, C_s, LE_{adv} and H_{adv}, since they are deemed negligible (Thom, 1975) and presented as:

$$Rn = G + H + LE \quad (5.2)$$

Equation 5.2 can be rearranged such that LE is the subject of the equation and is equivalent of ET by conversion (Savage et al., 2004).

Eddy covariance (EC) is a technique based on estimation of eddy fluxes. The H use in estimation of and is expressed as:

$$H = \overline{\rho_a} c_p \overline{w'Tair'} \tag{5.3}$$

Where, ρ_a is the density of dry air (kg m^{-3}), c_p is the specific heat capacity for air at constant pressure (J kg^{-1} K^{-1}), w' is the vertical WS (m.s^{-1}) and T_{air} is the air temperature (°C). The w' and T_{air} are measured using the sonic anemometer (Supplementary Figure 5.1) and the primes denote fluctuation from a temporal average and the overbar represents a time average. The averaging period of the instantaneous fluctuations of w' and T_{air} should be long enough (30 to 60 min) to capture all the eddies that contribute to the flux and fulfil the assumption of stationarity (Meyers and Baldocchi 2005). The vertical flux densities of H (ET indirectly derived by Equation 5.1) were estimated by the mean covariance calculation of sensible heat flux (Equation 5.2).

<u>5.4.2.1 Two-year-old and six-year-old *A. mearnsii* measurements</u>

The Two-Streams research catchment has now been used as an experimental catchment for over two decades (January 2000 to September 2021) to measure amongst other things, the energy fluxes and ET over *A. mearnsii* (Clulow et al. 2011, Everson et al. 2014). The trees were planted in 2006 and EB and ET were measured when the trees were between 1.4 and 2.4 years old (October 2007 to September 2008, which is referred to as $Amear_2$). The energy flux measurements were conducted using a large aperture scintillometer (LAS, described in detail by Clulow et al. 2011). The energy flux was measured using the large aperture scintillometer (LAS, Kipp and Zonen, Delft, Netherlands) and calculated from the changes in the refractive index of air between a transmitter of monochromatic infrared radiation (at beam wavelength of 880 nm) and receiver along a fixed transect about 1000 m long (Fig. 1) using the following equation (Wang et al. 1978):

$$C_n^2 = 1.12\sigma_{lnI}^2 D^{7/3} L^{-3} \tag{5.4}$$

where D is the aperture diameter (m) and L is the path length (m). The effective LAS beam height above the canopy was 7.6 m. The middle of the transect where most of the signal originates was dominated by the $Amear_2$, and the signal influence of other vegetation types can be considered negligible. A detailed description of LAS measuring technique can be found in Clulow et al (2011). In a second measurement period, October 2012 to September 2013, the *A.*

mearnsii trees were between 6.0 and 7.0 years old and are referred to as $Amear_6$. During these measurements of the more mature $Amear_6$ trees an EC system was used to measure H using a three-dimensional sonic anemometer (CSAT3, Campbell Scientific Inc., Logan, Utah, USA) and measurements of R_n and G were conducted simultaneously on the study site. The zero plain displacement and roughness layer were determined to be at 12.0 m and 24.2 m, respectively. Therefore, the instrument measurement height was 25 m above tree canopy. For both $Amear_2$ and $Amear_6$ crops, the energy balance (LE) was calculated as a residual term using equation 5.2 and equated to ET by conversion (Savage et al., 2004).

5.4.2.2 Two-year-old *E. dunnii* trees

After the harvesting of *A. mearnsii* and planting of the *E. dunnii* trees, H measurements were measured using a three-dimensional CSAT3 sonic anemometer (Campbell Scientific) and an unshielded chromel constantan (Type-E) fine wire thermocouple (0.76 µm TCs) from October 2019 to September 2020 over two-year-old *E. dunnii* trees ($Edun_2$) (Supplementary Figure 5.1). The sonic anemometer was installed above the tree canopy (at a height of 18 m), affixed to a lattice mast and oriented to face the north (predominant wind direction) to minimise air flow distortion by the mast. The zero plain displacement was 7.2 m while the roughness layer was determined to be 16.2 m. Data were recorded on a CR3000 datalogger (Campbell Scientific Inc., Logan, Utah, USA), powered by a 100 Ah deep-cycle lead-acid battery.

5.4.3 Data processing

A variety of reasons have been discussed by Twine et al. (2000) which may affect the accuracy of LAS and EC which include, 1) incorrect measurement of variables in equation 2, 2) bias associated with measuring instrumentation, 3) energy sinks that are neglected, and 4) measurement errors related to placement of equipment such as alignment, sensor separation and interference from the mounting structures. In our study, (2) could be significant due to different measurement techniques used (LAS and EC). Therefore, in addition to careful instrument maintenance and periodic calibration, the quality of data was ensured through rigorous post-processing. The processing of the EC and the LAS data are discussed in the following sections.

5.4.3.1 Eddy covariance system

The EC data processing included detecting spikes, sonic virtual temperature correction, correcting for density fluctuation (WPL-correction) and frequency response correction. The Eddy Pro® 7 software (Licor Inc., Lincoln, Nebraska, USA, available for free download at https://www.licor.com/env/support/EddyPro/software.html) was used to conduct the above corrections. In addition to these processing steps, the 30-min flux data were screened using the following criteria 1) data obtained when the sensor malfunctions were removed from the analysed dataset 2) data on rainy days were excluded due to the negative impact of rainfall on turbulent fluxes as reported by Zhang et al. (2016) 3) incomplete 30-min data were removed, when the missing ratio was greater than 5% in the 30-min raw data 4) night-time data ($R_n < 0$) was removed from the analysis due to potentially large nocturnal influences at night-time (Blanken et al. 1998; Wilson et al. 2001).

5.4.3.2 Large aperture scintillometer

There were three steps taken to ensure quality of the LAS data, first, data for C_n^2 above the saturation criterion (7.25 x 10^{-14} $m^{-2/3}$) was removed from the dataset, which was determined according to Ochs and Wilson (1993). Saturation occurs when the scintillation intensity rises above the limit of the theory, when this occurs, the relationship between scintillation and the structure parameter of the refractive index of air fails (Ochs and Wilson 1993). Second, data measured during rainfall periods were removed from dataset and finally, data when the sensor was malfunctioning was removed from the dataset.

5.4.4 Ancillary measurements during measurement periods

Soil heat flux was measured using two HFP01-L soil heat flux plates and parallel TCAV-L averaging TCs probes (Campbell Scientific Inc., Logan, Utah, USA). The soil heat flux plates and TCs were buried in the middle of the compartment (approximately 2 m away from the EC system) at a depth of 0.08 m and 0.06 m below the soil surface, respectively, to estimate the heat stored in the soil for all measurement periods. The soil water content (*SWC*) was measured using a CS616 volumetric soil water content sensor (Campbell Scientific Inc., Logan, Utah, USA), buried in the middle of the compartment (approximately 2 m away from the EC system) at a depth of 0.6 m for all measurement periods. All measurements were conducted every 10 s and recorded on a CR3000 datalogger every 30 min. In addition, Rn was measured using a net radiometer (NRLite, Kipp and Zonen, Delft, Netherlands) attached to the lattice mast on a horizontal boom 2.5 m away from the lattice mast at a height of 22 m.

5.4.5 Tree growth measurements

Measurements of DBH were conducted between the period October 2007 to September 2008 and October 2012 to September 2013 using manual diameter tape on *A. mearnsii*. From September 2019, DBH measurements were conducted monthly on *E. dunnii* using manual dendrometer bands (D1, UMS, Muchin, Germany) permanently attached to a tree, with an accuracy of 0.1 mm. Data were manually collected from September 2019 to October 2020. The quadratic mean diameter (D_q) was calculated for 48 trees using (Curtis and Marshall, 2000):

$$Dq = \sqrt{\frac{(\sum(DBH)^2}{n}} \quad (5.5)$$

Tree heights (h) were measured simultaneously using a hypsometer (Vertex Laser VL402, Haglof, Sweden).

The conical over bark volume (v, m^3) for a period, January 2006 to February 2018 was calculated based on data availability, while monthly v was calculated for the period September 2019 to August 2021 using equation 4.3 (White et al. 2014):

$$v = \left(\frac{\pi}{12}\right)\left(\frac{Dq}{100}\left(\frac{h}{h-1.3}\right)\right)^2 h \quad (5.6)$$

The productive stand volume (V, m^3 ha^{-1}) was calculated using:

$$V = \frac{10\ 000}{A}\sum_{i=1}^{n} vi \quad (5.7)$$

where vi was the productive volume of the ith tree, A was the total area (m^2) of the plot where measurements were conducted, n is the total number of trees within a plot and 10 000 represents one hectare (equivalent to 10 000 m^2).

The monthly leaf area index (LAI) measurements were conducted on the *Edun₂* using a LAI-2200 Plant Canopy Analyzer (Licor Inc., Lincoln, Nebraska, USA). Measurements were conducted on a transect that was identified within the study site for eight months in the year 2020 (March to April, June to September and November to December). For $Amear_2$ and $Amear_6$ LAI, measurements were conducted periodically by Clulow et al. (2011) in a transect within the study site using the LAI 2000 (Licor Inc.) and LAI 2200 Plant canopy Analyzer (Licor Inc.), respectively. LAI measurements were conducted in year 2007 (October and November), 2008 (April, August and November) and 2009 (February) for $Amear_2$, while $Amear_6$ LAI measurements were conducted in year 2011 (October), 2012 (January, July and November) and 2013 (March).

5.4.6 Plantation water productivity

The plantation water productivity (PWP_{WOOD}) was calculated annually for the three periods of assessment: October 2007 to September 2008, October 2012 to September 2013 and October 2019 to September 2020 for $Amear_2$ and $Amear_6$ and $Edun_2$, respectively. It was calculated as a ratio of V to ET.

5.4.7 FAO Penman-Monteith reference evaporation

The Penman-Monteith method is an internationally recognised technique of calculating FAO reference evaporation (ETo). This method has been reported to provide consistent ETo values in many regions and climates and has been accepted worldwide as a good estimator of ETo compared with other methods (Chiew etal., 1995; Jacobs and Sattii; Temesgen et al., 2005). The technique is popular for reasons including, calculating a crop factor (Allen et al., 1998) using:

$$K_c = \text{ET} / ET_o \tag{5.8}$$

where K_c is a crop factor. The calculated K_c allows for an estimation of ET from standard weather station data. It is important to note that the estimation of ET using K_c assumes that the crop is not subjected to water stress. In this study, monthly K_c values were calculated for each measurement period.

5.4.8 Statistical analysis

The statistical analysis was performed using the R statistical computing software (R Development Core team 2008) using Random Forests (RF) regression algorithm (Breiman 2001), where ET was made a response variable and meteorological data (I_s, FAO ETo, VPD, T-Max, T-Min, SWC, rainfall, WS and RH) as predictor variables This machine learning approach doesn't make the assumptions of linear regression and performs well when the relationship among the response variable and independent variables are complex and non-linear. The RF regression model was optimised in terms of the parameters *ntree* (number of trees built by the model) and *mtry* (number of variable predictors used at each node split using the Caret package (Kuhn 2008). The RF regression was evaluated using the R^2 metric and the contribution of each variable to the model accuracy was determined by developing a variable importance plot. Each variable was scored based on the Mean Decrease Accuracy for $Amear_2$, *Amear*$_6$ and *Edun*$_2$ measurement period, which is calculated as the loss of accuracy when a variable is removed from the pool of predictors.

5.5 Results

5.5.1 Weather

The microclimate within our study site reflected typical warm temperate climatic conditions with warm wet summers and cool dry winters for the three measurement periods (Figure 5.2). The daily I_s was lowest in June (mean range: 5.1–12 MJ m^{-2} day^{-1}) and most consistent, whereas December and January experienced higher and more variable I_s (reaching a peak of 30 MJ m^{-2} day^{-1}) across all measurement periods. These conditions were consistent with clear winter days and cloudy summer season. The daily maximum T_{air} of 38.6º C, 33.8° C and 37.5º C were measured in January 2008, December 2012 and January 2020, respectively, while the lowest measured T_{air} was -1° C in June across all the measurement periods. The lowest average daytime RH across all the measurement periods was measured in September (approximately 30%), while the mean daytime VPD was the highest (*Amear*$_2$ = 2.6 kPa, *Amear*$_6$ = 2.5 kPa and *Edun*$_2$ = 3.4 kPa) during September which is well known for dry, warm Berg winds. The average WS were notably high in July for year 2019/ 20 and in October for 2007/ 08 and 2012/ 13. The prevailing wind direction was from the north-east and the south for all measurement periods. Most of the rainfall (70%) occurred during summer from September to April of each measurement period (Figure 5.2). Many rainfall events occurred during the daytime, which most likely affected EC flux measurements as reported by Zhang et al (2016). Therefore, daytime flux measurements during rainy days were excluded in the flux data analysis as ET is low during these periods.

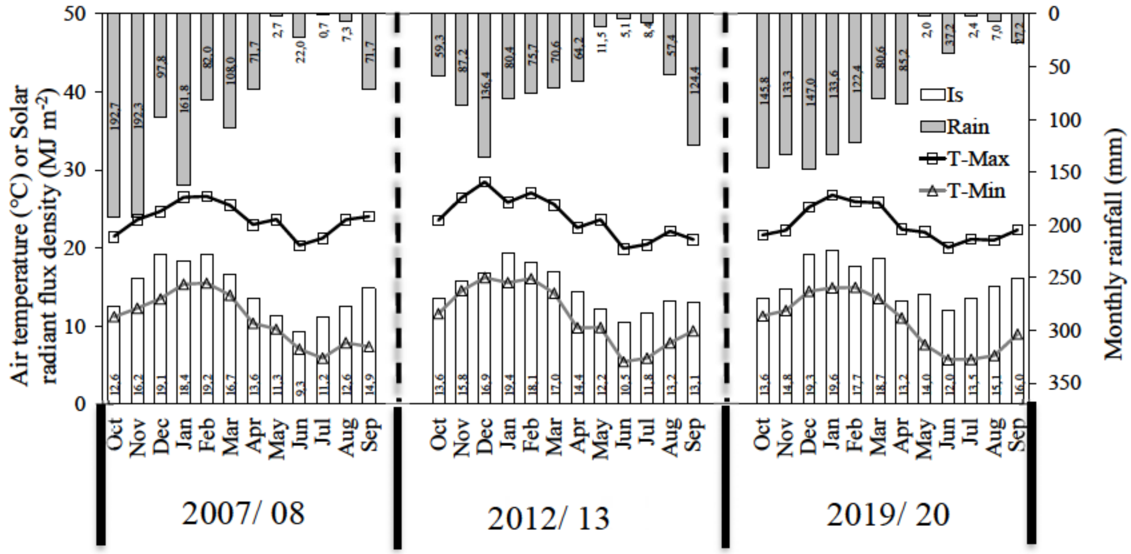

Figure 5.2: Monthly values of mean daily radiant flux density (Is, MJ m^{-2} day^{-1}), maximum (T-Max) and minimum (T-Min) air temperatures (°C) and corresponding total monthly rainfall measured at Two Streams Research Catchment in 2007/ 08, 2012/ 13 and 2019/ 20 hydrological years.

5.5.2 Soil water content

There was a distinct seasonal variation in *SWC* dynamics for all measurement periods (Fig. 3). The annual rainfall between measurement periods was not significantly different ($p > 0.05$), however, the *SWC* was generally higher for the $Amear_2$ (Fig. 3), followed by $Amear_6$ and $Edun_2$. The $Amear_2$ *SWC* was significantly greater during the wet season (maximum: 0.40 m^3 m^{-3}) compared to 0.25 and 0.28 m^3 m^{-3} for $Edun_2$ and $Amear_6$, respectively (Fig. 3). Commercial forest plantations are known to have a very deep rooting system and are able to access soil water stored in deep soil layers from previous wet years (Christina et al. 2016). A study by Everson et al. (2014) on the same catchment, reported that the six-year-old *Acacia mearnsii* tree roots were as deep as 8 m into the soil profile. Similar results were reported by Dye (1996) in the Mpumalanga province of South Africa, where three-year-old *Eucalyptus grandis trees* abstracted water down to 8 m below the soil surface. The deep soil profile with the presence of weathered bedrock (saprolite) at the Two Streams research catchment suggests that trees were capable of rooting deep into the soil profile and were probably restricted by the bedrock (grey fine-grained shale). Therefore, there a high possibility in this study that tree roots, even for the young crops, accessed soil water stored deep in the soil profile from previous wet years.

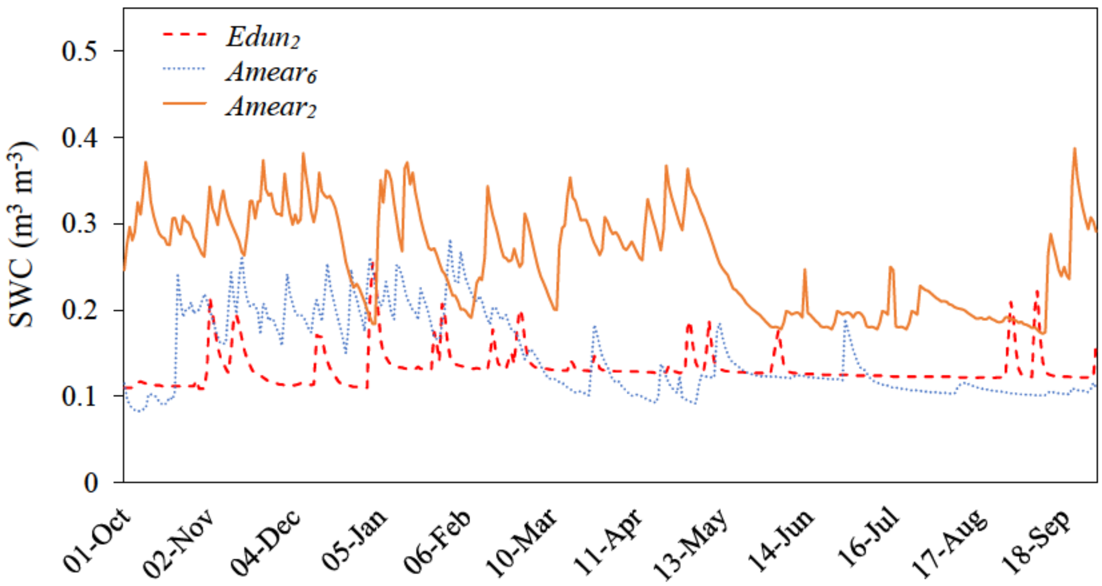

Figure 5.3: The daily mean soil water content (*SWC*, $m^3\ m^{-3}$) measured in the top 0.6 m of soil in the middle of the plantation on a study site planted with two-year-old *A. mearnsii* (*Amear₂*, October 2007 to September 2008), two-year-old *E. dunnii* (*Edun₂*, October 2019 to September 2020) and six-year-old *Acacia mearnsii* (*Amear₆* October 2012 to September 2013).

5.5.3 Flux measurements

The daily Rn indicated seasonal fluctuations, however, the half-hourly flux data indicated that most measurement days in summer were affected by periodic cloud cover, even during the dry season. The impact of cloud cover on Rn was translated through to H and LE, causing these fluxes to be positive during the daytime. To clearly describe the energy partitioning into different EB components during different seasons, the diurnal patterns of the 30-min averages of Rn, H, LE and G, on a clear and calm day in a hot wet summer (October to March) and cold dry winter (May to August) for each measurement period were selected and compared. The comparison of 30-min averages of R_n, H, LE and G in wet summer (October to March) and cold dry winter (May to August) and cold dry winter (May to August) indicated that there were no statistically ($p > 0.05$) significant differences in Rn in both summer and winter measurement periods (Table 5.2). However, during summer, energy partitioning of Rn into LE and H in all crops was dominated by LE ($p < 0.05$, Table 5.2) accounting for 55%, 61% and 53% of Rn for the *Amear₂*, *Amear₆* and *Edun₂*, respectively. The peak LE values corresponded with maximum

Rn values greater than 900 W m^{-2} for all crops. The LE fluxes continued to dominate ($p < 0.05$) during the winter season for the $Amear_2$ (66%) and $Edun_2$ (60%), however, the H and LE fluxes were statistically ($p > 0.05$) similar for the $Amear_6$ (LE= 132.3 W m^{-2}, H = 117 W m^{-2}). Summer LE for the $Edun_2$ increased sharply early in the morning (~09h00), reaching a peak around midday (~11h30), whereas the response of H was more gradual, reaching a peak in the late afternoon (~15h00). By comparison, H and LE for the $Amear_2$ and $Amear_6$ showed a similar diurnal pattern, reaching peak values around midday. The smallest portion of AE was accounted for by G on all crops, with the $Edun_2$ statistically ($p < 0.05$) lower than both the $Amear_6$ and the $Amear_2$, which were statistically similar ($p > 0.05$).

Table 5.2: Comparison of the analysis of variance (ANOVA) results for daily energy fluxes during October to March (wet season) and April to September (dry season) measurement period between the two-year-old *E. dunnii* trees ($Edun_2$), two-year-old *A. mearnsii* ($Amear_2$) and six-year-old *A. mearnsii* ($Amear_6$). Significant mean differences are indicated using different letters at 5% level of significance.

	$Amear_2$ (2007/ 08)	$Edun_2$ (2019/ 20)	$Amear_6$ (2012/ 13)
	October to March measurement period (W m^{-2})		
Rn	577.6	577.2	599.1
H	205.9a	229.9a	289.7b
LE	325.2a	289.2b	319.2a
G	23.1a	10.1b	24.9a
	April to September measurement period (W m^{-2})		
Rn	241.7	256.9	278
H	30.7 a	126.7b	117b
LE	160.6 a	148.9b	132.4b
G	19.2 a	12.1b	10.6b

5.5.4 Measured annual actual total evaporation

The three periods of ET measurements transition from when the Two Streams research catchment was planted with $Amear_2$, $Amear_6$ and $Edun_2$ are presented in Figure 5.4. In early summer (November to January), mean daily ET for young crops ($p = 0.31$) was statistically greater ($p < 0.05$) than the mature crop. In the middle of the dry season (June and July), *$Edun_2$* ET was significantly ($p < 0.01$) greater than both the *$Amear_2$* and the *$Amear_6$*, which were not significantly ($p > 0.05$) different from each other. The summer daily ET SD and CV was high in the *$Amear_2$* (SD=2.4, CV=48.4) compared to *$Amear_6$* (SD= 1.5, CV=35) and *$Edun_2$* (SD=1.7, CV=41). For the dry season, SD ranged from 0.6 to 0.8 for all crops, but CV differed with the highest in *$Amear_2$* (34.1) followed by *$Edun_2$* (30.3) and lowest in *$Amear_6$* (24.3), indicating a higher variability in daily ET of the younger two-year-old crops.

On an annual basis, *$Amear_2$* and *$Edun_2$* accumulated ET was statistically ($p > 0.05$) similar, but both 12% greater than the *$Amear_6$* crop (Figure 5.4). The total accumulated rainfall for each measurement year was similar across the three years. The accumulated ET exceeded rainfall for all crops (Figure 5.4), with the least margin for *$Amear_6$* (16.5%), while young crops ET were 27.5% and 30% greater for *$Amear_2$* and *$Edun_2$*, respectively. FAO ETo varied over the three years, ranging from 918 mm to 1061 mm for the *$Edun_2$* and *$Amear_2$* respectively (Figure 5.4).

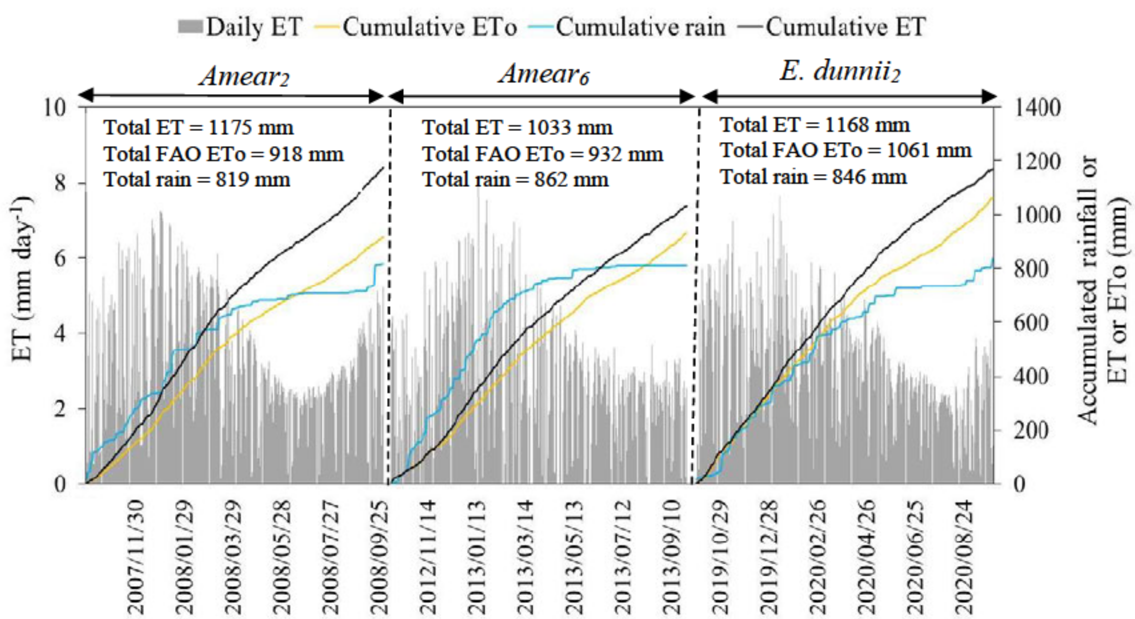

Figure 5.4: Comparison between total evaporation (ET) by two-year-old *A. mearnsii* (*$Amear_2$*, measured using large aperture scintillometer from Oct 2007 to Sep 2008), six-year-old *A. mearnsii* (*$Amear_6$*, measured using eddy covariance from Oct 2012 to Sep 2013) and two-year-old *E. dunnii* (*$Edun_2$*, measured using eddy covariance from Oct 2019 to Sep 2020) with corresponding accumulated rainfall, ET and FAO reference evaporation (FAO ETo, mm day^{-1}).

5.5.5 Response of actual total evaporation to meteorological variables

The RF model performed well in predicting ET for all measurement periods, producing a coefficient of determination (R^2) of 0.91, 0.85 and 0.91 for $Amear_2$, $Edun_2$, and *Amear6*, respectively. The mean square error was 0.23 for $Amear_2$ and $Amear_6$ and 0.33 for $Edun_2$, indicated a very good predictive power.

The RF predictive model rated I_s as the most important predictor of ET in $Edun_2$ (Figure 5.5b). Meteorological variables, FAO ETo, VPD, T-Max, WS and *SWC* in descending order of importance were also scored as important. By comparison $Amear_2$ and $Amear_6$ most important predictor variables were I_s and FAO ETo while VPD, T-Max, T-min and *SWC* were important variables in decreasing order of importance (Figure 5.5a and 5.5 c). Rainfall, RH and T-Min were the least important variables in a model in $Edun_2$, while WS, rainfall and RH were not good predictors of ET in $Amear_2$ and $Amear_6$. The model indicated that ET is influenced by micrometeorological variables at varying levels of influence.

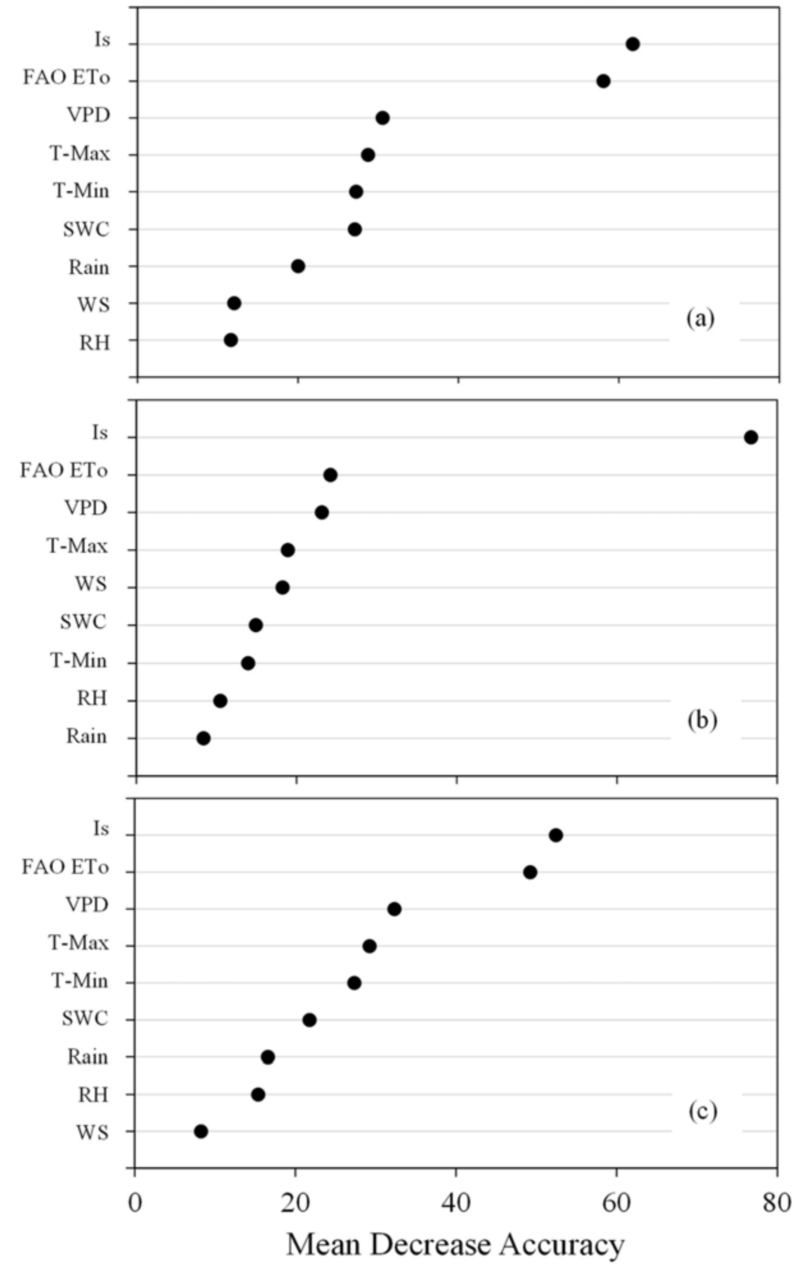

Figure: 5.5: Variable importance plots of (a) two-year-old *Acacia mearnsii*, (b) two-year-old *E. dunnii* and (c) six-year-old *Acacia mearnsii* from the random forest regression model using solar radiation (I_s), FAO reference evaporation (FAO ETo), vapor pressure deficit (VPD), maximum air temperature (T-Max), minimum air temperature (T-Min), volumetric water content (VWC), rainfall, relative humidity (RH) and wind speed (WS) as predictor variables. Mean Decrease Accuracy is a measure of how much the model error increases when a particularly variable is randomly permuted.

5.5.6 Crop factors

The K_c was calculated at a daily interval from the ET (ET_{LAS} for the *Amear₂* and ET_{EC} for the *Edun₂* and *Amear₆*) and FAO ETo, using equation 5.8, and thereafter averaged for each month of the measurement period for each crop (Figure 5.6). When $K_c = 1$, the Two Streams catchment ET equals to FAO ETo. However, a K_c of <1 or >1 indicated that the catchment actual ET is less than or greater than the FAO ETo, respectively. Comparison of K_c between our crops indicated that the K_c was between 0.7 and 1.3 throughout the year for all crops, except during a distinct period when the $Amear_2$ K_c (September 2008), $Amear_6$ K_c (June and July 2013) and $Edun_2$ K_c (May and June 2020) were 1.4, 1.4 and 1.6, respectively (Fig. 5.6). This is an indication that the ET significantly exceeded the FAO ETo during these periods.

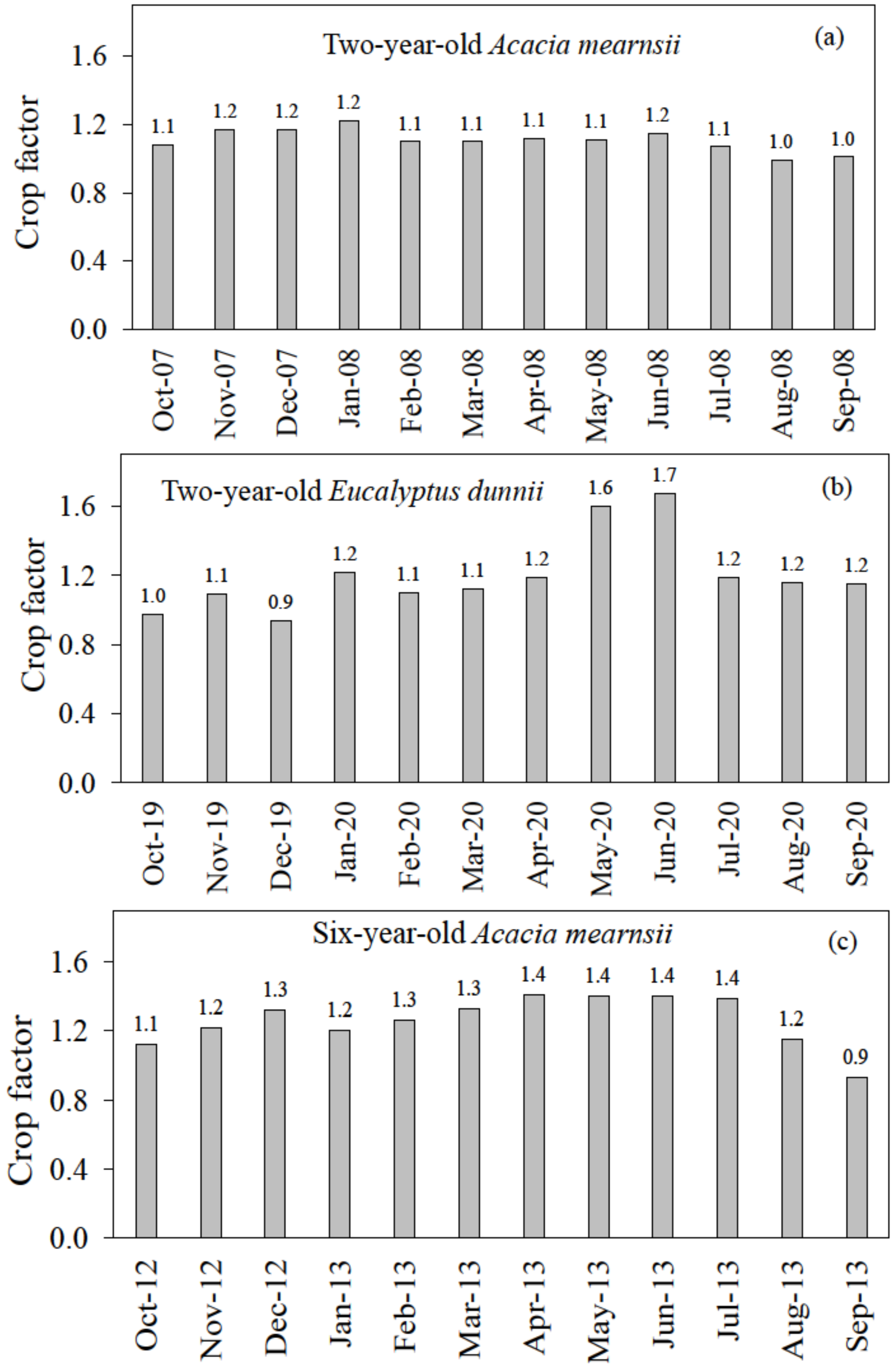

Figure 5.6: Monthly crop factors (K_c) for (a) two-year-old *Acacia mearnsii* (b) six-year-old *Acacia mearnsii* and two-year-old *Eucalyptus dunnii* derived at Two Streams research catchment for 2007/ 08, 2012/ 13 and 2019/ 20 hydrological years, respectively.

5.5.7 Comparison between the leaf area index

The LAI for the *Edun*$_2$ showed a typical seasonal pattern (Figure 5.7), while for the *A. mearnsii* crops, there was a linear increase in LAI over time. In summer, the *Edun*$_2$ LAI was significantly ($p < 0.05$, peak LAI=4.11) greater than both the *A. mearnsii* crops, which were significantly ($p < 0.05$) different from each other (*Amear*$_2$ = 2.45, *Amear*$_6$ = 2.85). A significant decrease in LAI was observed for the *Edun*$_2$ (reaching a low LAI of 2.1) just before the onset of a wet season (September). The *A. mearnsii* crops showed no significant decrease in LAI during the dry season (Figure 5.7).

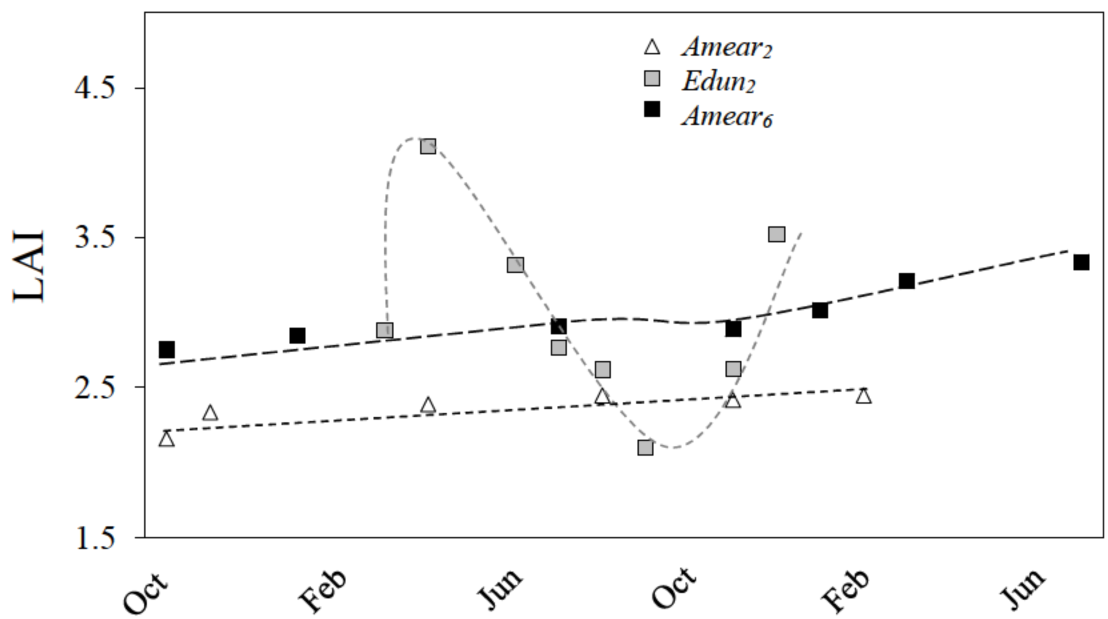

Figure 5.7: The leaf area index (LAI) measured at Two Stream research catchments for the two-year-old *Acacia mearnsii* (*Amear*$_2$), two-year-old *Eucalytus dunnii* (*Edun*$_2$) and six-year-old *Acacia mearnsii* (*Amear*$_6$). For *Amear*$_2$, the LAI measurements were conducted in year 2007 (October and November), 2008 (April, August and November) and 2009 (February). In *Amear*$_6$ measurements were conducted in year 2011 (October), 2012 (January, July and November) and year 2009 (January and March). Monthly LAI measurements for *Edun*$_2$ were conducted in 2020 (March and April, June to September and November and December).

5.5.8 Plantation water productivity

A comparison between *Amear*$_2$ and *Edun*$_2$ PWP_{WOOD} indicated that *Edun*$_2$ had significantly ($p < 0.05$) greater PWP_{WOOD} than *Amear*$_2$. The mature crop (*Amear*$_6$) produced a statistically ($p < 0.05$) greater PWP_{WOOD} than the two young crops (Figure 5.8).

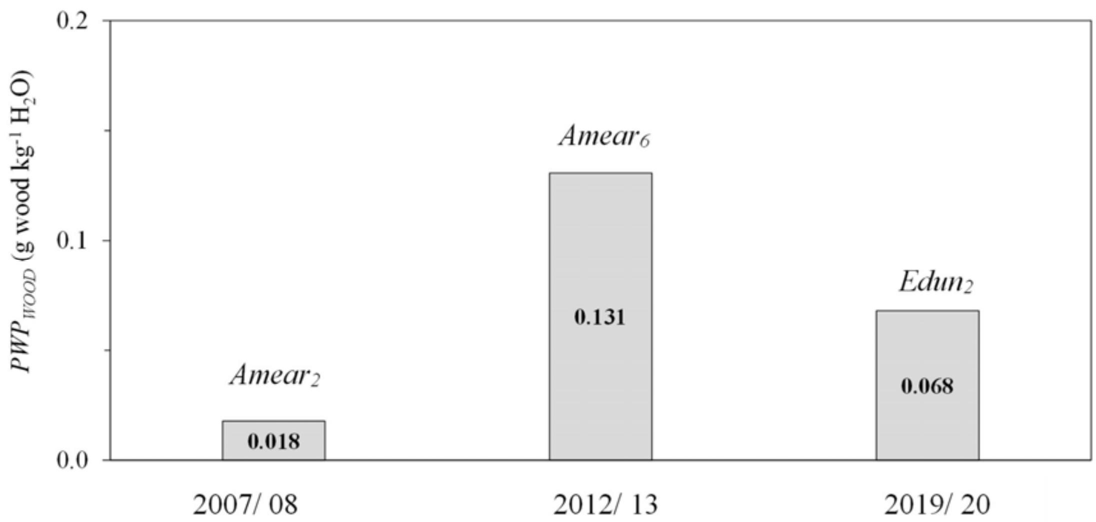

Figure 5.8: The plantation water productivity (*PWP_{WOOD}*) of two-year-old *Acacia mearnsii* (*Amearn*$_2$), six-year-old *Acacia mearnsii* (*Amearn*$_6$) and *Eucalyptus dunnii* (*Edun*$_2$) in 2007/ 08 (September 2007 to October 2008), 2012/ 13 (September 2012 to October 2013) and 2019/ 20 (September 2019 to October 2020), respectively, at Two Streams research catchment.

5.6 Discussion

Expanding and understanding the water-use knowledge, through measuring ET, of commercial forestry species, particularly *Eucalyptus* and *Acacia* is extremely important in better estimating the regional scale water-use, particularly with the imminent exchange of existing genera to new clones and hybrids of *Eucalyptus* species by the South African forestry industry. In addition, a widespread invasion of *Acacia* in the Western Cape (Le Maitre et al. 2000) and the Eastern Cape (Reynolds 2022) of South Africa, have raised concerns on the detrimental impact this species has on the ecosystem and water resources. The LAS and EC techniques are internationally recognised to be suitable and accurate methods for estimating water-use in commercial trees (Hutley et al. 2001, Cabral et al. 2010). The availability of historical ET data for *A. mearnsii* at different stages within its rotation, followed by a change to *Eucalyptus,* at the same site, with ongoing measurements of ET from the *E. dunnii* have provided a unique opportunity to conduct comparisons between the species at the same study site. However, investigating stand water-use at different measurement periods can be confounded by significant differences in annual weather conditions over time. However, the years of comparison presented were selected when weather conditions were representative of the long-term mean of the study area (Schulze and Lynch 2007), implying that differences in EB and ET were predominantly a result of tree age or species although long-term differences in soil water resources may have played a role.

5.6.1 Energy balance components and seasonal influence

The EB for each measurement period was mainly driven by local meteorological variables such as Rn and changes in vegetative characteristics. For example, during the summer wet season when Rn was high (>900 W m^{-2}), SWC was not limiting and LAI was high, LE was the main energy consumer in all crops (> 53%). Similar results have been reported in other studies (Hutley et al. 2001, Liu et al. 2011). Surprisingly, LE also dominated the EB (> 60%) during the dry season for all crops, which was contrary to results from other studies (Hutley et al. 2001, Oliphant et al. 2004; Liu et al. 2011), which reported H as a dominant EB flux during the dry season in forests. Domination of LE during the dry season may be an indication that trees were not limited by water in winter. A study by Clulow et al. (2011) on young *A. mearnsii* at the same study site indicated the possibility of roots accessing groundwater through capillary rise. As expected from a commercial forestry species and a closed canopy, G accounted for a relatively small proportion of the AE for all the crops (1.7 to 4.1%) indicating a likelihood that soil water evaporation is a small component in comparison to ET. The $Edun_2$ G was significantly lower than for other crops in summer, which was probably caused by the tree canopy shading the soil surface. This is supported by a significantly high LAI (maximum summer LAI of 4.11) for the $Edun_2$ compared to *A. mearnsii* crops (LAI range: 2.4 to 3.52).

5.6.2 Total evaporation comparison between measurement periods

The annual measured ET for $Amear_2$, $Edun_2$ and $Amear_6$ were 30%, 27.5 % and 16.5% greater than rainfall, respectively. These results are similar to two previous ET studies conducted on the same catchment; 1) Dye and Jarmain (2004) used Bowen ratio technique on four-year-old *A. mearnsii* and found ET to exceed precipitation by 18%, and 2) Clulow et al. (2011) using LAS on *A. mearnsii* reported 46% greater ET than rainfall. These two studies plus our study indicated a negative water-balance between input and output and suggests that trees sourced water external to the catchment and most likely from regional groundwater or soil water accumulated from fallow periods or unplanted nearby areas. It is common knowledge that post planting, exotic tree species develop a dimorphic root structure (deep tap root and superficial roots) to increase the chances of accessing water near the soil surface as well as in deep soil layers (Kimber 1974, Sands and Mulligan 1990). A South African study by Dye (1996) on three-year-old *E. grandis* in South Africa excluded rainfall using plastic sheeting and found that there was no decline in ET as soil water deficit increased. This was attributed to the capability of the three-year-old *E. grandis* to source water at least 8 m deep. In our study, the water table was measured to be ~ 26.3 m, which was probably too deep for roots of our young crops to come into direct contact with ground water resources as the roots would still have been relatively shallow. However, it was shown by Clulow et al. (2011) that plant available water increased beyond the 1.5 m soil profile depth and tree roots may be in contact with the ground water through capillary rise. Another possible water source could be the lateral and vertical movement of soil water in response to gradients in soil water potential as reported by Dye et al. (1996), however, this needs to be quantified.

Annual ET between young crops ($Amear_2$ and $Edun_2$) were statistically similar, however, the $Amear_6$ annual ET was 12% less than both the young crops, despite 16 mm and 43 mm more precipitation during the periods of $Amear_2$ and $Edun_2$ measurement, respectively. These results were not surprising, as literature reports that water-use in exotic forest species increases sharply in the early stages of growth, reaching a peak in the middle of the rotation (~ 5–7 years), thereafter, declines as the stand matures (Kostner et al. 2002, Delzon and Loustau 2005; Soares and Almeida 2001). Our results indicated that the total water use of the $Amear_6$ stand was starting to decline by year 6. In a Brazilian study by Almeida et al. (2007), maximum annual T (> 1000 mm) was measured when *E. grandis* hybrid trees were between 2.75 and 5.6 years old and a significant decrease in water-use was observed when trees were older than 5 years. Similar results were reported by Kostner et al. (2002) and Delzon and Loustau (2005). This age-related decline in water-use was reported to be driven by 1) a decrease in LAI with increasing stand age (Soares and Almeida 2001, Delzon and Loustau 2005, Almeida et al. 2007) 2) the fact that mature trees are taller and have a lower T per unit leaf area than young trees (Delzon and Loustau 2005, Scott and Prinsloo 2008). This is because water needs to be transported higher, which increases the hydraulic constraints resulting in a decrease in soil-to-leaf water potential gradient, and a decrease in stomatal conductance and consequently lower ET and T (Delzon et al. 2004). In our study, $Edun_2$ LAI was significantly greater than the $Amear_6$, which may explain the significantly greater annual ET, however, the *Amear*$_2$ LAI was statistically lower than the *Amear*$_6$ and soil-to-leaf water potential gradient may have influenced greater ET.

There are many other external regulators that have been described to have a strong relationship with ET, which includes readily available soil water in the rooting area (Oren and Pataki 2001), the atmospheric micrometeorological conditions (Lundblad and Lindroth 2002) and aerodynamic resistance (Hall 2002). However, these relationships are complex, because exotic trees can have several internal mechanisms, which can vary between species, tree age and tree physiology (Zweifel et al. 2005). Nevertheless, in most actively growing tree species, there is a consensus that certain meteorological variables can highly influence ET (Albaugh et al. 2013). Results from multiple regression analysis using RF showed that I_s, FAO ETo, VPD and T-Max are very good predictors of ET, in a decreasing order of importance for all measurement periods. These results were expected, as other studies have linked tree water use with micrometeorological variables (Albaugh et al. 2013, Medhurst and Beadle 2002, Lakmali et al. 2022), particularly I_s (Zeppel et al. 2004). However, a study by Calder (1998) indicated that total evaporation in evergreen forests, unlike shorter vegetation which is highly influenced by the supply of I_s, is highly influenced by advection energy greater than I_s. This suggests that I_s on its own can not be used to estimated total evaporation in commercial forests. Surprisingly, rainfall was found to be a weak predictor of ET. This was probably caused by a delay in the rainfall availability to trees. For example, during the wet season when the soil profile already has sufficient *SWC*, more rainfall would have no significant impact on trees (Xue and Gavin 2008). Nevertheless, with FAO ETo being the second most important predictor of ET, this suggested that K_c is a suitable method of estimating ET in commercial forest stands, a conclusion shared by Clulow et al. (2011).

The K_c values ranged from 0.7 to 1.3, an indication that ET was either lower or greater than FAO ETo, which was within the expected K_c values (less than 1.4) in actively growing *Eucalyptus* trees (Allen et al. 1998, 2011, Pereira et al. 2021). The K_c values greater than 1 and less than 1.4 in our study suggest that trees were not limited by soil water availability and were probably sourcing water other than the surface precipitation over the stand. Alternatively, the possible contribution of mist interception and the contribution of interception to the water balance requires further research as the site is in a mist-belt area. Surprisingly, *Amear*$_2$ experienced high K_c values reaching a maximum of 1.7. Such high K_c values were probably caused by conditions such as high advection and “clothesline” and “oasis” effect (Allen et al.

1998, Borin et al. 2011, Pereira et al. 2021) whereby warm dry air can contribute to heat input and ET losses well in excess of ET losses caused by solely I_s (Allen et al. 1998). If such conditions occur, K_c values are generally greater than FAO ETo and the peak K_c values exceed the 1.2 to 1.4 limit (Allen et al. 1998, Allen et al. 2011), which was the case in our study.

5.6.3 Plantation water productivity

Comparison of PWP_{WOOD} for young crops ($Amear_2$ and $Edun_2$) indicated that $Edun_2$ produced more wood per total water used than the $Amear_2$. These results corroborated with previous studies (Forester et al. 2010, Albaugh et al. 2013) which suggested that *Eucalyptus* uses water more efficiently than pine and wattle. The mature crop ($Amear_6$) produced more wood per total water used than both the young crops. This finding is supported by Skubel et al. (2015) who found that WUE in trees increases with tree age. This increase was shown by the increase in LAI which increased with tree growth, enabling trees to use more water, and produce more biomass (Kostner et al. 2002). In addition, high LAI minimises soil evaporation through more shading, which in turn improves PWP_{WOOD}.

5.7 Conclusion

This study compared EB and water-use by young exotic tree species ($Edun_2$ and $Amear_2$) and a mature crop ($Amear_6$) using internationally recognised techniques, EC and LAS in the same catchment over different measurement periods. The EB fluxes were dominated by LE during summer for all crops, even during the dry season, which was an indication that these crops were accessing stored soil water or groundwater reserves. Comparison between $Edun_2$ and $Amear_2$ ET losses indicated similar responses, however, the ET of the mature crop ($Amear_6$) was significantly lower than both the $Edun_2$ and $Amear_2$ crops, which was expected as literature reports that the exotic species reach their peak water-use in the middle of their rotation (~ 5 years), thereafter decreasing. Recommendations are that measurements on *E. dunnii* are continued for a full rotation and expanded to other commercial forest plantations. Multiple regression analysis indicated that micrometeorological variables, I_s and FAO ETo, are very good predictors of ET, which enabled a development of monthly K_c values which will assist in predicting ET using AWS variables in future modelling studies. A young *Eucalyptus* crop produced more biomass per volume of water than the young *A. mearnsii* crop, while the mature *A. mearnsii* crop produced high PWP_{WOOD} than both the young crops.

While this study showed that at an early stage of development water-use of $Edun_2$ and $Amear_2$ was similar, the mature $Amear_6$ water-use was lower than the young crops. It was concluded that commercial forest plantation, at any stage of development, have a potential to negatively impact the water yield. It would be beneficial to continue the measurements of ET of the actively growing *E. dunnii* trees at Two Streams for the full rotation. The long-term measurements of *E. dunni* trees will assist in understanding the long-term water balance and in particular the deficit in the water balance repeatedly measured in the catchment.

5.8 Acknowledgement

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5.9 References

Albaugh JM, Dye PJ, King JS. 2013. *Eucalyptus* and water use in South Africa. International Journal of Forestry Research 2013: 1–8.

Allen RG, Pereira LS, Raes D, Smith M. 1998. Crop Evapotranspiration: guidelines for Computing Crop Water Requirements. FAO Irrigation and Drainage Paper no. 56. Rome: Food and Agriculture Organization of the United Nations.

Allen RG, Pereira LS, Howell TA, Jensen ME. 2011. Evaporation information reporting: I. factors governing measurement accuracy. Agricultural Water Management 98: 899–920.

Almeida AC, Soares JV, Landsberg JJ, Rezende GD. 2007. Growth and water balance of *Eucalyptus* grandis hybrid plantations in Brazil during a rotation for pulp production. Forest Ecology and Management 251: 10-21.

Almeida AC, Siggins A, Batista TR, Beadle C, Fonseca S, Loos R. 2010. Mapping the effect of spatial and temporal variation in climate and soils on *Eucalyptus* plantation production with 3-PG, a process-based growth model. Forest Ecology and Management 259: 1730–1740.

Borin M, Milani M, Salvato M, Toscano A. 2011. Evaluation of *Phragmites australis* (*Cav*) *Trin*. Evapotranspiration in northern and southern Italy. Ecological Engineering 37: 721-728.

Breiman L. 2001. Random forests. Machine Learning 45: 15–32

Buckley TN, Turnbull TL, Pfautsch S, Gharun M, Adams MA. 2012. Differences in water use between mature and post-fire regrowth stands of subalpine *Eucalyptus delegatensis* R. Forest Ecology and Management: 270, 1–10.

Bulcock HH, Gush MB, Jewitt GPW. 2012. Field data collection and analysis of canopy and litter interception in commercial forest plantations in KwaZulu-Natal Midlands, South Africa. Hydrological Earth Systems Sciences 16: 3717-3728.

Cabral OMR, Rocha HR, Gash JHC, Ligo MAV, Freitas HC, Tatsch JD. 2010. The energy and water balance of a *Eucalyptus* plantation in southeast Brazil. Journal of Hydrology 388: 208-216.

Calder IR. 1998. Water use by forests, limits and controls. Tree physiology 18: 625-631.

Clulow AD, Everson CS, Gush MB. 2011. The long-term impact of *Acacia mearnsii* trees on evaporation, streamflow and ground water resources, WRC Report No: TT 505/11, Water Research Commission, Pretoria, South Africa (ISBN: 978-1-4312-0020-3).

Curtis RO, Marshall DD. 2000. Technical Note: Why Quadratic Mean Diameter? Western Journal of Applied Forestry 15(3): 137-139.

Delzon S, Sartore M, Burlett R, Dewar R, Loustau D. 2004. Hydraulic responses to height growth in maritime pine trees. Plant, Cell and Environment 27: 1077-1087.

Delzon S, Loustau D. 2005. Age-related decline in stand water use: sapflow and transpiration in a pine forest chronosequence. Agricultural and Forest Meteorology 129: 105-119.

DTIC (Department of Trade, Industry and Competition). 2020. Master plan for the commercial forestry sector in South Africa 2020-2025. http://Masterplan-Forestry_Sector.pdf (thedtic.gov.za) [last access 08 February 2023].

DWS (Department of Water and Sanitation). Government Gazette. Department of Water and Sanitation Notice 1027 of 2012, Report No. 39324, 2015.

Dye PJ. 1996. Response of *Eucalyptus grandis* trees to soil water deficits. Tree Physiology 16: 233-238.

Dye PJ, Poulter AG, Soko S, Maphanga D. 1997. The determination of the relationship between transpiration rate and declining available water for *Eucalyptus grandis*. WRC Report no. 441/1/97. Pretoria: Water Research Commission.

Dye PJ, Jarmain C. 2004. Water use by black wattle (*Acacia mearnsii*): implications for the link between removal of invading trees and catchment streamflow response. South African Journal of science 100: 40-44.

Everson CS, Clulow AD, Becker M, Watson A, Ngubo C, Bulcock H, Mengistu M, Lorentz S, Demlie M. 2014. The long-term impact of *Acacia mearnsii* trees on evaporation, streamflow, low flows and ground water resources. Phase II: Understanding the controlling environmental variables and soil water processes over a full crop rotation. WRC Report K5/2022

Foken T. 2008. The energy balance closure problem: An overview. Ecological Applications 18: 1351-1367.

Foken T, Mauder M, Liebethal C, Wimmer F, Beyrich F, Leps JP, Raasch S, De Bruin HAR, Meijninger WML, Bange J. 2010. Energy balance closure for the LITFASS-2003 experiment, Theoretical Applied Climatology 101: 149–160.

Forestry South Africa. 2018. Forestry statistics : 2017 https://www.forestry.co.za/uploads/File/industry_info/statistical_data/statistical/South%20African%20Forestry%20&%20Forest%20Products%20Industry%20-%202018.pdf [accessed: 21 April 2022].

Forrester DI, Collopy JJ, Moriis JD. 2010. Transpiration along an age series of *Eucalyptus globulus* plantations in southeastern Australia. Forest Ecology and Management, 259(9): 1754–1760.

Godsmark R, Oberholzer F. 2017. South African forestry and forest products industry 2017. Available at https://www.forestry.co.za/uploads/File/industry_info/statistical_data/new%20layout/South%20African%20Forestry%20&%20Forest%20Products%20Industry%20-%202017.pdf [accessed 15 June 2019].

Griffin AR, Midgley SJ, Bush D, Cunningham PJ, Rinaudo AT. 2011. Global uses of Australian Acacia-recent trends and future prospects. Biodiversity Review 17: 837-847.

Gush MB, Scott DF, Jewitt GPW, Schulze RE, Hallowes IA, Gorgens AHM. 2002. A new approach to modelling streamflow reductions resulting from commercial afforestation in South Africa. *Southern African forestry Journal* 196: 27–36.

Gush M, Dzikiti S, van der Laan M, Steyn M, Manamathela S, Pienaar H. 2019. Field quantification of the water footprint of an apple orchard, and extrapolation to watershed scale within a winter rainfall Mediterranean climate zone. Agricultural and Forestry Meteorology 271: 135-147.

Hall RL. 2002. Aerodynamic resistance of coppiced poplar. Agricultural and Forest Meteorology 114: 83-102.

Hinchee MAW, Mullinax LN, Rottmann WH. 2010. Woody biomass and purpose-grown trees as feedstocks for renewable energy. Plant Biotechnology for Sustainable Production of Energy and Co-products 66: 155-208.

Hutley LB, O'Grady APO, Eamus D. 2001. Evapotranspiration from Eucalypt open-forest savanna of Northern Australia. Functional Ecology 14: 183-194.

Iglesias G. Wilstermann D. 2009. Global cultivated eucalypt forest map 2009. Version 1.0.1. http://git-forestry-blog.blogspot.com/2008/09/eucalyptus-global-map-2008-cultivated.html [accessed 22 December 2022].

Jackson RB, Jobbagy EG, Avissar R, Roy SB, Barrett DJ, Cook CW, Farley KA, Le Maitre DC, McCarl BA, Murria BC. 2005. Trading water for carbon with biological carbon sequestration. Science 310: 1944–1947.

Kimber PC. 1974. The root system of jarrah (*Eucalyptus marginata*). Research Paper no. 10. Perth: Forests Department of Western Australia.

Kostner B, Falge E, Tenhunen JD. 2002. Age-related effects on leaf area/sapwood area relationships, canopy transpiration and carbon gain of Norway spruce stands (*Picea abies*) in the Fichtelgebirge, Germany. Tree Physiol. 22, 567–574.

Kuhn M. 2008. Building predictive models in R using the caret package. *Journal of Statistical software* 28 (5): 1-26.

Lakmali SL, Benyon RG, Sheridan GJ, Lane PNJ. 2022. Change in fire frequency drives a shift in species composition in native *Eucalyptus regnans* forests: implications for overstorey forest structure and transpiration. Ecohydrology 15: 1-17.

Lane PNJ, Morris J, Ningnan Z, Guangyi Z, Guoyi Z, Daping X. 2004. Water balance of tropical eucalypt plantations in south-eastern China Agricultural and Forest Meteorology 124: 253-267

Le Maitre DC, Verfeld DB, Chapman RA. 2000. The impact of invading alien plants on surface water resources in South Africa: a preliminary assessment. Water Research Commission 26 (3): 397-408.

Leuning R, Cleugh H, Zegelin S, Hughes D. 2005. Carbon and water fluxes over a temperate *Eucalyptus* forest and tropical wet/dry savanna in Australia. Agricultural Forest Meteorology 129: 151–173.

Liu SM, Xu ZW, Wang WZ, Jia ZZ, Zhu MJ, Bai J, Wang JM. 2011. A comparison of eddy-covariance and large aperture scintillometer measurements with respect to the energy balance closure problem. Hydrology Earth System Science 15: 1291-1306.

Lundblad M, Lindroth A. 2002. Stand transpiration and sapflow density in relation to weather, soil moisture and stand characteristics. Basic and Applied Ecology 3: 229-243.

Medhurst JL, Beadle CL. 2002. Sapwood hydraulic conductivity and leaf area-sapwood area relationship following of a thinning of a *Eucalyptus nitens* plantation. Plant, Cell and Environment 25: 1011-1019.

Michiles AAS, Gielow R. 2008. Above-ground thermal energy storage rates, trunk heat fluxes and surface energy balance in a central Amazonian rainforest, Agricultural Forest Meteorology 148: 917– 930.

Meyers TP and Baldocchi DD. 2005. Current Micrometeorological Flux Methodologies with Applications in Agriculture, in: Micrometeorology in Agricultural Systems, edited by: Hatfield, J. L. and Baker, J. M., Agronomy Monograph no. 47, American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America, 381–396.

Midgley SJE, Lotze E. 2011. Climate change in the Western Cape of South Africa: trends, projections and implications for chill unit accumulation. Acta Horticulturae 903: 1127–1134.

Moore CJ, Fishc G. 1986. Estimating heat-storage in Amazonian tropical forest. Agricultural Forest Meteorology 38 (1-3): 147-168.

Muneri A. 1997. Kraft pulping properties of *Acacia mearnsii* and *Eucalyptus grandis* grown in Zimbabwe. Southern African Forestry Journal 179: 13-19.

Oliphant AJ, Grimmond CSB, Zutter HN, Schmid HP, Su HB, Scott SL, Offerle B, Randolph JC, Ehman J. 2004. Heat storage and energy balance fluxes for the temperate deciduous forest. Agricultural and Forest Meteorology 126: 185-201.

Oren R, Pataki D. 2001. Transpiration in response to variation in microclimate and soil moisture in southeastern deciduous forests. Oecologia 127: 549-559.

Ouyang L, Zhao P, Zhou G, Zhu L, Huang Y, Zhao X, Ni G. 2017. Stand-scale transpiration of a *Eucalyptus urophylla* x *Eucalyptus grandis* plantation and its potential hydrological implication. *Ecohydrology* 11: 1-10.

Pereira LS, Paredes P, Hunsaker DJ, Urrea RL, Shad ZM. 2021. Standard single and basal crop coefficients for field crops. Updates and advances to the FAO 56 crop water requirements method. Agricultural Water Management 243: 106466.

R Development Core Team. 2008. R: a language and environment for statistical computing. Vienna: R Foundation for Statistical Computing. Available at http://www.R-project.org [accessed 21 January 2023].

Reynolds JM. 2022. Community narratives and local impacts of invasion in the Eastern Cape: A critical invasion ethnography of black wattle. Nature and Space 5: 1639-1653.

Sands R, Mulligan DR. 1990. Water and nutrient dynamics and tree growth. Forest Ecology and Management 30: 91–111.

Savage MJ, Everson CS, Metelerkamp BR. 1997. Evaporation measurement above vegetated surfaces using micrometeorological techniques, Water Research Commission Report No. 349/1/97, Water Research Commission, Pretoria, South Africa, 248 pp.

Savage MJ, Everson CS, Odhiambo GO, Mengistu MG and Jarmain C. 2004. Theory and of practice of evaporation measurement, with a special focus on SLS as an operational tool for the estimation of spatially-averaged evaporation, Water Research Commission Report No. 1335/1/04, Pretoria, South Africa, 204 pp.

Scott DF, Lesch W. 1997. Streamflow responses to afforestation with *Eucalyptus grandis* and *Pinus patula* and to felling in the Mokobulaan experimental catchments, South Africa. *Journal of Hydrology* 199, 360–377.

Scott DF, Prinsloo FW. 2008. Longer-term effects of pine and eucalypt plantations on streamflow. Water Resources Research 44: W00A08.

Schulze RE, Lynch SD. 2007. Monthly rainfall and its inter-annual variability. In: Schulze RE (ed.), South African atlas of climatology and agrohydrology, WRC Report no. 1489/1/06. Pretoria: Water Research Commission.

Silberstein R, Held A, Hatton T, Viney N, Sivapalan M. 2001. Energy balance of a natural jarrah (*Eucalyptus marginata*) forest in Western Australia: Measurements during the spring and summer. Agricultural and Forest Meteorology109: 79–104.

Skubel R, Arain MA, Peichl, Brodeur JJ. 2015. Age effects on the water-use efficiency and water-use dynamics of temperate pine plantation forests. Hydrological Processes 29: 4100-4113.

Soares JV, Almeida AC. 2001. Modelling the water balance and soil water fluxes in a fast-growing Eucalyptus plantation in Brazil. Journal of Hydrology 253: 130–147.

Thom AS. 1975. Momentum, mass and heat exchange in plant communities, in: Vegetation and the Atmosphere, vol. 1, Principals, edited by: Monteith JL, Academy Press, London, 57–109.

Twine TE, Kustas WP, Norman JM, Cook DR, Houser PR, Meyers TP, Prueger JH, Starks PJ, Wesely ML. 2000. Correcting eddy-covariance flux underestimates over grassland. Agricultural and Forest Meteorology 103: 279-300.

Vanclay JK. 2009. Managing water use from forest plantations. Forest Ecology and Management 257: 385-389.

Wilson KB, Hanson PJ, Mulholland PJ, Baldocchi DD, Wullschleger SD. 2001. A comparison of methods for determining forest evapotranspiration and its components: sap-flow, soil water budget, eddy covariance and catchment water balance. Agricultural Forest Meteorology 106, 153–168.

WMO. 2008. Guide to Meteorological Instruments and Methods of Observation, WMO-No. 8, 7th Edn., Geneva.

White DA, McGrath JF, Ryan MG, Battaglia M, Mendham DS, Kinal J., Downes GM, Crombie DS, Hunt M E. 2014. Managing for water-use efficient wood production in *Eucalypts globulus* plantations. Forest Ecology and Management 331: 272–280

White DA, Silberstein RP, Contreras FB, Quiroga JJ, Meason DF, Palma JHN, de Arellano PR. 2021. Growth, water use, and water use efficiency of *Eucalyptus globulus* and *Pinus radiata* plantations compared with natural stands of Roble-Hualo forest in the coastal mountains of central Chile. Forest Ecology and Management 501: 119675-119676.

Xue J, Gavin K. 2008. Effect of rainfall intensity on infiltration into partly saturated slopes. Geotechnical and Geological engineering 26: 199–209.

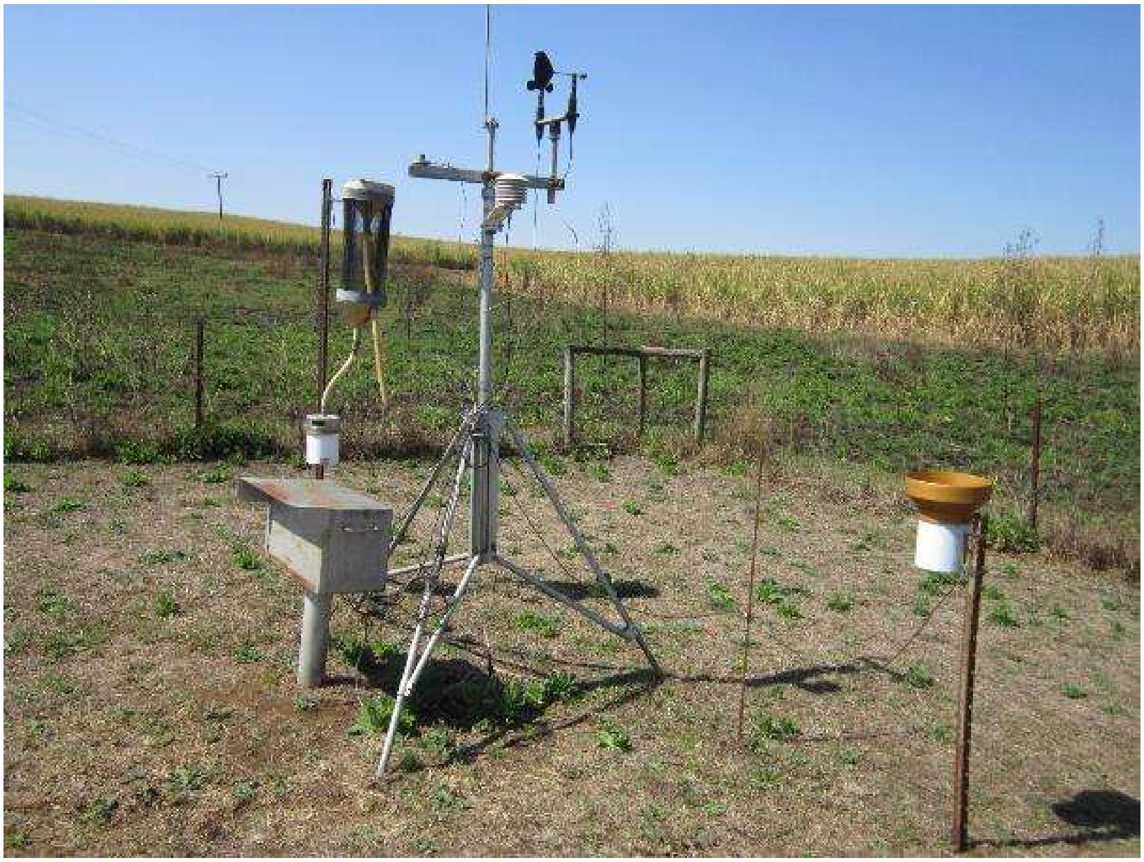
Zeppel MJB, Murray BR, Barton C, Eamus D. 2004. Seasonal responses of xylem sap velocity to VPD and solar radiation during drought in a stand of native trees in temperate Australia. Functional Plant Biology 31 (5): 461-470.

Zhang R, Huang, Wang X, Zhang JA, Huang F. 2016. Effects of precipitation on sonic anemometer measurements of turbulent fluxes in the atmospheric surface layer. Journal of Ocean University of China 15: 389-398.

Zweifel R, Zimmermann L, Newbery DM. 2005. Modelling tree water deficit from microclimate: an approach to quantifying drought stress. Tree Physiology 25: 147-156.

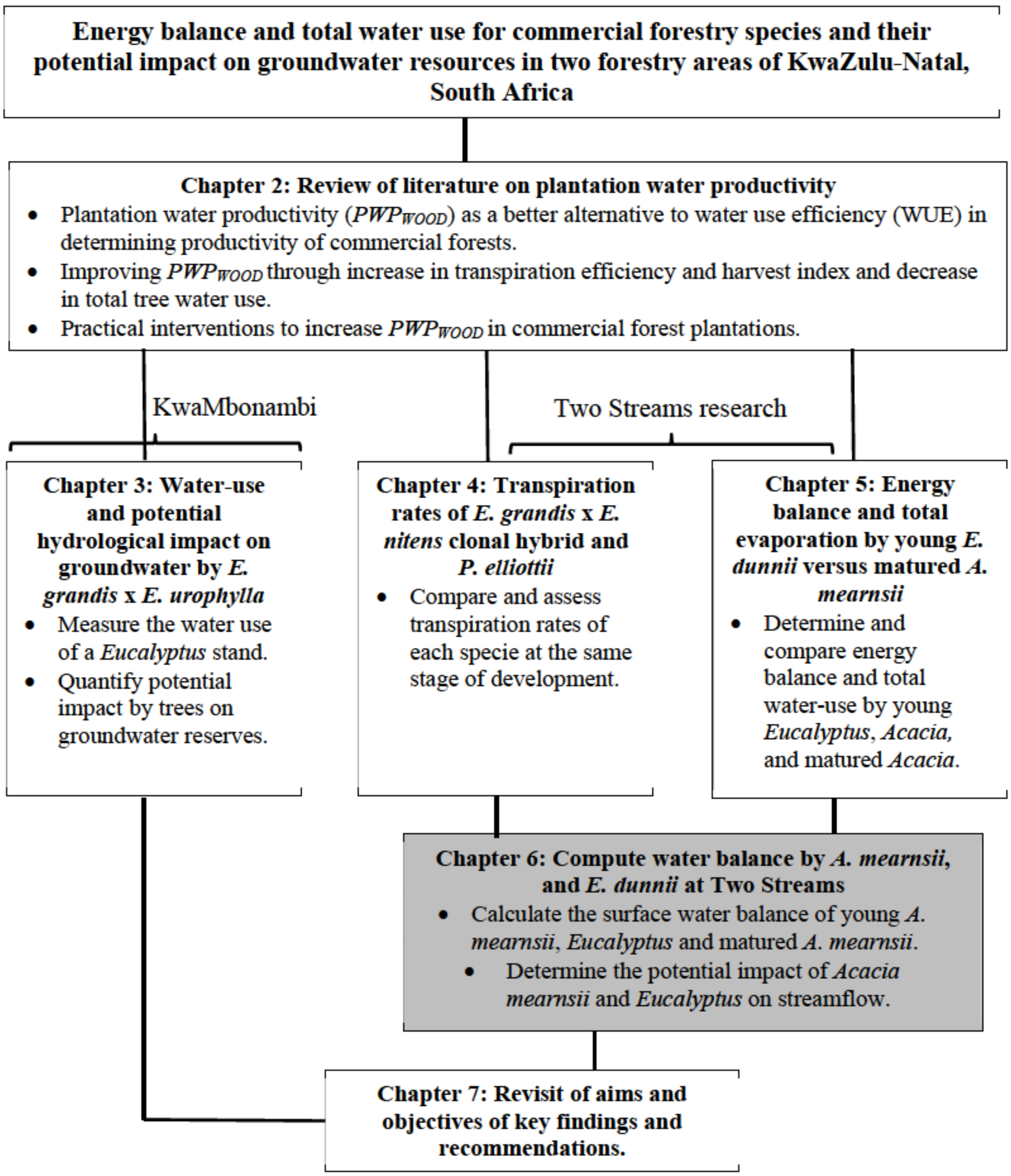
5.10 Supplementary information

Supplementary Figure 5.1: A 24 m lattice mast that was setup within the study site to provide anchor to sensors, while the inset is the sonic anemometer that was used to measure eddies.



5002 **Supplementary Figure 5.2: An automatic weather station adjacent to the study site used**
5003 **to measure weather variables.**

Lead into Chapter 6: The findings from chapter 3, 4 and 5 have demonstrated that forest plantations have high transpiration and evapotranspiration rates with potential negative impacts on the streamflow. Consequently, reduction in streamflow will impact downstream water users negatively. Therefore, chapter 6 aimed to experimentally quantify the surface water balance of the Two Streams research catchment and test the impact, or lack of, young *E. dunnii* and *A. mearnsii* on the streamflow.



CHAPTER 6: THE INFLUENCE OF DIFFERENT TREE SPECIES AND AGE ON THE SURFACE WATER BALANCE OF A SMALL COMMERCIAL FORESTRY CATCHMENT

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6.1 Abstract

Acacia mearnsii and *Eucalyptus dunnii* plantations play an important role in the South African economy as a source for a variety of wood products. However, these species are commonly associated with high total water use due to their deep rooting ability, which may have a negative impact on the streamflow (Q), and hence water availability for other water users. The potential future increase in exotic plantations in South Africa, due to the demand for forest products, necessitates understanding the impact of these different species on the water balance and therefore quantifying their potential impact on the streamflow. The Two Streams research catchment is one of the few catchments in South Africa where intense hydrological observations (streamflow, total evaporation and weather) have been conducted on *A. mearnsii* for almost two decades (1999 to 2018). In 2018, the catchment was clear-felled with subsequent replanting of *E. dunnii* and hydrological measurements continued. This provided an opportunity to present observations of the surface water balance of the catchment. However, gaps in components of the water balance at various times prevented a compilation of a continuous hydrological record. Therefore, three window periods, with complete records of streamflow, total evaporation and precipitation, and with similar weather conditions, were compared to understand the different hydrological conditions resulting from changes in tree age and species. Only the interception loss was estimated using the Von Hoyningen-Huene method. During the first window period, the catchment was afforested with three-year-old *A. mearnsii* (*Amear*$_3$). During the second window period, the *A. meanrsii* (*Amear*$_7$) were seven years old and during the third window period, the catchment had been afforested with three-year-old *E. dunnii* (*Edun*$_3$). This provided water use, of *A. mearnsii* at two different ages, and between two different species (*A. mearnsii* and *E. dunnii*) of the same age, on the same site, and during similar weather conditions. Results indicated a negative catchment surface water balance for all three window periods, with a slightly greater margin for the *Edun*$_3$ followed by *Amear*$_7$ and lastly *Amear*$_3$. During the *Amear*$_7$ crop window period, the interception loss was highest compared to the young crops, which reduced effective precipitation, in turn contributing to the lowest streamflow measured over the window periods. The negative surface water balance and high total evaporation, suggests that trees were accessing water external to the catchment, possibly from water stored deep in the soil profile from previous wet years. Crops of all three window periods were found to have the potential to significantly impact the streamflow through high total evaporation and rainfall interception. This will, over time, reduce the water available for recharging groundwater. The approach of comparing window periods of different species and different ages at the same site and for similar weather conditions was useful where records were incomplete, but at an annual cycle do not accommodate lags that may exceed these window periods. Further research using isotopes to trace the sources of water used by the trees to understand lags in the system is suggested.

Keywords: Acacia mearnsii, Eucalyptus dunnii, Streamflow, Total evaporation.

6.2 Introduction

Exotic forest plantations play an important role in the South African economy through a contribution of R14 billion in foreign revenue, R1.5 billion in taxes for the fiscus per annum

(Thiel et al. 2019). In addition, forest plantations contribute to the socio-economy through employment (1.35%) and agricultural GDP (11%), and if well managed, can improve soil infiltration rates (van Dijk and Keenan 2007), significantly reduce soil erosion due to forest litter at the soil surface, minimise soil evaporation (Wichert et al. 2018) and mitigate air pollution and climate change (Ferreto et al. 2021).

There has been an expansion in the bioeconomy markets for dissolving wood pulp products such as short fine fibre and *Eucalyptus* are the preferred species by this market due to superior fibre and pulping properties (Dougherty and Wright, 2012). *Acacia mearnsii* is an equally important plantation species in South Africa, mainly grown for bark tannin and wood chips exported to Brazil (Griffin et al., 2011). The current area planted to *A. meansii* in South Africa amounts to 110 000 ha (6.8 % of total commercial forestry) of which the high wood density and pulp yield offers an economic advantage for pulp production and long-distance transport capability (Muneri, 1997). Despite the crucial role played by *Eucalyptus* and *A. mearnsii* species, research in different parts of the world (including South Africa) have indicated that evapotranspiration by both species is significantly higher than indigenous forest stands and grasslands (Dye et al. 2001; Dye and Jarmain 2004; Albaugh et al. 2013; Almeida et al. 2016, Reichert et al. 2017), which may negatively impact water resources availability (Farley et al 2005, Jackson et al. 2005). In addition, commercial forest plantations, especially the genetically improved *Eucalyptus* hybrids have a deep taproot (Dye 1996), providing the capability to access groundwater reserves during the dry season (van Dijk and Keenan 2007). This usually results in perennial streamflow reduction and lowering of the groundwater table (Scott and Prinsloo 2008, Lu et al. 2018). Scott and Lesch (1997) reported that afforestation of the entire catchment with *Eucalyptus* and pines significantly reduced the streamflow (Q) after three and four years of planting, respectively. A complete cessation of Q was observed at year nine for *Eucalyptus,* and year twelve for pines, with full perennial Q returning five years after clear-felling.

The Two Streams research catchment (in Mistley Canema, KwaZulu-Natal) is one of the few catchments in South Africa where detailed hydrological observations have been conducted (Dye and Jarmain 2004, Clulow et al. 2011, Everson et al. 2014) on *A. mearnsii* for extended periods. These results indicated that *A. mearnsii* total evaporation (ET) exceeded precipitation in the first 6 years of growth by as much as 46%, and there was sufficient evidence suggesting that trees can access deep underground water reserves using their deep taproots. In February 2018, after a 12-year rotation, the *A. mearnsii* trees were harvested and *E. dunnii* was planted in March 2018. The hydrological measurements resumed in September 2019. This presented a unique opportunity to quantify the catchment surface water balance for *A. mearnsii* (at two different stages of growth) and *E. dunnii* (in the early stages of growth) in the same study site and catchment. However, the various components of the water balance were incomplete at various times, due to research funding constraints at times as well as various equipment failures, and compiling a continuous surface water balance record was not possible. Therefore, annual measurement window periods were identified in the dataset when, 1) measurement records were complete, and 2) climatic conditions were representative of the long-term mean of Mistley Canema. The aim of this study was therefore to compare the surface water-balance for young *A. mearnsii* (~three years old), matured *A. meanrsii* (~seven years old) and young *E. dunnii* (~three years old). Since the hydrological data for measurement windows were conducted on the same study site and for similar climatic conditions, the differences in the water-balance are attributed mainly to changes in the landcover providing a unique comparison of the surface water balance for trees of different ages and species at the same site.

6.3 Material and methods

6.3.1 Description of the study site

The catchment location is at Mistley Canema (29°12'19.78°S, 30°39'3.78°E) in the Seven Oaks area, northeast of Pietermaritzburg in the KwaZulu-Natal province of South Africa (Figure 6.1). The catchment is in a part of the midlands mist-belt grassland Bioregion, mostly dominated by forb-rich, tall, sour *Thermeda triandra* of which few patches remain due to *Aristida junciformis* invasion (Everson et al. 2014). The catchment size is approximately one km^2 with hilly topography and rolling landscapes that dips towards the southeast, resulting in the northwest to southeast surface drainage. Climatically, the catchment experiences rainy, hot and humid summers, whereas winter season is dry and cold as detailed in Table 6.1. *Acacia mearnsii* trees were planted in March 2006 (for a full rotation of 12 years) with hydrological monitoring including streamflow gauging (Q), total evaporation (ET), soil water content (SWC) and groundwater reserves conducted by Clulow et al (2011) and Everson et al (2014). In February 2018, the *A. mearnsii* trees were harvested. The catchment was subsequently planted to *E. dunnii* in March 2018. Hydrological processes measurements (Q, ET, SWC and depth to groundwater) resumed in September of 2019. A study by Clulow et al. (2011) and Everson et al. (2014) classified the soil profile in the catchment to be as deep as 13 m (Table 6.2) and below consists of a weathered bedrock (saprolite) and fractured basement rock under the soil

profile. The soil form was classified as Hutton (Soil Classification Working Group 1991). Both the *A. mearnsii* and *E. dunnii* crops were planted at a spacing of 2 x 3 m (1667 trees ha^{-1}).
Three hydrological years (measurement windows) with complete dataset of hydrological measurements including Q, ET, SWC and depth to groundwater were identified for comparison. They were considered suitable as their annual precipitation and general climate was statistically similar over the window periods. The trees were between 2.7 and 3.7 years old in the first measurement period (October 2008 to September 2009, referred to as $Amear_3$). They were 6.7 to 7.7 years old (October 2012 to September 2013, referred to as $Amear_7$) in the second measurement period. After replanting *E. dunnii* trees in March 2018 a final measurement window from the age of 2.6 to 3.6 years old (October 2020 to September 2021, referred to as $Edun_3$) was compared.

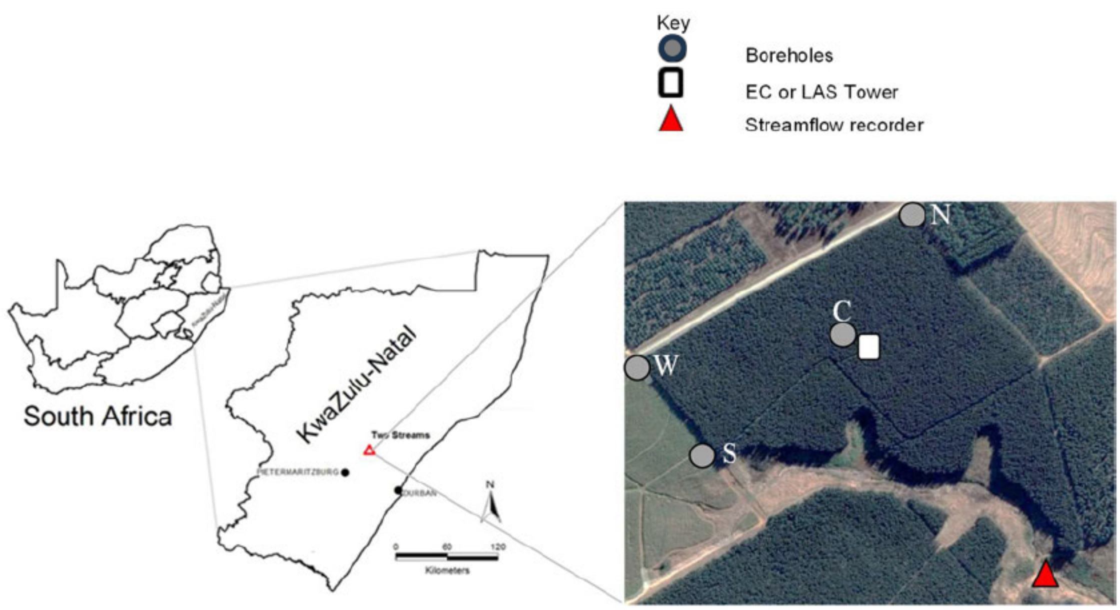

Figure 6.1: Location of the study area at Two Streams Research Catchment. The Google Earth extract (extreme right) provides aerial view of the catchment with location of measurements points.

Table 6.1: The general characteristics of the Two Streams Research catchment (South African taxonomic system).

Characteristics	Our study site
Minimum MAT (ºC)	4.5
Maximum MAT (ºC)	31.7
MAP (mm)	778
Climate	Warm subtropical
Altitude (meters above sea level)	1060 – 1110
Soil bulk density (g. cm^3)	1.25
Soil texture	Sandy clay
Lithology	Shale

[a]Soil Classification Working group (1991)

Table 6.2: A description of soil characteristics of the Two Streams research catchment (sourced from Everson et al. 2014).

Horizons	Approximate depth (m)
Orthic A	0 – 0.25 m
Red apedal B	0.26 – 13 m
Saprolite	14 – 20 m
Grey fine-grained shale	21 – 40 m
Grey fractured basement granite	41 – 80 m

6.3.2 Climatic conditions

An automatic weather station was installed on a flat uniform grassland area adjacent to the study site to provide supporting meteorological measurements. Measurements of air temperature (Tair) (HMP 60, Vaisala Inc., Helsinki, Finland), relative humidity (RH) (HMP60, Vaisala Inc., Helsinki, Finland), wind speed (WS) and direction (Model 03003, R.M. Young, Traverse City, Michigan, USA), solar radiation (Is) (Kipp and Zonen CMP3) and gross precipitation (TE525, Texas Electronics Inc., Dallas, Tx, USA) were conducted every 10 s. The sensors were installed according to recommendations of the World Meteorological Organisation (WMO, 2008) with rain gauge orifice at 1.2 m and the remaining sensors at 2 m above the ground surface. The sensor outputs were recorded on a CR1000 datalogger (Campbell Scientific Inc., Logan, Utah, USA) at 30 min intervals. The datalogger was programmed to calculate the vapour pressure deficit (VPD) using Tair and RH measurements according to Savage et al. (1997). The reference evaporation (ETo) was calculated using the technique described in Allen et al (2011).

The monthly effective precipitation (P_{eff}) was calculated using:

$$P_{eff} = P_g - I_l \tag{6.1}$$

where P_g is the gross precipitation (mm) and I_l is the plant canopy interception loss (mm). The negative P_{eff} values were rounded off to 0 mm.

6.3.3 Streamflow measurements

The Q was measured from a 457.2 mm 90° V-notch using a CS450 pressure transducer (Campbell Scientific Inc., Logan, Utah, USA) with data recorded in a CR200X datalogger (Campbell Scientific) for all three measurement periods. The CS450 pressure inducer sensor consists of a piezoresistive sensor housed in a water resistance stainless steel package to enhance reliability (Campbell Scientific 2010). The sensor provides accurate measurements of water pressure and level that are fully temperature compensated. The water level measurements from the CS450 sensor were calibrated by directly measuring the water level from the V-notch using a measuring tape.

6.3.4 Evapotranspiration

All data for the first two window periods were sourced from the Centre for Water Resources Research (CWRR) at the University of KwaZulu-Natal in Pietermaritzburg (details of measurement techniques and equipment used can be found in Clulow et al (2011) and Everson et al (2014)). For *Edun₃*, the ET was measured using an eddy covariance system (EC) to derive sensible heat flux (H), using a three-dimensional sonic anemometer (CSAT3, Campbell Scientific Inc., Logan, Utah, USA) and measurements of net radiation (Rn) and ground heat flux (G) were conducted simultaneously on the study site. The Rn was measured using a net radiometer (NRLite, Kipp and Zonen, Delft, Netherlands) attached to the lattice mast on a horizontal boom 2.5 m away from the lattice mast at a height of 18.5 m. The sonic anemometer was mounted on the lattice mast at a height of 18 m. The G was measured using two HFP01-L soil heat flux plates and parallel TCAV-L averaging thermocouples (Campbell Scientific Inc., Logan, Utah, USA). The soil heat flux plates and thermocouples were buried in the middle of the compartment (approximately 2 m away from the EC system) at a depth of 0.08 m and 0.02 m below the soil surface, respectively, to estimate the heat stored in the soil.

The EC is a technique based on estimation of eddy fluxes. The H used in estimation is expressed as:

$$H = \overline{\rho_a} c_p \overline{w'Tair'} \qquad (6.2)$$

Where, ρ_a is the density of dry air (kg m^{-3}), c_p is the specific heat capacity for air at constant pressure (J kg^{-1} K^{-1}), w' is the vertical wind speed (m s^{-1}) and Tair is the air temperature (°C). The w' and Tair are measured using the sonic anemometer and the primes denote fluctuation from a temporal average and the overbar represents a time average. The averaging period of the instantaneous fluctuations of w' and Tair should be long enough (30 to 60 min) to capture all the eddies that contribute to the flux and fulfil the assumption of stationarity (Meyers and Baldocchi 2005). The zero plain displacement and roughness layer were determined to be at 12.0 m and 24.0 m, respectively. Therefore, the sonic anemometer height was 18 m above tree canopy. The energy balance (LE) was calculated as a residual term using the simplified energy balance equation:

$$Rn = G + H + LE \qquad (6.3)$$

where, Rn is the net irradiance, H is the sensible heat flux, LE is the latent heat flux (equivalent to ET by conversion, Savage et al. (2004)) and G is the ground heat flux. The EC data was processed using the Eddy Pro® 7 software (Licor Inc., Lincoln, Nebraska, USA) for spikes in the data, sonic temperature corrections, co-ordinate rotation and planar fit. In addition to these processing steps, the 30-min flux data were screened using the following criteria 1) data obtained when the sensor malfunctions were removed from the analysed dataset 2) data on rainy days were excluded due to the negative impact of precipitation on turbulent fluxes as reported by Zhang et al. (2016) 3) incomplete 30-min data were removed, when the missing ratio was greater than 5% in the 30-min raw data 4) night-time data ($R_n < 0$) was removed from the analysis due to potentially large nocturnal influences at night-time (Blanken et al. 1998; Wilson et al. 2001).

6.3.5 The leaf area index

The leaf area index (LAI) measurements were conducted monthly on *Amear₃*, *Amear₇* and *Edun₃* measurement periods using a LAI-2200 Plant Canopy Analyzer (Licor Inc., Lincoln, Nebraska, USA). Measurements were conducted on a transect that was identified in the middle of the study site for each measurement window to avoid the impact of edge effect on LAI measurements (Woodgate et al. 2015). The transect was 250 m in length and measurements were conducted every 5 m, producing a total 50 LAI measurements, which were thereafter averaged to a single LAI measurement per month.

6.3.6 Precipitation and interception loss

The Von Hoyningen-Huene approach was designed for calculating precipitation interception loss (I_l) in agricultural crops, however, Schulze (1995) found that the approach performed very well in estimating I_l in commercial forest plantations (*P. patula*). The I_l in this study was calculated using the Von Hoyningen-Huene equation (Von Hoyningen-Huene 1983):

$$I_l = 0.30 + 0.27P_g + 0.13LAI - 0.013P_gLAI - 0.007LAI^2 \quad (6.4)$$

where, P_g is the gross precipitation (mm) measured using the automatic raingauge and the LAI is the leaf area index. The Von Hoyningen-Huene equation has been found to be only stable for P_g daily precipitation amounts of less than 18 mm, above which it is assumed that no I_l occurs (Schulze 1995). In this study, I_l was calculated monthly using Von Hoyningen-Huene equation and monthly values were summed up to annual total I_l for each measurement period.

6.3.7 Surface water balance

The monthly catchment surface water balance for *Amear₃*, *Amear₇* and *Edun₃* was calculated based on P_g precipitation, ET, I_l and Q using:

$$\pm\Delta S = water\ inflow - water\ outflow \quad (6.5)$$

where, $\pm\Delta S$ is the change in the catchment water storage, $water\ inflow$ is water recharging the catchment and $water\ outflow$ is the total water loss from the catchment. Equation 6.5 was further expressed using the measured variables in the surface water balance as follows:

$$\pm\Delta S\ water\ storage = P_g - ET - I_l - Q \quad (6.6)$$

where, P_g is gross precipitation (mm, *water inflow*), ET is the total measured evaporation (mm, water outflow), I_l is the interception loss (mm, water outflow) and Q is the total direct runoff (mm, water outflow). A positive value in ΔS indicates an increase in water availability to the soil and groundwater store, whereas a negative value indicates a loss in the soil and groundwater storage.

6.3.8 Statistical analysis

The statistical analysis was performed using the R statistical computing software (R Development Core team 2008). An analysis of variance (ANOVA) was used to assess the differences in hydrological parameters (Q, ET, I_l and climatic variables) between $Amear_3$, $Amear_7$ and $Edun_3$. Variables were transformed as appropriate to meet the assumption of normality. Where the overall F-statistic was significant ($p < 0.05$), treatment means were compared using Fischer's Least Significant Difference at the 5% level of significance ($LSD_{5\%}$).

6.4 Results

6.4.1 Weather conditions

The weather for three measurement periods reflected typical warm temperate climatic conditions with warm wet summers and cool dry winters (Figure 6.2). The daily *Is* over all window periods was lowest in June (mean range: 3.1–11.7 MJ m^{-2} day^{-1}) but more consistent, whereas December and January experienced higher and more variable *Is* (reaching a peak of 30 MJ m^{-2} day^{-1}). These conditions were consistent with clear winter days and a wetter summer season with thunderstorms at times. The maximum Tair (range: 34.1 to 38.2 °C) was measured in January for all measurements periods, while the lowest measured Tair was between 0 and -1 °C in June. The total measured gross annual precipitation in 2008/09, 2012/13 and 2020/21 was 819 mm, 862 mm and 844 mm, respectively, which mostly (70%) occurred during summer from September to April of each measurement period. The VPD was low in the summer season and increased during the winter season (Figure 6.2) with a mean of 0.59 kPa for $Amear_3$, 0.62 kPa for $Amear_7$ and 0.72 kPa for $Edun_3$. The $Edun_3$ period had 15% greater annual ETo (1060 mm) compared to $Amear_3$ (903 mm) and $Amear_7$ (907 mm). The lowest daytime RH measured occurred during berg wind conditions in September (31.8%), December (27.5%) and October (21%) for $Amear_3$, $Amear_7$ and $Edun_3$, respectively. The average wind speeds were notably high in July for $Edun_3$ (maximum 37 m s^{-1}) and in October for $Amear_3$ and $Amear_7$ (maximum 32 m s^{-1}).

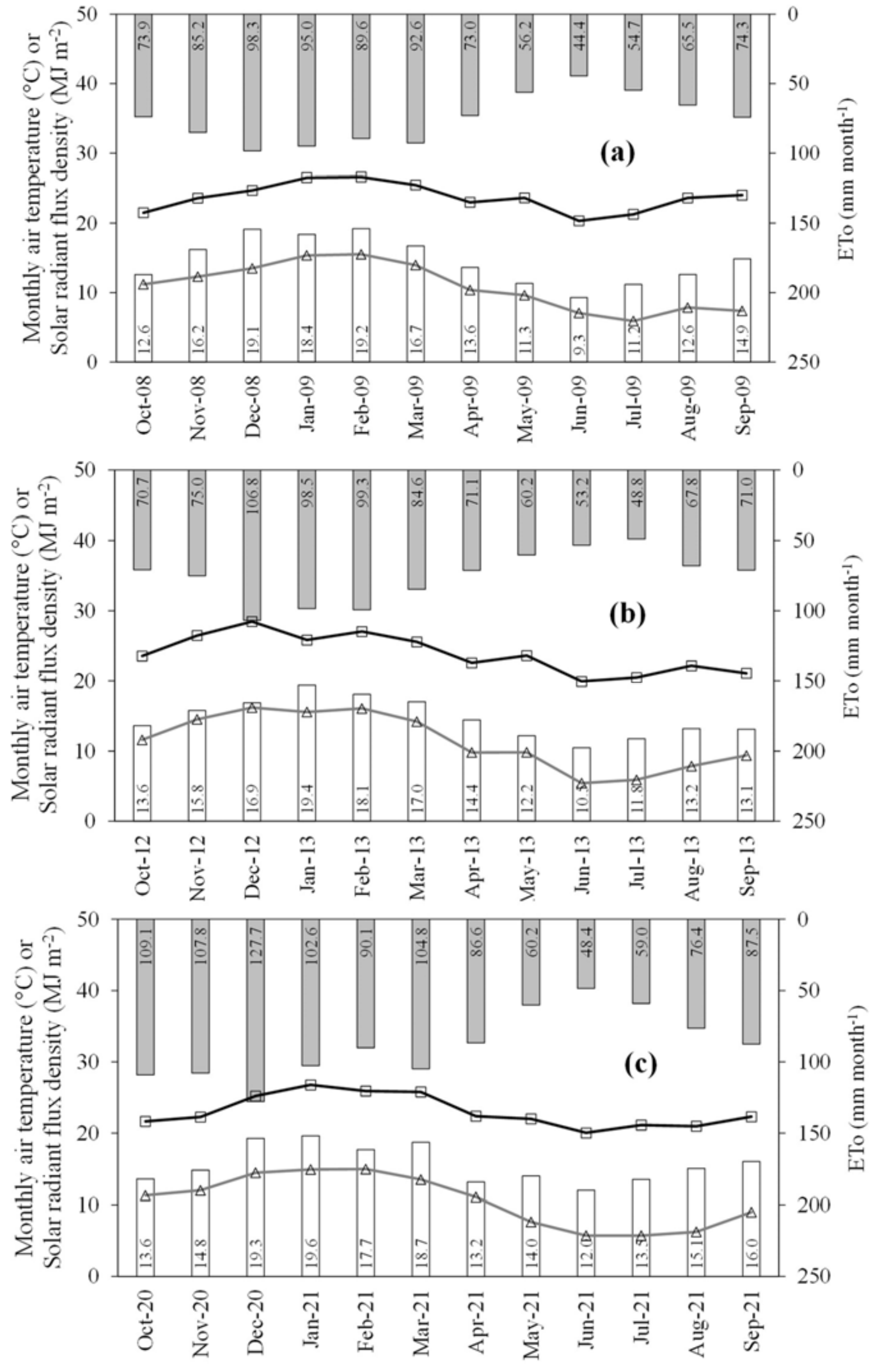

Figure 6.2: Monthly values of mean daily radiant flux density (MJ m^{-2}), maximum (T-Max) and minimum (T-Min) air temperatures (°C) and corresponding monthly reference evaporation (ETo, mm month-1) measured at Two Streams Research Catchment in (a) 2008/ 09 (*Amear$_3$*), (b) 2012/ 13 (*Amear$_7$*) and (c) 2020/ 21 (*Edun$_3$*) hydrological years.

6.4.2 Effective precipitation and interception loss

The monthly effective rainfall for all measurement windows was generally higher during the wet season (October to February), ranging from 57 to 90% for $Amear_3$, 65 to 88% for $Amear_7$ and 52 to 90% for $Edun_3$ of gross precipitation (Table 6.3). During the dry season (May to August), the monthly effective rainfall was low, reaching the lowest value of zero in $Amear_3$ and $Edun_3$ (May and June) while zero effective rainfall values were measured in July in $Amear_7$. The total annual effective rainfall was calculated to be 650 mm for $Amear_3$, 617 mm for $Amear_7$ and 649 mm for $Edun_3$ with no statistical differences ($p > 0.05$).

Precipitation interception losses depended on gross precipitation and the LAI of the specific crop. The $Edun_3$ was found to have the highest LAI reaching a maximum of 4.11, compared to a peak LAI of 2.45 and 3.34 for $Amear_3$ and $Amearn_7$, respectively. The summer monthly I_l ranged from 19.6–29.9 mm, 17.8–44.3 mm and 14.8–33.1 mm for $Amear_3$, $Amearn_7$ and $Edun_3$ of monthly gross precipitation, respectively. The annual I_l was highest for the $Amearn_7$ (225 mm, 19.8% of annual precipitation), followed by $Edun_3$ (195.2 mm, 25% of annual precipitation) and finally $Amear_3$ (169.1 mm, 22% of annual precipitation), with the $Amearn_7$ crop statistically ($p < 0.05$) greater than the $Amear_3$ and statistically similar ($p > 0.05$) to $Edun_3$. The I_l was obviously influenced by the LAI but also by the quantity of gross precipitation received per event. For example, gross precipitation events of less than 3 mm, resulted in almost 100% interception, while high gross precipitation events (> 10 mm) resulted to less interception loss (Figure 6.3). The I_l comparison between measurement windows indicated that $Amearn_7$ crop I_l was 25% and 13.2% greater than $Amear_3$ and $Edun_3$, respectively, which, was as a result of a combination of higher LAI and precipitation event characteristics.

Table 6.3: The monthly gross precipitation (P_g, mm), effective precipitation (P_{eff}, mm) and a ratio of P_g to P_{eff} expressed as a percentage for the Two Streams research catchment in 2008/ 09 (*Amear₃*), 2012/ 13 (*Amear₇*) and 2020/ 21 (*Edun₃*) hydrological years.

2008/ 09 (*$Amear_3$*)												
	Oct	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**
P_g (mm)	151	121	68	130	70	95	75	3	21	2	7	79
P_{eff} (mm)	131	98	39	100	42	85	67	0	19	0	1	67
P_{eff} / P_g x 100 (%)	**87**	**81**	**57**	**77**	**61**	**90**	**90**	**6**	**92**	**12**	**11**	**85**
2012/ 13 (*$Amear_7$*)												
	Oct	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**
P_g (mm)	150	143	148	150	71	59	35	33	15	6	22	32
P_{eff} (mm)	124	98	120	132	46	40	24	28	6	0	12	6
P_{eff} / P_g x 100 (%)	**83**	**69**	**82**	**88**	**65**	**68**	**70**	**85**	**41**	**5**	**53**	**20**
2020/ 21 ($Edun_3$)												
P_g (mm)	35	151	160	134	122	81	85	2	37	2	7	27
P_{eff} (mm)	18	136	136	105	89	59	68	0	24	0	1	11
P_{eff} / P_g x 100 (%)	**52**	**90**	**85**	**79**	**73**	**73**	**80**	**10**	**65**	**8**	**19**	**39**

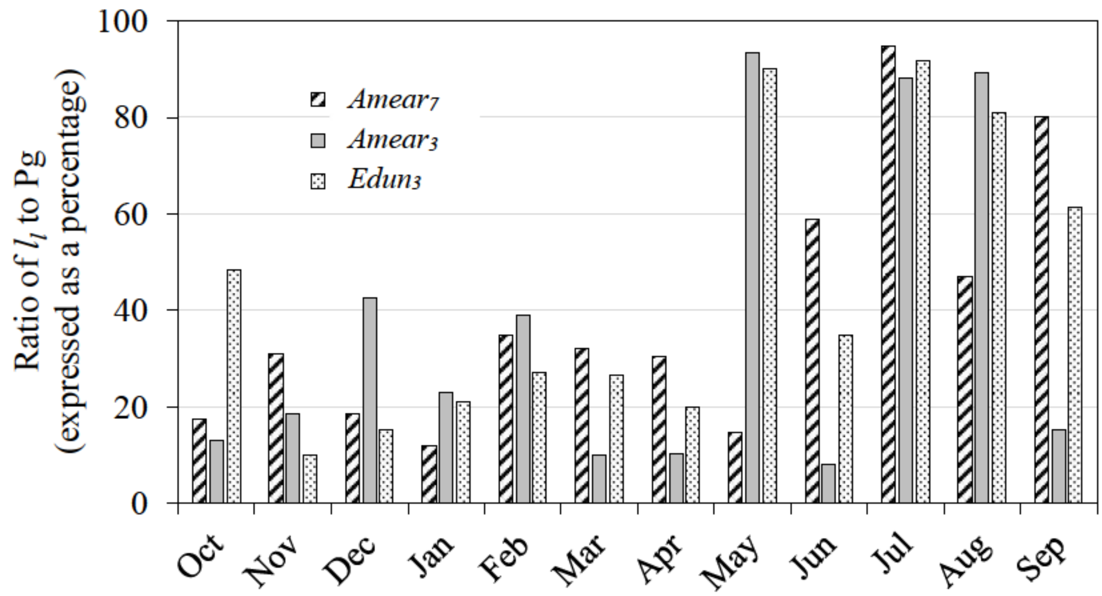

Figure 6.3: The ratio of canopy interception loss (I_l, mm) to gross precipitation (P_g, mm) expressed as a percentage for (a) 2008/ 09 (*$Amear_3$*), 2012/ 13 (*$Amear_7$*) and 2020/ 21 (*$Edun_3$*) hydrological years.

6.4.3 Streamflow

The Q for all measurement periods was seasonal (Figure 6.4) and did not respond significantly to effective precipitation events of less than 10 mm, 16.9 mm and 12.2 mm for *$Amear_3$*, *$Amear_7$* and *$Edun_3$* cropping periods, respectively, except after consecutive effective precipitation events where antecedent conditions played a role.

During summer, (November to February) Q was generally high, reaching peaks of 18.3, 8.2 and 12.2 mm month^{-1} for *$Amear_3$*, *$Amear_7$* and *$Edun_3$* cropping windows, respectively. The summer water yield (expressed as a ratio of total annual streamflow to total annual effective precipitation, Q/Peff*100) for *$Amear_7$* (mean water yield: 4.4%) was found to be statistically lower ($p < 0.05$) than both the young crops (mean water yield: *$Amear_3$* = 9.26% and *$Edun_3$* = 7.9%), which were statistically similar ($p > 0.05$) to each other. These results suggested that when the catchment was afforested with young trees (*$Amear_3$* and *$Edun_3$*), more effective precipitation was converted to runoff, than when the catchment was planted to matured trees (Figure 6.5a and 6.5b), which was evident in annual effective rainfall for *$Amear_7$* (617 mm) which was lower ($p > 0.05$) than both *$Amear_3$* (650 mm) and *$Edun_3$* (649 mm). During the dry season (May to August), the Q was low at 2.1 mm month^{-1} for *$Amear_3$*, 2.2 mm month^{-1} for *$Amear_7$* and 1.8 mm month^{-1} for *$Edun_3$*. The water yield was high in the dry season compared to the wet season, reaching a peak of 105% for $Amear_3$, 98% for $Edun_3$ and 44% for $Amear_7$, which was caused by low effective precipitation in the dry season (Figure 6.5b). The total annual Q for $Amear_3$ (65.9 mm) and $Edun_3$ (59.8 mm) was statistically similar ($p = 0.30$), while $Amear_7$ (44.7 mm) was significantly ($p < 0.05$) lower than both the $Amear_3$ and $Edun_3$ crops.

The differences in seasonal patterns are best illustrated using the accumulated Q, gross precipitation and effective precipitation comparison (Figure 6.6). The accumulated Q for the two young crop window periods ($Amear_3$ = 65.9 mm and $Edun_3$ = 59.8 mm) exceeded the matured crop Q ($Amear_7$ = 44.7 mm) by 32% and 25% for $Amear_3$ and $Edun_3$, respectively. The accumulated ET exceeded gross precipitation for all measurement windows by 27%, 24.5% and 25.1% for $Amear_3$, $Amear_7$ and $Edun_3$, respectively (Figure 6.6).

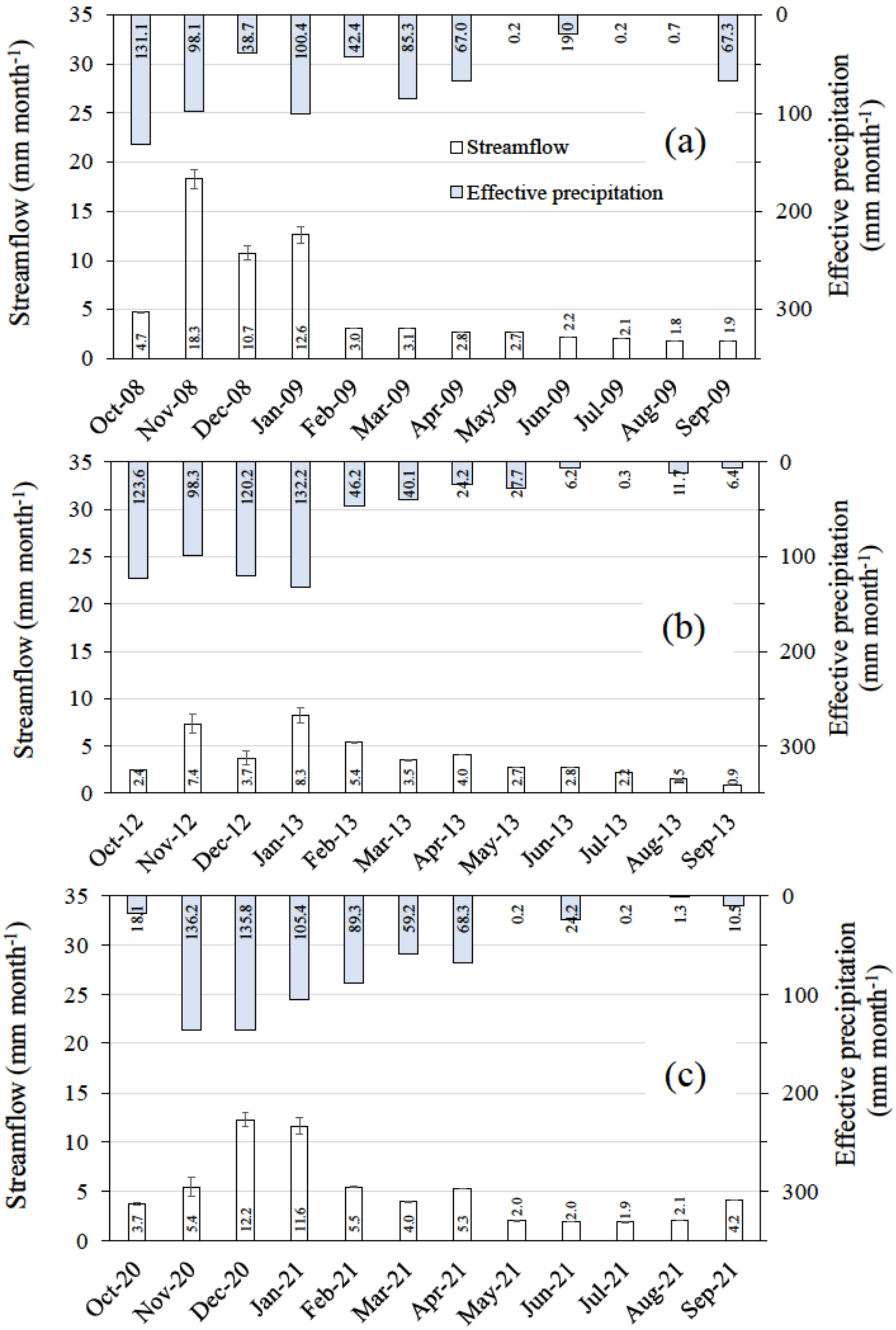

Figure 6.4: The total monthly streamflow (mm month^{-1}) and corresponding total monthly gross and effective precipitation (mm month^{-1}) for hydrological years (a) 2008/ 09 (*Amear*$_3$), (b) 2012/ 13 (*Amear*$_7$) and (c) 2020/ 21 (*Edun*$_3$).

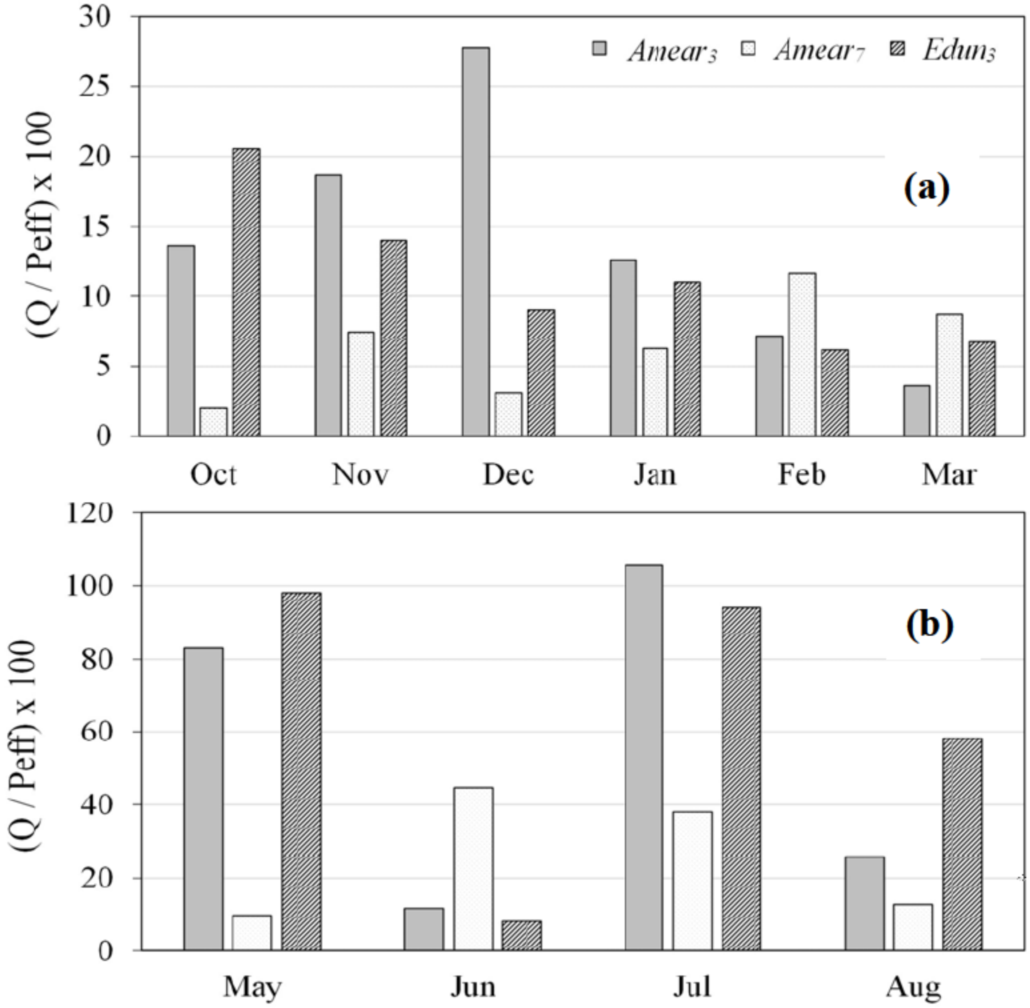

Figure 6.5: A ratio of streamflow (Q) to effective precipitation (Peff) expressed as a percentage for *Amear3* (three-year-old *A. mearnsii*, in 2008/ 09 hydrological year), *Amear7* (seven-year-old *A. mearnsii*, in 2012/ 13 hydrological year) and *Edun*$_3$ (three-year-old *E. dunnii*, in 2020/ 21 hydrological year) in (a) the wet season (September to March) and (b) the dry season (May to August).

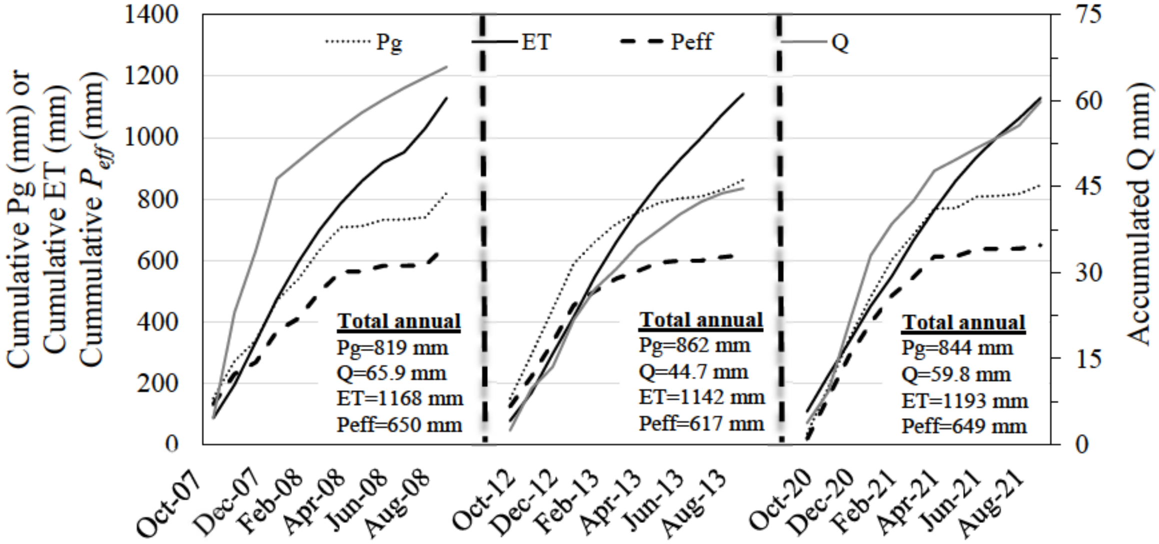

Figure 6.6: Comparison between accumulated gross precipitation (Pg, mm), effective precipitation (Peff, mm), the streamflow (Q, mm) and evapotranspiration (ET, mm) of the three-year-old *Acacia mearnsii* (*Amear*$_3$, for a period Oct 2007 to Sep 2008), seven-year-old *Acacia mearnsii* (*Amear*$_7$, for a period Oct 2012 to Sep 2013) and three-year-old *Eucalyptus dunnii* (*Edun*$_3$, for a period Oct 2020 to Sep 2021). Total annual Pg, Q and ET is indicated for each hydrological year.

6.4.4 Total evaporation

The total evaporation for the three measurement periods was seasonal, with the ET being higher in the wet season (November to February) and lower in the dry season (June to July) (Figure 6.7). In summer (November to January), mean monthly ET for *Amear*$_3$ was statistically greater ($p < 0.05$) than the *Amearn*$_7$ and *Edun*$_3$, whereas during the dry season (May to July) both *Amearn*$_7$ and *Edun*$_3$ was statistically greater ($p < 0.05$) than *Amear*$_3$ (Figure 6.7). The annual ET followed the descending order *Edun*$_3$ (1193 mm) > *Amear*$_3$ (1168 mm) > *Amearn*$_7$ (1142 mm) with no statistically significant differences ($p = 0.9$).

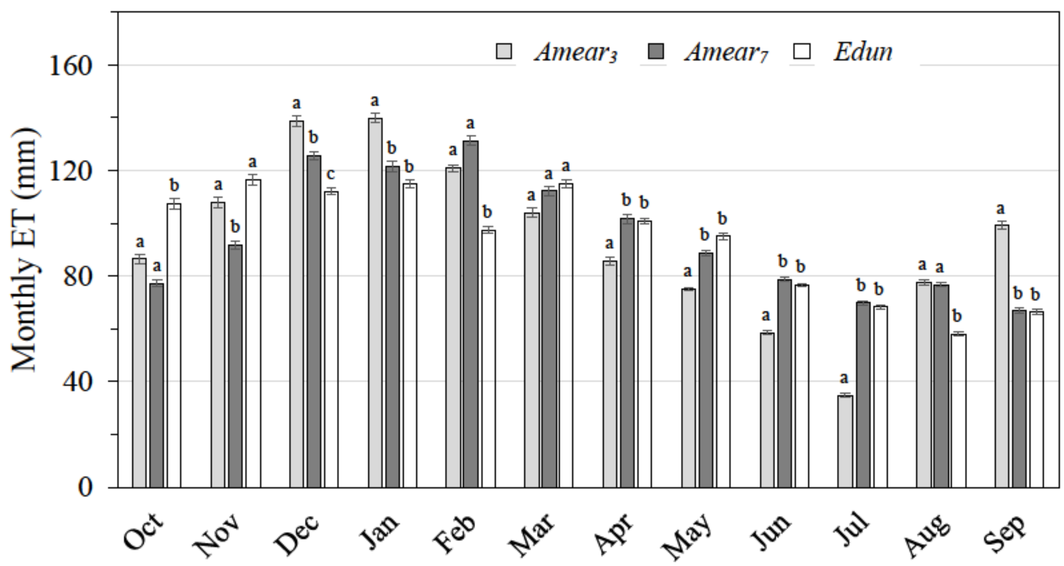

Figure 6.7: The monthly total evaporation (ET, mm) measured at Two Streams research catchment in 2008/ 09 (*Acacia mearnsii* trees approximately three years old, *Amear*$_3$), 2012/ 13 (*A. mearnsii* tree approximately six years old, *Amear*$_7$) and 2020/ 21 (*Eucalyptus dunnii* tree approximately three years old, *Edun*$_3$) hydrological years. Different letters indicate statistically significant differences at $p < 0.05$ between measurement years.

6.4.5 Surface catchment water balance

The monthly surface catchment water balance produced a negative result for all months in all three measurement periods, except for October 2008 in *Amear*$_3$, October 2012 and January 2013 in *Amear*$_7$ and November and December 2020 in *Edun*$_3$ where the catchment surface water balance was positive (Table 6.4). On an annual basis, ET for all measurement periods exceeded gross annual precipitation by 30%, 25% and 30% for *Amear*$_7$, *Edun*$_3$ and *Amear*$_3$, respectively. The annual intercepted rainfall of 44.7 mm for *Amear*$_3$, 63.5 mm for *Amear*$_7$ and 43.4 mm for *Edun*$_3$ played a significant role in inducing the negative surface water balance. As a result, the *Edun*$_3$ had a greatest deficit in the surface water balance (–604 mm) followed by the *Amear*$_3$ (–585 mm) and *Amear*$_7$ (–552 mm) (Table 6.4).

Table 6.4: The monthly surface water balance for the Two Streams research catchment for a duration 2008/ 09, 2012/ 13, and 2020/ 21 hydrological years. The negative numbers in the table indicates a water loss. P_g is the gross precipitation, I_l the interception loss and Q is the total direct runoff. Units for all terms is mm.

2008/ 09 (*Amear₃*)													
	Oct	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Total**
P_g	151	121	68	130	70	95	75	3	21	2	7	79	**819**
I_l	-20	-23	-29	-30	-27	-10	-8	-3	-2	-2	-6	-12	**-169**
ET	-86	-128	-139	-140	-121	-114	-86	-75	-59	-35	-78	-109	**–1168**
Q	-5	-18	-11	-13	-3	-3	-3	-3	-2	-2	-2	-2	**–66**
Δ catchment storage	40	-48	-111	-53	-81	-32	-22	-78	-42	-37	-79	-44	**-585**
2012/ 13 (*Amear₇*)													
	Oct	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Total**
P_g	150	143	148	150	71	59	35	33	15	6	22	32	**862**
I_l	-26	-44	-27	-18	-25	-19	-11	-5	-9	-6	-10	-26	**-226**
ET	-77	-92	-126	-122	-131	-112	-102	-89	-79	-70	-77	-67	**-1142**
Q	-2	-7	-4	-8	-5	-4	-4	-3	-3	-2	-2	-1	**-45**
Δ catchment storage	45	0	-9	2	-90	-76	-82	-64	-76	-72	-67	-62	**-552**
2020/ 21 (*Edun₃*)													
	Oct	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Total**
P_g	35	151	160	134	122	81	85	2	37	2	7	27	**844**
I_l	-17	-15	-24	-28	-33	-21	-17	-2	-13	-2	-6	-17	**-195**
ET	-108	-126	-122	-124	-107	-115	-101	-95	-77	-68	-63	-86	**-1193**
Q	-4	-5	-12	-12	-5	-4	-5	-2	-2	-2	-2	-4	**-60**
Δ catchment storage	-94	5	2	-30	-23	-59	-38	-97	-55	-70	-64	-80	**-603**

6.5 Discussion

Studies that quantify the surface water balance of a catchment are not common, due to high implementation and maintenance costs associated with such studies as well as the complexity of the interactions of natural systems. The availability of historical hydrological data (ET, meteorological and Q) for *Acacia mearnsii* at different growth stages within its rotation, followed by the exchange of genus to *E. dunnii*, at the same site, with ongoing hydrological measurements from the *E. dunnii*, provided a unique opportunity to compare the surface water balance of *A. mearnsii* at two different ages and between two species at the same site. The challenge with such comparisons is that there can be differences in the water balance due to difference in weather conditions. In this study, there were differences in the weather conditions across the three window periods, but generally the weather over the long-term was comparable and unlikely to confound the comparison of the surface water balance between the three measurement periods. This implies that differences in the surface water balance were predominantly due to species differences or tree age, however, lags in the water-balance and long-term differences in soil water resources may have played a role in introducing some differences.

6.5.1 Catchment surface water balance

The concept of water balance provides an opportunity for studying the behaviour of the catchment with an assumption that water entering the catchment is equivalent to water leaving the catchment, plus or minus any change in soil water storage (Brassington 2006). In this study, gross precipitation (P) was the only input of water into the system, while evapotranspiration (ET), precipitation interception loss (I_l) and total direct runoff (Q) were extractions from the system. A negative value indicates a loss of water from the soil and or groundwater, while a positive value indicates a contribution to the soil and or groundwater storage.

6.5.1.1 Evapotranspiration

Evapotranspiration is one of the variables that is not commonly available in water balance studies, and it is a significant strength of this data set to have measured values of ET. In the studied catchment, ET for the three measuring periods significantly exceeded gross precipitation by 25 to 30%, resulting in a negative catchment water balance, even more so if effective precipitation is considered. These results are consistent with two previous ET studies conducted on the same catchment; 1) Dye and Jarmain (2004) used the Bowen ratio technique on four-year-old *A. mearnsii* and found ET to exceed precipitation by 18%, and 2) a study by

Clulow et al. (2011) using large aperture scintillometer on two-year old *A. mearnsii* reported 46% greater ET than precipitation. In our study, the two young crops ($Amear_3$ and $Edun_3$) had a slightly higher ET than the mature crop, although not statistically different. These results were expected as literature reports that ET by commercial forestry species decreases with an increase in tree age (Roberts et al. 2001; Kostner et al., 2002; Delzon and Loustau, 2005; Soares and Almeida 2001). For example, in a Brazilian study by Almeida et al. (2007), maximum annual transpiration (> 1000 mm) was measured when *E. grandis* hybrid trees were between 2.75 and 5.6 years old and a significant decrease in transpiration was observed when trees were older than 5.6 years. This age-related decline in water-use was reported to be driven by the fact that mature trees are taller and have a lower transpiration per unit leaf area than young trees (Delzon and Loustau 2005, Scott and Prinsloo). In our study, the slightly lower ET in the mature trees ($Amear_7$), compared to the younger crops ($Amear_3$ and $Edun_3$), could be associated with lower transpiration per unit leaf area in $Amear_7$.

Evapotranspiration consistently exceeding precipitation at the Two Streams research catchment suggests that trees have access to water not quantified in the surface water balance such as, (1) soil water accumulated from periods when the catchment was fallow, (2) water from unplanted nearby areas moving laterally and vertically in response to gradients in soil water potential (Dye et al. 1996) or (3) water from the regional groundwater. Isotope studies are needed to determine the source of the water, although extracting isotope samples from soil and tree sap is challenging (Penna et al. 2018).

6.5.1.2 Impact of commercial forestry plantations on streamflow

Several South African studies (van Lill et al., 1980; Smith and Scott, 1992; Scott and Lesch, 1997; Scott and Smith, 1997; Scott et al., 2000) have quantified the impact of commercial forest plantations on the Q. The study by Scott and Lesch (1997) on the Q response to afforestation with *E. grandis* and *P. patula* in Mokobulaan experimental catchment in South Africa indicated that eucalypts cause a faster reduction in Q (90–100%) compared to afforestation with pines (40–60%). These results were verified in a study conducted by Scott et al (2000) where peak reductions in Q were reported between 5 and 10 years after establishing eucalypts, and between 10 and 20 years after planting pines, with the reduction driven by soil water availability. A study by Dye and Jarmain (2004) from various catchments in South Africa indicated that a complete removal of *A. mearnsii* resulted in a significant increase in Q.

Results from our study indicated that the annual Q was lowest when the catchment was afforested with the mature crop ($Amear_7$) and higher when the catchment was planted with the younger crops ($Amear_3$ and $Edun_3$). This could be caused, in part, by annual interception loss, which was higher for the $Amear_7$ (225 mm) than in $Amear_3$ (169.1 mm) and $Edun_3$ (195.2 mm), resulting in a reduced effective precipitation and thereby possibly reducing the Q. These results are corroborated by other studies. For example, Ferraz et al (2013) reported a significantly high annual Q (384 mm) in catchments planted with young *Eucalyptus* plantations (2-years-old) compared to matured plantation (5-years-old) in which annual Q was measured to be 235.1 mm. This difference was partly attributed to mature trees having high leaf area index and high forest litter, therefore intercepting water runoff to the stream. In our study, $Amear_7$ peak LAI was slightly higher than the $Amear_3$ LAI, but lower than $Edun_3$, whereas the forest litter, though not measured, is considered to be higher in mature crops than in young crops. This suggest the possibility that $Amear_7$ trees and litter intercepted more runoff than the younger crops. In another study by Farley et al (2005) where 26 catchments datasets were modelled to understand the effect of afforestation on Q, results indicated 1) a runoff reduction of more than 10% of Q in the first two to three years after catchment afforestation 2) on average, *Eucalyptus* reduced runoff by 75% as trees matured, compared with 40% average decrease by pines.

6.5.2 Implications of negative catchment water balance

The results from this study and those of previous studies, including the long-term paired catchment studies in South Africa, have all indicated a negative catchment water balance as a result of commercial afforestation, particularly eucalypts. Of the components of the catchment surface water balance, tree ET was found to be the greatest loss, while Q was found to be the least and particularly so for the mature *Amear7* window period. These results are critical in terms of planning, since most commercial forest plantations are established in high precipitation regions and are planted adjacent to catchments that provide freshwater for downstream users (Albaugh et al. 2013). Therefore, the management of commercial forestry plantations should consider the principles of human rights, ecosystem resilience and ecosystem services sustainability. Afforestation of commercial plantation in water-limited areas should consider water use for drinking and downstream activities, such that forest management balances wood production and water resource conservation.

The previous paired catchment experiments in South Africa showed the impact of forestry on streamflow and current legislation has focussed on blue water and the impact of commercial forestry through streamflow reduction activity (SFRA). This led to forestry being declared a

SFRA and a licensing system for planting was put in place. However, these studies typically didn't have measured ET and didn't show the immediate difference in ET with age and between species.

6.6 Conclusion

Studies that investigate catchment surface water balances in South Africa with actual measurements of ET are few, due to time and costs associated with conducting such studies. Other confounding factors in determining the differences in ET with age and between species, include differences in site characteristics such as slope and soil type. This study provides the surface water balance by young *Acacia mearnsii*, mature *Acacia mearnsii* and young eucalypts at the same site and with similar climatic conditions, eliminating site characteristic differences. The strategy of comparing measurement windows periods with complete records and of similar climatic conditions, due to missing water balance records at various times, worked well, but does not accommodate lags in the water balance annual cycle.

Surface water balance results for all our measurement windows indicated a negative catchment surface water balance. This is similar to results from previous studies on the same catchment, suggesting that trees are accessing water deep in the soil profile or in areas adjacent to the catchment. The total water use by trees was found to be the largest contributor to the negative catchment surface water balance relative to other terms, suggesting that adequate planning is necessary in terms of water conservation and distribution before catchment can be afforested with commercial forestry species. It was concluded that at any stage of development, both *A. mearnsii* and *E. dunnii* have a potential to have a negative impact on streamflow. Despite the challenges in using isotopes, it would be beneficial to use isotope studies to understand the source of the water used by the trees in the Two Streams research catchment.

6.7 Acknowledgements

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6.8 References

Albaugh JM, Dye PJ, King JS. 2013. *Eucalyptus* and water use in South Africa. *International Journal of Forest Research* 11: 852540.

Allen RG, Pereira LS, Howell TA, Jensen ME. 2011. Evaporation information reporting: I. factors governing measurement accuracy. *Agricultural Water Manage*ment 98: 899–920.

Almeida AC. Smerthurts PJ, Siggins A, Cavalcante RBL, Borges N. 2016. Quantifying the effects of *Eucalyptus* plantations and management on water resources at plot and catchment scales. *Hydrological Processes* 30: 4687-4703.

Almeida AC, Soares JV, Landsberg JJ, Rezende GD. 2007. Growth and water balance of *Eucalyptus grandis* hybrid plantations in Brazil during a rotation for pulp production. *Forest Ecology and Management* 251: 10-21.

Blanken PD, Black TA, Neumann HH, Hartog GD, Yang PC, Nesic Z, Staebler R, Chen W, Noval MD. 1998. Turbulent flux measurements above and below the overstory of a Boreal Aspen forest. *Boundary-Layer Meteorology* 89: 109-140.

Brassington R. 2006. Field Hydrogeology (Geological society of London hand book series). Open University Press, London.

Campbell Scientific. 2010. Instruction manual for CS450/ CS455 pressure transducer. Available at: https://s.campbellsci.com/documents/us/manuals/cs450-cs455.pdf (Accessed: 10 July 2023).

Clulow AD, Everson CS, and Gush MB. 2011. *The long-term impact of Acacia mearnsii trees on evaporation, streamflow and ground water resources*, WRC Report No: TT 505/11, Water Research Commission, Pretoria, South Africa (ISBN: 978-1-4312-0020-3).

Delzon S, Loustau D. 2005. Age-related decline in stand water use: sapflow and transpiration in a pine forest chronosequence. *Agricultural and Forest Meteorology* 129: 105-119.

Dougherty D, Wright J. 2012. Silviculture and economic evaluation of eucalypt plantations in the Southern US, *BioResources*, 7, 1994–2001.

Dye PJ. 1996. Response of *Eucalyptus grandis* trees to soil water deficits. *Tree Physiology* 16: 233–238.

Dye PJ, Vilakazi P, Gush M, Ndlela R, Royappen M. 2001. Investigation of the feasibility of using trunk growth increments to estimate water use of *Eucalyptus grandis* and *Pinus Patula* plantation. Water Research Commission Report No. 809/1/01, ISBN 1868458164, South Africa, 229 pp.

Dye P, Jarmain C. 2004. Water use by black wattle (*Acacia mearnsii*): implications for the link between removal of invading trees and catchment streamflow response. *South African Journal of science* 100: 40-44.

Everson CS, Clulow AD, Becker M, Watson A, Ngubo C, Bulcock H, Mengistu M, Lorentz S, Demlie M. 2014. *The long-term impact of Acacia mearnsii trees on evaporation, streamflow, low flows and ground water resources. Phase II: Understanding the controlling environmental variables and soil water processes over a full crop rotation*, Water Research Commission Report K5/2022, ISBN 9781431205165, South Africa, 155 pp. 2014.

Farley KA, Jobbagy EG, Jackson RB. 2005. Effects of afforestation on water yield: a global synthesis with implications for policy. *Global Change Biology* 10: 1565-1576.

Ferraz SFB, Lima WP, Rodrigues CB. 2013. Managing Forest plantation landscapes for water conservation. *Forest Ecology and Management* 301: 58-66.

Ferretto L, Bruzzone F, Nocera S. Pathways to active mobility planning. *Research in Transportation Economics* 86: 101027.

Griffin AR, Midgley SJ, Bush D, Cunningham PJ, Rinaudo AT. 2011. Global uses of Australian Acacia-recent trends and future prospects. *Biodiversity Review* 17: 837-847.

Jackson RB, Jobbagy EG, Avissar R, Roy SB, Barrett DJ, Cook CW, Farley KA, Le Maitre DC, NcCarl BA, Murray BC. 2005. Trading water for carbon with biological carbon sequestration, *Science* 210: 1944 – 1947.

Kimber PC. 1974. The root system of jarrah (*Eucalyptus marginata*). Research Paper no. 10. Perth: Forests Department of Western Australia.

Kostner B, Falge E, Tenhunen JD. 2002. Age-related effects on leaf area/sapwood area relationships, canopy transpiration and carbon gain of Norway spruce stands (*Picea abies*) in the Fichtelgebirge, Germany. Tree Physiol. 22, 567–574.

Lu C, Zhao T, Shi X, Cao S. 2018. Ecological restoration by afforestation may increase groundwater depth and create potentially large ecological and water opportunity costs in arid and semiarid China. *Journal of Cleaner production* 176: 1213-1222.

Meyers TP and Baldocchi DD. 2005. Current Micrometeorological Flux Methodologies with Applications in Agriculture, in: Micrometeorology in Agricultural Systems, edited by: Hatfield, J. L. and Baker, J. M., Agronomy Monograph no. 47, American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America, 381–396.

Muneri A. 1997. Kraft pulping properties of *Acacia mearnsii* and *Eucalyptus grandis* grown in Zimbabwe. Southern African Forestry Journal 179: 13-19.

Penna D, Hopp L, Scandellari F, Allen ST, Benettin P, Beyer M et al. 2018. Ideas and perspectives: Tracing terrestrial ecosystem water fluxes using hydrogen and oxygen stable isotopes-challenges and opportunities from an interdisciplinary perspective. *Biogeosciences* 15: 6399-6415.

Pongpinyopap S, Mungcharoen T. 2012. Comparative study of green water footprint estimation methods for Thailand: a case study of Cassava-based Ethanol. Environment and Natural Resources Journal 10 (2): 66-72.

R Development Core Team. 2008. R: a language and environment for statistical computing. Vienna: R Foundation for Statistical Computing. Available at http://www.R-project.org [accessed 21 January 2023].

Reichert JM, Rodrigues MF, Pelaez JJZ, Lanza R, Minella JPG, Arnold JG, Cavalcante RBL. 2017. Water balance in paired watersheds with eucalyptus and degraded grassland in Pampa biome. *Agricultural and Forest Meteorology* 237: 282–295.

Roberts S, Vertessy R, Grayson R. 2001. Transpiration from *Eucalyptus sieberi* (L.Johnson) forests of different age. *Forest Ecology and Management* 143:153-161.

Savage MJ, Everson CS, Metelerkamp BR. 1997. Evaporation measurement above vegetated surfaces using micrometeorological techniques, Water Research Commission Report No. 349/1/97, Water Research Commission, Pretoria, South Africa, 248 pp.

Savage MJ, Everson CS, Odhiambo GO, Mengistu MG and Jarmain C. 2004. Theory and of practice of evaporation measurement, with a special focus on SLS as an operational tool for the estimation of spatially-averaged evaporation, Water Research Commission Report No. 1335/1/04, Pretoria, South Africa, 204 pp.

Schulze RE. 1995. Hydrology and Agrohydrology: A Text to Accompany the ACRU 3.00 Agrohydrological Modelling System. Water Research Commission, Pretoria, RSA, WRC Report No. TT69/95, 1995.

Scott DF, Lesch W. 1997. Streamflow responses to afforestation with *Eucalyptus grandis* and *Pinus patula* and to felling in the Mokobulaan experimental catchments, South Africa. *Journal Hydrology* 199: 360-377.

Scott DF, Smith RE. 1997. Preliminary empirical models to predict reductions in total and low flows resulting from afforestation. *Water SA* 23: 135-140.

Scott DF, Prinsloo FW, Moses G. 2000. A re-analysis of the South African catchment afforestation experimental data. Water Research Commission Report 810/1/00, ISBN 1868456722, South Africa, 160 pp.

Scott DF, Prinsloo FW. 2008. Longer-term effects of Pine and *Eucalyptus* plantations on streamflow. *Water Resources Research* 44: 1–8.

Sherry S.P. 1971. The black wattle (*Acacia mearnsii* De Wild.). University of Natal Press, Pietermaritzburg.

Smith RE, Scott DF. 1992. The effect of afforestation on low flows in various regions of South Africa. *Water SA* 18: 185-194.

Soares JV, Almeida AC. 2001. Modelling the water balance and soil water fluxes in a fast-growing *Eucalyptus* plantation in Brazil. *Journal of Hydrology* 253: 130–147.

Soil Classification Working Group. 19991. Soil classification-a taxonomic system for South Africa. Department of Agricultural Development, Pretoria. 257 pp.

Thiel AN, Ngcobo S, Peter M. 2019. Forestry - PPGI Sector 5. Available at 648 https://forestry.co.za/uploads/File/Industry%20News/2019/PPGI%20Meeting% 649 2011%20April%202019%20Union%20Build-2.pdf [accessed 05 June 2019].

Van Dijk AI, Keenan RJ. 2007. Planted forests and water in perspective. *Forest Ecology and Management* 251: 1-9.

Van Lill WS, Kruger FJ, Van Wyk DB. 1980. The effect of afforestation with *Eucalyptus grandis* Hill ex Maiden and *Pinus patula* Schlecht. et. Cham. on streamflow from experimental catchments at Mokobulaan, Transvaal. *Journal of Hydrology* 48, 107-118.

Von-Hoyningen-Huene L. 1983. The interception of recipitation in agricultural plants stands. Verlag Paul Parey-Hamburg, Schirften, 57, 1–66.

Wichert MCP, Alvares CA, Junior JCAJ, Stape JL. 2018. Site preparation, initial growth and soil erosion in *Eucalyptus grandis* plantations on steep terrain. *Scientia Forestalis* 46: 17-30.

Wilson KB, Hanson PJ, Mulholland PJ, Baldocchi DD, Wullschleger SD. 2001. A comparison of methods for determining forest evapotranspiration and its components: sap-flow, soil water budget, eddy covariance and catchment water balance. *Agricultural Forest Meteorology* 106, 153–168.

WMO. 2008. Guide to Meteorological Instruments and Methods of Observation, WMO-No. 8, 7th Edn., Geneva.

Woodgate W, Jones SD, Suarez I, Hill MK, Armson JD, Wilkes P, Berelov MS, Haywood A, Mellor A. 2015. Understanding the variability in ground-based methods for retrieving canopy openness, gap fraction and leaf area index in diverse forest systems. *Agricultural Meteorology* 205: 83-95.

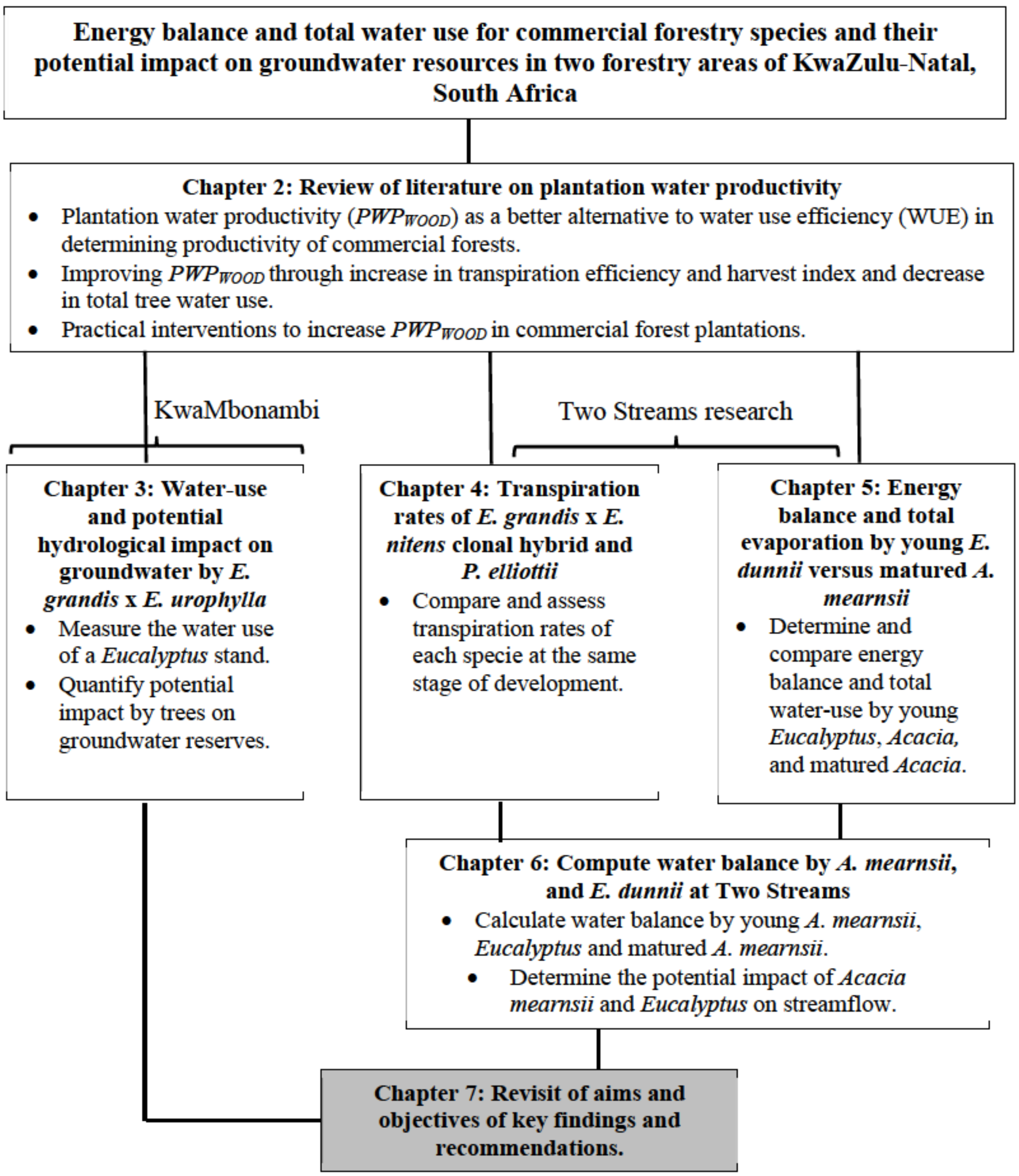
Zhang M, Liu N, Harper R, Li Q, Liu K, Wei X, Ning D, Hou Y, Liu S. 2017. A global review on hydrological responses to forest change across multiple spatial scales: Importance of scale, climate, forest type and hydrological regime. *Journal of Hydrology* 546: 44-59.

6.9 Supplementary information

Supplementary Figure 6.1: The main weir with sieve that prevents the V-notch from getting blocked by debris at Two Streams research catchment.

Supplementary Figure 6.2: A sonic anemometer that was mounted on a 24 m lattice mast within the study site to provide anchor to sensors, while the inset is the CR3000 datalogger mounted in the waterproof enclosure.

Lead into Chapter 7: The overall aim of the study was to expand water use knowledge, determine plantation water productivity and to quantify the impact of commercial forest plantations on streamflow and has been addressed in chapters 3 to 6. Chapter 7 emphasizes the main findings of this study and recommends knowledge gaps for future research.



CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

7.1 Introduction

The commercial forestry industry plays an important role in South Africa through agricultural GDP contribution, provision of employment (Bennett 2011) and mitigation of air pollution and climate change (van Dijk and Keenan 2007, Wichert et al. 2018, Ferreto et al. 2021). Despite these benefits, research around the world indicated that commercial forestry has higher evapotranspiration rates than other vegetation types and they are capable of rooting very deeply, accessing deep groundwater reserves (Bosch and Hewlett 1982, Gush et al. 2002, Bruijnzeel et al. 2005, Jackson et al. 2005, Dye and Versfeld 2007, Scott and Prinsloo 2008, Vanclay 2009). South Africa has made advances in understanding the water use by different commercial forestry species, however, existing research focused mainly on few commercial forestry species; *Eucalyptus grandis*, *Pinus patula* and *A. mearnsii*. In the last three decades, changes have occurred (Morris 2022), and *E. grandis* species has been replaced by *Eucalyptus* clonal hybrids, while *P. elliotti* has become an important pine planting option by the commercial forestry industry (Morris 2022). There is an urgent need to expand water use knowledge on species currently planted by the commercial forestry industry and quantify their potential impact on water resources. Furthermore, a relationship between total water use by forest plantation and forest productivity needs to be investigated to improve plantation forests yields.

The research in this thesis was centred around expansion of water use knowledge by *Eucalyptus* clonal hybrids (*Eucalyptus grandis* x *E. nitens* and *E. grandis* x *E. urophylla*), *E. dunnii*, *A. mearnsii* and *Pinus elliottii* and quantify the potential impact by each specie the streamflow. To achieve this, complex micrometeorological techniques as well as sap flow techniques were used to measure commercial forestry stand water use and quantify the potential impact by each species on the streamflow at two experimental sites: the Two Streams research catchment and the KwaMbonambi forestry area in the northern Zululand region of South Africa. In addition, total water use measurements were paired with biomass measurements to calculate plantation water productivity (PWP_{WOOD}) aimed to determine biomass production by each species per volume measure of total water used. This research contributes to a unique set of measurements of the water use of *E. grandis* x *E. nitens* and *E. grandis* x *E. urophylla* clonal hybrids and *Pinus elliottii* species in South Africa, providing insights into the potential impact by these species on water resources and differences in water-use from previously planted *A. mearnsii* at different stages of growth and the young *E. dunnii*.

The study clearly demonstrated the invaluable contributions that can be achieved from field-based measurements, which require a great deal of time and involve delicate and expensive equipment which was exposed to the risk of damage and theft. However, the results in this thesis have justified the allocated resources. A significant contribution to the expansion of water use knowledge by species and clonal hybrids currently planted by the commercial forestry industry was achieved. Furthermore, the PWP_{WOOD} and the potential impact by each species and clonal hybrids on water resources was quantified. The quantity and quality of data produced for this thesis provides a baseline for future hydrological and modelling studies.

7.2 Revisiting aims and objectives, research hypothesis and contribution to new knowledge

The overall aim of research in this thesis was to create new knowledge and advance our understanding of total water use and PWP_{WOOD} by commercial forestry species, that are mostly planted by the commercial forestry industry, at Two Streams research catchment and KwaMbonambi study site in northern Zululand of South Africa. In addition, it aimed to quantify the potential impact by these commercial forestry species on the streamflow. With South Africa being a water limited country, and with the ongoing competition for water resources between the forestry industry and downstream water users, this improved knowledge around tree water use is critical. This knowledge will empower decision-makers in terms of understanding the impact, or lack of, by the commercial forestry industry on water resources at Two Streams research catchment and KwaMbonambi area and ultimately the greater KwaZulu-Natal forest plantation areas.

The specific objectives of this research were to:

a) Review literature on PWP_{WOOD} as an alternative to water use efficiency in determining the productivity of commercial forest plantations
b) Quantify water use by fast-growing *E. grandis* x *E. urophylla* clonal hybrid and the potential impact on water resources in KwaMbonambi, northern Zululand regions of South Africa

c) Measure water use by fast-growing *E. grandis* x *E. nitens* and *Pinus elliottii* at the same stage of development near the Two Streams research catchment, KwaZulu-Natal midlands, South Africa
d) Assess the impact of catchment afforestation with *A. mearnsii* and young *E. dunnii* on streamflow at Two Streams research catchment, KwaZulu-Natal midlands, South Africa
e) Understand the differences in energy balance and total evaporation over young *E. dunnii,* young *A. mearnsii* and matured *A. mearnsii* plantations on the same site at the Two Streams research catchment, KwaZulu-Natal midlands, South Africa

The specific research hypothesis in this study were:

a) The PWP_{WOOD} is a good determinant of commercial forest plantation productivity and a better alternative to water use efficiency, which is the currently used determinant of productivity by the commercial forestry industry.
b) The nine-year-old *E. grandis* x *E. urophylla* water use is statistically lower than *Eucalyptus* species water use conducted in the KwaMbonambi and adjacent areas.
c) Water use by the eight-year-old *E. grandis* x *E. nitens* clonal hybrid will be statistically greater than the twenty-year-old *Pinus elliottii* at Two Streams research catchment.
d) The young crop total water use (two-year-old *E. dunnii* and two-year-old *A. mearnsii*) is hypothesised to be statistically greater than the mature crop (six-year-old *A. mearnsii*) at the Two Streams research catchment.
e) The *A.mearnsii* and *E. dunnii* is hypothesised to have a significant impact on the streamflow.

The specific contributions to new knowledge of this research and revisiting the research hypothesis by chapter (Chapter 2 to chapter 6) are summarised as follows:

Chapter 2

- Identified the limitations of using water use efficiency as a tool to determine commercial forest productivity and benefits of using PWP_{WOOD} as an alternative.

- Highlighted several international case studies where PWP_{WOOD} has been successfully used to improve forest productivity. To our knowledge, there is no documented literature in South Africa where PWP_{WOOD} has been implemented in a commercial forestry stand and it is recommended that the approach be adopted.

- Provided practical practices that can be implemented by the South African commercial forestry industry to enhance PWP_{WOOD} and ultimately improve yield in their plantations.

- The PWP_{WOOD} was calculated in each chapter and shown to be a good determinant of plantation productivity.

Chapter 3

- Quantified water-use by *E. grandis* x *E. urophylla*, a clonal hybrid, in the heavily afforested KwaMbonambi region of northern Zululand using modern water use measuring equipment.

- Derived a relationship between *E. grandis* x *E. urophylla* clonal hybrid stand water-use and micrometeorological variables in the KwaMbonambi area of the Zululand coastal plains. This data can be used in future modelling studies where stand water use can be estimated using micrometeorological variables beyond the KwaMbonambi region.

- Calculated PWP_{WOOD} by *E. grandis* x *E. urophylla*, providing the first productivity values by this species in the northern Zululand of South Africa

- The *E. grandis* x *E. urophylla* clonal hybrid was shown to have high water use, comparable to other *Eucalyptus* species measured in the KwaMbonambi and adjacent areas.

Chapter 4

- Verified the accuracy of water use measurements conducted by the heat ratio method using portable lysimeters. This calibration provided confidence in our water use dataset and will provide assurance to other researchers in the accuracy of the heat ratio technique as a measure of tree water use.

- Measured PWP_{WOOD} and water use of the *E. grandis* x *E. nitens* clonal hybrid and *Pinus elliottii*, within close proximity to each other and at the same phase of development, near the Two Streams research catchment, KwaZulu-Natal midlands, South Africa.

- The results from this short-term study showed that *P. elliotti* used more water than *E. grandis* x *E. nitens* in the first season, whereas water use between species in the second season was statistically similar, which was probably cause by water stress conditions experienced at the *GN* site. These results showed that in countries such as South Africa where streamflow reductions by commercial forestry is modelled for water use licensing purposes, soil water stress in hydrological models must be able to constrain tree water use.

Chapter 5

- Contributed towards an improved understanding of changes in energy balance and total water use that occur in afforestation with tree age and due to genus exchange at a site. Historic measurements over young *A. mearnsii* and mature *A. mearnsii* were combined with measurements over a young *E. dunnii* stand, all on the same site at the Two Streams research catchment. Results confirmed our hypothesis that the water use of young *A. mearnsii* and *E. dunnii* were statistically similar and that the water use for young crops is significantly greater than for matured crops. The information produced in this study will benefit the forestry industry and government when planning future afforestation.

- Derived FAO-56 Penman-Monteith crop factors and established relationship between micrometeorological variables and ET for young *A. mearnsii*, young *E. dunnii* and matured *A. mearnsii* at Two Streams research catchment. The developed crop factors and the relationship with micrometeorological variables will benefit hydrologists in estimating the difficult to measure total tree water use from easily measured meteorological variables and improve hydrological modelling of streamflow reduction activity assessment.

Chapter 6

- Calculated the surface water balance of the two Streams research catchment when the catchment was afforested with three-year old *A. mearnsii*, three-year-old *E. dunnii* and seven-year-old *A. mearnsii*. Results indicated a negative catchment water balance, similar results to previous studies conducted on the same catchment, with total tree water use by tree being the significant contributor to water loss in the catchment.

- The research conducted in this study confirmed our hypothesis that afforesting the catchment with *A. mearnsii* and *E. dunnii* at any stage of development pose a negative impact on catchment, by reducing the streamflow. These findings will assist decision makers at a government level in policy development and serve as a guide to the commercial forestry industry in planning catchment afforestation.

7.3 Challenges faced during this research

The greatest challenge in this research at both Two Streams research catchment and KwaMbonambi study sites, besides choosing an appropriate study site and the most suitable tree water-use measuring techniques, was the remote nature of the study sites with continuous threat by animals, theft and vandalism.

Continuous measurements of tree water-use were logistically challenging since rigorous maintenance and monitoring of the equipment was required. The main limitations to achieving complete and precise datasets were mainly from: power supply failure, sensor failure, insect damage and rodents damaging sensor cables. Furthermore, both study sites were subjected to constant theft of batteries (though housed in strong steel boxes), cellphone modem and antennas used for remote communication with logging devices and general vandalism of the instrumentation. This unfortunately resulted in some data loss in the early stages of the research.

To achieve long-term datasets of water use measurements required innovation. The need for long-lasting power was addressed by using large capacity batteries (110 A/h batteries) which minimised the need to replace batteries frequently. The electrical components were sealed to prevent insect damage and silica gel was used to prevent corrosion by high humidity levels. The equipment theft and vandalism were prevented using fake witchcraft at each study site. Coloured candles, fake human and animal bones, fake baboon skulls and some chicken feathers were randomly placed across the study site to scare thieves and vandalisers. This worked well on all study sites, particularly the KwaMbonambi site where theft and vandalism were most prominent.

This research was conducted during the global Covid-19 pandemic, and South Africa was placed under lockdown where all citizens were forced to remain indoors for an extended period. This caused problems in visiting study sites to change batteries, general site maintenance and growth data collection, and resulted in some data loss. There was about one month and two months of water use and growth data loss at Two Streams and KwaMbonambi sites, respectively. The lost tree water use data was patched using the FAO reference evaporation while the growth data was irrecoverable.

The logging instrumentation that was used to record the streamflow data was located adjacent to the stream and housed in a strong steel box. Unfortunately, the box was not waterproof, and the instrumentation was periodically subjected to flooding, resulting in data loss. Though every effort was made to insulate the logging instrumentation, there was a severe flood event in which the whole strong box was swept away and it could not be found.

7.4 Future research opportunities

The work presented in this study provided an in-depth analysis of literature on PWP_{WOOD} and quantified water-use by different commercial forestry industry species and clonal hybrids, expanding our water use knowledge, however, due to time and resources limitations, this study highlighted the following for future research consideration:

- In Chapter 2, literature was reviewed suggesting PWP_{WOOD} as a better alternative to water use efficiency in determining productivity of commercial forestry. No research on PWP_{WOOD} could be found in South Africa, with experimental investigation on PWP_{WOOD} in commercial forestry. It is recommended that future research compare water use efficiency and plantation water productivity experimentally in different forestry species and clonal hybrids to confirm the benefit of using PWP_{WOOD} under South African forestry conditions.

- The Two Streams research catchment has been an experimental catchment for the past 21 years with intense hydrological measurements in a *A. mearnsii* plantation, which was monitored for a full rotation (Clulow et al. 2011, Everson et al. 2014). Subsequently, the catchment was replanted with *E. dunnii*, where hydrological processes were monitored for about three years. In South Africa, there is limited knowledge on water use and the impact by commercial forestry of streamflow and groundwater resources, particularly for *E. dunnii* since it is the most planted *Eucalyptus* specie in South Africa. Continued measurement of hydrological processes on the currently planted *E. dunnii* for the full rotation is suggested. This will assist in enhancing our knowledge and offer an opportunity to compare *A. mearnsii* and *E. dunnii* water use and impact of water resources for the full rotation to determine long-term impacts on water resources.

- Remote sensing technologies and computer models, using satellite earth observation data, have been used with good results in estimating total water use over large areas (Wang et al. 2007, Gibson et al. 2013, Shoko et al. 2015). However, these technologies still require ground truthing using ground-based measurements. Measurements of total water use and energy balance over commercial forestry provides an ideal opportunity to validate existing remote sensing tools and hydrological models such as Surface Energy Balance System (Gibson et al. 2013), surface energy balance algorithm (Le and Liou 2021) and Normalised Difference Vegetation Index (Pervez et al. 2021). It is therefore suggested that expansion of total water use by other commercial forestry species are conducted to enable validation of remote sensing and modelling studies.

- Research in this study provided evidence that trees can access groundwater resources even in the early stages of growth though capillary rise. Although challenging, research using isotopes to partition water use by trees into soil profile water and groundwater sources is recommended.

7.5 References

Bennett BM. 2011.Naturalising Australian trees in South Africa: Climate, exotics and experimentation. *Journal of Southern African Studies* 37: 265–280.

Bosch JM, Hewlett JD. 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. *Journal of Hydrology* 55: 3–23.

Bruijnzeel LA, Bonell M, Gilmour DA, Lamb D. 2005. Conclusion: forests, water and people in the humid tropics: an emerging view. In: Bonell M, Bruijnzeel LA (eds), Forests, water and people in the humid tropics: past, present and future hydrological research for integrated land and water management. Cambridge: Cambridge University Press. pp 906–925.

Clulow AD, Everson CS, Gush MB. 2011. *The long-term impact of Acacia mearnsii trees on evaporation, streamflow and ground water resources*, WRC Report No: TT 505/11, Water Research Commission, Pretoria, South Africa (ISBN: 978-1-4312-0020-3).

Dye PJ, Versfeld D. 2007. Managing the hydrological impacts of South African plantation forests: an overview. *Forest Ecology and Management* 251: 121–128.

Everson CS, Clulow AD, Becker M, Watson A, Ngubo C, Bulcock H, Mengistu M, Lorentz S, Demlie M. 2014. *The long-term impact of Acacia mearnsii trees on evaporation, streamflow, low flows and ground water resources*. Phase II: Understanding the controlling environmental variables and soil water processes over a full crop rotation. WRC Report K5/2022.

Gibson LA, Jarmain C, Su Z, Eckardt FE. 2013. Review: Estimating evapotranspiration using remote sensing and Surface Energy Balance System-A South African perspective. *Water SA* 39: 477-484.

Gush MB, Scott DF, Jewitt GPW, Schulze RE, Hallowes IA, Gorgens AHM. 2002. A new approach to modelling streamflow reductions resulting from commercial afforestation in South Africa. *Southern African Forestry Journal* 196: 27–36.

Jackson RB, Jobbágy EG, Avissar R, Roy SB, Barrett DJ, Cook CW, Farley KA, Le Maitre DC, McCarl BA, Murray BC. 2005. Trading water for carbon with biological carbon sequestration. *Science* 310: 1944–1947.

Le MS, Liou YA. 2021. Spatio-temporal assessment of surface moisture and evapotranspiration variability using remote sensing techniques. *Remote Sensing* 13(9): 1667-1675.

Morris AR. 2022. Changing use of species and hybrids in South African forest plantations. *Southern Forests: a journal of forest science* 84(3): 1-13.

Pervez S. McNally A, Arsenault K, Buddee M, Rowland J. 2021. Vegetation monitoring optimisation with Normalised Difference Vegetation Index and Evapotranspiration using remote sensing measurements and land surface models over East Africa. *Frontiers in Climate* 3: 58-67.

Scott DF, Prinsloo FW. 2008. Longer-term effects of pine and eucalypt plantations on streamflow. *Water Resources Research* 44: W00A08.

Shoko C, Dube T, Sibanda M, Adelabu S. 2015. Applying the Surface Energy Balance System (SEBS) remote sensing model to estimate spatial variations in evapotranspiration in southern Zimbabwe. Transactions of the Royal Society of South Africa 1: 47-55.

Vanclay JK. 2009. Managing water use from forest plantations. *Forest Ecology and Management* 257: 385–389.

Van Dijk AI, Keenan RJ. 2007. Planted forests and water in perspective. *Forest Ecology and Management* 251: 1-9.

Wang K, Wang P, Li Z, Cribb M, Sparrow M. 2007. A simple method to estimate actual evapotranspiration from a combination of net radiation, vegetative index and temperature. *Journal of Geophysical Research Atmospheres* 112: 1-14.

Wichert MCP, Alvares CA, Junior JCAJ, Stape JL. 2018. Site preparation, initial growth and soil erosion in Eucalyptus grandis plantations on steep terrain. *Scientia Forestalis* 46: 17-30.