# THE EXPANSION OF KNOWLEDGE ON EVAPOTRANSPIRATION AND STREAM FLOW REDUCTION OF DIFFERENT CLONES/ HYBRIDS TO IMPROVE THE WATER USE ESTIMATION OF SFRA SPECIES (I.E. PINUS, EUCALYPTUS, AND WATTLE SPECIES)

*Clulow, A., Kaptein, N., Everson, C.S., Germishuizen, I., Kunz, R.P., Gokool, S. and Toucher, M.L.*

## VOLUME 1: IMPROVED WATER USE ESTIMATION OF SFRA SPECIES

WATER RESEARCH COMMISSION

TT 898/1/22

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## *VOLUME 1*: IMPROVED WATER USE ESTIMATION OF SFRA SPECIES

Report to the

WATER RESEARCH COMMISSION

*Prepared by*: Clulow, A.[1], Kaptein, N. [1], Everson, C.S., Germishuizen[2], I., Kunz, R.P.[1], Gokool, S.[1] and Toucher, M.L.[1,3]

[1] Centre for Water Resources Research
[2] Institute for Commercial Forestry Research
[3] South African Environmental Observation Network

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*Report to the:*
WATER RESEARCH COMMISSION

*Physical Address:*
Lynnwood Bridge Office Park
Bloukrans Building
4 Daventry Street
Lynnwood Manor
PRETORIA

*Postal Address:*
Private Bag X03
GEZINA, 0031, South Africa

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*Project Leader:*
Dr Alistair Clulow

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*Obtainable from:*
Water Research Commission, Private Bag X03
GEZINA, 0031

orders@wrc.org.za or download from www.wrc.org.za

# EXECUTIVE SUMMARY

## BACKGROUND

Pine plantations are still the most planted species in South Africa occupying 49% of the total commercial forest plantation area. However, fast-growing *Eucalyptus* species are now considered an alternative to pine by the dissolving woodpulp markets due to their superior pulping properties, high productivity rates and short rotation. The literature suggest that *Eucalyptus* species are heavy water users compared to pine and may cause a reduction (or cessation) of streamflow and depletion of underground water resources. However, this information is limited to a few commercial forestry species mainly *Eucalyptus grandis* and *Pinus Patula*. The forestry industry breeding programmes have produced several clonal hybrids whose total water use (ET) and impact on water resources is not fully understood. The eucalypts, *E. dunnii*, *E. grandis* x *E. urophylla* and *E. grandis* x *E. nitens* are the first, third and fourth most planted species in South Africa, whereas, *P. elliottii* is the second most planted pine specie and ET and the impact on water resources has not been quantified for each of these species. There is an urgent need to expand water use knowledge by these species using high quality scientific research to inform policy (National Water Act of 1998) and forest management decisions. This need has become more important with the proposed Genus exchange regulation, which outlines that any existing water user that wishes to exchange a genus is required to apply to the relevant authority to implement the proposed exchange.

## PROJECT AIMS

Considering this water use knowledge gap identified above, the aims of this research were:

1. To expand the knowledge of the estimates of water use of different clones and hybrids of eucalypt, wattle and pine species (e.g. clones/hybrids most commonly used, clones/hybrids planted in optimal sites).
2. To address shortcomings in the availability of leaf area index information for different SFRA species, clones and hybrids.
3. To improve existing tools used for the estimation of the impacts of SFRA through the inclusion of improved soils data and baseline land cover data, as well as the inclusion of the latest process results related to water use (i.e. evapotranspiration) of SFRA clones, hybrids and species.

The outcomes, findings and products of the project are comprised of two final reports. This document details the research undertaken to address Aim 1, which focuses on the improved water use estimation of SFRA species, while the other deliverable speaks to Aims 2 and 3 and documents the SFRA Utility.

## RESEARCH SITES

The Two Streams Research Catchment is one of the few remaining catchment areas in South Africa that have been intensively studied with over 22 years of detailed hydrological process observation. The previous projects have focused on understanding the impact of *Acacia mearnsii* on surface and groundwater resources, ET and riparian zone management. In 2018, post clearing of *A. mearnsii*, a change in genus was proposed, with subsequent planting of *E. dunnii*. This presented a unique research opportunity to understand the impact of changing a genus from A. *mearnsii* to *E. dunnii* on the soil water balance. Therefore, hydrological processes observations were conducted on a two-year-old *E. dunnii* for comparison with two-year old *A. mearnsii* and a mature crop (six-year-old *A. mearnsii*). Due to a long historical data for the catchment, two additional study sites in the same stage of development were identified adjacent to Two Stream Catchment, one planted to eight-year-old *E. grandis* x *E. nitens* (*GN*) and second to twenty-year-old *P. elliottii*. Measurements of transpiration and estimates of ET for each specie were compared and implications to water yield quantified. A fourth site was selected on the north coast of KZN (KwaMbonambi), planted to nine-year-old *E. grandis* x *E. urophylla* (*GU*), due to favourable growing conditions for this specie in subtropical conditions. Concomitantly, practical techniques that may be used to improve tree productivity by the commercial forestry industry were investigated and are reported.

# METHODOLOGY

This research involved conducting a detailed literature on $PWP_{WOOD}$ as a tool to improve productivity in commercial forestry. Case studies in other countries indicating improvement in plantation productivity using $PWP_{WOOD}$ instead of water use efficiency were highlighted. Practical interventions that can be implemented by the commercial forestry industry in South Africa to improve $PWP_{WOOD}$ are emphasised.

The most up-to-date techniques for measuring water use (heat ratio method), total water use (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 Two Streams research catchment were conducted and potential impact on water resources quantified. Second, total water use by previously planted *A. mearnsii* crop (two-year-old *A. mearnsii* and six-year-old *A. mearnsii*) was compared to a newly planted *E. dunnii* crop (two years old) to providing 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, compared to its mother plant, *E. grandis* and *E. urophylla* and the potential impact of *GU* on groundwater resources was quantified. Fourth, the major total water balance components of the Two Streams research catchment, and the streamflow were determined, providing an important understanding into the systems hydrological function.

# RESULTS

The Two Streams research catchment was found in previous studies to have water-use losses that exceed rainfall. This study found similar results and 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 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 Two Streams catchment water balance indicated that tree evapotranspiration was the main consumer of water loss in the catchment, contributing 96% relative to total runoff and baseflow.

Comparison of water use by *GN* and *P. elliottii* showed that, in the first year *P. elliottii* 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 previous *Eucalyptus* and *Pinus* comparative studies where *Eucalyptus* water use was statistically greater than pine, and this was attributed to water stress conditions experienced at the *GN* study site. The $PWP_{WOOD}$ 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. The genus exchange ratio between *GN* and *P. elliottii* was found to be on average 0.92, however, these results were based on measurements conducted on two sites, with one site subjected to drought stress. A recommendation is that these measurements are conducted over several forestry sites to include different soil and climatic conditions. Based on these results a conclusion was drawn that conversion from *P. elliottii* to *GN* in water stressed sites and where groundwater resources are too deep for access by trees may not affect groundwater resources, however, during the wet season, trees may deplete the recharged soil profile soil water content which may lead to streamflow reduction in the long term.

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 higher, decreasing as the stand approaches maturity. The genus exchange ratio between young crops was calculated to be one, while between young crop and mature crop was 0.92. A suggestion is that measurements are continued for the full *E. dunnii* rotation to allow for comparison with *A. mearnsii* rotation. 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. Afforesting the catchment with *E. dunnii* or *A. mearnsii*, at any stage of development, could have a negative impact on the streamflow and groundwater reserves. These findings were supported by a reduction in streamflow when the catchment was afforested by either *E. dunnii* or *A. mearnsii*, while the streamflow increased when the catchment was cleared.

The heat ratio technique indicated that the *GU* mean daily water use was 2.3 to 3.3 mm corroborating with previous water use studies conducted on *E. grandis* and *E. urophylla* in northern Zululand region. These results suggested that the *GU* water use is statistically similar to its mother plants water use (*E. grandis* and *E. nitens*). The $PWP_{WOOD}$ 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 produce 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 groundwater reserves with possible long-term consequences on the streamflow and depletion of groundwater reserves.

The Random Forests predictive model was used to determine the relationship between tree transpiration and total evaporation versus micrometeorological variables (rainfall, soil water content, vapour pressure deficit, relative humidity, air temperature, solar radiation). The model indicated that solar radiation, FAO reference evaporation, soil water content and vapour pressure deficit are good predictors of transpiration and total evaporation. The model further indicated that streamflow was highly correlated with water yield (defined as a ratio of streamflow to precipitation) and rainfall. This relationship will form a good background for future modelling studies where water use can be estimated from weather measurements.

# CONCLUSIONS

This report indicates 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 species currently planted by the commercial forestry industry in South Africa, which is now available in this report through the use of the most up-to-date measuring techniques. This report not only present the first measurements of water use by *GU*, *GN* an *P. elliottii* in South Africa and first comparative water use by *P. elliottil* and *GN*, but is also one of the few studies that quantified the impact of *A. mearnsii* and young *E. dunnii* on groundwater reserves and streamflow in South Africa. The study provides decision makers, such as government officials with an opportunity to update policies using water use information from species and hybrids currently planted by the South African commercial forestry industry. Data captured in this report will also be a useful resource in future modelling studies where water use could potentially be estimated from weather and growth 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.

# ACKNOWLEDGEMENTS


| Reference Group | Affiliation |
|---|---|
| Mr W Nomquphu | Water Research Commission (Chairman) |
| Ms P Jaka | Water Research Commission |
| Ms N Fourie | Department of Water and Sanitation (DWS), Compliance Monitoring Afforestation |
| Ms N Muthraparsad | DWS Compliance Monitoring Afforestation (SFRA) |
| Ms D Maluleke | DWS Stream Flow Reduction |
| Ms A Madonsela | DWS Compliance Monitoring Afforestation |
| Mr J Bester | DAFF Scientific Services |
| Mr F Fourie | DWS Groundwater (Water Resources Planning Systems) |
| Dr I Thompson | (Retired DWS Planning official) Private |
| Mr B Mdluli | Department of Water and Sanitation |
| Prof BE Kelbe | University of Zululand/HRTS |
| Dr MB Demlie | University of KwaZulu-Natal |
| Mr JC Nel | TWK Agri |
| Dr RN Heath | Forestry South Africa |
| Dr AR Morris | Institute for Commercial Forestry Research |
| Dr S Dovey | SAPPI |
| Dr M Govender | South African Sugar Association |
| Dr DC Le Maitre | CSIR |
| | |
| **Others** | |
| Mr David Borain | Mondi Forests |
| Mr Xolani Colvelle | Institute for Commercial Forestry Research |
| Mr Jimmy Nhlangulela | Institute for Commercial Forestry Research |
| Mxolisi Gumede | University of KwaZulu-Natal |

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# LIST OF SYMBOLS

| | |
|---|---|
| α | Alpha |
| π | Pie (approximately 3.14, unitless) |
| A | Total ground area ($m^2$) |
| AE | Available energy ($Wm^{-2}$) |
| $c_p$ | Specific heat capacity for air at constant pressure ($J\ kg^{-1}\ K^{-1}$) |
| D | Energy balance ratio |
| DBH | Diameter at breast height (cm) |
| DM | Total dry matter accumulated by a tree (g) |
| Dq | Quadratic mean diameter (cm) |
| EB | Energy balance ($Wm^{-2}$) |
| EBc | Energy balance closure |
| 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 ($Wm^{-2}$) |
| HI | Harvest index ($g\ g^{-1}$) |
| Is | Solar irradiance ($Wm^{-2}$) |
| Kc | Crop factor |
| $K_T$ | Transpiration crop coefficient (mm) |
| LTMAP | Long term mean annual precipitation (mm) |
| MAP | Mean annual precipitation (mm) |
| MAT | Mean annual temperature (mm) |
| LE | Latent heat flux ($Wm^{-2}$) |
| $LSD_{5\%}$ | Fischer's Least Significant Difference at 5% level of significance |
| ρ | Density of wood (kg m-3) |
| $\rho_a$ | Density of dry air ($kg\ m^{-3}$), |
| P | Precipitation (mm) |
| *PAW* | Plant available water (kPa) |
| *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 |
| Rn | Net irradiance ($Wm^{-2}$) |
| 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) |
| Tair | 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) |

# LIST OF ABBREVIATIONS

| | |
|---|---|
| AI | Aridity index |
| *Amear*$_2$ | Two-year-old *Acacia mearnsii* trees |
| *Amear*$_6$ | Six-year-old *Acacia mearnsii* trees |
| ANOVA | Analysis of variance |
| AWS | Automatic weather station |
| $C_I$ | Canopy interception |
| 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 |
| 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 |
| WY | Water yield |

# REPOSITORY OF DATA

For details related to the project's data, please contact:

Richard Kunz (Researcher)
Centre for Water Resources Research
School of Agricultural, Earth and Environmental Sciences
University of KwaZulu-Natal
Private Bag X01, Scottsville 3209
Pietermaritzburg, South Africa
Email: kunzr@ukzn.ac.za

# 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 species and quantified the potential impact these species have 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).

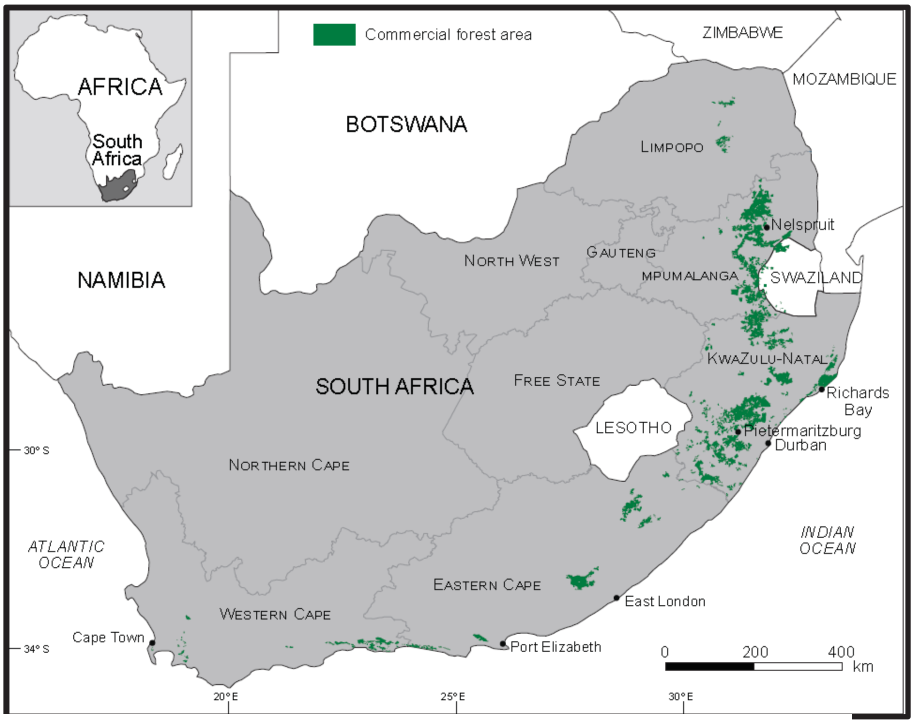


Figure 1-1: Distribution of commercial forestry in South Africa.

**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* species (ha$^{-1}$) | | Pine species (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 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 Project aims

The following were the aims of the project:

1. To expand the knowledge of the estimates of water use of different clones and hybrids of eucalypt, wattle and pine species (e.g. clones/hybrids most commonly used, clones/hybrids planted in optimal sites).
2. To address shortcomings in the availability of leaf area index information for different SFRA species, clones and hybrids.
3. To improve existing tools used for the estimation of the impacts of SFRA through the inclusion of improved soils data and baseline land cover data, as well as the inclusion of the latest process results related to water use (i.e. evapotranspiration) of SFRA clones, hybrids and species.

The outcomes, findings and products of the project are comprised of two final reports. This document details the research undertaken to address Aim 1, which focuses on the improved water use estimation of

SFRA species, while the other deliverable speaks to Aims 2 and 3 and documents the SFRA Utility. Initially the project included an aim 'to expand the knowledge on the water use of different stand densities', however, it was recommended at a stakeholder workshop, and support by the reference group, that this aim was beyond the reach of the project and should not be a focus of the project.

## 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, water use by 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* specie 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 specie 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 specie 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. Secondly, this study will contribute towards the proposed Genus exchange regulation.

## 1.4 Outline of report and structure

An overview of the report 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 report, with the relevant part of the figure highlighted in grey. This report is written in a paper format, using a set of papers which are either intended for submission or submitted to a peer-reviewed journal.

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 inevitably, 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. 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 drop 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 to water-use, the total water use was estimated and 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 hybrid 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, total water use by each crop was estimated and the potential impact by each specie on groundwater reserves was investigated. Furthermore, the heat ratio method was calibrated using lysimeters to allow for the dataset to be corrected.

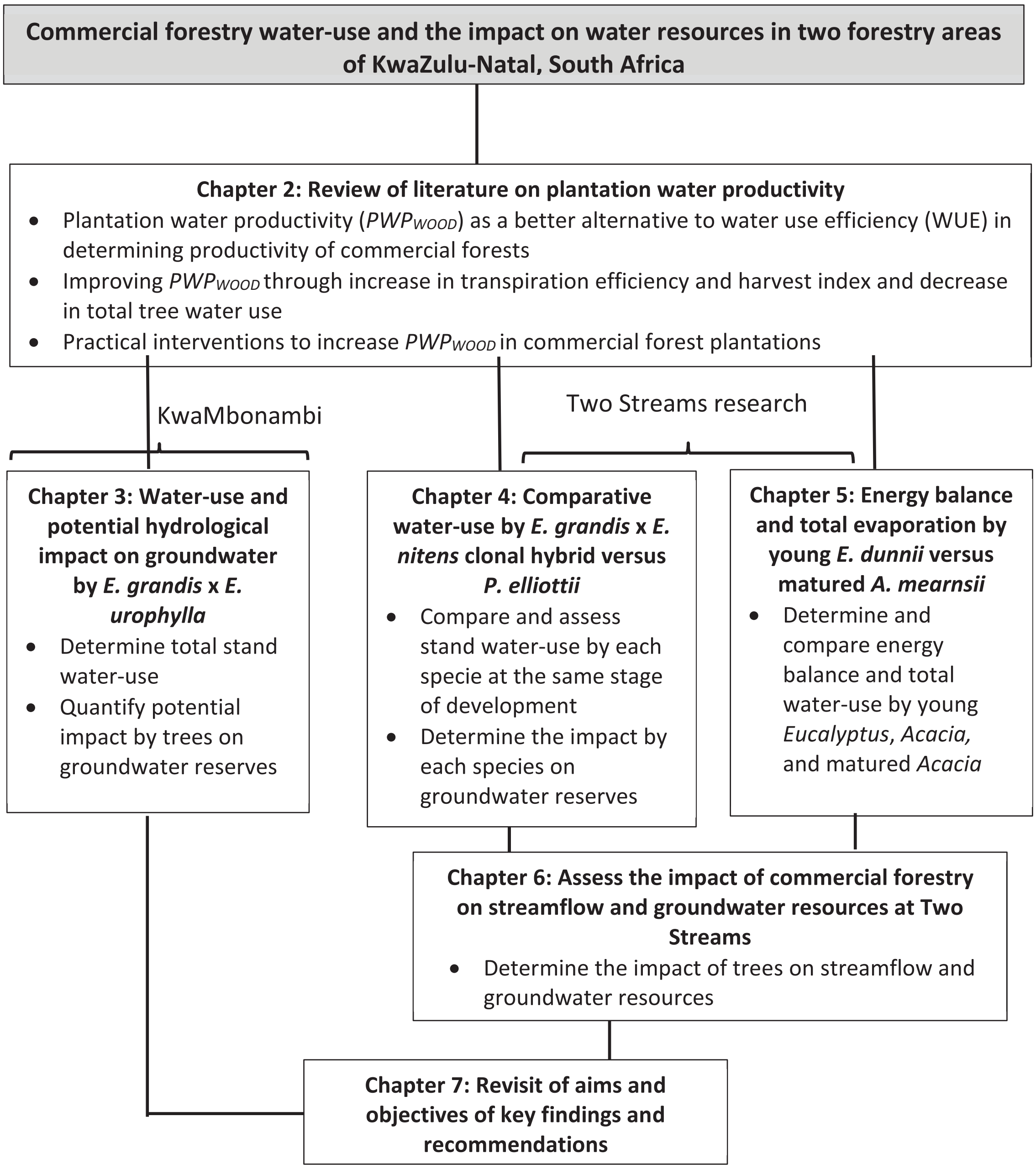


**Figure 1-2: A conceptual framework of the research**

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 investigates the potential impact of catchment afforestation with young *E. dunnii* and matured *A. mearnsii* on groundwater resources and streamflow. Streamflow gauging and depth to groundwater was monitored over two years for *E. dunnii* and 12 years for *A. mearnsii*.

The last chapter, Chapter 7, combines and synthesizes the research. The overall aim and objectives 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.

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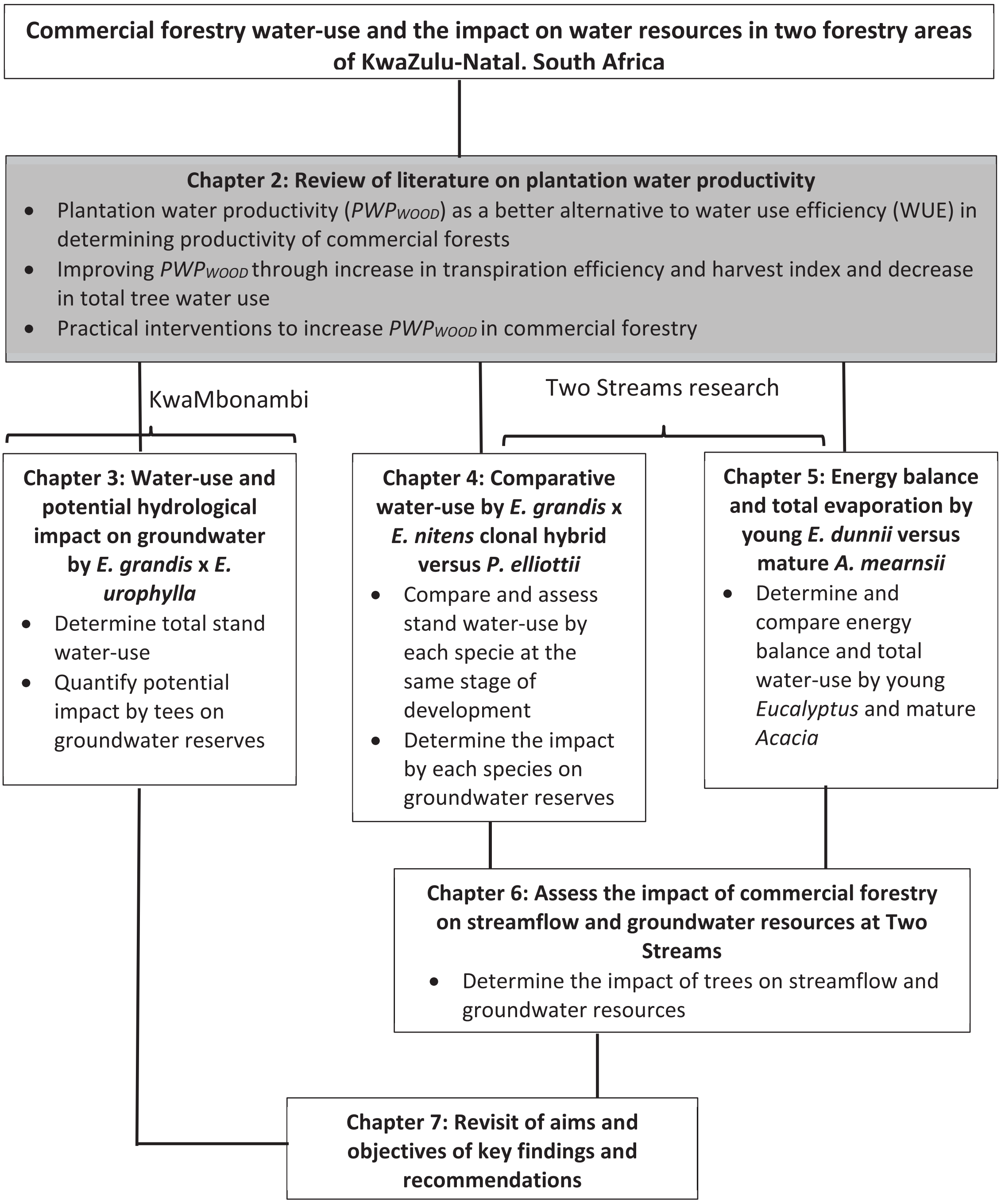
**Lead into Chapter 2**: Sets the scene and provides evidence locally and internationally of using plantation water productivity ($PW_{PWOOD}$) to enhance plantation yield of commercial forest plantations. The following literature review introduces the concept of $PW_{PWOOD}$ as a better alternative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



# CHAPTER 2. PLANTATION WATER PRODUCTIVITY AND NOT WATER USE EFFICIENCY (WUE) AS A MEASURE OF COMMERCIAL PLANTATION YIELD IMPROVEMENT: A REVIEW

**Nkosinathi D Kaptein[1*], Alistair D Clulow[1,2], Michele L Toucher[2,3] Colin S Everson[2,4], Ilaria Germishuizen[5], Steven B Dovey[6]**

[1]*Discipline of Agrometeorology, University of KwaZulu-Natal, Pietermaritzburg, 3201, South Africa*
[2]*Centre for Water Resources Research, University of KwaZulu-Natal, Pietermaritzburg, 3201, South Africa*
[3]*Grassland-Forests-Wetlands Node, South African Environmental Observation Network, Pietermaritzburg, 3202, South Africa*
[4]*Department Plant and Soil Sciences, University of Pretoria, Pretoria, South Africa*
[5]*Institute for Commercial Forestry Research, Pietermaritzburg, 3201, South Africa*
[6]*Shaw Research Institute, Sappi Forests, Howick, 3290, South Africa*

Corresponding author: Nkosinathi Kaptein, kapteinnd@gmail.com, *University of KwaZulu-Natal, Pietermaritzburg, 3201, South Africa*

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* Referencing adheres to format of Southern Forests: a Journal of Forest Science.

## 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*) and the harvest index (HI, the tree stemwood, 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 (*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 less 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, 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 government 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 (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):

$$WUE = {}^{D_M}/_{T} \tag{2.1}$$

where, $D_M$ is the total dry matter accumulated by a tree 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 (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):

$$W = T \times TE_{DM} \times HI \tag{2.2}$$

where, $TE_{DM}$ is the transpiration efficiency of accumulated dry matter (g 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 dry matter $kg^{-1}$ $H_2O$). The $W$ can be converted to wood volume (V, $m^3$) by dividing $W$ with the specific gravity of wood. The total plantation water use (ET, mm) is the sum of $T$, total evaporation from the soil ($Es$, mm) and canopy interception ($C_I$, mm) losses. Based on this information, the $PWP_{WOOD}$ (g wood $kg^{-1}$ $H_20$) can simply be calculated as:

$$\frac{Total\ dry\ stemwood}{Total\ plantation\ water\ use} \tag{2.3}$$

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):

$$PWP_{wood} = \frac{T \times TE_{DM} \times HI}{T + Es + C_I} \tag{2.4}$$

Equation 2.4 can be simplified to Equation 2.6

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

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

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 *PWPWOOD* 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 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 $PWP_{WOOD}$.

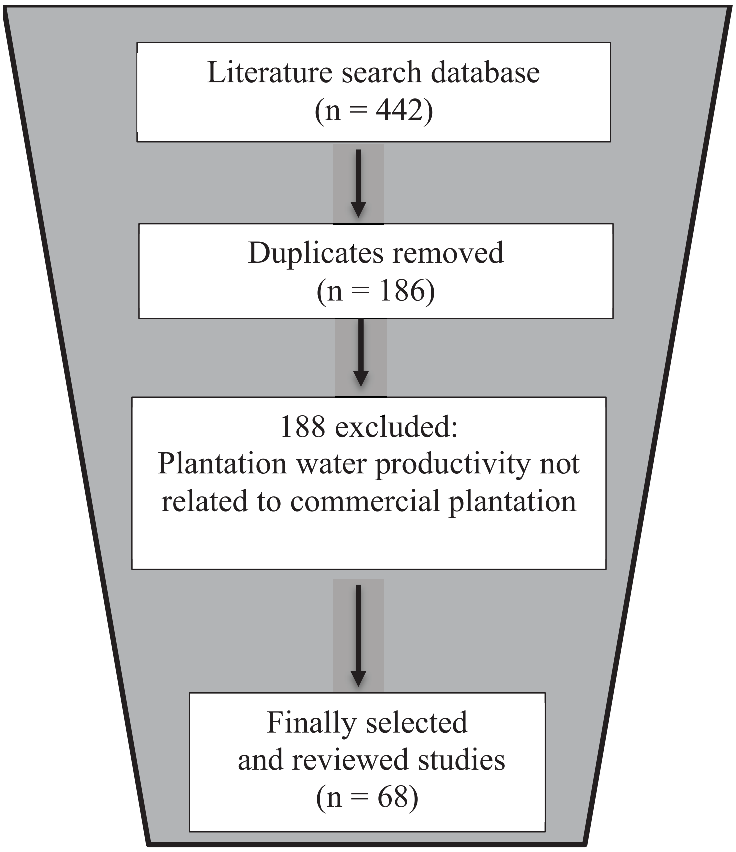


**Figure 2-1: The schematic diagram showing the process followed in the literature search using various databases.**

## 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 *Is,* $CO_2$ in the air, air temperature (Tair), soil water and nutrients. At a given site, little can be done to optimise *Is*, $CO_2$ and Tair directly. 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:

$$TE = \frac{V\rho}{T} \tag{2.7}$$

where, V is the volume of biomass produced per ground area ($m^3$ $m^{-2}$) and $\rho$ 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).

From Equation 2.6, significantly increasing *TE* greater than $1 + \left(\frac{E_{s+C_I}}{T}\right)$, will result in an improvement 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 (i.e. *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 a mechanical harvesting technique.

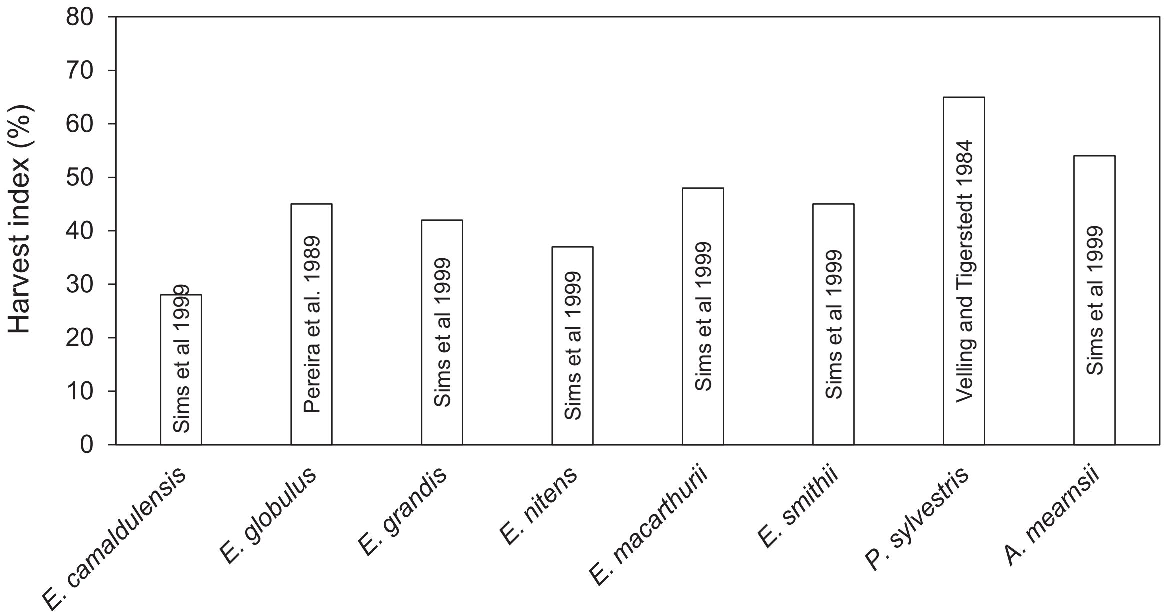


**Figure 2-2: The harvest index for different Eucalyptus, pine and Acacia species**

## 2.7 Tree water losses

In a typical forest plantation, soil water can be lost through *Es*, $C_l$ 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 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 $PWP_{\mathrm{WOOD}}$. For example, doubling *T*, while keeping all other variables constant increases $PWP_{\mathrm{WOOD}}$ 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 *Es*.

**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

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 (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. Interception loss depends on precipitation characteristics and factors that affect *ET* such as Tair, wind speed, *Is* and relative humidity. Canopy 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 $C_I$ losses of 14.9% by five-year-old *E. grandis*, 27.7% by five-year-old *Acacia mearnsii* and 21.4% by sixteen-year-old *P. patula*. 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 canopy interception 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 rainfall (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 Practical practices to enhance plantation 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 cultural 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 (i.e. 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 Tair (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 specie for 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 specie 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 specie of choice (Morris, 2022). These changes have been associated with statistically significant improvements in crop yields of 2 to 47% depending on the specie 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 specie, while *E. macarthurii* was found to be the most tolerant to frost (Morris, 2008).

In addition, matching the specie to a site is assist 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 specie 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 demonstrateed 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/…

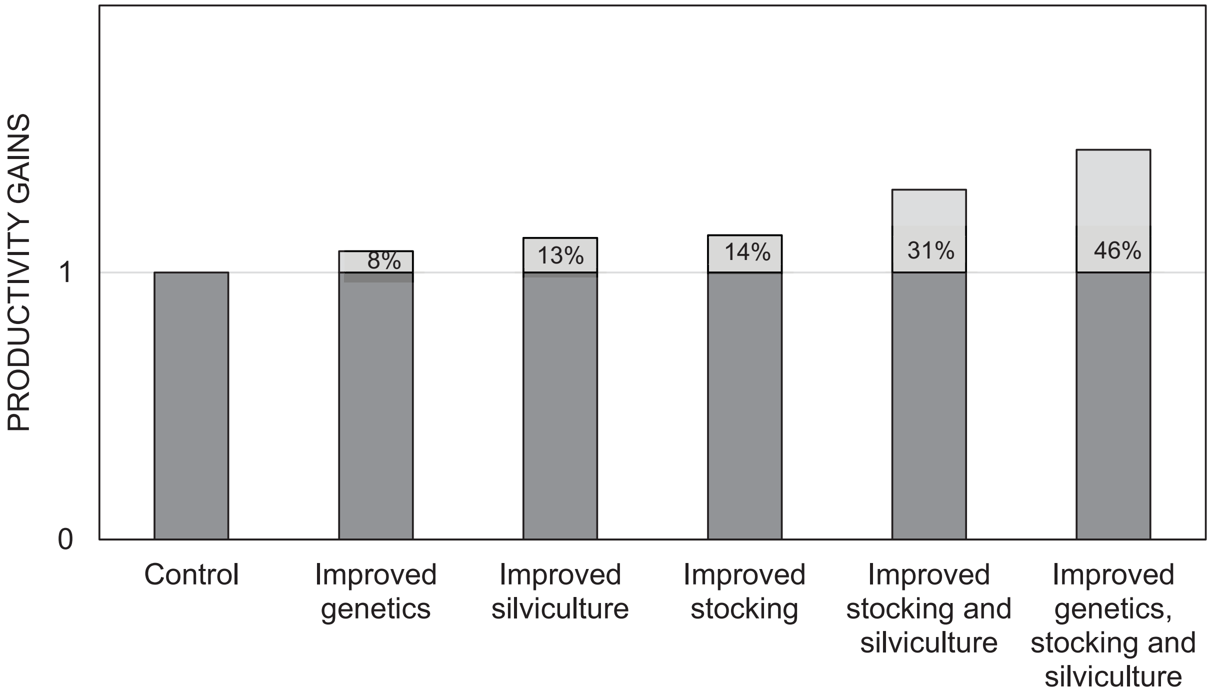


**Figure 2-3: Middle of the rotation yield gains as influenced by tree improvements (genetics), intensive silviculture, stocking, a combination of stocking and intensive culture and genetics plus stocking plus intensive silviculture. Reproduced from Boreham and Pallet (2009).**

## 2.9 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 $PWP_{\mathrm{WOOD}}$ 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 $PWP_{\mathrm{WOOD}}$ has many benefits.

## 2.10 Acknowledgements

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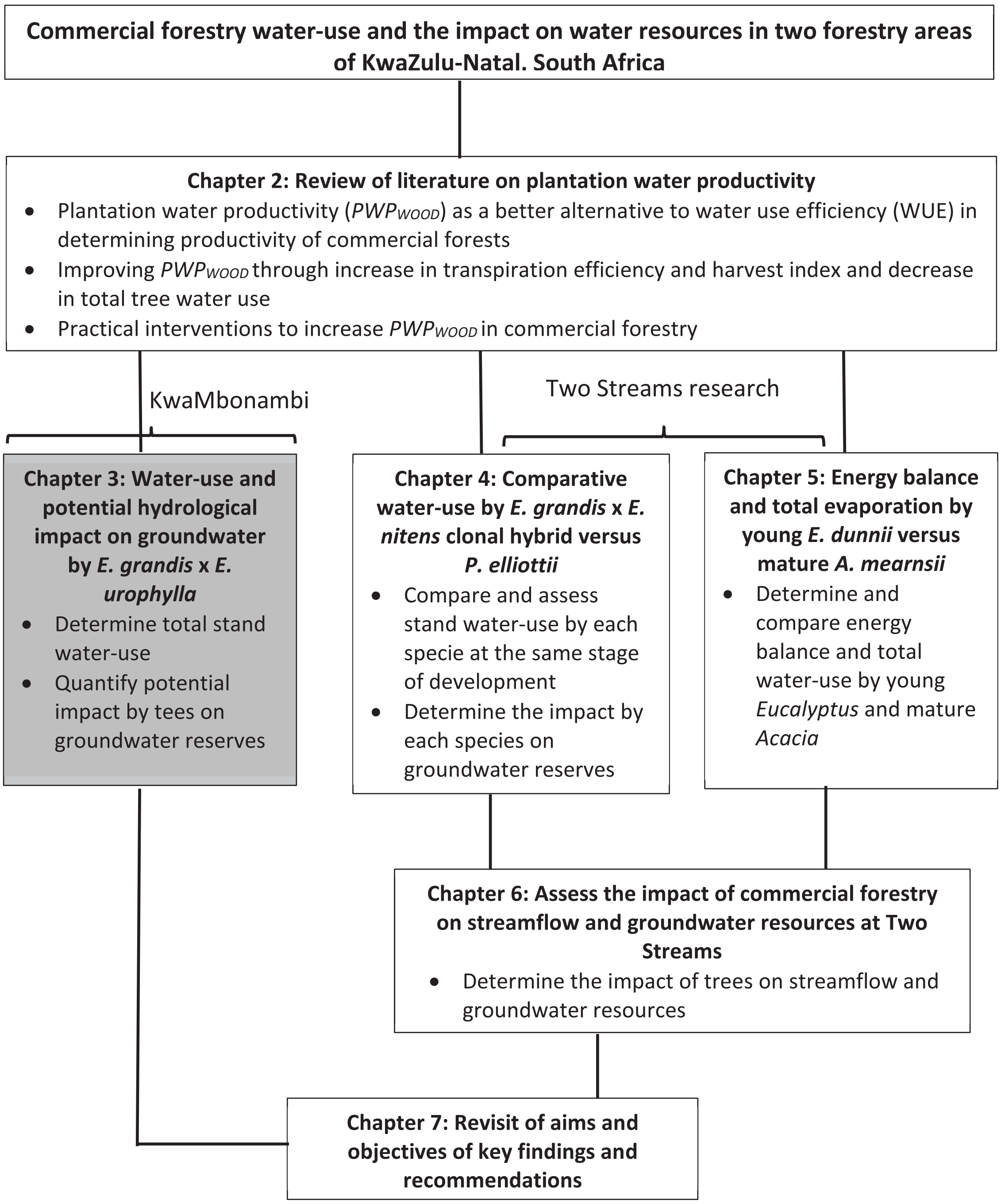
**Lead into Chapter 3**: While previous *Eucalyptus* tree water use studies in humid northern Zululand of KwaZulu-Natal have made a significant contribution on stand water use and hydrological implications over the years, none have measured water use by fast growing *Eucalyptus grandis* x *E. urophylla* clonal hybrid (*GU*), which is the most planted *Eucalyptus* specie 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 BY FAST-GROWING NINE-YEAR OLD E. GRANDIS X E. UROPHYLLA HYBRID, NORTHEN ZULULAND, SOUTH AFRICA

**Nkosinathi D. Kaptein[1], Colin S. Everson[2,3], Alistair D. Clulow[1,2], Michele L. Toucher[2,4], Ilaria Germishuizen[5]**

[1]*Discipline of Agrometeorology, University of KwaZulu-Natal, Pietermaritzburg, 3209, South Africa*
[2]*Centre for Water Resources Research, University of KwaZulu-Natal, Pietermaritzburg, 3209, South Africa*
[3]*Department Plant and Soil Sciences, University of Pretoria, Pretoria, South Africa*
[4]*Grasslands-Forests-Wetlands Node, South African Environmental Observation Network, Pietermaritzburg, 3201, South Africa*
[5]*Institute for Commercial Forestry Research, Scottsville, 3201, South Africa*

Corresponding author: Nkosinathi Kaptein, kapteinnd@gmail.com, *University of KwaZulu-Natal, Pietermaritzburg, 3201, South Africa*

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* Referencing style conforms to Water SA.

## 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. Additional measurements of leaf area index (LAI), quadratic mean diameter 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 (15.5 L) and 3.3 mm day$^{-1}$ (19.7 L) for 2019’ 20 and 2020’ 21 years, respectively, corroborating with previous studies. Annual sapflow and ET were higher than previous studies on *Eucalyptus* of a similar age, probably due to significantly high rainfall events. Sapflow accounted between 78-87% of annual rainfall on both measurement years. 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. Monthly transpiration crop factors were derived from transpiration and the FAO reference evaporation, which provides a convenient and transferable method of estimating tree water use from meteorological data. The total water use (ET) of the stand was calculated using published values of soil evaporation and canopy rainfall interception to further understand the overall impact of forestry on local water reserves. The estimated ET was 18 and 12% greater than rainfall for 2019’ 20 and 2020’ 21, respectively, however, the *GU* did not show any signs of water stress, regardless of very low SWC. It is inferred that the *GU* trees were able to access groundwater reserves, with the possible long-term consequence of streamflow reduction and depletion of groundwater reserves. Plantation water productivity ($PWP_{WOOD}$) was calculated as a ratio of stand volume to ET. The $PWP_{WOOD}$ was higher than other published studies, attributed to a very high productive potential of the study site together with limited soil water availability, forcing trees to produce more wood per drop of water used. Further research is suggested with long-term measurements of sapflow, ET, soil water storage and an isotope study to partition the sources of water use by the *GU* trees to confirm the use of ground 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 have several benefits to the environment that negative impacts (Casson, 1997), for example commercial forests improve soil infiltration (Van Dijk and Keenan, 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 specie 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. Due to the importance of ET in understanding the overall impact of *Eucalyptus* on water resources, total water use was estimated using published values of soil evaporation and canopy rainfall interception from similar studies (ET = transpiration (T) + canopy interception ($C_I$) + soil evaporation (Es)). 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.

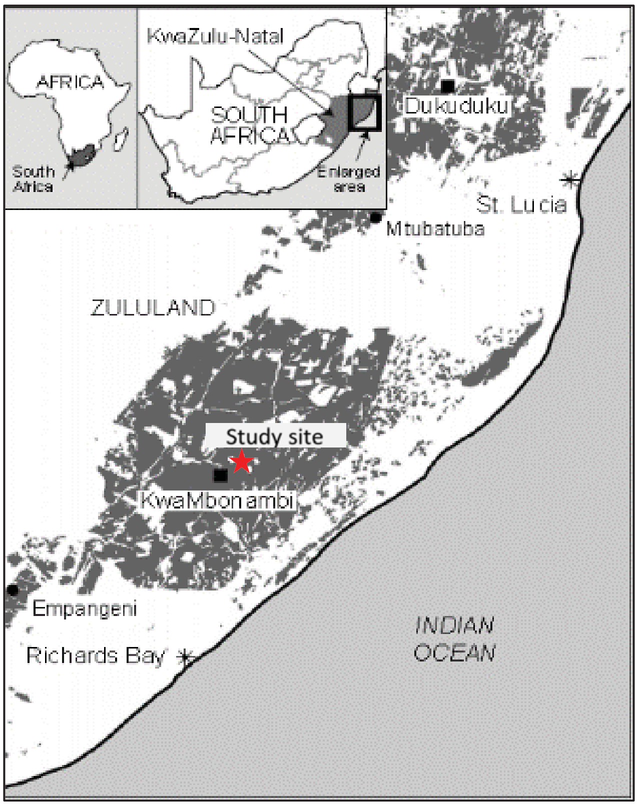


**Figure 3-1: Location of KwaMbonambi study site in the north-eastern area of KwaZulu-Natal. Grey areas indicate the distribution of commercial forestry areas.**

**Table 3.1: Characteristics of the Kwambonambi study site**

| Characteristics | *E. grandis* x *E. urophylla* site |
|---|---|
| Soil lithology | Arenite |
| Soil form | Fernwood |
| Soil texture | Sand |
| Bulk density (g. $cm^3$) | 0.88 |
| Mean annual precipitation (mm) | 1260 |
| Mean annual temperature (°C) | 21.9 |
| Altitude (m) | 24 |

### 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 (Tair, ºC), relative humidity (RH, %), solar radiation (Is, MJ $m^{-2}$), wind speed (WS, $m.s^{-1}$), vapour pressure deficit (VPD, kPa), FAO reference evaporation (FAO ETo, mm) and rainfall (mm) from this station were available for download online at: https://sasri.sasa.org.za/rtwd/541/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). 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 (cm), and $V_1$ and $V_2$ are temperature increases in upstream and downstream probe (°C) at equidistant points from the heater probe. Soil water content (SWC) was measured in the upper 0.60 m of the soil profile (0.2-, 0.4- and 0.6-m depth) using CS616 sensors (Campbell Scientific Inc.) (Supplementary Figure 3.4). Measurements were taken hourly to coincide with the sapflow measurements.

**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. 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 weighted as per individual tree contribution to a stand.

### 3.3.4 Estimated total water use

Water loss from $C_I$ and Es were not measured in this study, however, these components are important and must be considered when measuring species water use and evaluating the impact it has on water resources. These factors are highly variable, making it difficult to generalize as they can depend on a variety of factors such as rainfall intensity, the LAI, weather variables and canopy architecture (Cannell, 1999; Maier et al., 2017). Canopy interception was estimated using published data, from a study on *Eucalyptus* of a similar age (Bulcock et al., 2012a; Benyon and Doody, 2015; Momolli et al., 2019), which measured a mean $C_I$ of 14% of total annual rainfall. Studies by Bulcock et al. (2012a), Bulcock et al. (2012b) and Benyon and Doody (2015) measured the range in Es to be 13.4-29.0% of total rainfall. The Es in our study was most likely within this range based on LAI values of the *GU* site which compared well with other *Eucalyptus* studies (O'Grady et al., 1999, Benyon and Doody, 2015).

### 3.3.5 Growth measurements

Measurements of DBH (cm) were conducted once every two months 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 (Dq, cm) was calculated for 48 trees using (Curtis and Marshall, 2000):

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

Tree heights (h, cm) for the 48 trees were measured at the same time 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)

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

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

$$V = \frac{10\,000}{A}\sum_{i=1}^{n} vi \tag{3.4}$$

where $vi$ was the productive volume of the $i$th tree and $A$ was the total area (m$^2$) of the plot where measurements were conducted

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 Transpiration crop coefficient

The Penman-Monteith method is an internationally recognised technique of calculating FAO reference evaporation (FAO ETo) and this method is popular for reasons including, calculating a crop factor:

$$Kc = \frac{ET}{ETo} \tag{3.5}$$

where Kc is a crop factor. The ET losses are made of T, Es and I, however, in commercial forest plantations, T losses are significantly greater (> 80%) than Es and I, particularly after canopy closure (Soares and Almeida, 2001). Therefore, Equation 3.5 can be adjusted to calculate transpiration crop efficient ($K_T$):

$$K_T = \frac{T}{ETo} \tag{3.6}$$

The calculated $K_T$ enables research in the field of hydrology to estimate T from the automatic weather station variables, which are easy to acquire. In this study, monthly $K_T$ values were calculated for two measurement periods (2019’ 20 and 2020’ 21).

### 3.3.7 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 ET for 2019'20 (October 2019 to September 2020) and 2020'21 (October 2020 to September 2021) hydrological years. The Es and $C_I$ were not measured in this study and were estimated from rainfall using published studies from similar age *Eucalyptus* under similar environmental conditions.

### 3.3.8 Statistical analysis

The statistical analysis was performed using the R statistical computing software (R Development Core team 2008). The analysis was conducted using two approaches, first, a simple linear regression model was used to establish a relationship between sapflow and growth parameters (T, Dq, 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), with sapflow as the response variable and meteorological data (Tair, RH, Is, WS, rainfall, FAO ETo, VPD and SWC) 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, which is calculated as the loss of accuracy when a variable is removed from the pool of predictors.

## 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 Is on clear days in winter was approximately 14 MJ $day^{-1}$, while in summer, 31.5 MJ $day^{-1}$ for 2019' 20 and 30.6 MJ $day^{-1}$ 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 Tair in summer for both years was 38.8 °C, which is an indication of warm summer months. Minimum daily Tair 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 Tair and Is, although 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.

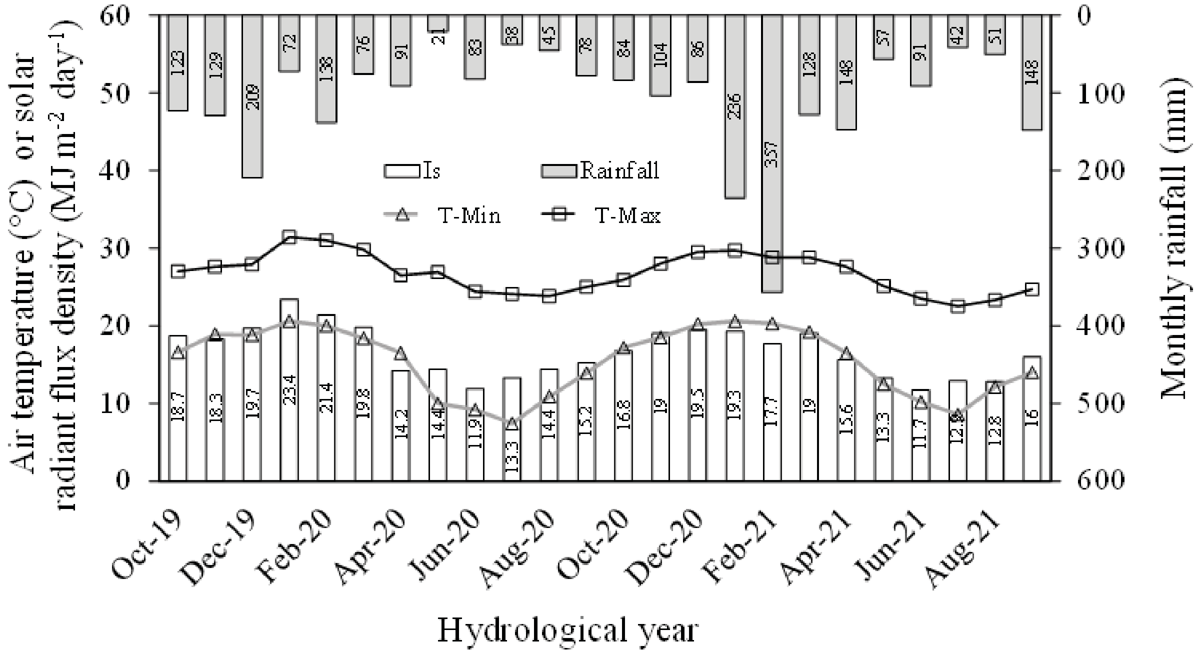

**Figure 3-2: Monthly values of mean daily maximum (T-Max) and minimum (T-Min) air temperatures (°C), mean daily radiant flux density (MJ m$^{-2}$ day$^{-1}$) and corresponding total monthly rainfall (mm) measured near KwaMbonambi from October 2019 to September 2021.**

**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.

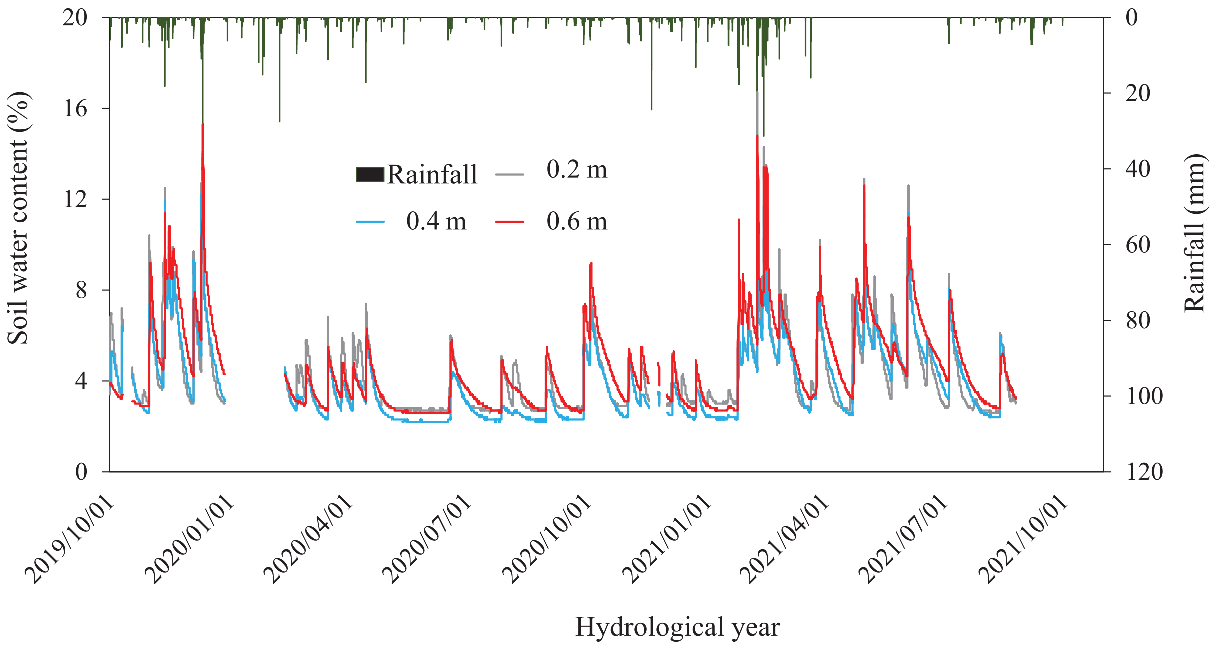


**Figure 3-3: The mean daily soil water content (%) measured at different soil depths (0.2 m, 0.4 m and 0.6 m) with corresponding rainfall over a duration of October 2019 to September 2021. Missing data typically occurred due to instrument failure or power interruption.**

### 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 (15.5 L) and 3.3 mm (19.7 L) day$^{-1}$, respectively. Daily peak summer sapflow of 6.5 mm (38.3 L) in 2019' 20 increasing to 6.8 mm (41 L) in 2020' 21 were measured in the middle of October for both years, which coincided with high values of Is and Tair. During the winter months (May to August), sapflow measurements were between 0.6-1.6 mm day$^{-1}$ (3.6-9.0 L day$^{-1}$) in 2019' 20, while 2020' 21 experienced 2.4-3.1 mm day$^{-1}$ (14.2-18.5 L 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 is available, the trees are able to use it.

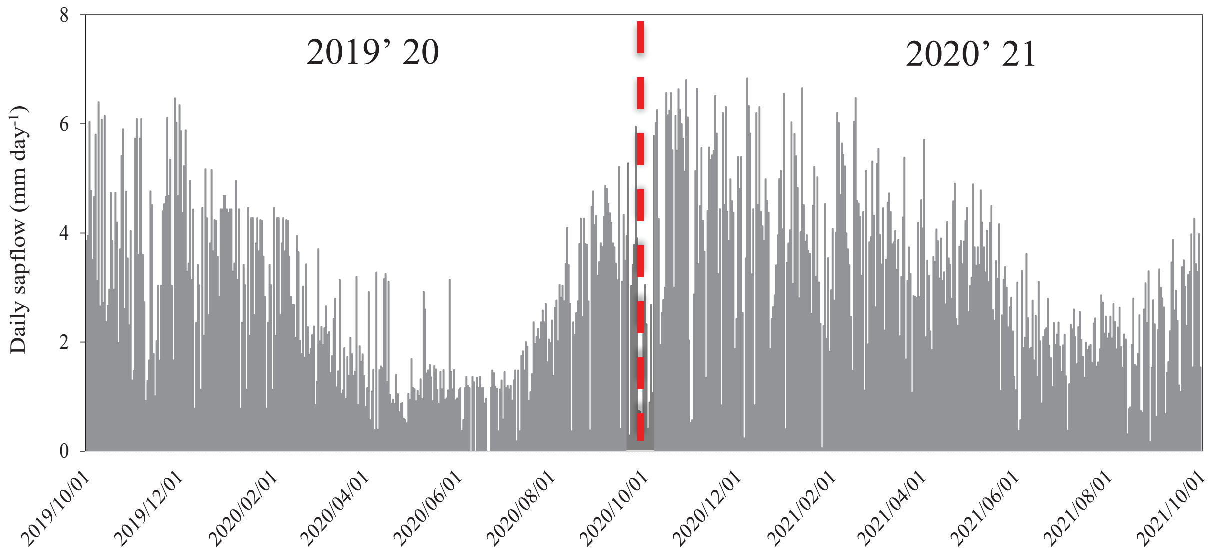


**Figure 3-4: Daily sapflow volumes (mm day$^{-1}$) measured using the heat ratio method of heat pulse velocity technique on a nine-year-old *Eucalyptus grandis* x *Eucalyptus urophylla* clonal hybrid over 2019' 20 (October 2019 to September 2020) and 2020' 21 (October 2020 to September 2021) hydrological years.**

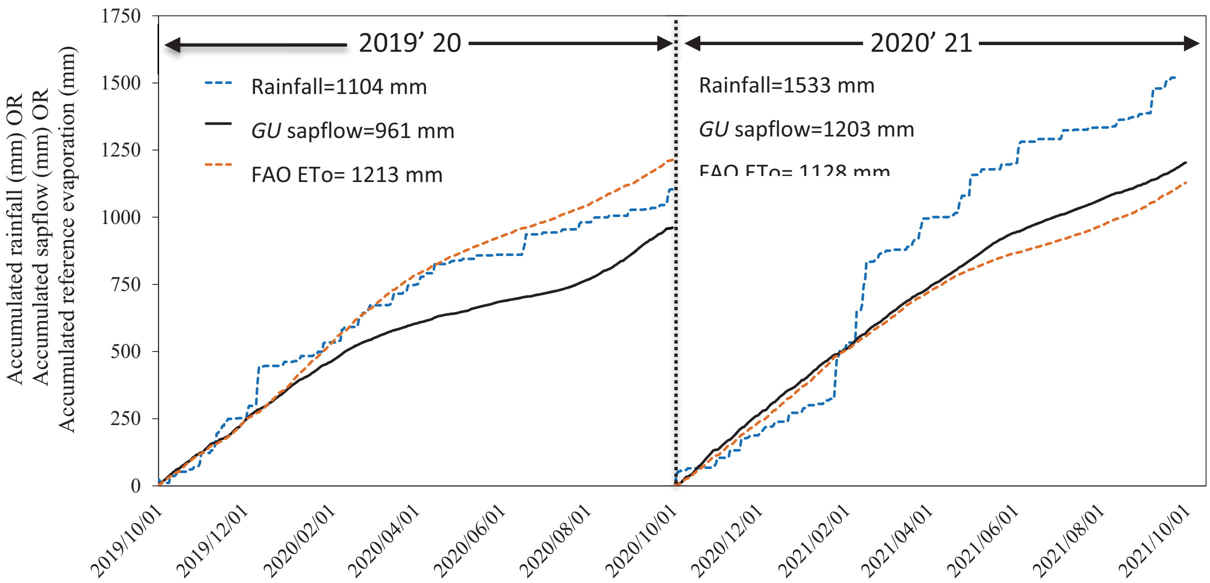


**Figure 3-5: The accumulated sapflow (mm), rainfall (mm) and FAO reference evaporation (ETo, mm) for 2019' 20 (October 2019 to September 2020) and 2020' 21 (October 2020 to September 2021) hydrological year.**

The simple regression on monthly sapflow were considered with growth parameters (Dq, 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, Is, SWC at 0.6 m, Tair 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.

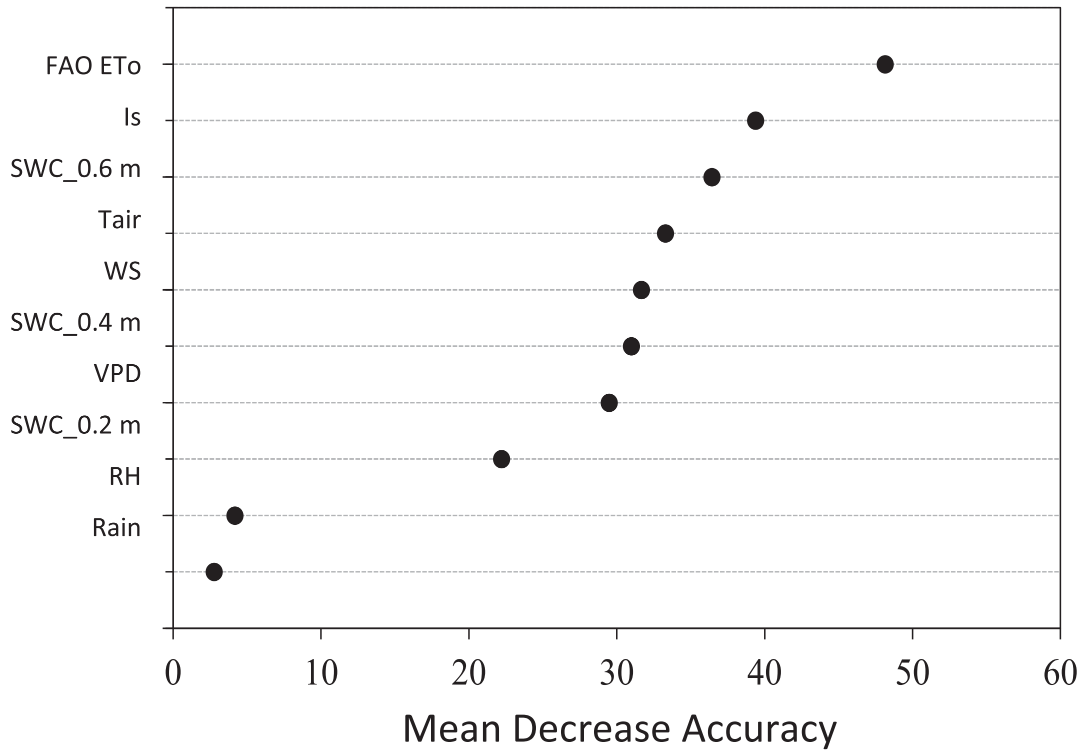


**Figure 3-6: Variable importance plot from the random forest model for FAO reference evaporation (FAO ETo), solar radiation (Is), air temperature (Tair), vapor pressure deficit (VPD), wind speed (WS), relative humidity (RH), soil water content (SWC) at a soil depth of 0.2-, 0.4- and 0.6 m. Mean Decrease Accuracy is a measure of how much the model error increases when a particularly variable is randomly permuted.**

### 3.4.4 Estimated total water use

The estimated annual $C_l$ for our study was 155 and 215 mm for 2019' 20 and 2020' 21 years, respectively. Based on the mean Es of 21% (from Es range: 13.4% to 29%), Es estimates from this study amounted to 234 mm for 2019' 20 and 325 mm for 2020' 21 years. The annual estimated ET for *GU* in 2020' 21 was 1743.1 mm and in 2019' 20 was 1350.3 mm, based on rainfall of 1104.0 and 1532.8 mm for 2019'20 and 2020' 21 years, respectively. The ET was 18% and 12% higher than the rainfall in the 1st and 2nd years respectively. It is evident from these estimated values and measured data that this site did not have sufficient rainfall to meet total evaporative demands and trees most likely accessed stored soil water from previous wet years held deep in the soil profile or water from lateral flows from surrounding areas.

### 3.4.5 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 (Dq 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.

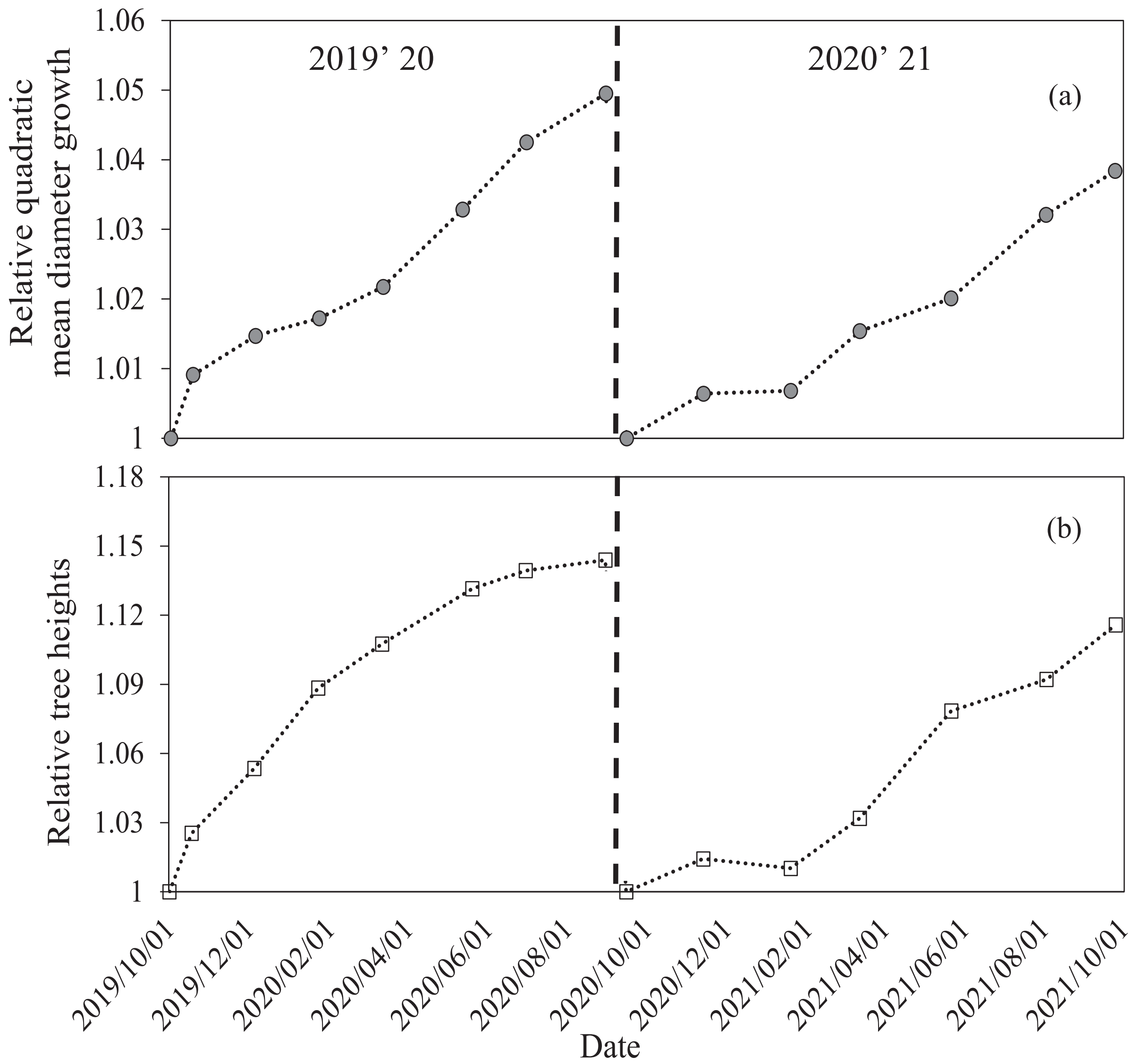


**Figure 3-7: (a) Relative quadratic mean diameters (calculated as a ratio of monthly diameters relative to initial diameter measurement, unitless) measured using manual dendrometers bands and (b) Relative tree heights (calculated as a ratio of monthly tree heights relative to initial tree height measurement, 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.**

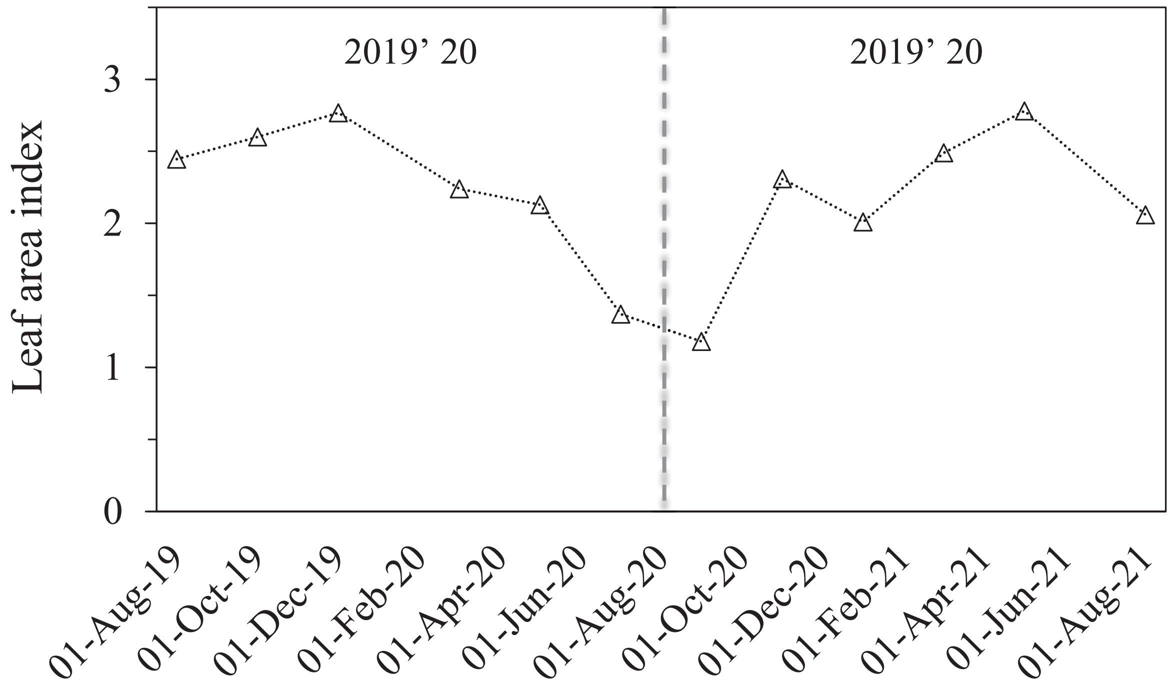


**Figure 3-8: A leaf area index of *Eucalyptus grandis* x *Eucalyptus urophylla* clonal hybrid measured in KwaMbonambi, Zululand from August 2019 to August 2021.**

### 3.4.6 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 ET in 2020’ 21 that was significantly ($p < 0.05$) greater than 2019’ 20 (2019’ 20=1350.3 mm vs 2020’21=1743.1 mm).

### 3.4.7 Transpiration crop coefficient

The $K_T$ was calculated at a daily interval from the T and FAO ETo, using Equation 3.6, and thereafter averaged for each month of the measurement period (Figure 3-9). When $K_T$ = 1, the T equals to FAO ETo. However, a $K_T$ of <1 or >1 indicated that the *GU* T was less than or greater than the FAO ETo. In 2019’ 20, T exceeded FAO ETo ($K_T$ >1) in October, November and December of 2019 and August and September 2020 (Figure 3-9a). From January to July of 2020, FAO ETo exceeded the T producing a KT range of 0.7 to 0.9. By comparison, $K_T$ in 2020’ 21 was equal to or greater than 1 (range: 1.0 to 1.7) throughout the year, except during a distinct period in January, August and September of 2021 where $K_T$ was 0.9, 0.8 and 0.9, respectively (Figure 3-9b). This is an indication that T for *GU* was greater that FAO ETo for most of the year.

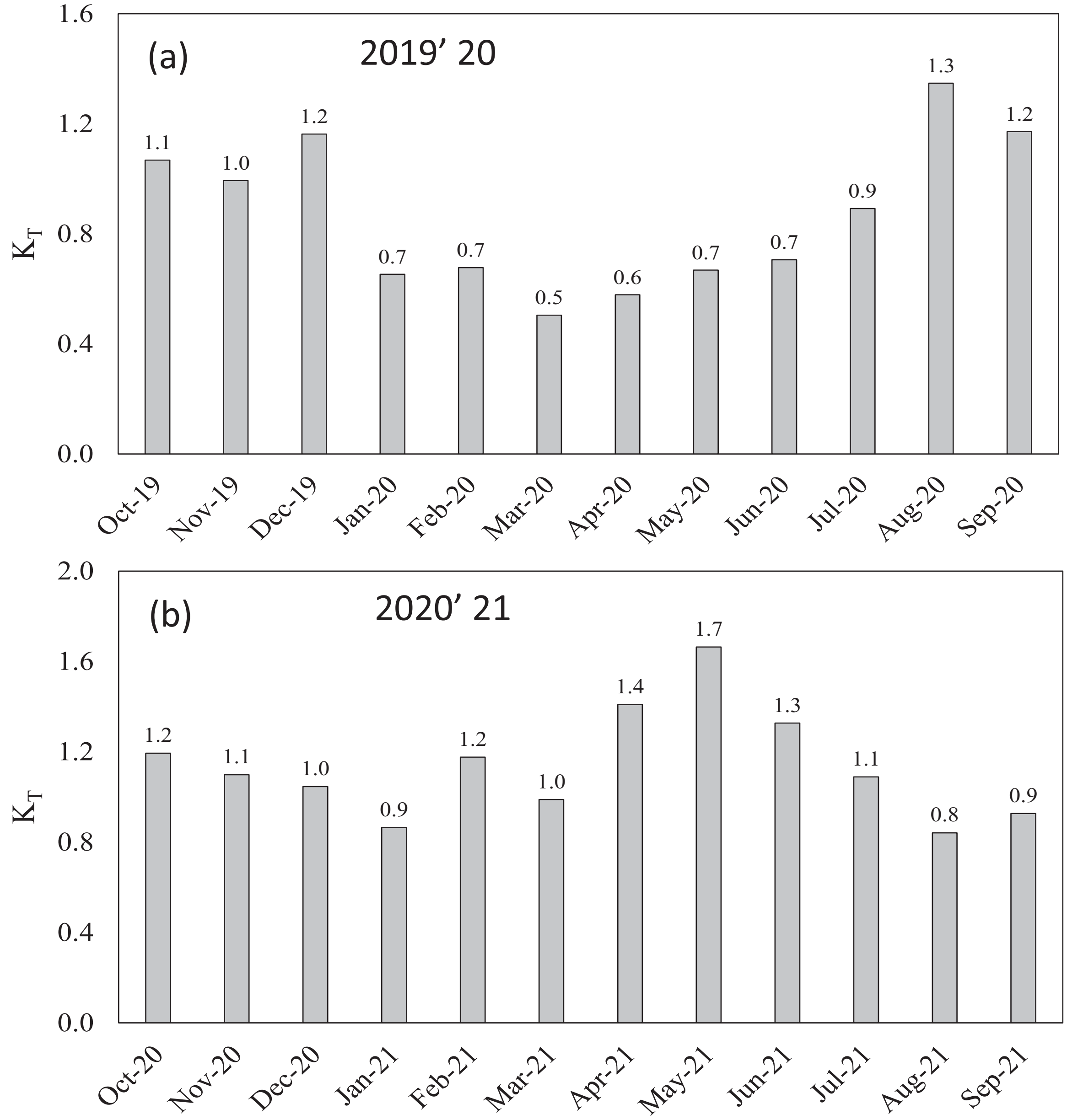


**Figure 3-9: The monthly transpiration crop coefficient ($K_T$) of a nine-year-old *Eucalyptus grandis* x *Eucalyptus urophylla* clonal hybrid in KwaMbonambi, Zululand for (a) 2019’ 20 and 2020’ 21 measurement period.**

## 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, Is and WS were all as expected with no unusual weather conditions over the study period.

### 3.5.2 Sapflow

The mean sapflow for *GU* increased from 2.7 mm day$^{-1}$ (15.5 L) in 2019' 20 to 3.3 mm day$^{-1}$ (19.7 L) in 2020' 21, reaching a peak of 6.5 (38 L) and 6.8 (48 L) mm 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 day$^{-1}$ on less productive sites, increasing to 30-64 L day$^{-1}$ on highly productive sites. Everson et al. (2019) reported summer mean sapflow of 18.04 L day$^{-1}$ decreasing to 7.76 L 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 day$^{-1}$ with peak of 49 L day$^{-1}$. Results from these studies compared to our study results suggest that the sapflow of the genetically improved *GU* is similar to its mother plant (*E. grandis* or *E. urophylla*).

Though the rates of daily sapflow agreed with other studies in KwaMbonambi (Dye et al. (1997), the annual accumulated sapflow (2019' 20=961.3 mm, MAP=1104.4 mm and 2020' 21= 1203.1 mm, MAP=1532.8 mm) was greater than other studies in the northern Zululand area and in our study the sapflow accounted for 87 and 78% of annual rainfall for 2019' 20 and 2020' 21 years, respectively. The results were much lower (43%) in a study by Dye et al. (2004) where they measured annual sapflow of 601 mm from a seven-year-old *E. grandis* x *camaldulensis* clonal hybrid in KwaMbonambi (MAP=1390 mm), however, this was a less productive site, which may have contributed to low sapflow rates. Similarly, a water use study in southern China (Morris et al., 2004) reported a *E. urophylla* annual sapflow of 542 mm, where the MAP was 1539 mm and the sapflow in this case only 35% of the MAP. These differences in sapflow against rainfall will clearly have impacts on the local water balance with less water being available for streamflow as well as soil and ground water recharge.

Sapflow 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, Is, SWC (measured at a depth of 0.6 m) and Tair 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 Is 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 Is, meaning that Is played a significant role in FAO calculation. These results suggest that one climatic variable, Is, can be solely used as an input in commercial forest plantation models to estimate sapflow rather than FAO ETo which requires more than one meteorological variable to calculate.

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.

The $K_T$ values followed a seasonal pattern in 2019' 20 where T exceeded FAO ETo on most summer months, while the opposite was observed in winter months. The high T is expected on actively growing *Eucalyptus* trees in summer months when SWC is not limiting and when Is is very high, with a steady decrease in T during winter responding to low plant available water and Is (Soares and Almeida, 2001; Kostner et al., 2002; Delzon and Loustau, 2005). The $K_T$ values in 2020' 21 were greater than one for most of the year, which was probably caused by a 30% greater rainfall in 2020' 21 than 2019' 20. The derived $K_T$ values for *GU* in KwaMbonambi will assist in estimating T using AWS variables.

### 3.5.3 Total water use

The estimated ET values in our study were much higher than *Eucalyptus* ET measurements across other regions of the world (Table 3.4), however, statistically similar to FAO ETo in 2019' 20, while in 2020' 21 ET was 35% greater than the FAO ETo. There was a shortage in the water balance between input (water supply by precipitation) and losses of 246 mm (18.2% of rainfall) and 210 mm (12% of rainfall) in 2019' 20 and 2020' 21, respectively. This deficit is seen in the low values of SWC, particularly in winter (a peak of 7.5% in 2019' 20 and 13% in 2020' 21) indicating that the sandy soils were dry and had poor water holding capabilities. However, *GU* did not show any visible signs of water stress, a common response reported by other studies (Tyree et al., 1988), throughout the monitoring period, which may be a strong indication that trees 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. *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). The tap root has been reported to be as deep as 28 m (Dye, 1996). For example, Soares and Almeida (2001) indicated that *E. grandis* used soil water at the soil surface during the wet season to meet ET demands. In dry periods, rates of T decreased, and water was supplied from underground water resources to balance T and maintain water potential above the critical limit of stomatal closure (approximately -1.2 MPa). This flux of water was quantified to be close to 1 mm day$^{-1}$ and used to keep trees alive until the high soil strata were again recharged by rainfall in the wet season. In our study the dry season daily average sapflows were 1.2 mm and 2.7 mm in 2019' 20 and 2020' 21, respectively. The dry soils and little to no rainfall, are strong indicators that the trees are sourcing water from the deeper soil profile.

**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 | Location | Species | Annual rainfall (mm) | Annual T (mm) | Annual ET (mm) |
|---|---|---|---|---|---|
| Our study | South Africa, KwaMbonambi | *E. grandis x E. urophylla* | 1104 and 1533 | 961 and 1203 | 1350 and 1743 |
| Dye et al. (1997) | South Africa, KwaMbonambi | *E. grandis clones* | 1107 | 601, 608, 740, 777, 1412, 1423 | – |
| Almeida et al. (2007) | Brazil | *E. grandis* | 1147 | 885 | 1092 |
| Lane et al. (2004) | China | *E. urophylla* | 1525-2226 | 498-548 | 667-833 |
| Engel et al. (2005) | Argentine | *E. camaldulensis* | 803 | 348-817 | 487-925 |
| Macfarlane et al. (2010) | Australia | *E. marginata* | 1135-1235 | 231-505 | 1236-1302 |
| Silveira et al. (2016) | Uruguay | *E. globulus* | 792-2523 | – | 551-1253 |

### 3.5.4 Potential implication of results on water resources

There has been much controversy around the impact of *Eucalyptus* plantations on the water balance both locally and regionally. Some authors have reported a negative impact (Almeida et al., 2007), while some studies found no significant negative impacts (Lane et al., 2004). Based on estimated ET values over a 2-year period, the results from our study indicate a negative effect due to rainfall being < ET and a possibility of tree roots accessing groundwater resources, which is shown by continued sapflow during the dry season when upper soil water levels were very dry. Access to deep water reserves by trees will most likely deplete groundwater causing a reduction in streamflow especially during dry season low flows, hence impacting downstream water users. In future it would be beneficial to measure ET directly or to improve the estimates of Es and $C_l$ that were used in this study. Using this ET data to model the hydrology would give a comprehensive picture of the water balance of the area. In this particular area, it would be an advantage to place emphasis on long-term measurement of T, ET, soil water storage due to variable annual precipitation including well documented droughts and floods in the area. Isotope studies to separate water use of trees into soil water and groundwater and understand how water partitioning responds to climate change and commercial plantation establishment over time would also be beneficial.

### 3.5.5 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 very productive. There are few studies that have quantified $PWP_{WOOD}$ in South Africa and international 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 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 heat ratio method (HRM). It has shown that water use measurements using the HRM provides reliable and continuous measurements but requires routine maintenance. Though our study site 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. In addition, ET was estimated using the actual T measurements, while $C_I$ and Es were estimates based on published data and it would be beneficial to confirm these measurements using actual ET values.

The model developed in this study indicated that FAO ETo, Is 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. In addition, the development of monthly $K_T$ values will assist in predicting T using AWS variables.

A conclusion from this study is that 1) water use by *GU* is not different from its mother plant, either *E. grandis* or *E. urophylla*, based on results from local (adjacent to study sites) and international studies conducted under similar conditions, suggesting that exchanging a genus from a *Eucalyptus* species to clonal hybrids will have similar implications on water resources 2) The eight-year-old *GU*, has a potential to access groundwater reserves during the dry season which may cause depletion of groundwater reserves, hence reduction in streamflow 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 ET 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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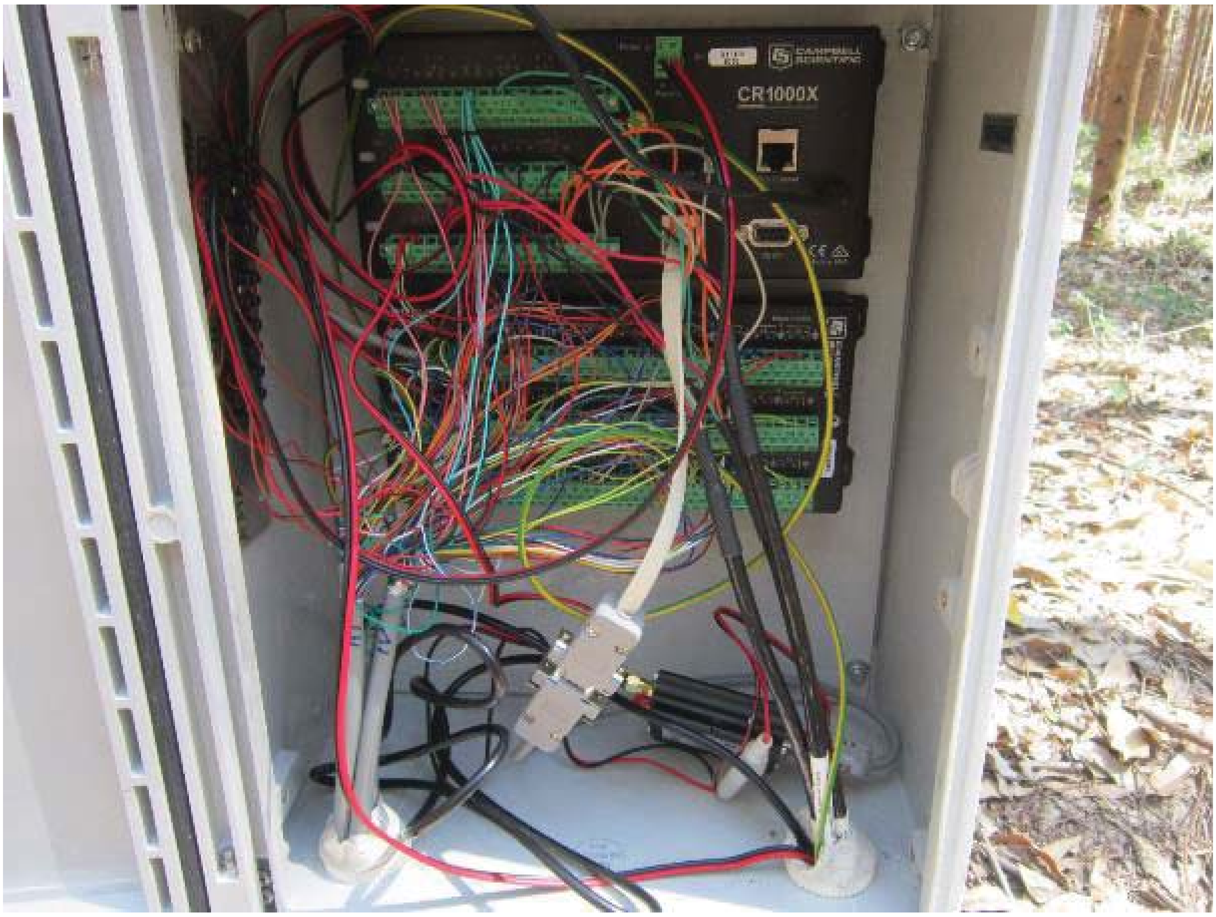
## 3.9 Supplementary material

**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.**

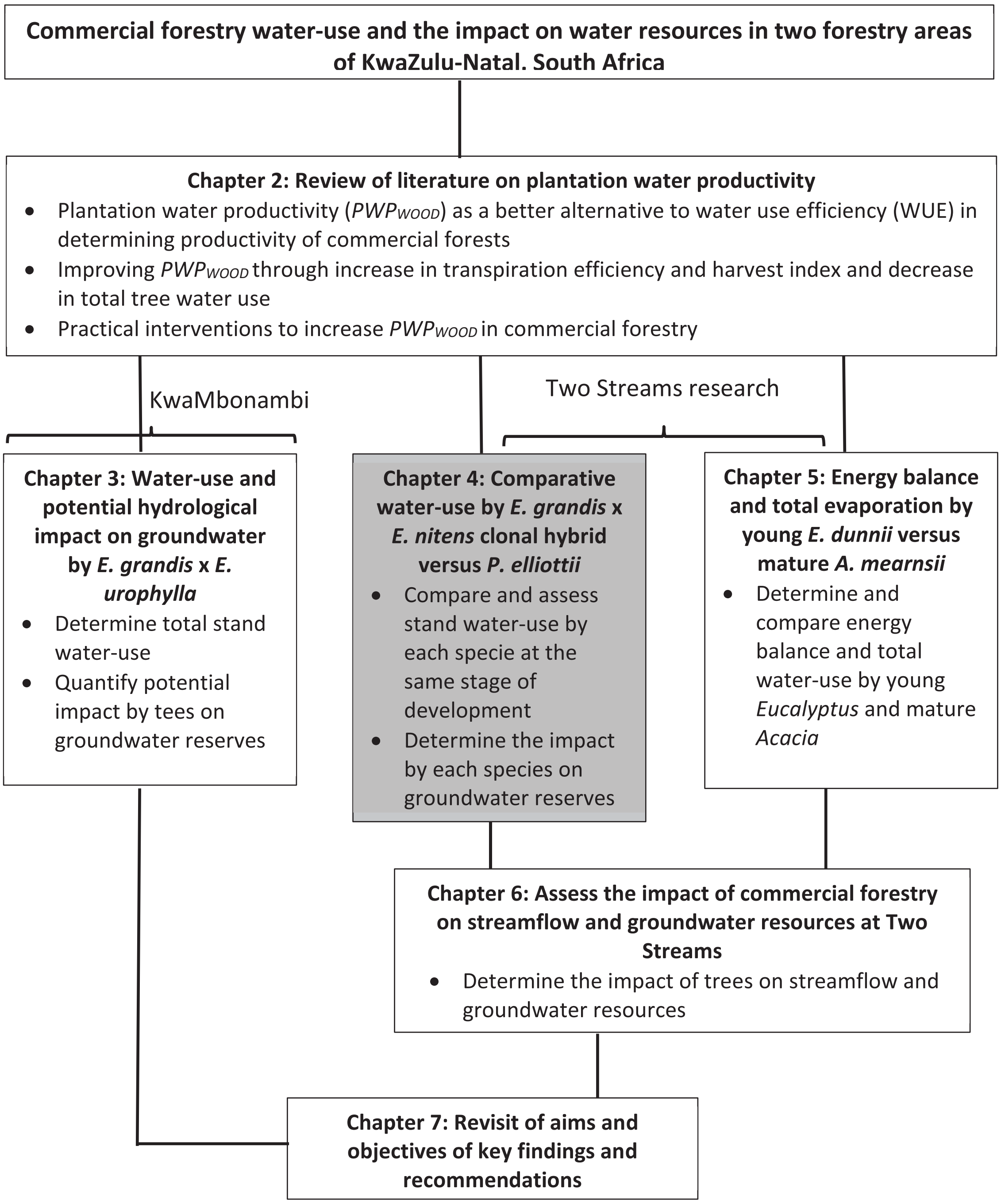



**Supplementary Figure 3.2: The main control box used to operate the heat ratio technique which consist of a CR1000 datalogger, a multiplexer and a cell phone modem used for communication in the KwaMbonambi study site.**

**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. COMPARATIVE WATER USE BY FAST GROWING *EUCALYPTUS GRANDIS* X *E. NITENS* CLONAL HYBRID AND *PINUS ELLIOTTII* NEAR THE TWO STREAMS RESEARCH CATCHMENT, SOUTH AFRICA

**Nkosinathi D. Kaptein[1], Colin S. Everson[2,3], Alistair D. Clulow[1,2], Michele L. Toucher[2,4], Ilaria Germishuizen[5], Steven B. Dovey[6]**

[1]*Discipline of Agrometeorology, University of KwaZulu-Natal, Pietermaritzburg, 3209, South Africa*
[2]*Centre for Water Resources Research, University of KwaZulu-Natal, Pietermaritzburg, 3209, South Africa*
[3]*Department Plant and Soil Sciences, University of Pretoria, Pretoria, South Africa*
[4]*Grasslands-Forests-Wetlands Node, South African Environmental Observation Network, Pietermaritzburg, 3201, South Africa*
[5]*Institute for Commercial Forestry Research, Scottsville, 3201, South Africa*
[6]*Shaw Research Institute, Sappi Forests, Howick, 3290, South Africa*

Corresponding author: Nkosinathi Kaptein, kapteinnd@gmail.com, *University of KwaZulu-Natal, Pietermaritzburg, 3201, South Africa*

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

## 4.1 Abstract

Pine plantations are the dominant specie 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 transpiration (T) and total evaporation rates (ET) than pine. We compared T (mm), diameter at breast height (DBH, cm), soil matric potential and leaf area index (LAI) of an eight-year-old *Eucalyptus grandis* x *Eucalyptus nitens* clonal hybrid (*GN*) with twenty-year-old *Pinus elliottii*. Transpiration was measured for two consecutive hydrological years (2019' 20 and 2020' 21) using a heat ratio sap-flow method. The ET was calculated using published values of soil evaporation and rainfall canopy interception to quantify the impact of each species on water resources. The annual plantation water productivity ($PWP_{WOOD}$) was calculated as a ratio of the productive stem volume to ET for 2019' 20 and 2020' 21. In 2019' 20, annual T for *P. elliottii* exceeded *GN* by 28%, while 2020' 21 showed no significant difference. This was associated with 17 and 21% greater LAI for *P. elliottii* than *GN* in 2019' 20 and 2020' 21, respectively, and low plant available water at the *GN* site. The genus exchange ratio between the two species was found to be very close to 1, however, additional measurements over different environmental conditions are needed to verify these results. Annual DBH increments for each species were statistically similar ($p > 0.05$) in 2019' 20, whereas the 2020' 21 produced significant differences ($p < 0.05$). Transpiration for *P. elliottii* responded linearly to solar radiation, LAI and shallow soil matric potential ($R^2 > 0.70$), while *GN* transpiration responded well only to solar radiation ($R^2 > 0.70$). The soil water potential was very low at the *GN* site, indicating that the site was water stressed. After rainfall and soil water profile recharge, there was a rapid depletion of soil water by the *GN* trees while the soil profile was generally wetter and depleted more gradually at the *P. elliottii* site after rainfall events. The *P. elliottii* ET was 18% greater than *GN* in 2019' 2020, with no significant differences in 2020' 21. It was concluded that on water stressed sites, T and ET of *GN* and *P. elliottii* may not necessarily be different (genus exchange ratio of 1:1) and can depend on water availability. Conversion from *P. elliottii* to *GN* in water stressed forestry sites, where groundwater reserves are too deep for access by trees, may not affect groundwater resources, however, in the wet season, trees may deplete recharged soil water within the soil profile, which may lead to streamflow reduction in the long-term. In forestry areas where groundwater is within reach by trees, such as through capillary rise, the impact on groundwater resources could be severe. Long-term total soil water balance studies in the same region would be beneficial to understand the impact of long-term commercial forestry on water resources.

***Keywords: heat pulse velocity, plantation water productivity, sapflow, soil water potential***

## 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, 2018). 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, 2018). There are now plans to replace as many as 300 000 ha of pine with *Eucalyptus* over the next 20 years (Forestry South Africa, 2018).

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 (T) and total evaporation (ET) (Stanturf et al., 2013). There is a wide body of knowledge indicating that *Eucalyptus* species T 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 make a direct comparison of T 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 and ET 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 and compares T and ET by these two species in South Africa and there are mixed reports in the international literature. The objective of this study was therefore to compare T and ET by *GN* and *P. elliottii* plantations and the impact posed by each species on plantation water yield. For fair comparison, both species were in the same stage of development, therefore, the *P. elliottii* plantation (age 20 years old) was 12 years older than *GN* (8 years old).

## 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 (Figure 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 the Ecca group with dolerite dykes and sills. Area is commonly covered in heavy mist which significantly contributes to precipitation (Mucina and Rutherford, 2006). Weather events such as moderate frost, droughts, hail, and berg winds are frequent in the area.

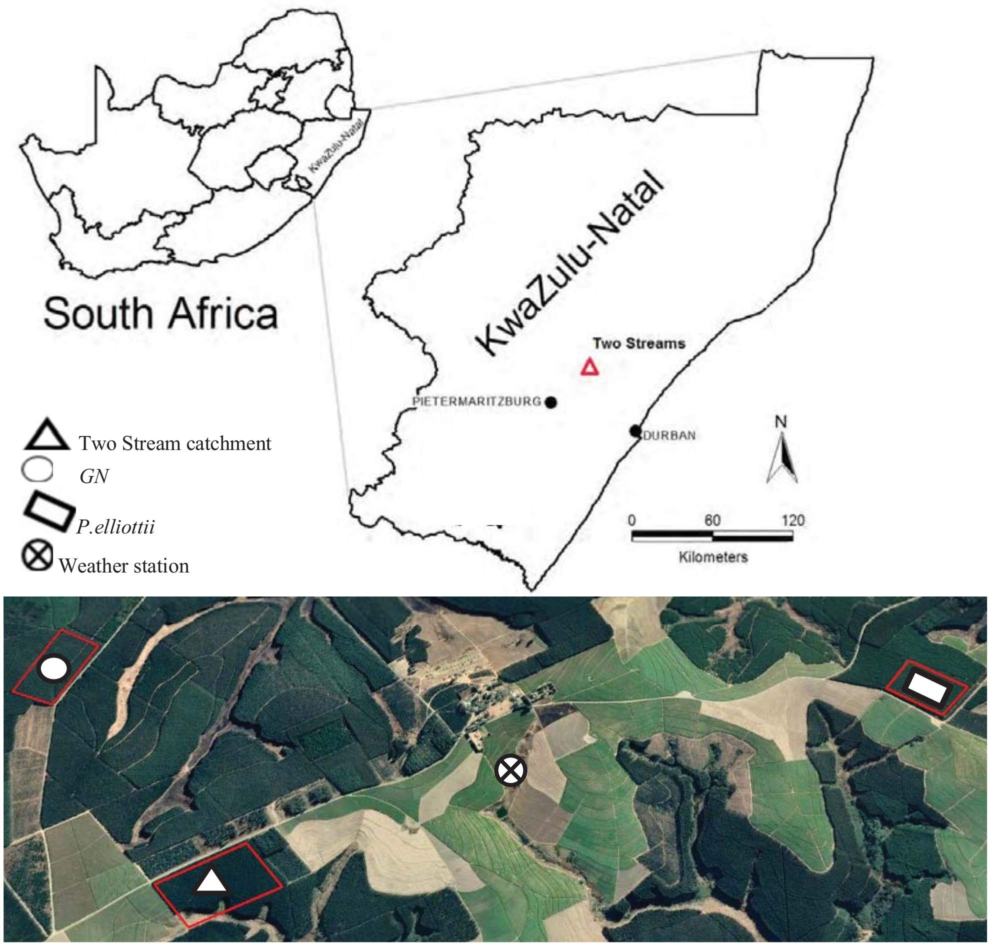


**Figure 4-1: Location of the study area next to Two Streams Research catchment. The Google Earth Pro extract (above) provides location of the two study sites, *E. grandis* x *E. nitens* (*GN*), *Pinus elliottii* and the automatic weather station.**

### 4.3.2 Description of study site

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 (Figure 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.* Basic characteristics for both study sites are presented in Table 4.1. 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 pre-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 |

### 4.3.3 Environmental monitoring

An automatic weather station 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 (Tair) (HMP 60, Vaisala Inc., Helsinki, Finland), the 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 rainfall (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 sensor outputs were recorded on a CR1000 datalogger. The datalogger (Campbell Scientific Inc., Logan, Utah, USA) recorded 5-min outputs and was programmed to calculate the Vapour Pressure Deficit (VPD) using Tair 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 (October 2020 to October 2021) years. 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 (Supplementary Figure 4.2). For *Pinus elliottii* trees, slightly longer heater probes (6 cm) were used due to the xylem being situated deeper in coniferous trees when compared to angiosperm trees. 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 (Supplementary Figure 4.2). 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 4.2) within a tree. Hourly measurements were executed and recorded using a datalogger (CR1000, Campbell Scientific Inc.) powered by a single 55-amp hour lead acid deep cycle battery. Thermocouples were connected to a multiplexer (AM16/32, Campbell Scientific Inc.), which was in turn connected to the datalogger 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 (Vh, cm $hr^{-1}$) was calculated using (Burgess et al., 2001),

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

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 (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 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. 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 area for individual stems. The T rates were then weighted as per individual tree contribution to provide a measure of whole stand T.

**Table 4.2: 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 soil water potential

At both sites, soil water content (SWC) was measured (CS616, Campbell Scientific Inc.) in the upper 600 mm of the soil profile (200-, 400- and 600-mm depth). Hourly measurements (CR1000, Campbell Scientific Inc.) coincided with the sap-flow measurements. SWC values were converted to matric potential using water retention relationship curves measured using a HyProp unit (MeterGroup, Pullman, USA) and WP4C (MeterGroup).

### 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, some uncertainties as to the accuracy of the absolute sap-flow results, due to, mainly tree species specific characteristics, 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). To overcome these concerns, a calibration experiment was run 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 drainage holes and were placed on a rubber mat to prevent root contact with soil and with drainage slots to allow water drainage 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 Es and induce water loss solely through T. Tree diameters at the start of the experiment were 4.2 and 3.6 cm for *GN* an *P. elliottii*, respectively. Each tree was instrumented with HPV sensors to measure hourly sap-flow and summed from sunrise to sunset 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.

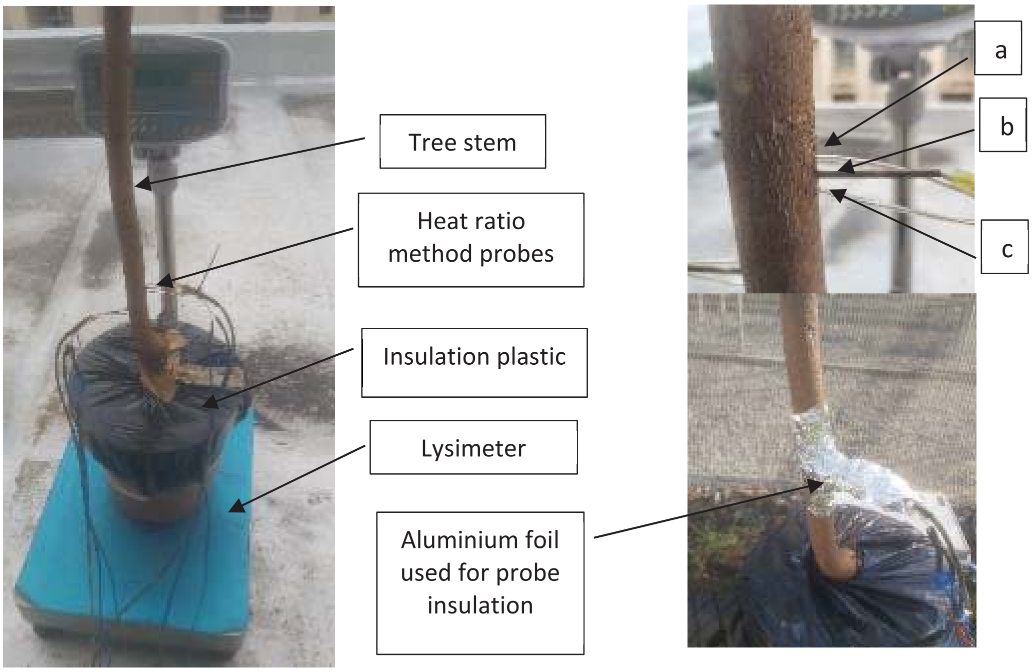


**Figure 4-2: An illustration of a calibration experiment setup showing a tree installed with the heat ratio probes, placed in a lysimeter. Insert: a= downstream probe, b= heater probe, c= upstream probe with aluminium foil used for insulation.**

### 4.3.7 Estimated total water use

The ET of a commercial forestry stand consists of T, Es and I losses. In this study T was measured, while Es and I were estimated due to their importance in the stand water balance and species impact on catchment water yield. These factors are highly variable, making it difficult to generalize as they can depend on a variety of factors such as rainfall intensity, the LAI, weather variables and canopy architecture (Cannell, 1999, Maier et al., 2017). Canopy interception was estimated using published data, with *Eucalyptus* (Soares and Almeida, 2001; Benyon and Doody, 2015) losing 19% through I, and pine 31% of total annual rainfall (Sun et al., 2010; Bulcock et al., 2014; Benyon and Doody, 2015). The Es was likely to be higher for *GN* than *P. elliottii*, as per the LAI at the pine site being significantly higher (17%) than at the *GN* site, resulting in more shading and less available energy. A study by Benyon and Doody (2015) compared I and Es across 18 plantations of *E. globulus* and *P. radiata* and reported an average Es of 15% for *P. radiata* and 29% for *E. globulus* of annual rainfall. These values were used to estimate I and $E_s$ from the rainfall data.

### 4.3.8 Genus exchange ratio from Pinus to Eucalyptus

Genus exchange regulation in South Africa currently permits a 1:1 exchange when converting from one genus to another in commercial forest plantation (DTIC, 2020). The Department of Water and Sanitation (DWS) issued a notice in October of 2015 for the draft of Regulations on Afforestation Genus Exchanges in Terms of the National Water Act, 1998 (Act No.36 of 1998). The draft Genus Exchange Regulations outlines that any existing forest producer who intends to conduct a genus exchange in their plantation needs to apply to the respective authority for authorisation to conduct the intended exchange (DWS, 2015). The DWS further expressed that an exchange to a genus with a higher water use than the existing genus, for example an exchange from *Pinus* to *Eucalyptus*, will lead to the adjustment of the original authorisation, leading to a much smaller areas that can be used for planting. This proposal was contested by Forestry South Africa, pending a review. A genus exchange ratio between *P. elliottii* and *GN* trees was determined.

### 4.3.9 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 the 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 (Dq) was calculated for 48 trees using (Curtis and Marshall, 2000):

$$Dq = \sqrt{\frac{(\sum(DBH)^2}{n}} \tag{4.2}$$

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 4.3 (White et al., 2014):

$$v = \left(\frac{\pi}{12}\right)\left(\frac{Dq}{100}\left(\frac{h}{h-1.3}\right)\right)h \tag{4.3}$$

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

$$V = \frac{10\ 000}{A}\sum_{i=1}^{n} vi \tag{4.4}$$

where $vi$ was the productive volume of the *i*th tree and $A$ was the total area ($m^2$) of the plot where measurements were conducted

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.

### 4.3.10 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.

### 4.3.11 Statistical analysis

Analysis of variance (ANOVA) was used to analyse species differences in stand characteristics (T, Dq, tree heights and LAI) 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).

## 4.4 Results

### 4.4.1 Automatic weather station

The minimum and maximum daily Tair were typical of the 30-year average of Mistley Canema. Maximum recorded Tair was 36.5 and 37.5°C for 2019' 20 and 2020' 21 hydrological years, respectively. There were several days where Tair were below freezing between May and July for both measuring years (Figure 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. The majority of this rainfall (70%) fell during summer months (November to March) for both measurement years (Figure 4-3d). By comparison, FAO ETo 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, respectively. Daily maximum VPD was 3.08 kPa for 2019' 20 increasing to 3.53 kPa for 2020' 21 during hot summer months (Figure 4-3c). Monthly average WS ranged from 2.2 to 7.7 m. $s^{-1}$ over the two measuring years with maximum WS up to 37 m.$s^{-1}$ in August/ September. The RH reached close to 100% on most nights, decreasing to as low as 20% during the day in hot summer months. Average Is for 2019' 20 and 2020' 21 was 15.5 and 16 MJ $m^{-2}$ $day^{-1}$, respectively, while both years experienced a maximum Is of 30 MJ $m^{-2}$ in summer (Figure 4-3b).

Figure 4.3/…

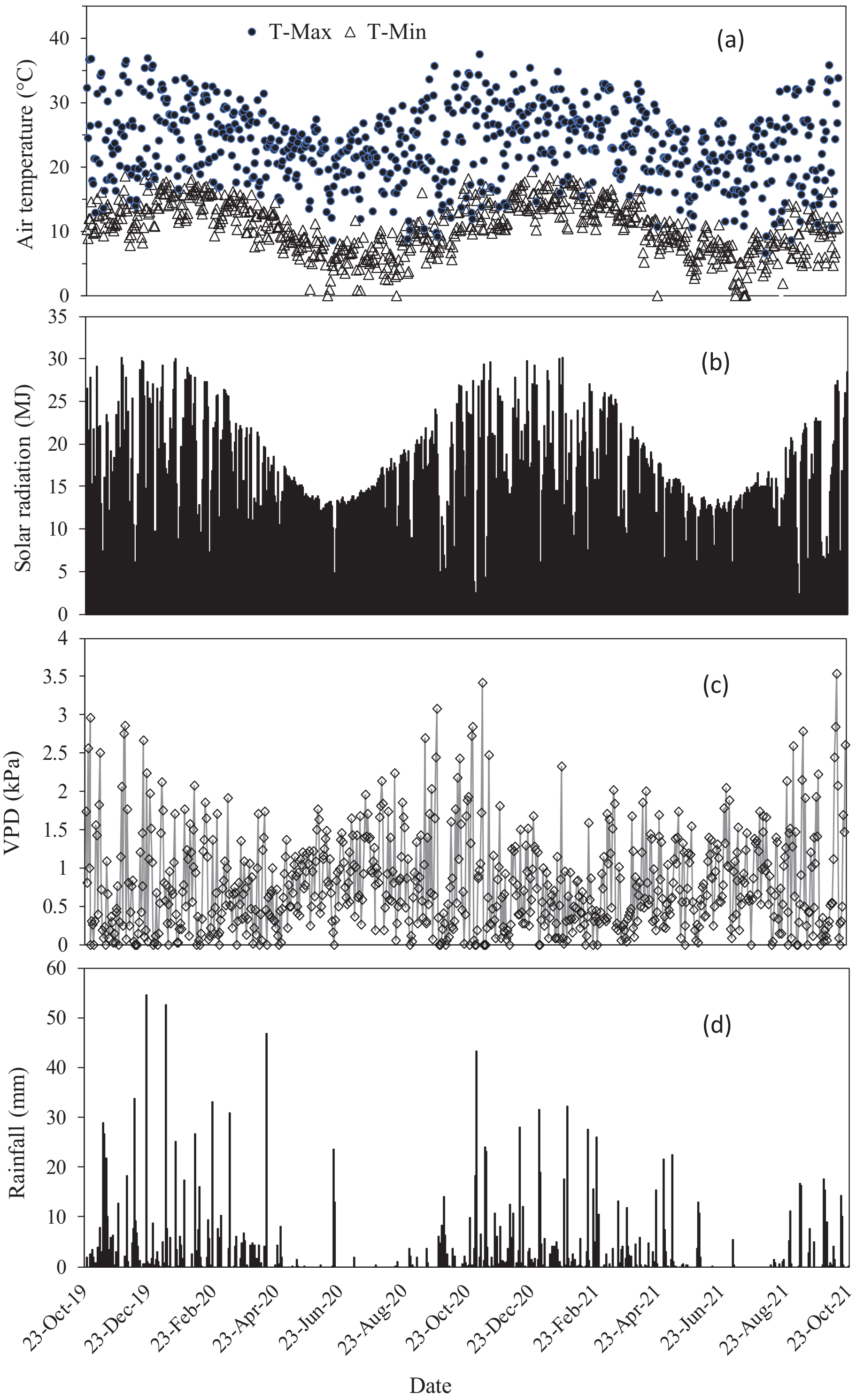


**Figure 4-3: (a) the daily minimum (T-Min) and maximum (T-Max) air temperature (°C) (b) daily total solar irradiance (MJ) (c) daily mean vapour pressure deficit (VPD, kPa) and (d) total daily rainfall (mm) for a duration October 2019 to October 2021.**

### 4.4.2 Soil matric potential

There was a high temporal variation in soil matric potential for all measuring sensors in response to wet and dry periods. Peak (wet conditions) plant available water (*PAW*) for the *P. elliottii* site during the wet summer months was -37, -110 and -60 kPa for 200-, 400- and 600-mm sensors, respectively. The 600 mm sensor was consistently wetter than the 400 mm sensor. Matric potential decreased (getting drier) to a minimum of -350 kPa in the winter season (June to August) (Figure 4-4a). The *GN* site was generally much drier than the *P. elliottii* site with the 400- and 600-mm sensor measuring *PAW* beyond -1500 kPa in most instances, except during and shortly after rainfall events (Figure 4-4b). The lowest *PAW* measured during the study period was -5000 and -12200 kPa for the 400 mm and 600 mm sensors, respectively, indicating exceptionally dry soil conditions and beyond the accurate measuring range of the sensors. The 200 mm sensor recorded its highest *PAW* of -52 kPa after rainfall during the study period. After a rainfall event, *PAW* for the *GN* site was depleted rapidly, within hours. This contrasts with the *P. elliottii* site, where water was depleted more gradually, lasting for a few days post rainfall. There was a linear relationship between daily T and matric potential for the top 200 mm of soil on both sites (Figure 4-5). This relationship was good ($R^2$=0.72) for the *P. elliottii* and weak ($R^2$=0.41) for the *GN* site, with a slightly higher RMSE for the *P. elliottii* site.

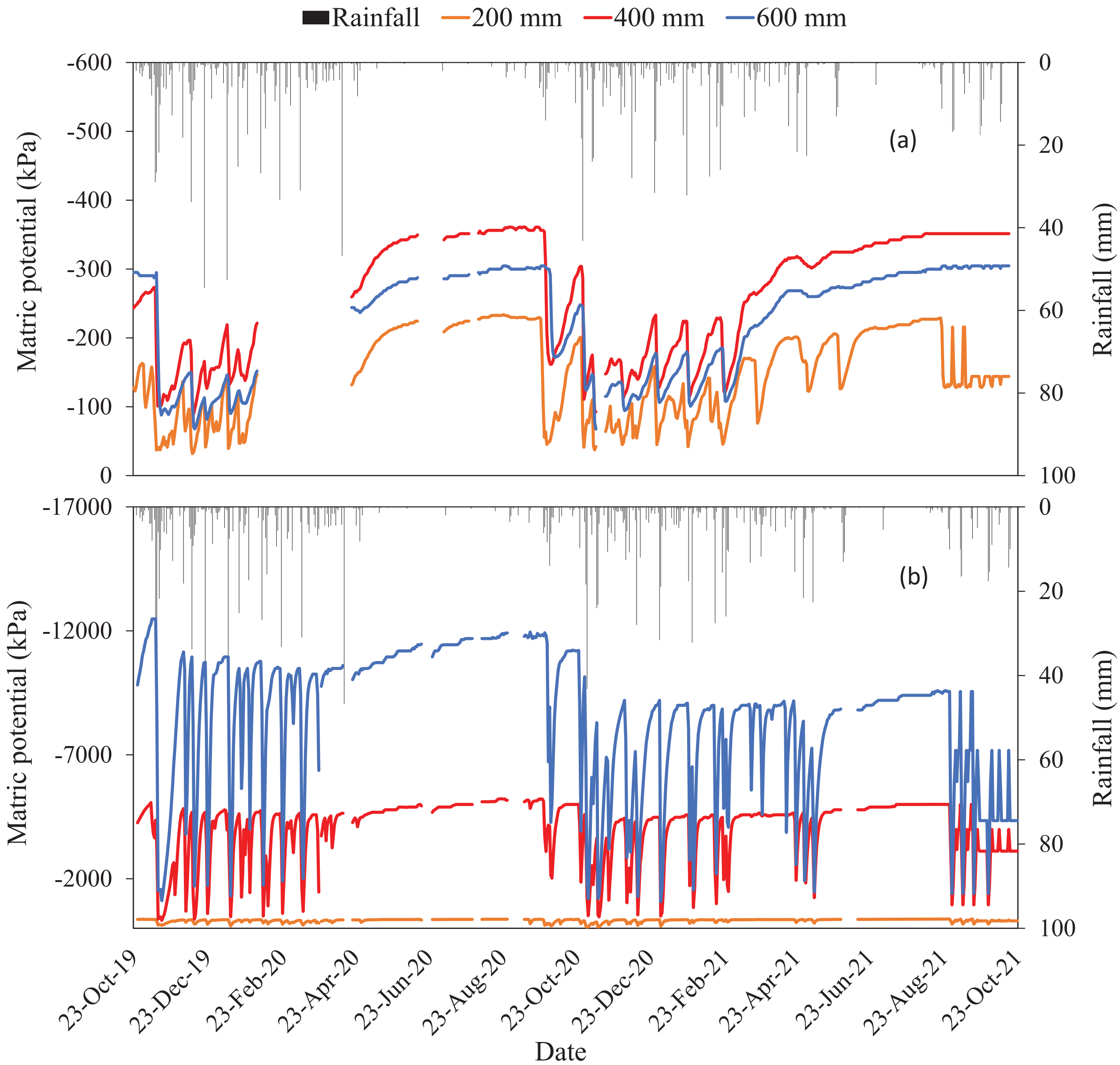


**Figure 4-4: Dynamics of plant available soil water (matric potential) at various depths in the root zone of (a) *Pinus elliottii* and (b) *E. grandis* x *E. nitens* clonal hybrid in response to rainfall events during the period October 2019 to October 2021. A gap in graphs indicates missing data.**

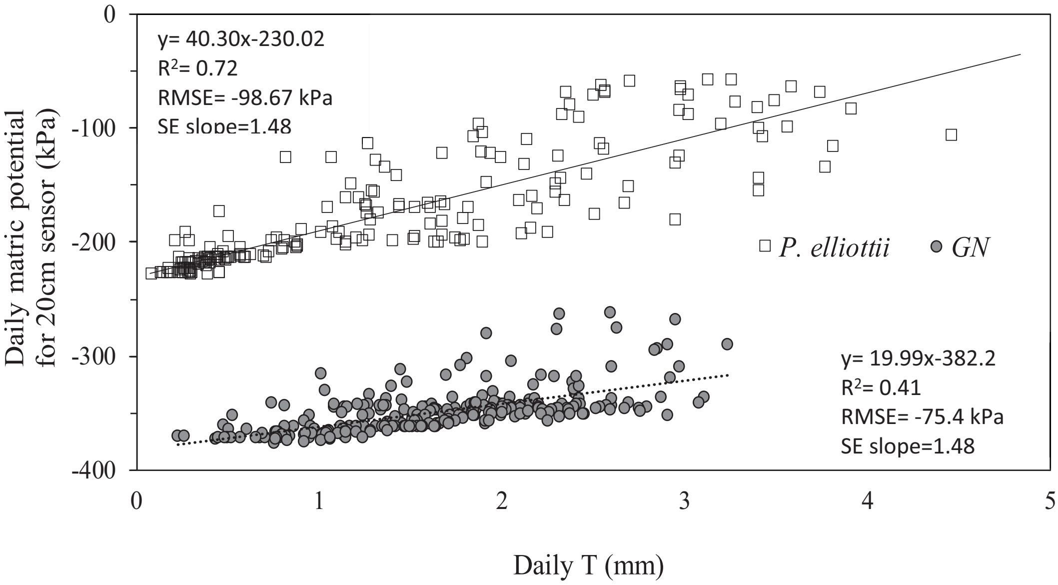


**Figure 4-5: Relationship between daily transpiration (T, mm) and daily 20 cm matric potential sensor (kPa) for *Pinus elliottii* and *E. grandis* x *E. nitens* clonal hybrid (*GN*). The equation of the regression line, regression coefficient ($R^2$), root mean square error (RMSE) and the standard error of the regression slope (SE slope) for each specie is presented.**

### 4.4.3 Heat ratio calibration

The HPV system slightly underestimated T compared to a lysimeter system. A simple regression between the two systems produced a good 2nd order polynomial relationship (*GN*: $R^2$=0.76, *P. elliottii*: $R^2$=0.80) for both tree species (Figure 4-6a and 4.6b), with RMSE of 0.52 and 0.29 L day$^{-1}$ for *GN* and *P. elliottii*, respectively. This relationship was used to correct the T results for both tree species:

$$GN = 0.54x^2 + 0.24x + 0.32 \qquad (4.5)$$

$$P.\ elliottii = 0.58x^2 - 0.10x + 0.37 \qquad (4.6)$$

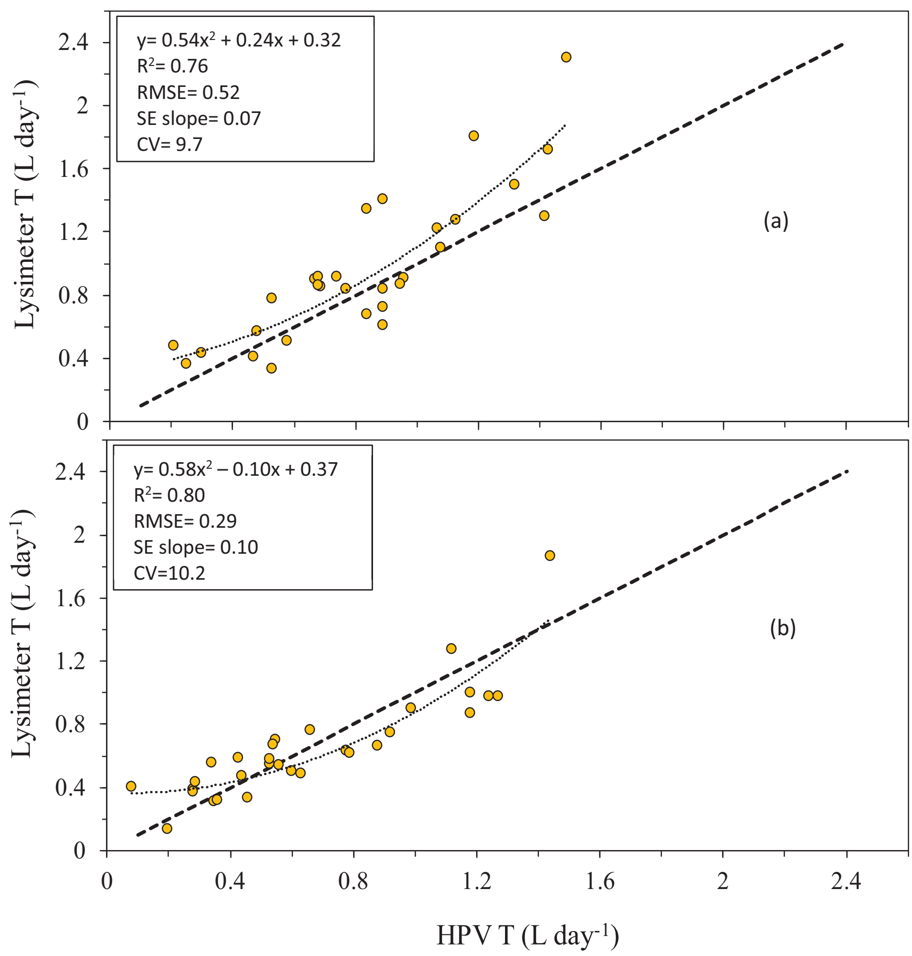


**Figure 4-6: Relationship between daily transpiration (T) measured using a heat ratio technique (HPV, L day$^{-1}$) and the T measured using a lysimeter (through a change in mass, L day$^{-1}$) for (a) two-year-old *Eucalyptus grandis* x *Eucalyptus nitens* clonal hybrid and (b) three-year-old *Pinus 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 specie 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 (Figure 4-7). *Pinus elliottii* had significantly ($p < 0.01$) higher mean daily T compared to *GN* ((Figure 4-7) 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 mm and 1.9 mm, respectively. By comparison, summer mean T values of 2020' 21 were 2.6 mm for *P. elliottii* and 2.1 mm for *GN* ($p < 0.05$). After a significant rainfall event (~10 mm), T for *GN* momentarily exceeded *P. elliottii* for a few days, thereafter, falling below *P. elliottii*. The maximum T for *GN* was 5.2 mm and 3.8 mm for 2019' 20 and 2020' 21, respectively, versus 5.6 mm 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 ((Figure 4-7). However, maximum T rates were reached mid-January for the 2020' 21 by both crops, which coincided with high Is, Tair and VPD. During winter months (June to July) of both the 2019' 20 and 2020' 21, no T could be detected by probes on *GN* trees on several days, despite clear weather conditions. This corresponded with low soil water potential of -360 kPa for the 200 mm and very low matric potential of < -1500 kPa for the 400 mm and 600 mm deep sensors. By comparison, T could be measured in *P. elliottii* trees where the soil was less dry in winter, however at very low T rates (~0.33 mm 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 (Figure 4-8).

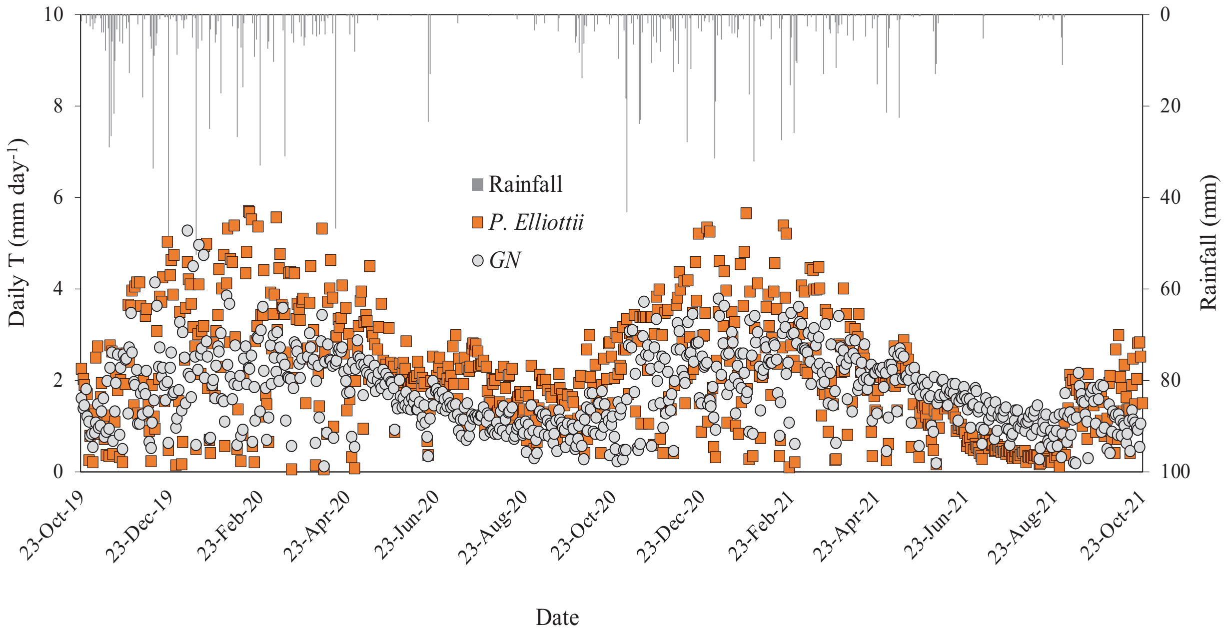


**Figure 4-7: Mean daily transpiration (T, mm day$^{-1}$) and corresponding rainfall in an 8-year old *E. grandis* x *E. nitens* clonal hybrid (*GN*) and 20-year old *P. elliottii* trees for a duration October 2019 to October 2021. Each point is a mean of four trees.**

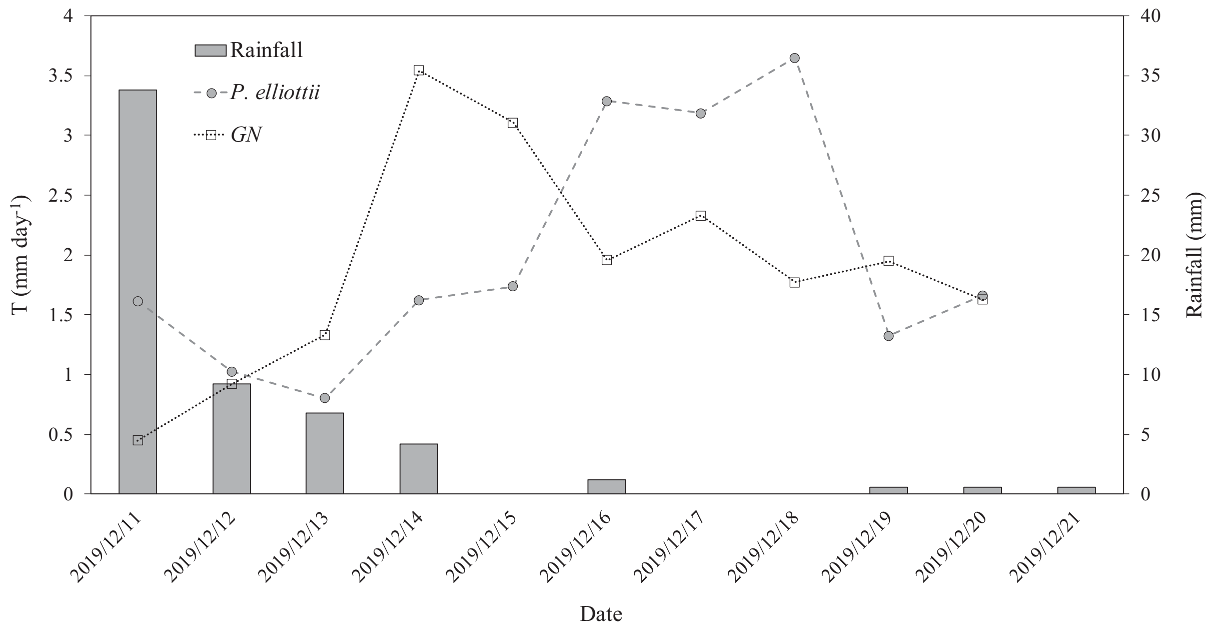


**Figure 4-8: Ten-day daily transpiration (T, mm day$^{-1}$) for 20-year-old *P. elliottii* and 8-year-old *Eucalyptus grandis* x *Eucalyptus nitens* clonal hybrid (*GN*) with corresponding rainfall (mm) showing T response by each specie to rainfall.**

The differences in seasonal patterns of T are better illustrated using daily accumulated T as presented in Figure 4-9. Over the 2019' 20, the total accumulated daily T for *P. elliottii* was 30% greater than *GN*, while the total accumulated rainfall exceeded *P. elliottii* and *GN* T by 21 mm and 258 mm, respectively Figure 4-9). In comparison, the total accumulated T rates in 2020' 21 were statistically similar *(p* > 0.05) throughout the season with accumulated rainfall 18 and 20% greater than T for *P. elliottii* and *GN*, respectively. The accumulated FAO ETo exceeded rainfall by 22% in both years of measurement. Total annual T rates for *GN* were slightly higher in 2020' 21 than 2019' 20 by 6%, while *P. elliottii* T rates reduced by 19% during the same period (Figure 4-9).

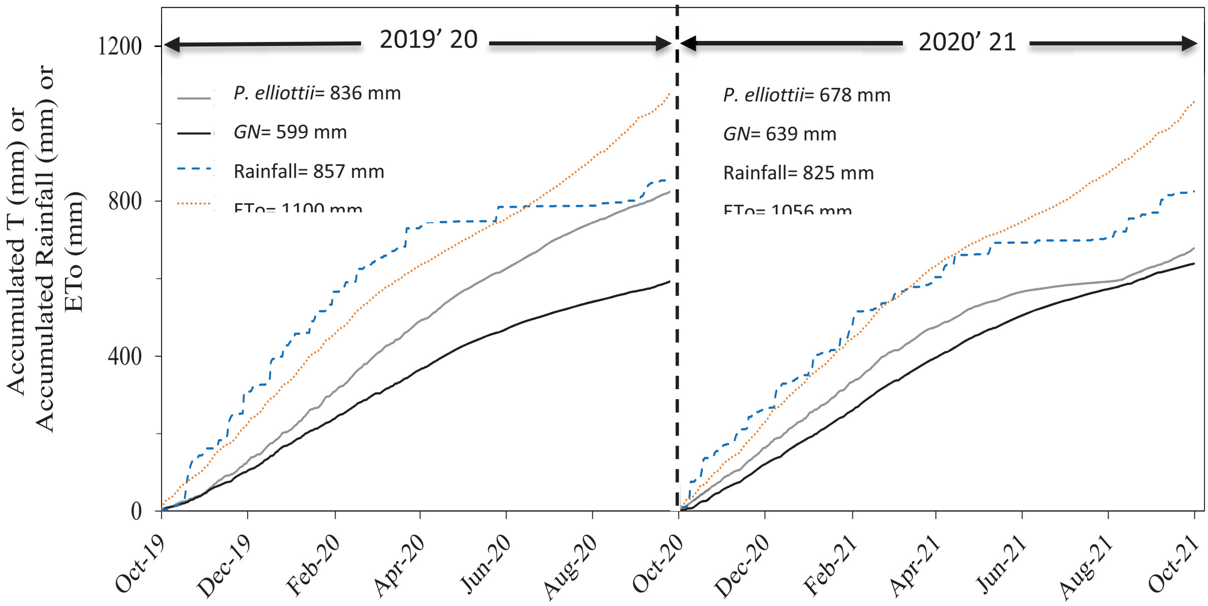


**Figure 4-9: The accumulated transpiration (T, mm), rainfall (mm) and FAO reference evaporation (ETo, mm) for 2019' 20 (Oct 2019 to Oct 2020) and 2020' 21 (Oct 2020 to Oct 2021).**

### 4.4.5 Estimated total water use

The annual estimated ET for *P. elliottii* (1231 mm) in 2019' 20 was 18% greater than *GN* (1010 mm), while there were no significant differences between species ET in 2020' 21 (*GN*=1036 mm vs. *P. elliottii*=1058 mm), based on a rainfall of 857 and 825 mm for 2019' 20 and 2020' 21, respectively. The ET for *P. elliottii* exceeded rainfall by 30% and 22% for 2019'20 and 2020'21, respectively. In comparison to *GN*, ET exceeded rainfall by 15% in 2019 '20 and increased to 20% in 2020' 21. It is evident from these estimated values and measured data that both study sites experienced water stress due to ET exceeding the rainfall. *Eucalyptus* species are known to root deeper than pine (Canadell et al., 1996) and can rely on groundwater to drive T (Morris and Collopy, 1999). However, in our study there is clear evidence that *GN* trees did not have access to underground water reserves due to shrinking of tree diameters and T rates below detection by our HPV system in the dry season.

The genus exchange ratio in terms of ET and T between *GN* and *P. elliottii* was found to be 0.84 in 2019' 20, while 2020' 21 produced a ratio of 1, with an average ratio of 0.92.

### 4.4.6 Response to weather variables

Tree T for each species was compared by multiple regression analysis to micrometeorological parameters including Is, VPD, rainfall, RH, WS and Tair to determine individual and combined drivers of T. The most related variable was Is for both tree species, where an increase in Is resulted in an increase in T ($R^2 > 0.75$), except in winter of 2019' 20 for *GN* and 2020' 21 for *P. elliottii* (Table 4.3). VPD significantly influenced *GN* T only in the summer months for both years, where a 2nd order polynomial relationship was produced ($R^2 > 0.62$). Transpiration increased with an increase in VPD, up to a threshold of approximately 2.8 mm $day^{-1}$, thereafter remaining constant (data not shown). In addition, there was hysteresis in *GN*, where at similar VPD, T was greater in the morning than in the afternoon. By comparison, *P. elliottii* showed no significant response to VPD on both years of measurement (Table 4.3). Tree T was also highly correlated with RH in *P. elliottii*, where T increased with decrease in RH, reaching a peak of 2.5 mm (RH=21%) and 5.6 mm (RH=23%) in 2019' 20 (winter) and 2020' 21 (summer), respectively. Rainfall, WS and Tair did not significantly influence T for both species.

**Table 4.3: Statistical significance (*p*-values derived ANOVA tests) of the *Eucalyptus grandis* x *E. nitens* (*GN*) *and Pinus elliottii* hourly mean transpiration over 2019' 20 and 2020' 21 (summer = November to February and winter = June to July) versus the mean hourly climatic variables (Is= solar radiation, VPD=vapour pressure deficit, RH=relative humidity, WS=wind speed and Tair=air temperature). Statistically significant ($p < 0.05$) values are shown in bold type.**

| | | | Dependant variable | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **Species** | **Season** | **Is** | **VPD** | **Rain** | **RH** | **WS** | **Tair** |
| **2019' 20** | *GN* | Summer | **<0.001** | **0.005** | 0.56 | 0.13 | 0.27 | 0.39 |
| | | Winter | 0.58 | 0.07 | 0.23 | 0.09 | 0.23 | 0.28 |
| | *P. elliottii* | Summer | **<0.001** | 0.67 | 0.30 | 0.35 | 0.21 | 0.12 |
| | | Winter | **0.03** | 0.81 | 0.71 | **0.03** | 0.27 | 0.58 |
| **2020' 21** | *GN* | Summer | **<0.001** | **<0.001** | 0.29 | 0.30 | 0.71 | 0.12 |
| | | Winter | **0.006** | 0.93 | 0.12 | 0.33 | 0.06 | 0.53 |
| | *P. elliottii* | Summer | **0.002** | 0.43 | 0.37 | **0.04** | 0.48 | 0.30 |
| | | Winter | 0.11 | 0.50 | 0.65 | 0.77 | 0.26 | 0.24 |

### 4.4.7 Tree growth

At the beginning of the study, *P. elliottii* trees were larger in diameter than *GN*. There was a seasonal pattern in Dq increment by both species (Figure 4-10), with no significant ($p > 0.05$) differences between species 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*, while growth increment remained constant for *P. elliottii* (Figure 4-10), which was probably caused by soil water deficit.

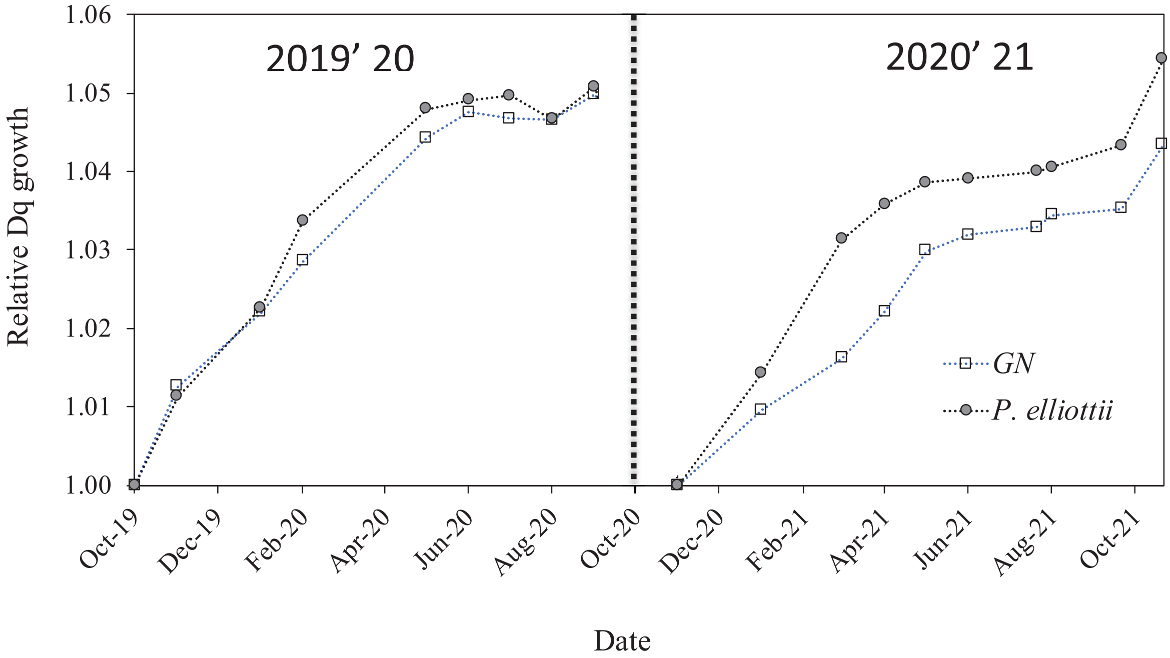


**Figure 4-10: Relative quadratic mean diameters (Dq, normalised) measured using manual dendrometers bands and for *Eucalyptus grandis* x *E. nitens* (*GN*) and *Pinus elliottii*. Measurements were conducted for hydrological years, 2019’ 20 (October 2019 to October 2020) and 2020’ 21 (October 2020 to October 2021). Each point represents an average of 48 trees for each specie.**

### 4.4.8 Leaf area index

The LAI showed seasonal patterns (Figure 4-11) with LAI increasing in the wet season (October to April), while the low LAI was measured in the dry season (May to September). 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 1.31 and 1.76 for *P. elliottii* and *GN*, respectively (Figure 4-11). Total monthly T was linearly related to monthly LAI of both *P. elliottii* and *GN* (Figure 4-12), with statistical differences in the regression ($p < 0.05$). However, there was a greater RMSE, SE intercept and SE slope in *P. elliottii* than in *GN*.

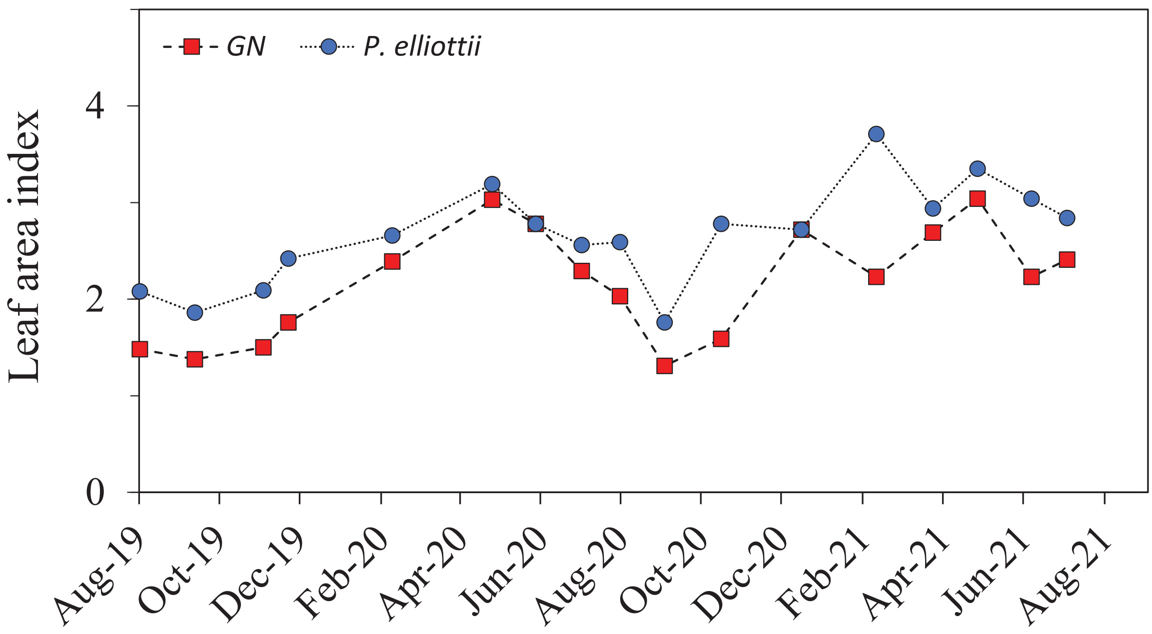


**Figure 4-11: A leaf area index of *Eucalyptus grandis* x *Eucalyptus nitens* clonal hybrid (*GN*) and *Pinus elliottii* measured near Two Streams research catchment from August 2019 to July 2021.**

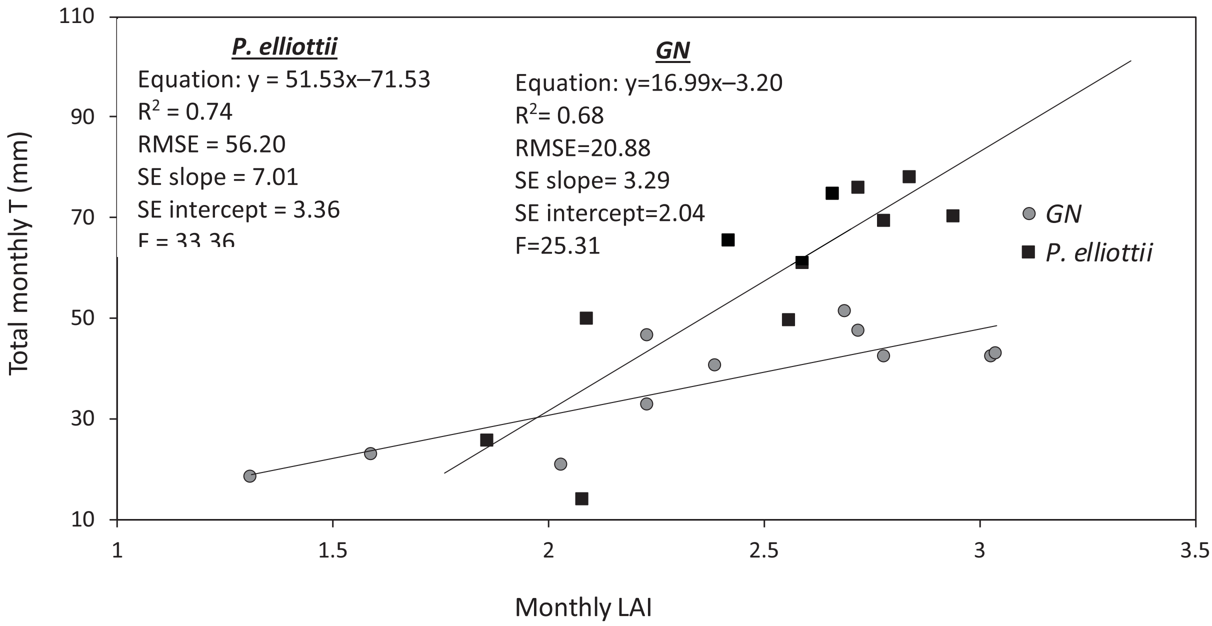


**Figure 4-12: A linear relationship between total monthly transpiration (T, mm) and monthly measured leaf area index (LAI) for *E. grandis* x *E. nitens* clonal hybrid (*GN*) and *P. elliottii*. The equation of the regression line, regression coefficient ($R^2$), root mean square error (RMSE), the standard 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.**

### 4.4.9 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, mainly influenced by Is. Differences in T between *GN* and *P. elliottii* could be attributed to the following reasons: 1) trees in the *GN* site were water stressed, this was observed through the extremely low *PAW* throughout the monitoring period, shrinking of tree diameters in winter, zero rates of T on some days during winter months and a significant decrease in LAI over winter and 2) sap-wood for *P. elliottii* was nearly twice the sap-wood area of *GN* due to species age difference. The *GN* mean T range of 0.9-5.2 mm and 0.5-3.8 mm 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 day$^{-1}$ (MAP=708 mm). David et al. (1997) measured daily T of 0.5-3.64 mm 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 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 day$^{-1}$ in this study agreed with other studies, such as Hatton and Vertessy (1990) who measured a maximum T of 5 mm 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 rainfall events and thereafter decreased as *PAW* was rapidly depleted, while *P. elliottii* responded more gradually. This suggests that *GN* trees have a different water use strategy to *P. elliottii,* that involves being able to respond rapidly when water becomes available after a period of dry conditions. 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). Interestingly, the *GN* responded rapidly to water availability, but the maximum rates of T still remained constrained to less than that of the *P. elliottii*.

An interesting pattern of hysteresis was noted in the diurnal pattern of T with VDP. Using VPD as an indicator of atmospheric demand, T was greater in the morning than in the afternoon for *GN*, for the same value of VPD. 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 very low *PAW* affected water uptake to a greater extent in winter.

### 4.5.2 Annual transpiration

On an annual basis, *P. elliottii* trees transpired 28% more water (836 mm) than *GN* (599 mm) in the 2019' 20, while the 2020' 21 saw no significant differences between the two species (*P. elliottii*=678 mm vs. *GN*=639 mm). The low rates of T in winter months (May to August) of 2021 of the *P. elliottii* site (Figure 4-7), which were probably caused by low *PAW*, resulted in the similar annual T rates in the 2020' 21 by both species. Studies (Moran et al., 2017; Samuelson et al., 2019) reported that the first reaction by pine species to a decrease in *PAW* 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 *PAW* 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. Similar findings were reported by White et al. (1999) and Eksteen et al. (2013) in *E. nitens*, where trees utilised *PAW* till permanent wilting point, which seems to be well beyond the -1500 kPa typically cited in literature for many plants (Santra et al., 2018).

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 a water balance), *Eucalyptus grandis* used 100 mm more water per year than *Pinus patula* (Scott and Lesch, 1997). However, this was in a high rainfall area where the soil water may not have been limiting as it was in our *GN* study site. 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. Similar findings were reported by a most recent study (White et al., 2022) where water use by *Eucalyptus* and *Pinus* plantations were not significantly different. Authors in this study re-iterated that there were periods within the rotation when *Eucalyptus* used more water than *Pinus*.

The good correlation between T and growth variables (e.g. LAI), T and weather variables (e.g. Is) and T and SWC is an indication that T was not explained by a single variable but could be a combination of factors as reported in other studies (Whitehead and Beadle, 2004; Samuelson et al., 2008; White et al., 2022). The good relationship reported in this study may present a future modelling opportunity to estimate T using growth (or remote sensing estimates of LAI) and weather parameters.

### 4.5.3 Differences in estimated total evaporation between species

The ET values reported in this study are comparable to other similar age *Eucalyptus* (Almeida et al., 2007, Macfarlane et al., 2010, Silveira et al., 2016) and *Pinus* studies (Powell et al., 2005, Grace et al., 2006, Sun et al., 2010). There was a shortage in the water balance for both species in 2019' 20 and 2020' 21, which was evident on trees through shrinking of tree diameters on both study sites and very low T, beyond detection by our HPV system on the *GN* site, during the dry season. The tree water stress signs observed was an indication that precipitation was the only source of water and trees were not able to access water in deep water reserves or from lateral flow in surrounding areas.

### 4.5.4 Genus exchange ratio from Pinus to Eucalyptus

Results from T and estimated ET produced a genus exchange ratio very close to 1 (average: 092) for both measurement years, which complements the current Genus exchange regulation permit ratio of 1:1 (DTIC, 2020). However, as previously mentioned, the *GN* study site was subjected to water stress, which influenced T and ET in this study. These results suggests that the exchange ratio is highly dependent on environmental conditions of a site such as climate and soils and may also be tree species depended. Recommendation are that more measurements are needed to cover a wider commercial forest plantation area.

### 4.5.5 Implications for the catchment water yield

Our results indicated that *P. elliottii* ET was significantly greater than *GN* in 2019’ 20, while 2020’ 21 ET amounts were statistically similar. These results were influenced by *PAW* and physiological response by each specie due to soil water deficit. It is most likely that *GN* trees would have used more water than *P. elliottii* if *PAW* was not limiting or if trees had been able to exploit groundwater reserves. This conjecture is supported by studies conducted by Calder (1992), Dye et al. (1996a) and O’Grady et al. (1999), where *Eucalyptus* T was higher during the dry season than during the wet season, largely due to exploitation of groundwater reserves.

These implications are significant in local planning by the commercial forestry industry, since current markets favour replacement of longer rotation pine with shorter rotation *Eucalyptus* plantations. However, the extremely dry soil profile at the *GN* site compared with the *P. elliottii* could have significant long-term impacts on the water-balance of such forestry catchments. Without comprehensive knowledge of long-term total water balance measurements, the implications over a number of rotations cannot be quantified. Studies have reported a negative effect of *Eucalyptus* to catchment water yield (Almeida et al., 2007), whereas others have reported no significant impacts (Lane et al., 2004; White et al., 2021, 2022). A conclusion based on results from our study site, is that specie conversion from *P, elliottii* to *GN* in forestry areas where groundwater resources are inaccessible, for example where these resources are too deep for roots to reach, may not adversely affect the catchment water yield due to limited *PAW* reducing T. Soil profiles could become very dry during dry periods and reduce streamflow at the onset of the wet season as the soil profile is recharged. However, in forestry areas where the groundwater reserves are shallow, the impact could be severe. 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 (ET, surface runoff, soil water storage and how water partitioning responds to climate change and afforestation over time).

### 4.5.6 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 comparative 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). Though the HRM is an internationally recognised technique for measuring water use in commercial forests, tree specific calibration was conducted in this study to validate our water use measurements. Our calibration results indicated that HRM provided reliable and continuous measurements of water use, but require routine maintenance. Annual water use results indicated that *P. elliottii* used 28% more water than *GN*, which contrasted with some previous pine and eucalypts comparative studies conducted in South Africa and internationally, which reported that *Eucalyptus* species are heavy water users compared to pine. Low water use by *GN* was most likely due to soil water deficit (even during summer) and inaccessible groundwater resources. In addition, ET was estimated using the actual T measurements, while $C_I$ and Es were estimates based on published data and it would be beneficial to confirm these measurements using actual ET values. The T and ET genus exchange ratio between *GN* and *P. elliottii* was found to be closer to 1. However additional measurements are needed to cover a much larger commercial forest plantation area.

There was a good relationship between T and LAI, T and Is and T and *PAW* at the soil surface, showing that T may be influenced by a combination of different growth and weather variables. This relationship will form a good background for modelling studies, where an easy to measure growth and weather parameters can be used to estimate a difficult water use measurement. The *GN* produced significantly greater $PWP_{WOOD}$ than *P. elliottii*, even though the *GN* site was water stressed, suggesting that *GN* is an efficient producer than *P. elliottii*, a finding corroborated by other comparative studies.

A conclusion from this study is that, regardless of common beliefs to the opposite, under conditions of our study sites at the Two Streams research catchment 1) *P. elliottii* uses water greater than *GN* (water stressed *GN* site) 2) conversion from *P. elliottii* to *GN* in forestry areas where groundwater is too deep, may not significantly affect the catchment water yield as trees will not be in contact with groundwater, however, trees are capable of reducing the recharged soil water within the profile during the wet season, which may lead to a reduction in streamflow 3) in forestry areas where groundwater is shallow, trees could be in contact with groundwater through capillary rise, which could results in significant negative impact to groundwater reserves. Further research is suggested to quantify the total water balance (ET, surface runoff, soil water storage and how water partitioning responds to climate change and afforestation over time).

## 4.7 Acknowledgements

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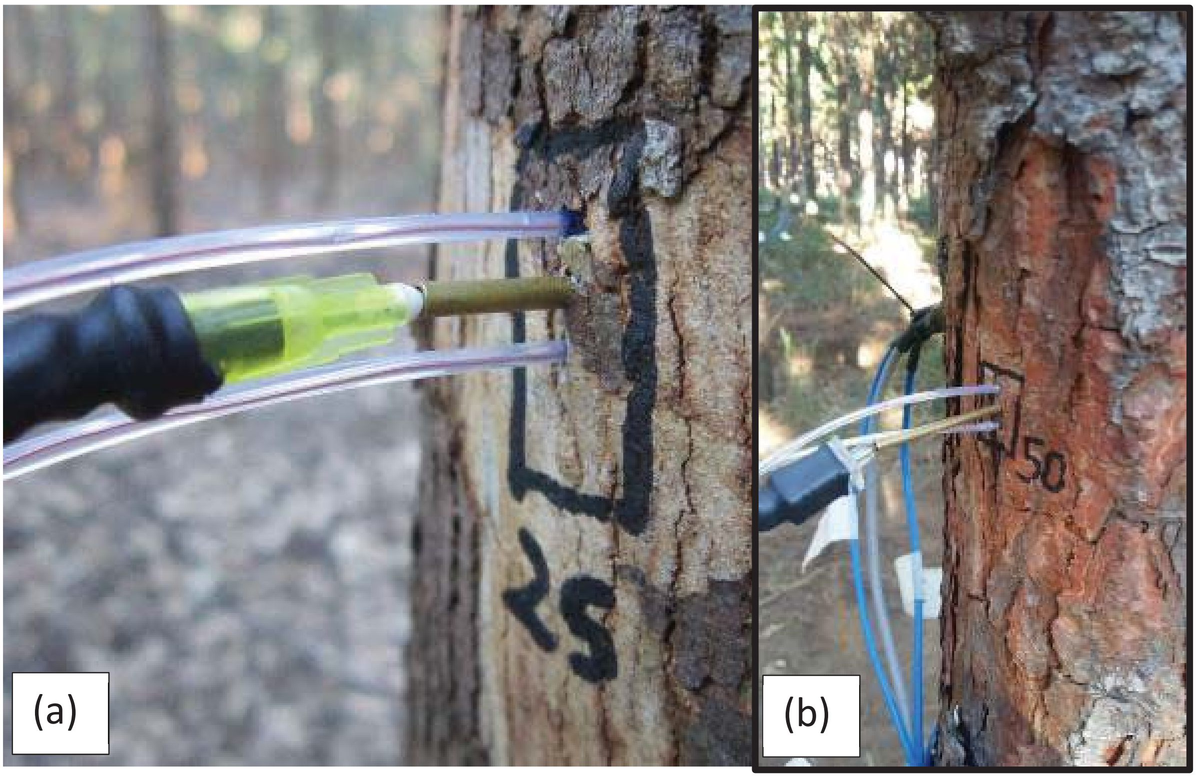
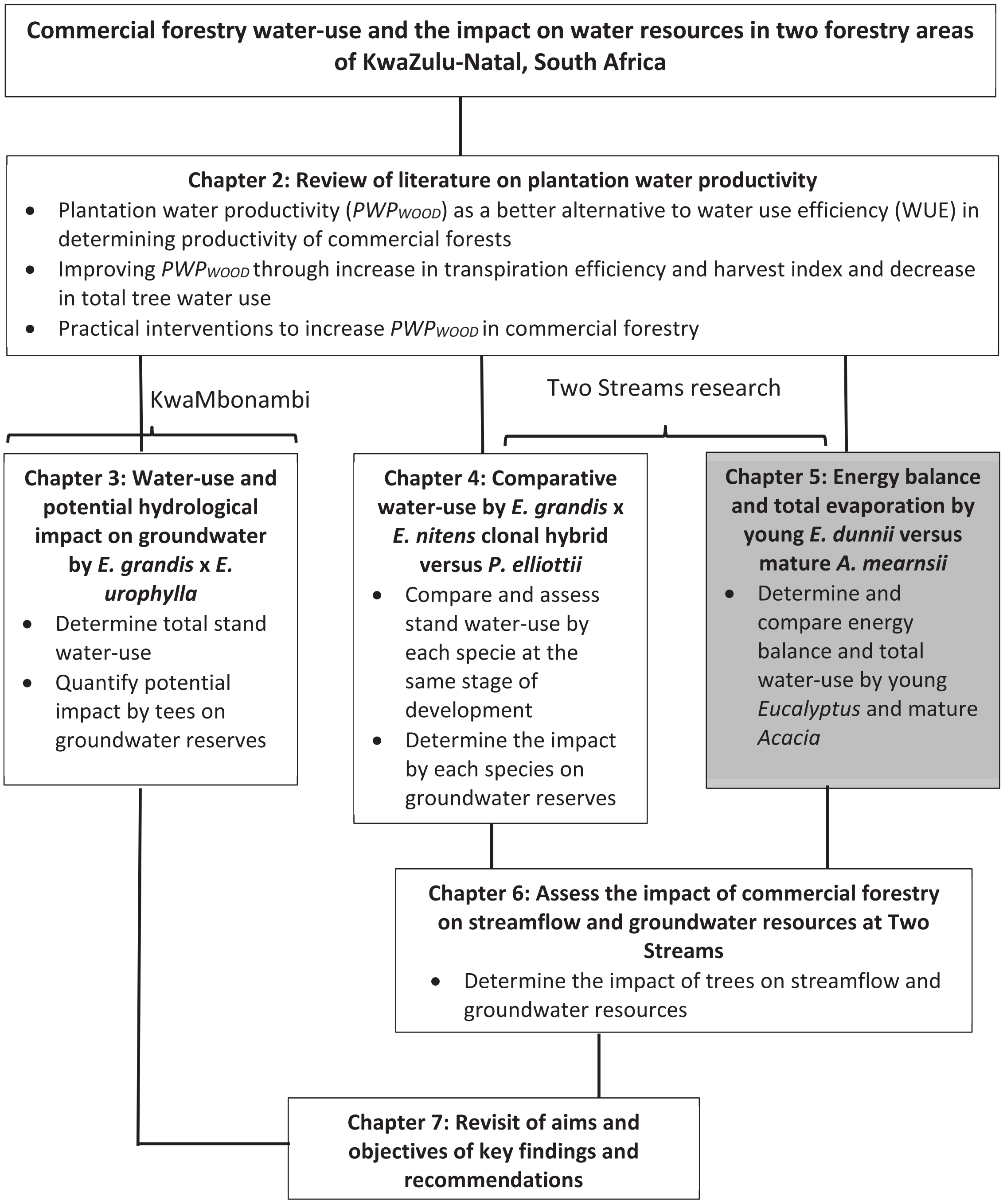
## 4.9 Supplementary information




**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 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 specie on water resources.



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

**Nkosinathi D. Kaptein[1], Colin S. Everson[2,3], Alistair D. Clulow[1,2], Michele L. Toucher[2,4], Ilaria Germishuizen[5]**

[1]*Discipline of Agrometeorology, University of KwaZulu-Natal, Pietermaritzburg, 3209, South Africa*
[2]*Centre for Water Resources Research, University of KwaZulu-Natal, Pietermaritzburg, 3209, South Africa*
[3]*Department Plant and Soil Sciences, University of Pretoria, Pretoria, South Africa*
[4]*Grasslands-Forests-Wetlands Node, South African Environmental Observation Network, Pietermaritzburg, 3201, South Africa*
[5]*Institute for Commercial Forestry Research, Scottsville, 3201, South Africa*

Corresponding author: Nkosinathi Kaptein, kapteinnd@gmail.com, *University of KwaZulu-Natal, Pietermaritzburg, 3201, South Africa*

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* Referencing conforms to Journal of Hydrology.

## 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. The genus exchange ratio between young crops was found to be 1, while a mature crop and young crops was 0.9. 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, 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. mearnsii* 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 requesting 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:

- Compare *A. mearnsii* seasonal energy balance and total evaporation at two-years-old and six-years-old.
- 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.
- 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.

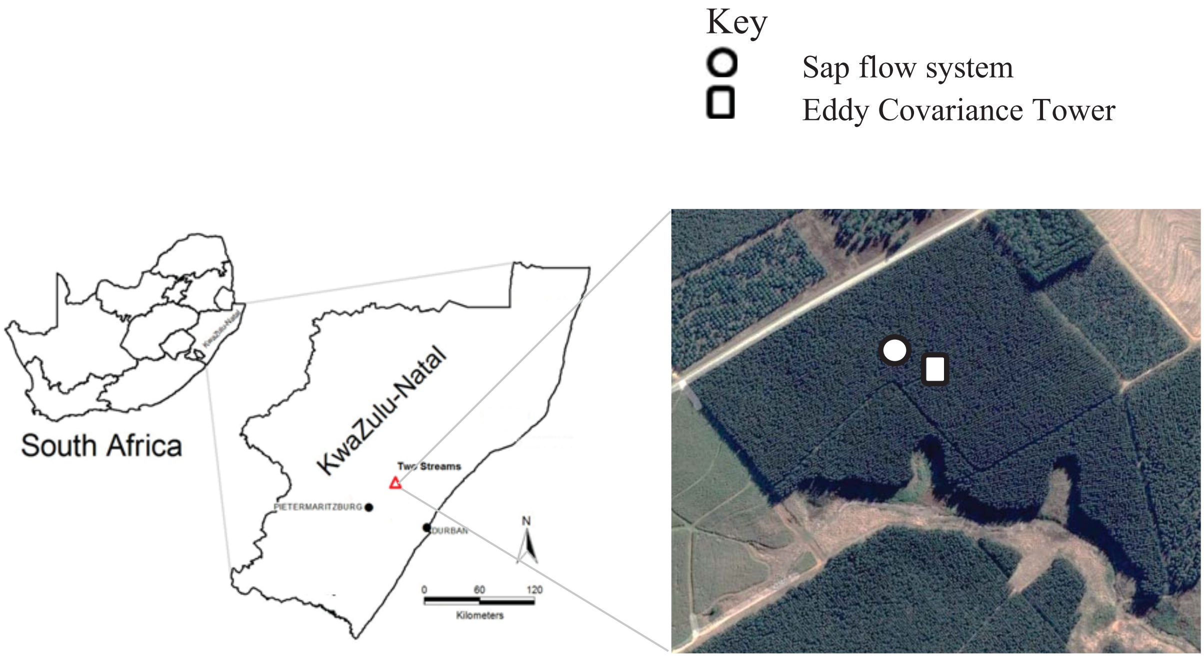


**Figure 5-1: Location of the study area at Two Streams Research Catchment. The Google Earth extract (extreme right) provides aerial view of the catchment.**

**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 (metres 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 5$^{th}$ 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).

The exchange of genus from *A. mearnsii* to *E. dunnii* presented an opportunity to determine a total water use ratio between the two species. Genus exchange regulation in South Africa currently permits a 1:1 exchange when converting from one genus to another in commercial forest plantation (DTIC, 2020). The Department of Water and Sanitation (DWS) issued a notice in October of 2015 for the draft of Regulations on Afforestation Genus Exchanges in Terms of the National Water Act, 1998 (Act No.36 of 1998). The draft Genus Exchange Regulations outlines that any current afforestation water user that wishes to conduct genus exchange in their plantation is required to apply to the respective authority for authorisation to conduct the intended exchange (DWS, 2015). The DWS further expressed that an exchange to a genus with a higher water use than the existing genus, for example an exchange from *A. mearnsii* to *Eucalyptus*, will lead to the change in the initial authorisation, leading to small areas that can be used for planting. This proposal was contested by Forestry South Africa, pending a review. A genus exchange ratio between *A. mearnsii* and *E. dunnii* trees was determined.

## 5.4 Material and methods

The detailed materials and methods 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 (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 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 Tair and RH measurements according to Savage et al. (1997).

### 5.4.2 Energy balance and flux measurements

The shortened energy balance equation (Equation 5.1) is an indirect technique to calculate ET by quantifying and partitioning the energy at the Earth's surface. This equation ignores fluxes that contributes insignificant energies such as respiration, energy stored in plant canopies and photosynthesis (Thom, 1975). The shortened energy balance is presented as:

$$Rn = G + H + LE \qquad (5.1)$$

where, Rn is the net irradiance, $G$ is the ground heat flux, $H$ is the sensible heat flux and $LE$ is the latent energy flux, which is the energy equivalent of ET by conversion (Savage et al., 2004).
Eddy covariance (EC) is a technique based on estimation of eddy fluxes and is expressed as:

$$H = \overline{\rho_a} c_p \overline{w'Tair'} \qquad (5.2)$$

Where, $\rho_a$ 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 Tair is the air temperature (°C). The $w'$ and Tair 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 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 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).

#### 5.4.2.1 Two-year-old and six-year-old *A. mearnsii* measurements

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). 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.

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

After the harvesting of *A. mearnsii* and planting of the *E. dunnii* trees, H was measured using a three-dimensional sonic anemometer (CSAT3, Campbell Scientific Inc., Logan, Utah, USA) 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. 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 Energy balance closure

If each component of Equation 5.1 is measured accurately and independently then $Rn - G - H - LE = EB_c$, where $EB_c$ is termed energy balance closure (Wm$^{-2}$), and should be equal to zero ($EB_c$= 0 Wm$^{-2}$) and the $EB_c$ is achieved. However, $EB_c$ could still be achieved if one or more variables in Equation 5.1 have been measured incorrectly as reported by Savage et al. (2004). Equation 5.1 can be rearranged such that $(Rn - G) = AE$ (available energy) and is equal to $H + LE$, which is considered a perfect closure (Wilson et al, 2001; Leuning et al., 2005; Foken, 2008). The $EB_c$ can also be measured using a closure ratio or energy closure discrepancy (Twine et al., 2000) as

$$D = \frac{H + LE}{Rn - G} \tag{5.3}$$

where, a $D$ of 1 represents a perfect closure. Many studies using various EB measuring methods over different surfaces have been unsuccessful in achieving $EB_c$ (Wilson et al., 2001; Barr et al., 2006). A variety of reasons have been discussed by Twine et al. (2000), which include, 1) incorrect measurement of variables in Equation 5.1, 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. Closure pitfalls in Equation 5.1 associated with (2) could be significant for our study due to different measurement techniques used (LAS and EC). The $EB_c$ in this study was calculated for the three measurement periods: October 2007 to September 2008 ($Amear_2$), October

2012 to September 2013 (*$Amear_6$*) and October 2019 to September 2020 (*$Edun_2$*). The $EB_c$ was determined using the daytime data values (Rn > 0) due to potentially large nocturnal influences in night-time data as reported by Wilson et al. (2001). In addition, data on rainy days were excluded due to the negative impact of rainfall on turbulent fluxes as reported by Zhang et al. (2016).

### 5.4.4 Two-year-old E. dunnii ancillary measurements

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 placed at a depth of 0.08 m and 0.06 m below the soil surface, respectively. Both these sensors were used together with a CS616 volumetric soil water content sensor (Campbell Scientific Inc., Logan, Utah, USA) to estimate the heat stored in the soil. These 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 (Dq) was calculated for 48 trees using (Curtis and Marshall, 2000):

$$Dq = \sqrt{\frac{(\sum(DBH)^2}{n}} \qquad (5.4)$$

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 each month for a period September 2019 to August 2021 using Equation 5.5 (White et al., 2014):

$$v = \left(\frac{\pi}{12}\right)\left(\frac{Dq}{100}\left(\frac{h}{h-1.3}\right)\right)h \qquad (5.5)$$

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

$$V = \frac{10\,000}{A}\sum_{i=1}^{n} vi \qquad (5.6)$$

where $vi$ was the productive volume of the *i*th tree and $A$ was the total area ($m^2$) of the plot where measurements were conducted

The monthly leaf area index (LAI) measurements were conducted on the *$Edun_2$* 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 a study site from October 2019 to September 2020. The quarterly LAI measurements of $Amear_2$ and $Amear_6$ were conducted by Clulow et al. (2011) also using the LAI-2200 Plant Canopy Analyzer.

### 5.4.6 Plantation water productivity

The plantation water productivity ($PWP_{WOOD}$), expressed in g wood $kg^{-1}$ of water, 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) and this method is popular for reasons including, calculating a crop factor:

$$\mathrm{Kc} = \mathrm{ET} \ / \ ET_o \qquad (5.7)$$

where Kc is a crop factor. The calculated Kc allows for an estimation of ET from standard weather station data. In this study, monthly Kc 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 (Is, 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 Is was lowest in June (mean range: 5.1-12 MJ $m^{-2}$) and most consistent, whereas December and January experienced higher and more variable Is (reaching a peak of 30 MJ $m^{-2}$) across all measurement periods. These conditions were consistent with clear winter days and cloudy summer season. The daily maximum Tair of 38.6º C, 33.8°C and 37.5°C were measured in January 2008, December 2012 and January 2020, respectively, while the lowest measured Tair 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.

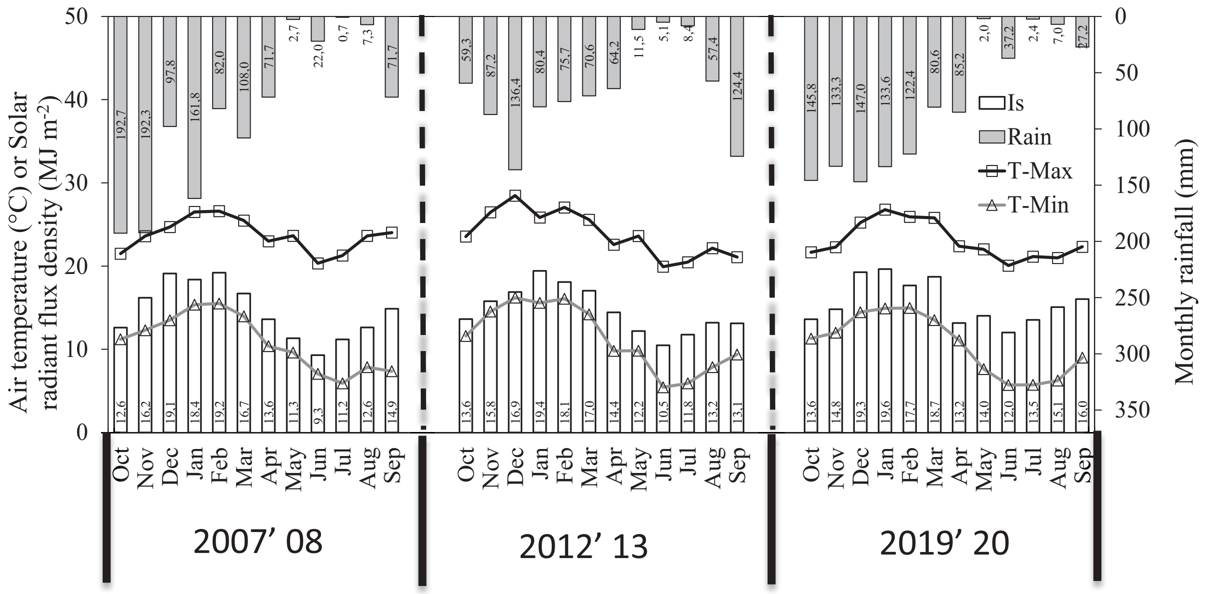


**Figure 5-2: Monthly values of mean daily radiant flux density (Is, MJ $m^{-2}$), maximum (T-Max) and minimum (T-Min) air temperatures (°C) and corresponding total monthly rainfall measured at Two Streams Research Catchment in 2007' 08, 2012' 13 and 2019' 20 hydrological years.**

### 5.5.2 Soil water content

There was a distinct seasonal variation in SWC dynamics for all measurement periods (Figure 5-3). The SWC was generally higher for the *Amear₂* followed by *Amear₆* and *Edun₂*. The *Amear₂* 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 *Edun₂* and *Amear₆*, respectively (Figure 5-3).

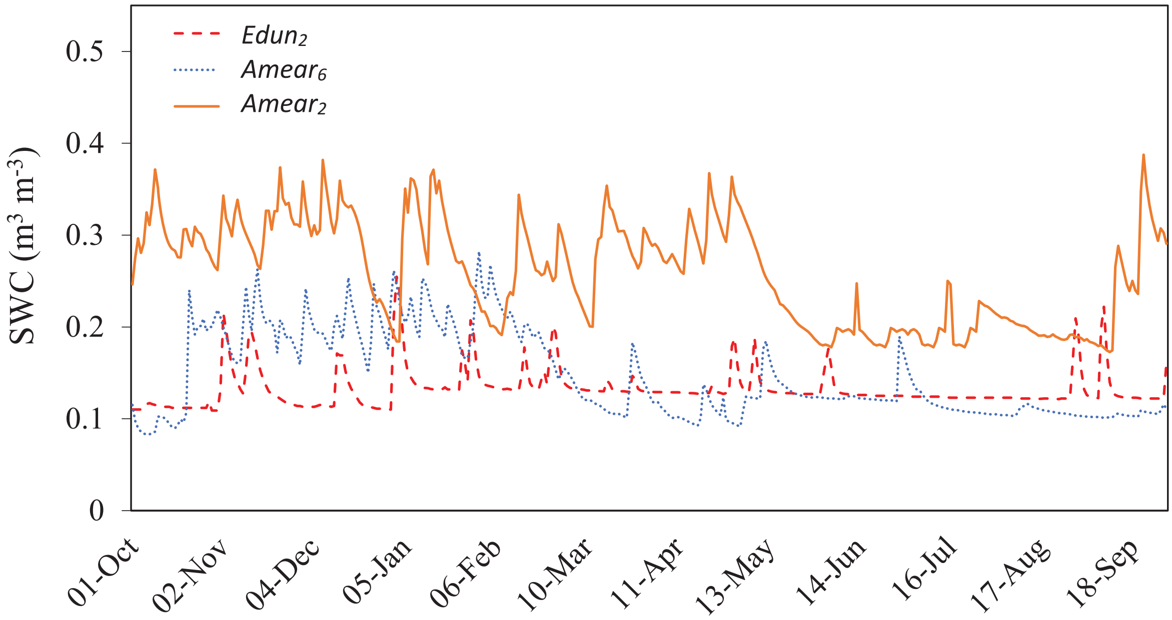


**Figure 5-3: The daily mean soil water content (SWC, $m^3$ $m^{-3}$) measured in the top 0.6 m of soil on a study site planted with two-year-old *A. mearnsii* (*$Amear_2$*, October 2007 to September 2008), two-year-old *E. dunnii* (*$Edun_2$*, October 2019 to September 2020) and six-year-old *Acacia mearnsii* (*$Amear_6$* October 2012 to September 2013).**

## 5.5.3 Flux measurements

### 5.5.3.1 Energy balance closure

There was a very good linear relationship between AE versus H+LE for all crops with an $R^2 > 0.97$, with the *$Amear_2$* having a slightly greater RMSE (Figure 5-4a, 5.4b and 5.4c). These results imply a very good accuracy by our EB measuring techniques. The D was different for each measurement period. Closure was good during summer (October to March), which were the hottest months of the season for the *$Edun_2$* (0.99), *$Amear_2$* (0.90) and *$Amear_6$* (1.045) measurements. During winter months (June to July), D for all crops was above one (*$Edun_2$*=1.02, *$Amear_2$*= 1.1 and *$Amear_6$*=1.04). These results of D are acceptable in terms of energy balance indicating that the components of the energy balance were well represented by the measurement techniques.

### 5.5.3.2 Seasonal variation of energy balance components

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 between measurement periods indicated that there were no statistically ($p > 0.05$) significant differences in Rn in both summer and winter measurement periods (Table 5.2). 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 *$Amear_2$*, *$Amear_6$* and *$Edun_2$*, respectively. The peak LE values corresponded with maximum Rn values greater than 900 $Wm^{-2}$ for all crops. The LE fluxes continued to dominate ($p < 0.05$) during the winter season for the *Amear₂* (66%) and *Edun₂* (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 $Wm^{-2}$). 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 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 ($Wm^{-2}$)** | | |
| 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 5-5. 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 5-5). The total accumulated rainfall for each measurement year was similar across the three years. The accumulated ET exceeded rainfall for all crops (Figure 5-5), 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 5-5).

The genus exchange ratio between the two young crops ($Amear_2$ and $Edun_2$) was determined to be 1, while a comparison between a mature $Amear_6$ crop and young crops produced a ratio of 0.9.

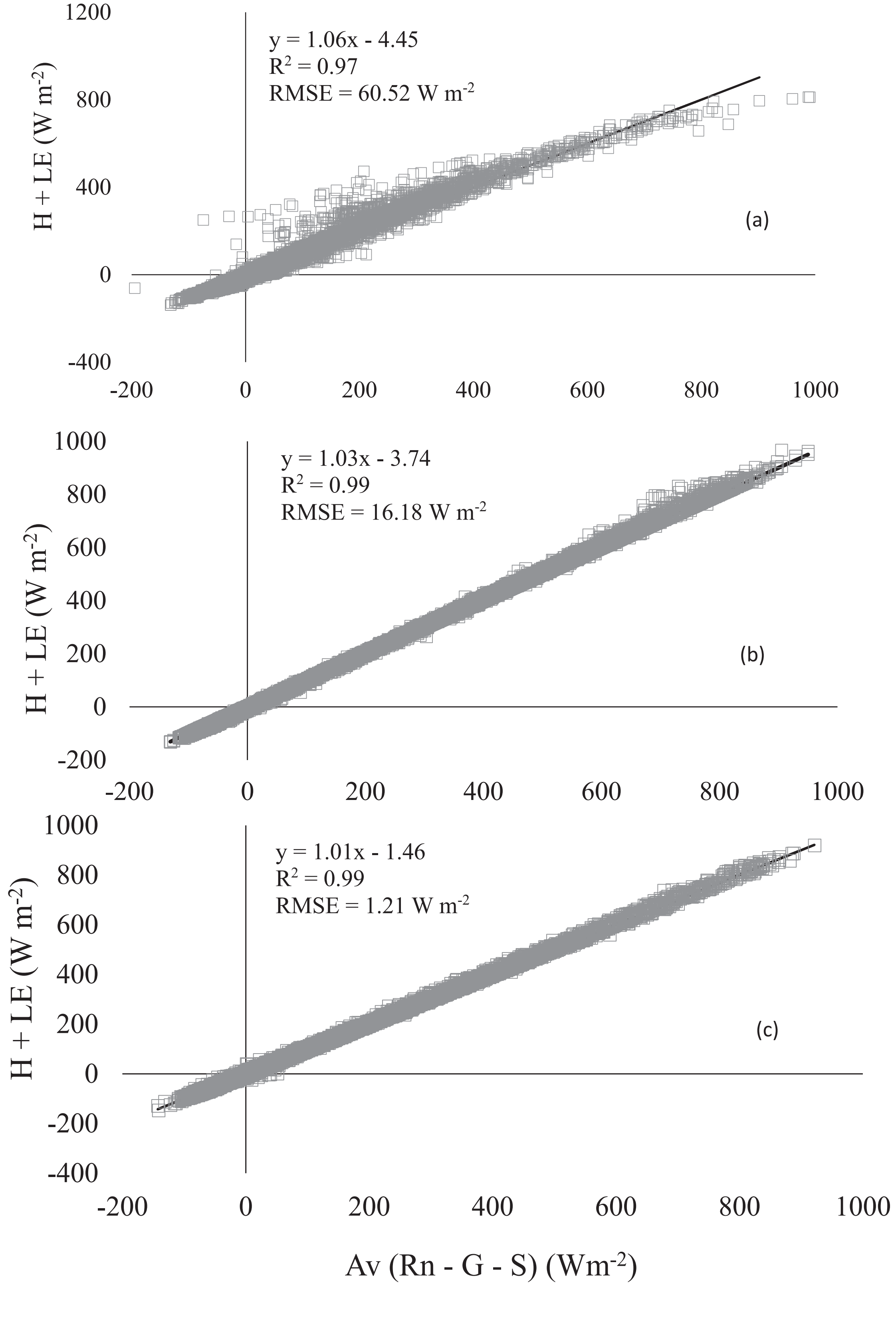


**Figure 5-4: Relationship between (H+LE) and available energy (AE = Rn – G) data measured in (a) two-year-old *Acacia mearnsii* (using large arpeture scintillometer), (b) six-year-old *Acacia mearnsii* (using the eddy covariance system) and (c) two-year-old *Eucalyptus dunnii* (using the eddy covariance system) at Two Streams research catchment.**

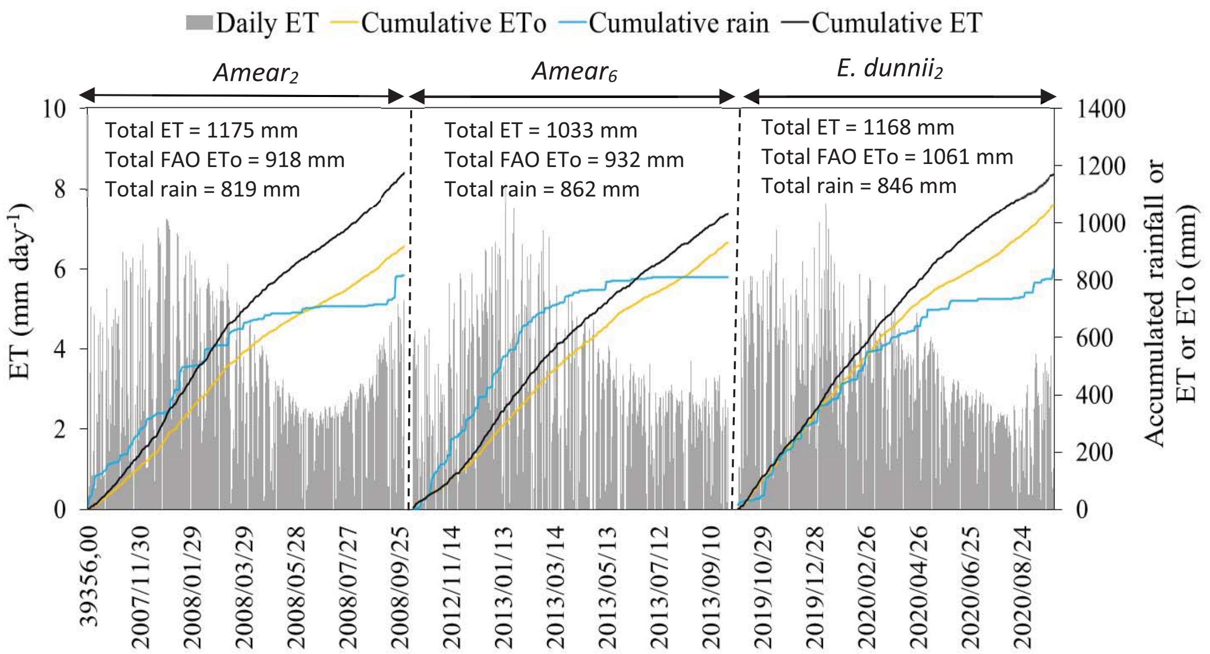


**Figure 5-5: Comparison between total evaporation (ET) by two-year-old *A. mearnsii* (*Amear₂*, measured using large aperture scintillometer from Oct 2007 to Sep 2008), six-year-old *A. mearnsii* (*Amear₆*, measured using eddy covariance from Oct 2012 to Sep 2013) and two-year-old *E. dunnii* (*Edun₂*, 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 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 Is as the most important predictor of ET in *Edun$_2$* (Figure 5-6b). 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 Is and FAO ETo while VPD, T-Max, T-min and SWC were important variables in decreasing order of importance (Figure 5.6a and 5.6 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.

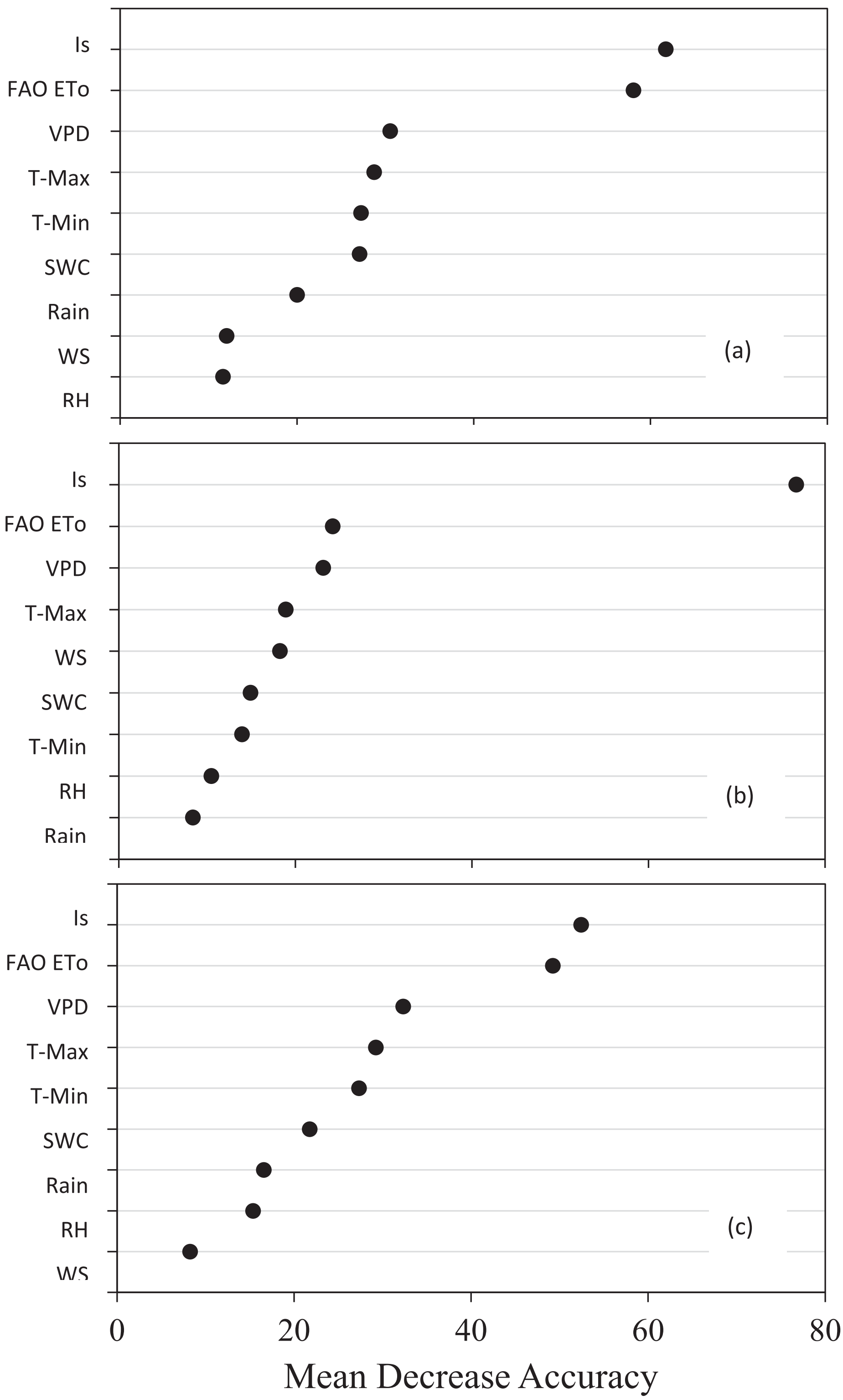


**Figure 5-6: Variable importance plots of (a) two-year-old *Acacia mearnsii*, (b) two-year-old *E. dunnii* and (c) six-year-old *Acacia mearnsii* from the random forest regression model using solar radiation (Is), FAO reference evaporation (FAO ETo), vapor pressure deficit (VPD), maximum air temperature (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 Kc 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 5.5, and thereafter averaged for each month of the measurement period for each crop (Figure 5-7). When Kc = 1, the Two Streams catchment ET equals to FAO ETo. However, a Kc of <1 or >1 indicated that the catchment actual ET is less than or greater than the FAO ETo, respectively. Comparison of Kc between our crops indicated that the Kc was between 0.9 and 1.4 throughout the year for all crops, except during a distinct period when the *Edun₂* Kc in August and September were 1.6 and 1.7, respectively (Figure 5.7). This is an indication that the *Edun₂* ET significantly exceeded the FAO ETo in these winter months.

Figure 5.7/…

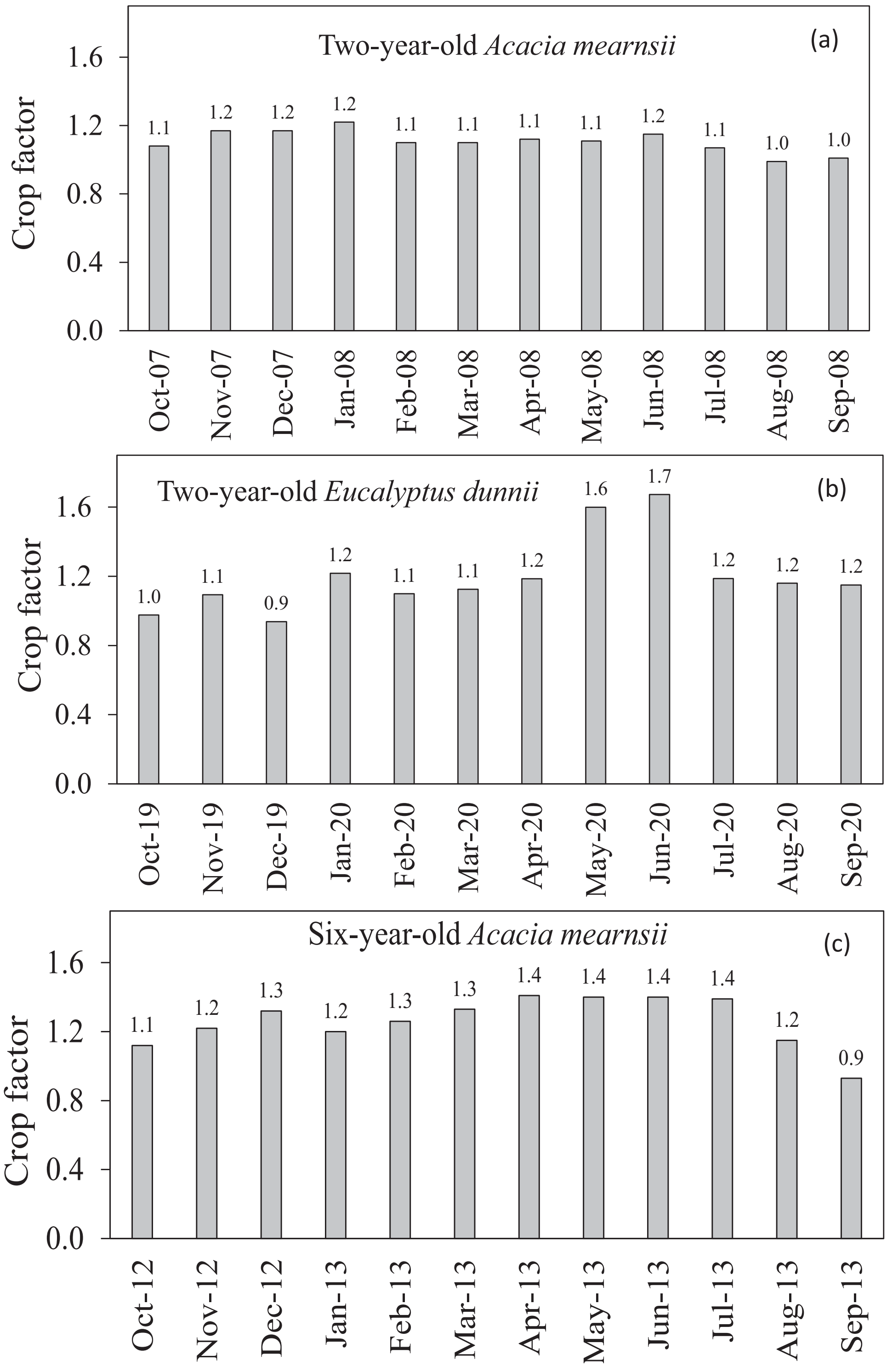


**Figure 5-7: Monthly crop factors (Kc) for (a) two-year-old *Acacia mearnsii* (b) six-year-old *Acacia mearnsii* and two-year-old *Eucalyptus dunnii* derived at Two Streams research catchment for 2007' 08, 2012' 13 and 2019' 20 hydrological years, respectively.**

### 5.5.7 Comparison between the leaf area index

The LAI for the *Edun₂* showed a typical seasonal pattern (Figure 5-8), 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 5-8).

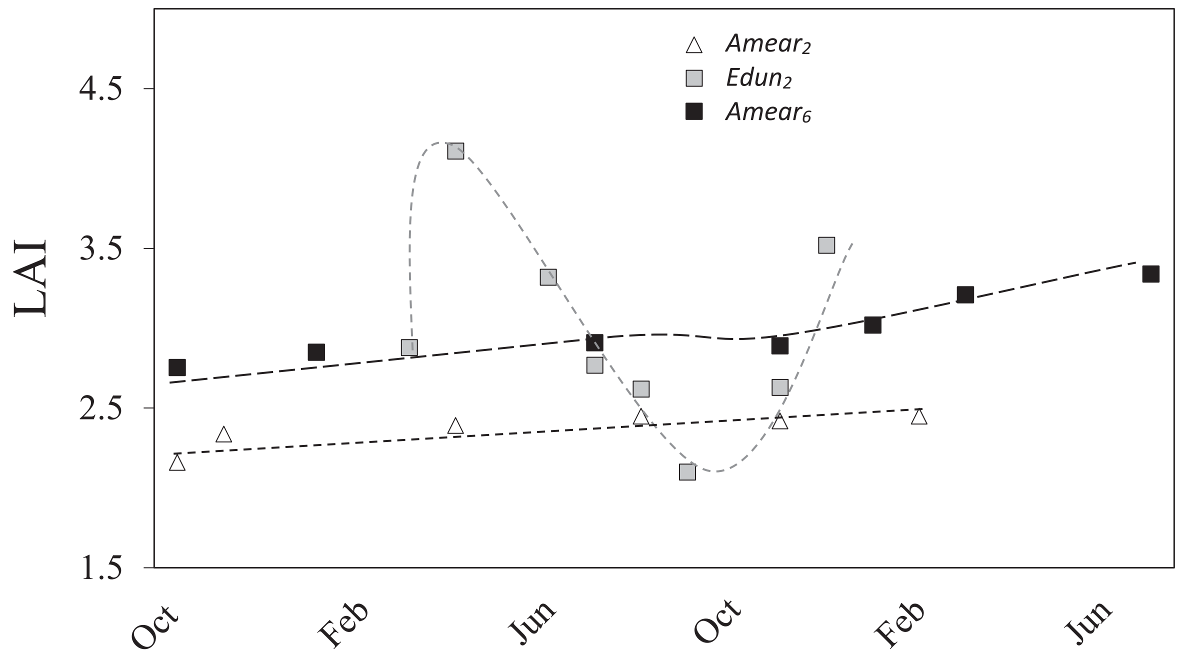


**Figure 5-8: The leaf area index (LAI) measured at Two Streams research catchment for the two-year-old *Acacia mearnsii* ($Amear_2$), two-year-old *Eucalyptus dunnii* ($Edun_2$) and six-year-old *Acacia mearnsii* ($Amear_6$). For $Amear_2$, LAI was conducted between October 2007 to February 2008, between February 2020 to December 2020 for $Edun_2$ and October 2011 to June 2012 for $Amear_6$.**

### 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 5-9).

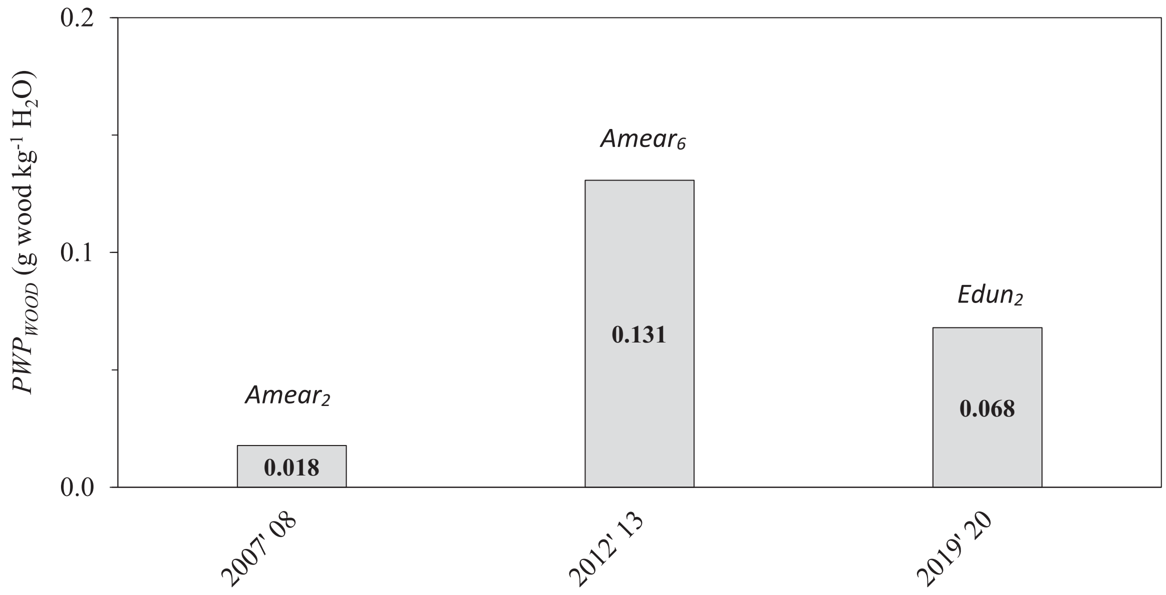


**Figure 5-9: The plantation water productivity (*$PWP_{WOOD}$*) of two-year-old *Acacia mearnsii* (*$Amearn_2$*), six-year-old *Acacia mearnsii* (*$Amearn_6$*) and *Eucalyptus dunnii* (*$Edun_2$*) in 2007’ 08 (September 2007 to October 2008), 2012’ 13 (September 2012 to October 2013) and 2019’ 20 (September 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 specie 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 closure

Energy balance preservation at the surface is a theoretical requirement of the first law of thermodynamics, where at the surface, *AE* should be equal to energy fluxes (Liu et al., 2011). Small variations in D occurred between measurement periods and were mainly attributed to 1) instrumentation bias due to different measuring instruments used (*$Amear_2$* = LAS, *$Amear_6$* and *$Edun_2$* = EC), however, this was minimised by careful maintenance and regular calibration of the EC system and beam alignment on the LAS 2) minor adjustments in the instrumentation during the measuring period 3) secondary circulations and large eddies which could not be captured by a single EC station (Foken, 2008; Foken et al., 2010) 4) heat canopy storage which has been reported to have a significant energy contribution in tall forest canopies (Moore and Fisch, 1986; Silberstein et al., 2001) and have been reported to improve D by up to 5% (Michiles and Gielow, 2008). However, the range in D (0.90 to 1.045) in this study is very good in comparison with other EB and ET studies. For example, Wilson et al. (2001) evaluated D across 22 international sites in FLUXNET using Equation 5.3 and results produced an average D of 0.84 for all study sites (range: 0.34 to 1.69).

### 5.6.2 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 $Wm^{-2}$), 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).

### 5.6.3 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). 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 Is, 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 Is (Zeppel et al., 2004). This suggests that Is can solely be used as an input in commercial forest plantation models to estimate sapflow rather than FAO ETo which requires more than one meteorological variable to calculate. Surprisingly, rainfall was found to be a weak predictor of ET. This could be due to high rate of rainfall interception reported in commercial forests of 14.9% for *Eucalyptus* and 27.7% for *A. mearnsii* (Bulcock and Jewitt, 2012). Nevertheless, with FAO ETo being the second most important predictor of ET, this suggested that Kc is a suitable method of estimating ET in commercial forest stands, a conclusion shared by Clulow et al. (2011).

The Kc values ranged from 1.0 to 1.3, an indication that ET was either equal to or greater than FAO ETo, which was expected during the wet summer months for actively growing trees due to higher Is and SWC less limiting. However, higher Kc values during the dry season, particularly on the *Edun*$_2$ was an indication 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.

### 5.6.4 Genus exchange ratio from Pinus to Eucalyptus

The ET genus exchange ratio between the two young crops was 1, indicating that in the early stages of development, both *Acacia* and *Eucalyptus* ET is similar. While a comparison between young crops and a mature crop (*$Amear_6$*) produced a ratio of 0.9. From a forest operations point of view, genus exchange is only possible at rotation end, and is less likely to occur in the early stages of tree development. A suggestion from these results is that measurements are continued on young *E. dunnii* trees at Two Streams research catchment for a full rotation to allow for a full rotation comparison between *A. mearnsii* and *E. dunnii*. In addition, measurements need to be conducted over a variety of commercial forest plantation sites to cover a variety of climatic and soil conditions.

### 5.6.5 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. Very good energy balance closure was achieved, despite the use of different energy balance instrumentation and neglected energy fluxes. 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. Genus exchange ratio between young crops was 1, while between young crops and a mature crop was 0.9. 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, Is and FAO ETo, are very good predictors of ET, which enabled a development of monthly Kc 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 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. dunnii* 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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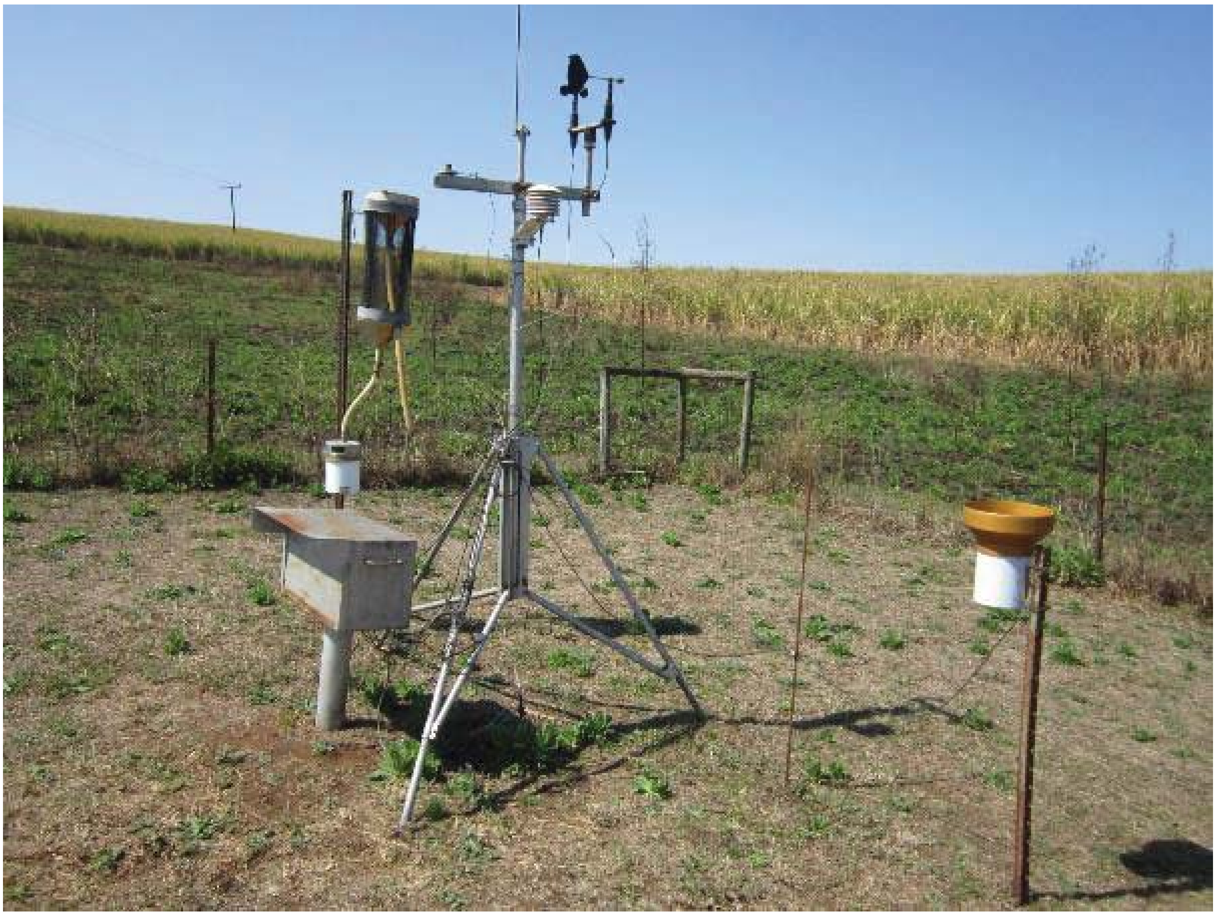
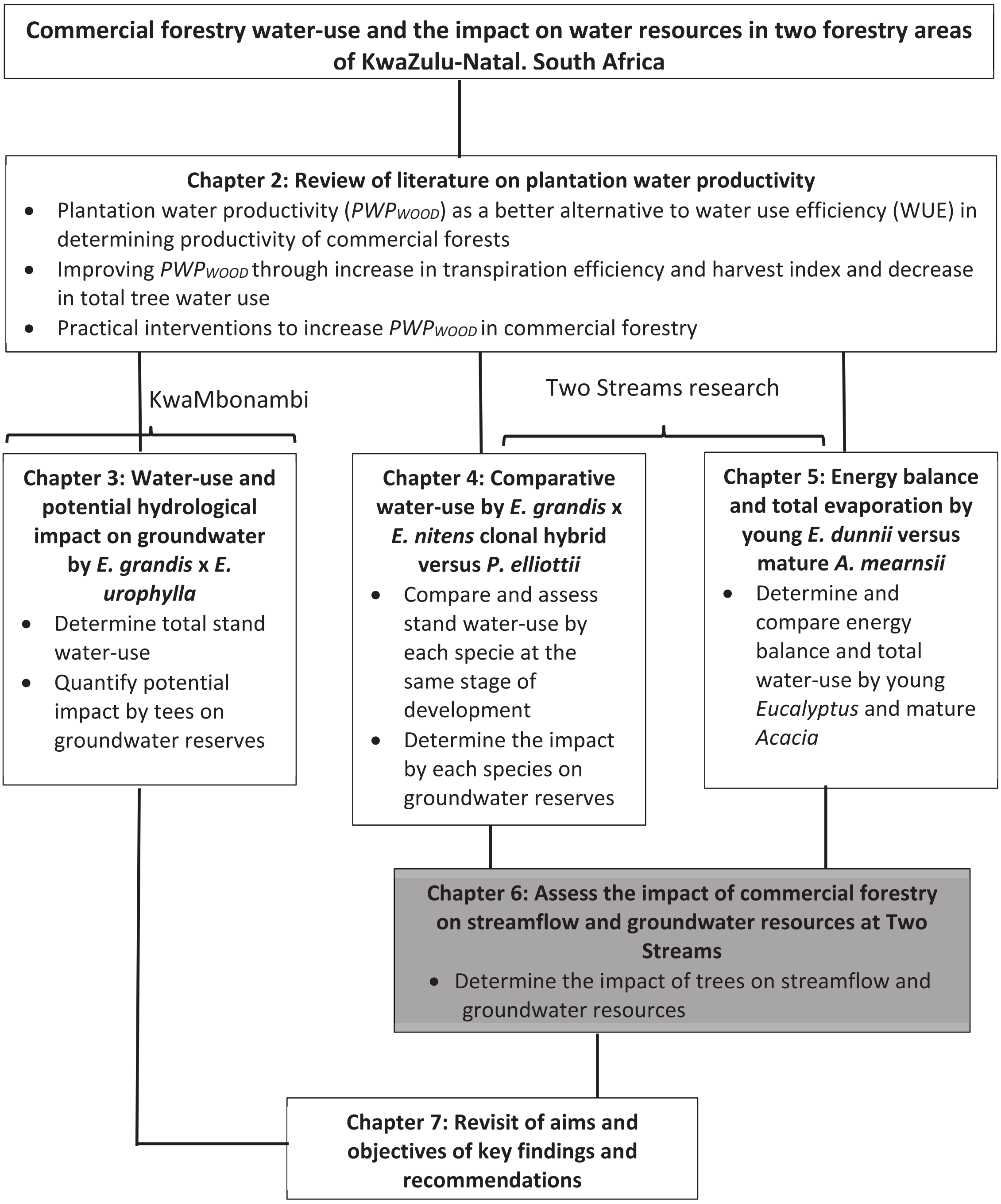
## 5.10 Supplementary information

**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.**



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

**Lead into Chapter 6**: The findings from chapter 3, 4 and 5 have demonstrated that commercial plantation uses water greater than other vegetation types and have a potential negative impact on groundwater reserves, hence the flow of the stream. Consequently, reduction in streamflow will impact downstream water users negatively. Therefore, chapter 6 aimed to experimentally test the impact, or lack of, young *E. dunnii* and *A. mearnsii* on streamflow and groundwater reserves at Two Streams research catchment.



# CHAPTER 6. THE LONG-TERM EFFECTS OF *ACACIA MEARNSII* AND YOUNG *E. DUNNII* PLANTATION ON STREAMFLOW AT TWO STREAMS RESEARCH CATCHMENT, SOUTH AFRICA

**Nkosinathi D. Kaptein[1], Alistair D. Clulow[1,2], Colin S. Everson[2,3], Michele L. Toucher[2,4], Ilaria Germishuizen[5]**

[1]*Discipline of Agrometeorology, University of KwaZulu-Natal, Pietermaritzburg, 3209, South Africa*
[2]*Centre for Water Resources Research, University of KwaZulu-Natal, Pietermaritzburg, 3209, South Africa*
[3]*Department Plant and Soil Sciences, University of Pretoria, Pretoria, South Africa*
[4]*Grasslands-Forests-Wetlands Node, South African Environmental Observation Network, Pietermaritzburg, 3201, South Africa*
[5]*Institute for Commercial Forestry Research, Scottsville, 3201, South Africa*

Corresponding author: Nkosinathi Kaptein, kapteinnd@gmail.com, *University of KwaZulu-Natal, Pietermaritzburg, 3201, South Africa*

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* Referencing adheres to format of Water SA.

## 6.1 Abstract

*Acacia mearnsii* and *E. 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 quantification of the impact by commercial forestry species on Q and groundwater resources. This study used 21 years of hydrological data from the Two Streams research catchment, where the Q, total evaporation (ET), depth to groundwater and precipitation (P) has been monitored since 1999 using a weir, large aperture scintillometer and eddy covariance, dip meter and automatic raingauge, respectively. The catchment water balance was calculated as a difference between water inflows and water outflows to the catchment. The aridity index (AI) and water yield were calculated as a ratio of ET to P and Q to P, respectively. Results indicated that the study period mean annual precipitation (MAP, 793 mm) was lower than long-term MAP of 853 mm, most likely influenced by El Niño events experienced over the study period. The Q responded positively to clearing of riparian areas, decreased post *Acacia mearnsii* afforestation, increased after clearfelling and decreased again after afforesting the catchment with *E. dunnii*. A similar response was produced by the AI, which correlated well with the water yield for both crops ($R^2 > 0.72$). The annual ET exceeded annual rainfall by 20%, indicating a negative catchment water balance, suggesting trees were sourcing water elsewhere, probably the groundwater. The random forests predictive model indicated that water yield and precipitation are good

predictors of Q. Results from this study suggest that afforesting the catchment with *A. mearnsii* or young *E. dunnii* has a negative impact on Q and groundwater reserves. Further research using isotopes to trace the sources of water used by the trees as well as continued monitoring of ET and Q are suggested.

***Keywords: Aridity index, catchment water balance, commercial forestry, groundwater reserves, water yield***

## 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 (Thiel et al., 2019). In addition, it contributes to the socio-economy through employment (1.35%) and agricultural GDP (11%), and it has been linked in some areas to improved infiltration rates (Van Dijk and Keenan, 2007), significant reduction of soil erosion due to forest litter at the soil surface and minimising soil evaporation (Wichert et al., 2018). Despite these benefits, other research in different parts of the world have indicated that evapotranspiration by commercial forestry species is significantly higher than indigenous forest stands and grasslands (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, the genetically improved exotic tree species have a deep taproot (Dye, 1996), providing capability to access groundwater reserves during the dry season (Van Dijk and Keenan, 2007). This usually results in perennial streamflow reduction and lowering of 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 clearfelling. Studies by Dye and Jarmain (2004) and Clulow et al. (2011) conducted detailed measurements of total water use and quantified the potential impact of *A. mearnsii* on water resources in KwaZulu-Natal midlands of South Africa. Results from these studies indicated that *A. mearnsii* ET exceeds precipitation by as much as 50%, and there was sufficient evidence suggesting that trees can access deep underground reserves using their deep taproots. The fact that a significant share of South Africa's commercial forest plantations is established adjacent to catchments that are used as freshwater, necessitates the expansion of knowledge on the impact of commercial afforestation on Q. However, research involving experimental catchments is very costly to implement and maintain.

The Two Streams research catchment has been used as an experimental site for more than 21 years to investigate the impact of *Acacia mearnsii* on hydrological processes, with the main focus being total evaporation, tree transpiration and soil hydrological processes. Results indicated that actual total evaporation rates exceeded rainfall by 46% over periods of measurement over *A. mearnsii* (Burger, 1999; Jarmain and Everson, 2002; Clulow et al., 2011; Everson et al., 2014). However, little attention was given to understanding the long-term impact of *A. mearnsii* on Q. The *A. mearnsii* plantations were harvested in February of 2018 and a change of genus was proposed, with subsequent planting of *E. dunnii* in March 2018. This presented a unique opportunity to understand the impact of genus exchange on the water balance of the catchment. Therefore, this research aims to investigate the early impacts of a change in genus from *A. mearnsii* to *E. dunnii* on the streamflow and groundwater recharge in the Two Streams research catchment.

## 6.3 Climate and location of the Two Streams 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 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.

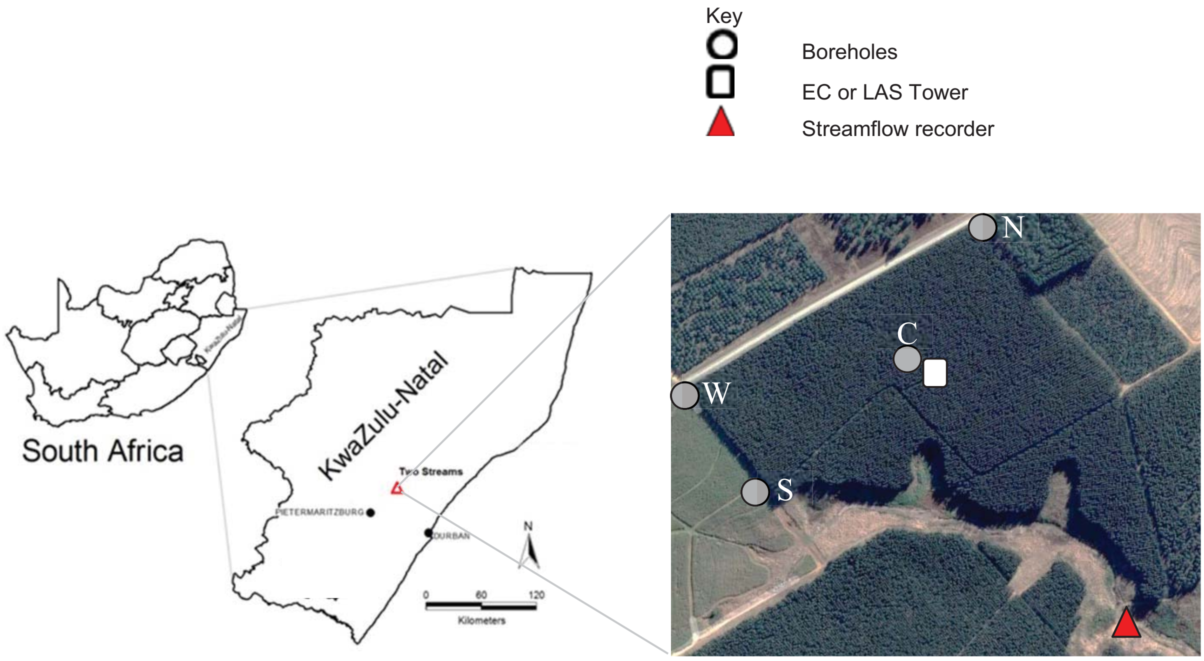


**Figure 6-1: Location of the study area at Two Streams Research Catchment. The Google Earth extract (extreme right) provides aerial view of the catchment with location of measurements points. Different letters, N, C, W and S denotes north, centre, west and south boreholes, respectively.**

**Table 6.1: The general characteristics of the Two Streams Research catchment. The abbreviations MAP and MAT denotes mean annual precipitation and mean annual temperature, respectively.**

| Characteristics | Our study site |
|---|---|
| Minimum MAT (ºC) | 4.5 |
| Maximum MAT (ºC) | 31.7 |
| MAP (mm) | 778 |
| Climate | Warm subtropical |
| Altitude (metres 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 |

## 6.4 History of the catchment

The Two Streams research catchment remain an important catchment in the KwaZulu-Natal regions of South Africa due to a long-term forest hydrological research conducted within the catchment. Streamflow measurement started in the year 1999 adjacent to a mature *A. mearnsii* trees. After a streamflow measuring equipment was calibrated, the trees in the riparian areas were removed in July 2020 (Clulow et al., 2011). The remainder of *A. mearnsii* trees were harvested in 2004 to 2005, thereafter a catchment replanted to

*A. mearnsii* a year later (August 2006). Trees were afforested for a full rotation (12 years) with intense hydrological monitoring which included streamflow gauging, tree transpiration, total evaporation and groundwater reserves conducted by Everson et al. (2014) and Clulow et al. (2011). In February 2018, *A. mearnsii* trees were harvested. Post harvesting of *A. mearnsii*, a change in genus was proposed for research purposes, with subsequent planting of *E. dunnii* in March 2018. Hydrological processes measurements resumed in September of 2019 for a period of two years (measurements stopped in September of 2021).

## 6.5 Material and methods

### 6.5.1 Water balance monitoring

The Q and rainfall have been monitored since year 2000 at the Two Streams research catchment, while ET and groundwater measurements commenced in September 2006 (Clulow et al., 2011 and Everson et al., 2014). The rainfall and Q data from 2000 to 2021 and ET and groundwater data from 2006 to 2021 for this study were sourced from the Centre for Water Resources Research (CWRR) at the University of KwaZulu-Natal in Pietermaritzburg. The Q was measured using a streamflow recorder (Supplementary Figure 6.1), whereas rainfall measurements were conducted in an automatic weather station (AWS) installed adjacent to the study site, according to World Meteorological Organisation (WMO, 2008). Levels of groundwater were measured from August 2006 to December 2021 in four groundwater boreholes surrounding the catchment (located at the centre, south, north and west of the catchment) using a 101 P7 water level dip meter (Solinst Ltd. Georgetown, Canada) (Supplementary Figure 6.1). A detailed explanation of measurement techniques and equipment used can be found in Clulow et al. (2011) and Everson et al. (2014).

### 6.5.2 Catchment water balance, aridity index and water yield

The water balance of the catchment was calculated for 2007 to 2021 hydrological years, due to availability of baseflow data only for this period, from rainfall, ET and direct runoff (including baseflow values sourced from Ngubo et al., 2022 for a period 2006 to 2017) using,

$$\pm\Delta S = water\ inflow - water\ outflow \qquad (6.1)$$

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 6.1 was further expressed using the most important variables in the water balance as follows:

$$\pm\Delta S\ water\ storage = P - ET - R - G \qquad (6.2)$$

where, P is precipitation (mm, *water inflow*), ET is the total measured evaporation (mm, water outflow), R is the direct runoff (mm, water outflow) and G is the contribution from groundwater (mm, water inflow or outflow).

The aridity index (AI) and water yield were calculated as follows:

$$AI = \left(\frac{ET}{P}\right) \qquad (6.3)$$

$$WY = \left(\frac{Q}{P}\right) \qquad (6.4)$$

Where *WY* is a water yield.

### 6.5.3 Statistical analysis

The statistical analysis was performed using the R statistical computing software (R Development Core team 2008). The analysis was conducted using two approaches, first, a simple linear regression model was used to establish a relationship between Q and growth parameters (Dq, tree heights and LAI) and groundwater reserves, 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), with Q as the response variable and rainfall, ET, AI and WY 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 (MDA) and Mean Decrease GINI (MDG). The MDA is calculated as the loss of accuracy when a variable is removed from the pool of predictors, while MDG calculation is sums up all the decreases in the GINI impurity when a given predictive variable is used to form a split at a node.

## 6.6 Results

### 6.6.1 Rainfall

Among 21 monitoring years, the mean annual precipitation (MAP) was 793 mm, varying from 490 mm to 1171 mm (Figure 6-2). The MAP for the monitoring period was lower than the long-term MAP of Mistley Canema (853 mm, Schulze and Lynch, 2007). This lower MAP was attributed to below average rainfall (< 663 mm) experienced between year 2014 and 2017, which was caused by El Niño conditions which affected southern African countries during this period (Baudoin et al., 2017; Blamey et al., 2018). Similarly, 2010 was unusually dry (Weldon and Reason, 2014), producing the second lowest rainfall year of 533 mm in this study. The above average rainfalls of 1171 mm, 1139 mm and 1106 mm were measured in 2002, 2005 and 2006, respectively. The year 2002 was categorised as a La Niña year in South Africa (Singleton and Reason, 2007). This year coincided with the maximum measured rainfall of 1171 mm during the study period.

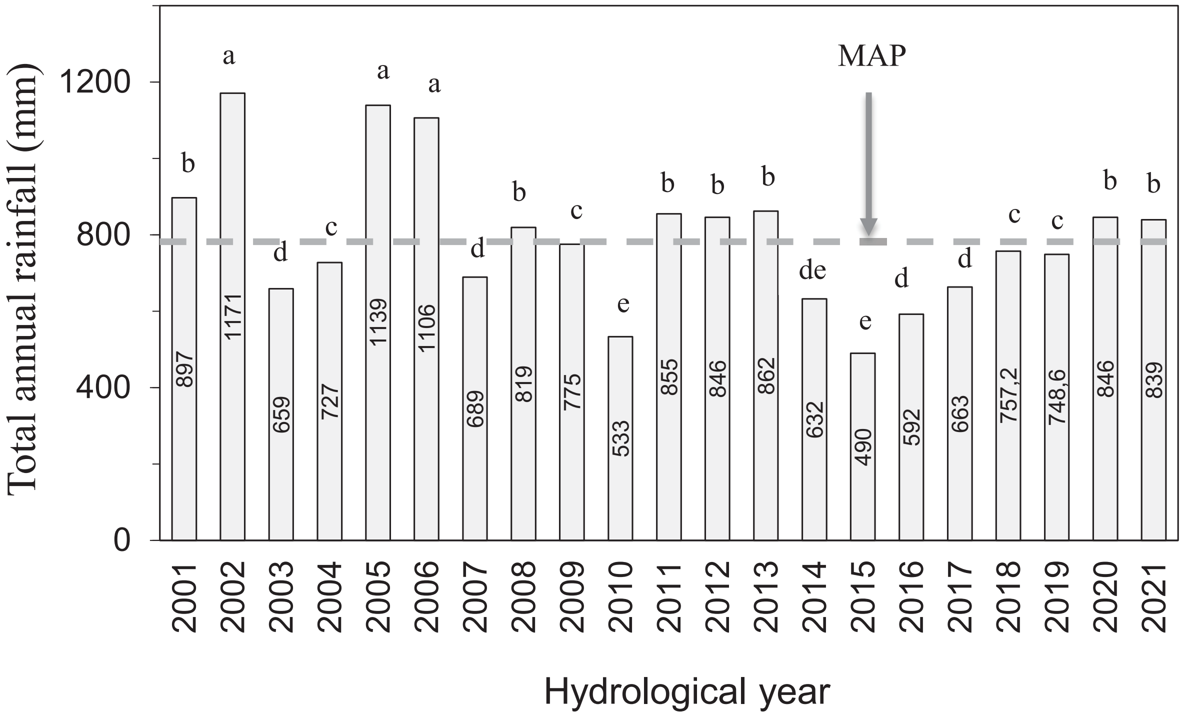


**Figure 6-2: The total annual rainfall measured at Two Streams research catchment from hydrological year 2001 to 2021. Dashed bars and different letters above bars denote mean annual precipitation (MAP) and significant differences at *p* < 0.05 between measurement years, respectively.**

### 6.6.2 Streamflow

The Q significantly increased by 19.45 mm (2001 = 26.6 mm vs 2002 = 46.05 mm) one year after clearing of riparian areas, which coincided with 274 mm greater rainfall for the year 2002 (rainfall: 2001 = 897 mm vs 2002 = 1171 mm). The *A. mearnsii* trees in the catchment were harvested in 2004, which overlapped with 74 mm increase in Q a year later (2004 = 17.8 mm vs 2005 = 91.77 mm), however, the year 2005 experienced 480 mm greater rainfall that 2004 (rainfall: 2003 = 659 mm vs 2005 = 1139 mm). In 2009, two years after the catchment was replanted to *A. mearnsii*, Q decreased by 44%, with a further decrease to the second lowest measured Q of 15.9 mm two years later (year 2011). This decrease may partly be attributed to drought conditions experienced in year 2010. A recovery of Q was observed in 2012 and 2013 producing an annual Q of 28.3 mm and 18.6 mm, respectively. A significant ($p < 0.05$) decrease in Q was observed between 2014 to 2016, which coincided with El Niño events. Unfortunately, the Q measuring equipment was damaged in 2017 and 2018 (two years before *A. mearnsii* harvesting), resulting in data loss. Streamflow measurement resumed in 2019, one year after replanting the catchment with *E. dunnii*, where the annual Q reached 74.4 mm. Post *E. dunnii* canopy closure in 2020, Q reduced by 17.3% to 61.5 mm.

The annual Q was on average 4.9% of rainfall for the period 2001 to 2021, with variations ranging from 1.0 to 8.8%. The annual WY (Q:P) median varied from 0.01 to 0.09 in 2005 to 2008 and 2020 to 2021, having statistically ($p < 0.05$) greater annual WY (Figure 6-3) and both marking periods of replanting. Considering the monthly observations, 62% (29 observations) and 71% (87 observations) presented an aridity index (ET/P) greater than one for *E. dunnii* and *A. mearnsii* afforestation periods, respectively. This implies that ET exceeded rainfall by 20% (range: 0.47 to 40.31%) over the monitoring period. The relationship between the average monthly catchment WY and the monthly AI (Figure 6-4) for the *A. mearnsii* and *E. dunnii* afforestation periods indicated a good 2nd order polynomial relationship ($R^2 > 0.75$, RMSE: 0.01 to 0.03), suggesting that both the Q and ET were influenced by rainfall.

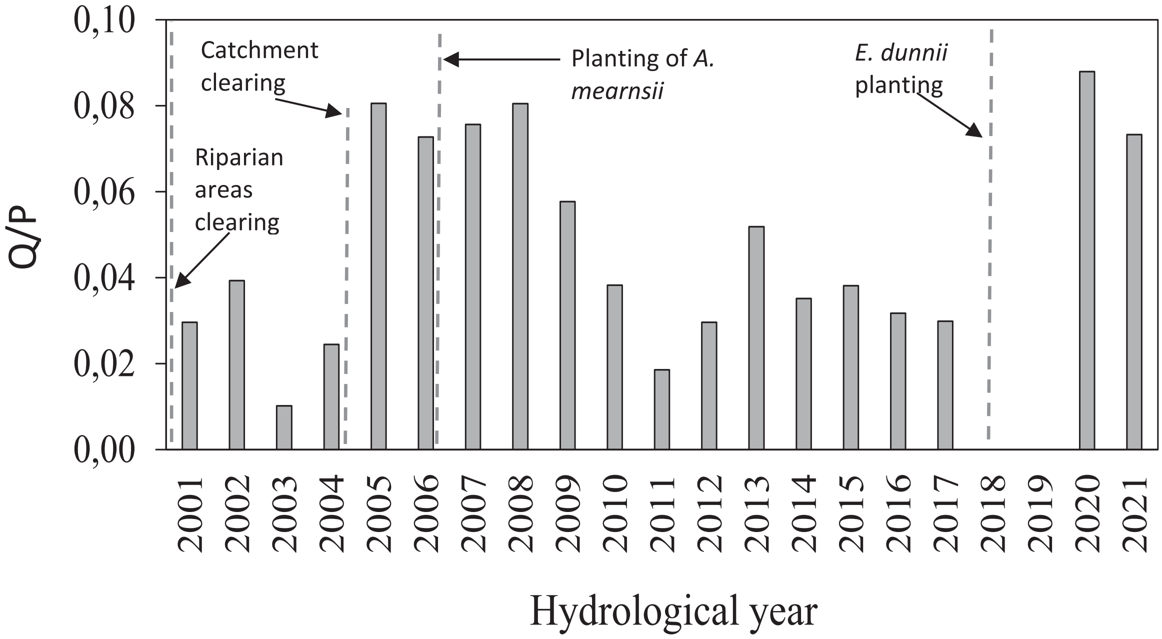


**Figure 6-3: The relative annual water yield values (expresses as total runoff (Q) divided by precipitation (P)) at Two Streams research catchment for a period 2000 to 2021. Gaps in the graph represent missing data, while horizontal dashed lines indicate landcover changes.**

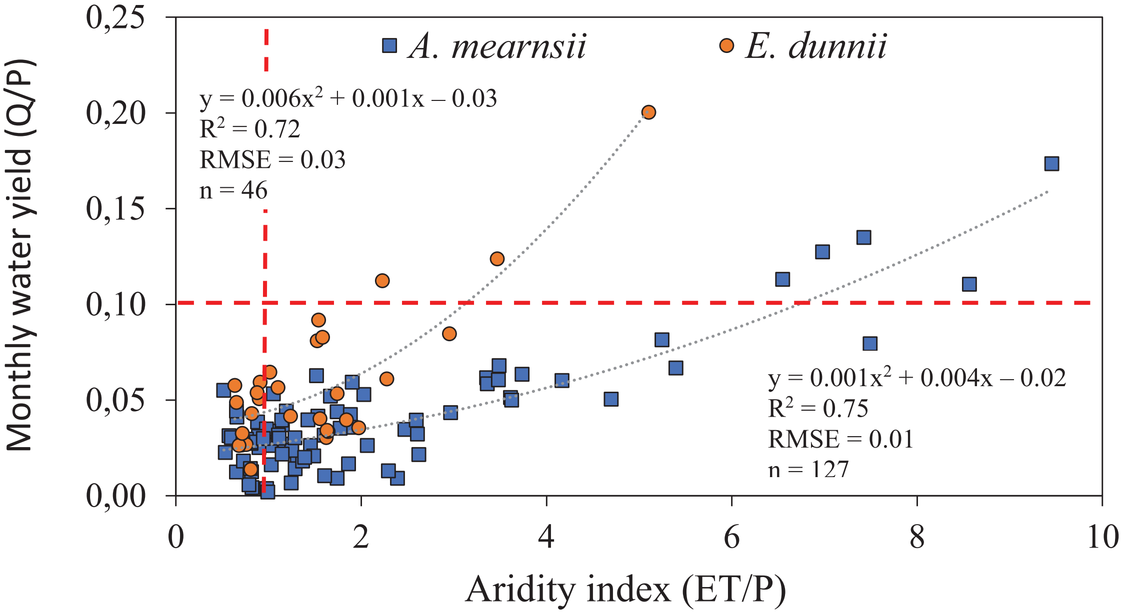


**Figure 6-4: The correlation between the monthly water yield (streamflow / precipitation, Q/P) and aridity index (AI) (total evaporation / precipitation (ET/P) at the Two Streams research catchment afforested with *Acacia mearnsii* (*A. mearnsii*) and *Eucalyptus dunnii* (*E. dunnii*). The dashed lines that are vertical indicates a threshold where ET equals to P (AI = 1), while the horizontal line indicates a ratio (Q:P = 10% of precipitation).**

### 6.6.3 Total evaporation and soil water content

The monthly ET and SWC followed a seasonal pattern, where an increase was observed during the wet season and a decrease in the dry season (Figure 6-5). After replanting the catchment with *A. mearnsii*, 2007 to 2009, SWC was measured to be approximately 0.26 $m^3$ $m^{-3}$ during the wet season, decreasing to ~ 0.17 $m^3$ $m^{-3}$ in the dry season (Figure 6-5). From 2008 to 2012, there was a decreasing trend in SWC. Unfortunately, measurements were interrupted between December 2013 to December 2019, and resumed in January 2020, with SWC reaching a peak of 0.10 and 0.15 $m^3$ $m^{-3}$ for dry and wet season, respectively. The annual ET ranged from 678 to 893 mm during the *A. mearnsii* cropping period (2006 to 2017), while a significant increase in ET (1118 to 1222 mm) was observed when the catchment was planted to *E. dunnii* (2020 to 2021).

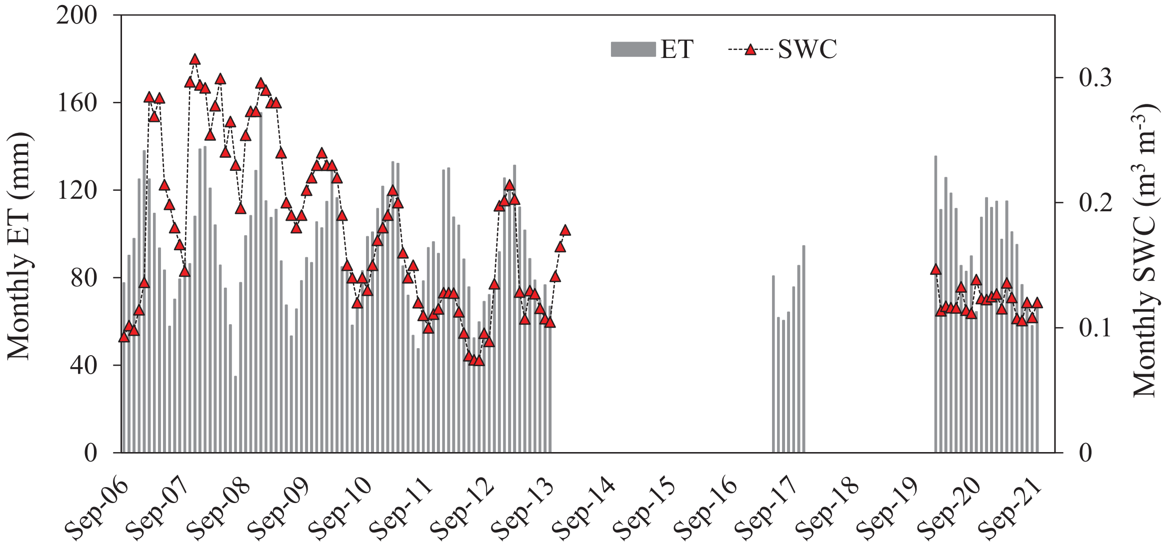


**Figure 6-5: The monthly total evaporation (ET) and soil water content (SWC) measured at Two Streams research catchment from hydrological year 2006 to 2021. Gaps in the graph represents missing data.**

### 6.6.4 Levels of groundwater and recharge

Borehole measurements indicated seasonal fluctuation of groundwater, where depth to groundwater increased in the dry season, and recharged in the wet season. The groundwater in the north borehole fluctuated the most (0.08-1.33 m), followed by south, the centre and then the west (Figure 6-6). In addition, the north borehole water level was consistently lower that the other three boreholes throughout the measurement period. From 2010 to 2012, when *A. mearnsii* trees were five years old, the south borehole failed to recharge, remaining at relatively similar depth of 32 m. Unfortunately, groundwater measurements were interrupted in July of 2013 and resumed in September 2020, two years after the catchment was replanted to *E. dunnii*. During this period, the boreholes didn't respond to rainfall as was seen in the first two years of afforestation with *A. mearnsii* ((Figure 6-6).

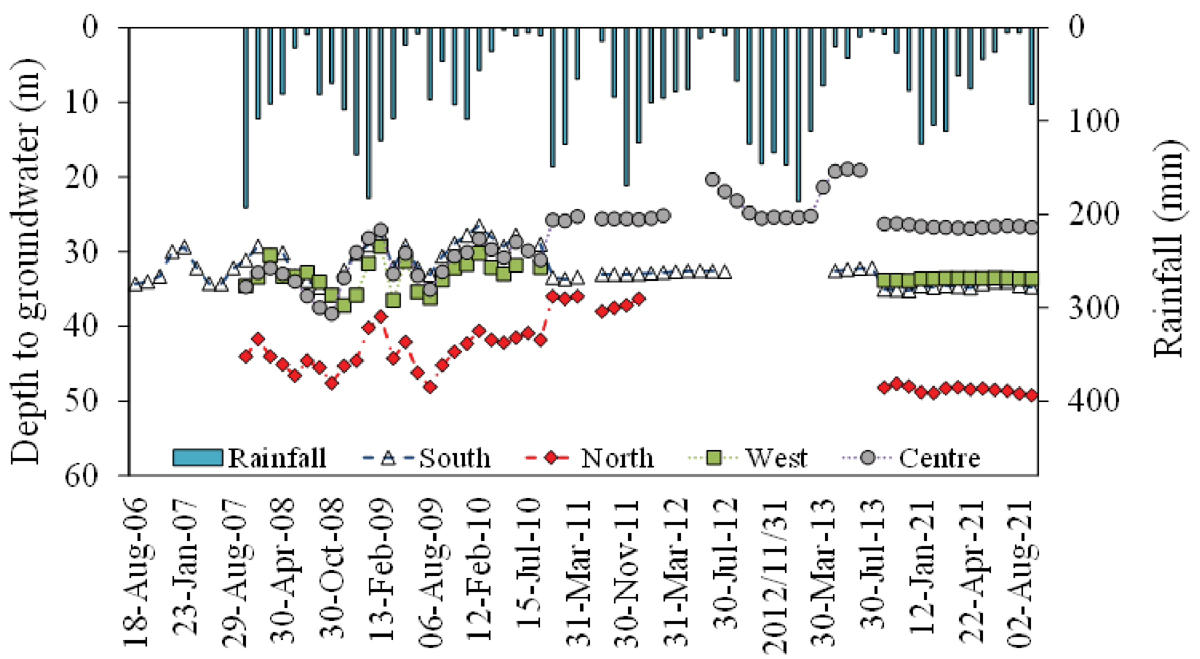


**Figure 6-6: Temporal patterns of precipitation (bars) and water table levels measured in four boreholes. Gaps in the graph represents missing data.**

### 6.6.5 Streamflow relationship with growth variables and groundwater reserves

The simple regression between Q and Dq and height produced a weak relationship with coefficient of determination less than 0.30 (Data not shown). There was a 2nd order polynomial relationship between Q and LAI when the catchment was afforested with *E. dunnii* ($R^2$ = 0.72, RMSE: 5.9 mm), where the Q increased with increase in LAI to a threshold of ~2.92, thereafter decreasing (Figure 6-7). This is likely where a physiological constraint of Q was reached. However, the relationship between Q and LAI was found to be weak, when the catchment was planted to *A. mearnsii*, with regression co-efficient of less than 0.3 (data not shown).

The south borehole, which was located in the upper slope position of a catchment, indicated a moderate inverse relationship ($R^2$ = 0.60, RMSE = 5.9 mm) with the Q (Figure 6-8). The Q decreased with increase in depth to groundwater up to a threshold of ~ 1.8 mm, thereafter, remained constant (Figure 6-8). The other borehole relationship with Q was very weak, with a coefficient of variation less than 0.2. The centre borehole, which was located at the centre of the catchment, followed a seasonal pattern indicating a strong relationship with precipitation ($R^2$ = 0.68). The other three boreholes appear to be independent of precipitation ($R^2$ < 0.10) or with lags between precipitation and groundwater levels (data not shown).

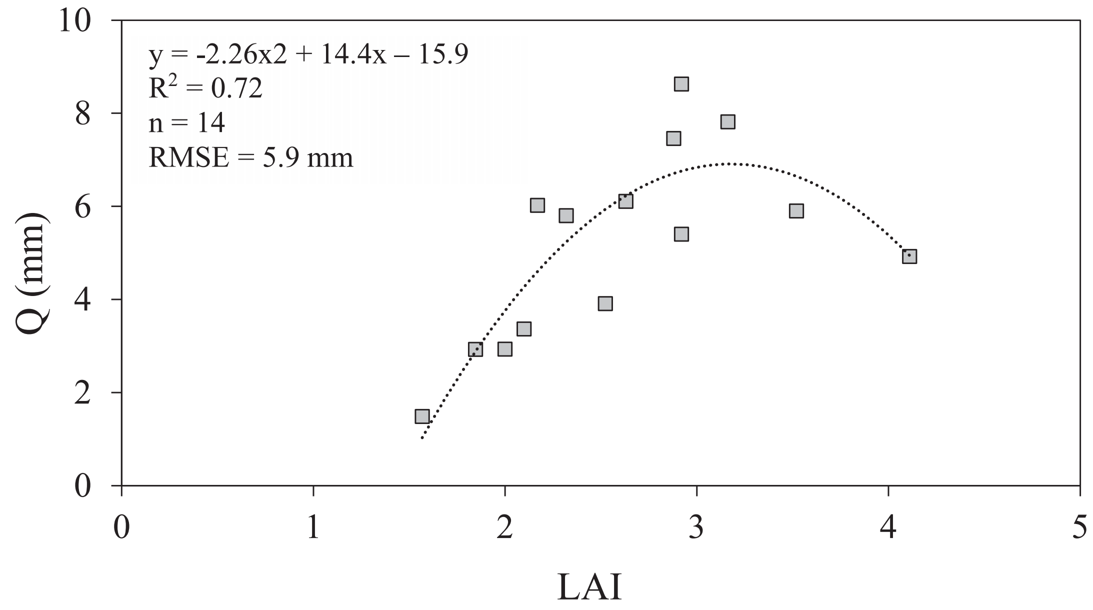


**Figure 6-7: The 2nd order polynomial relationship between the streamflow (Q, mm) and the leaf area index (LAI) at the Two Streams research catchment during the *Eucalyptus dunnii* afforestation period (August 2019 to May 2021). The equation of the regression line, regression coefficient ($R^2$) and the root mean square error (RMSE) is presented.**

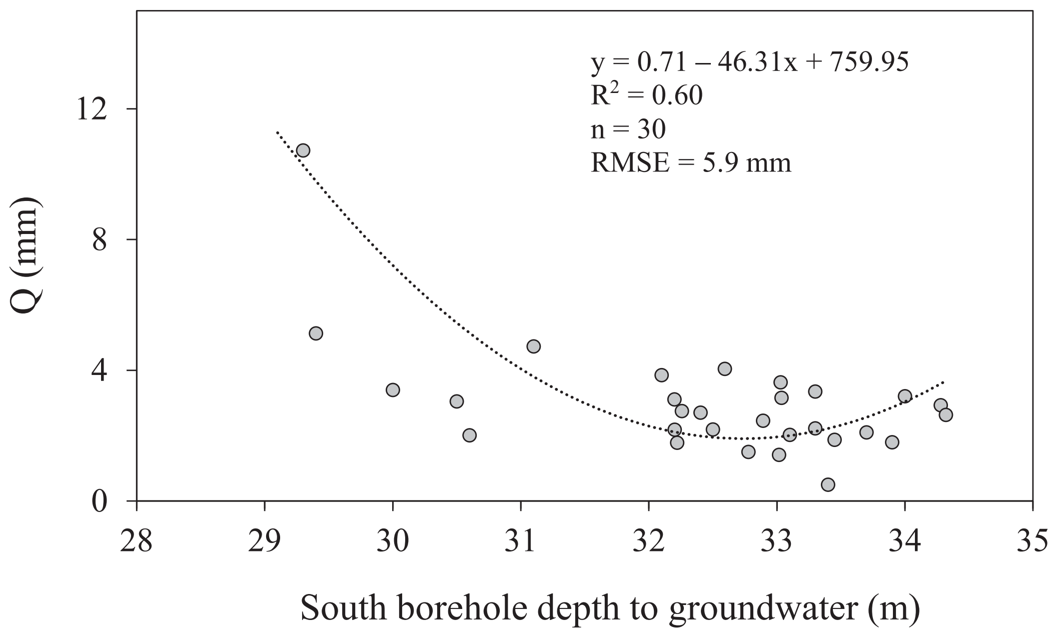


**Figure 6-8: The 2nd order polynomial relationship between the streamflow (Q, mm) and the south borehole depth to groundwater (m) at the Two Streams research catchment for the duration September 2006 to July 2013. The equation of the regression line, regression coefficient ($R^2$) and the root mean square error (RMSE) is presented.**

### 6.6.6 Streamflow prediction using water yield, aridity index, rainfall and total evaporation

The RF model performed very well in predicting Q producing a coefficient of determination greater than 0.92 with mean squared error of 0.43 with all four variables combined (WY, AI, ET and rainfall). The RF predictive model rated WY as the most important predictor of Q by both the MDA and MDG (Figure 6-8a and 6.8b). Variables, rain, ET and AI in descending order of importance were also found to influence Q. Overall, the model indicated that WY is a very good predictor of Q, while rainfall was found to be an important driver.

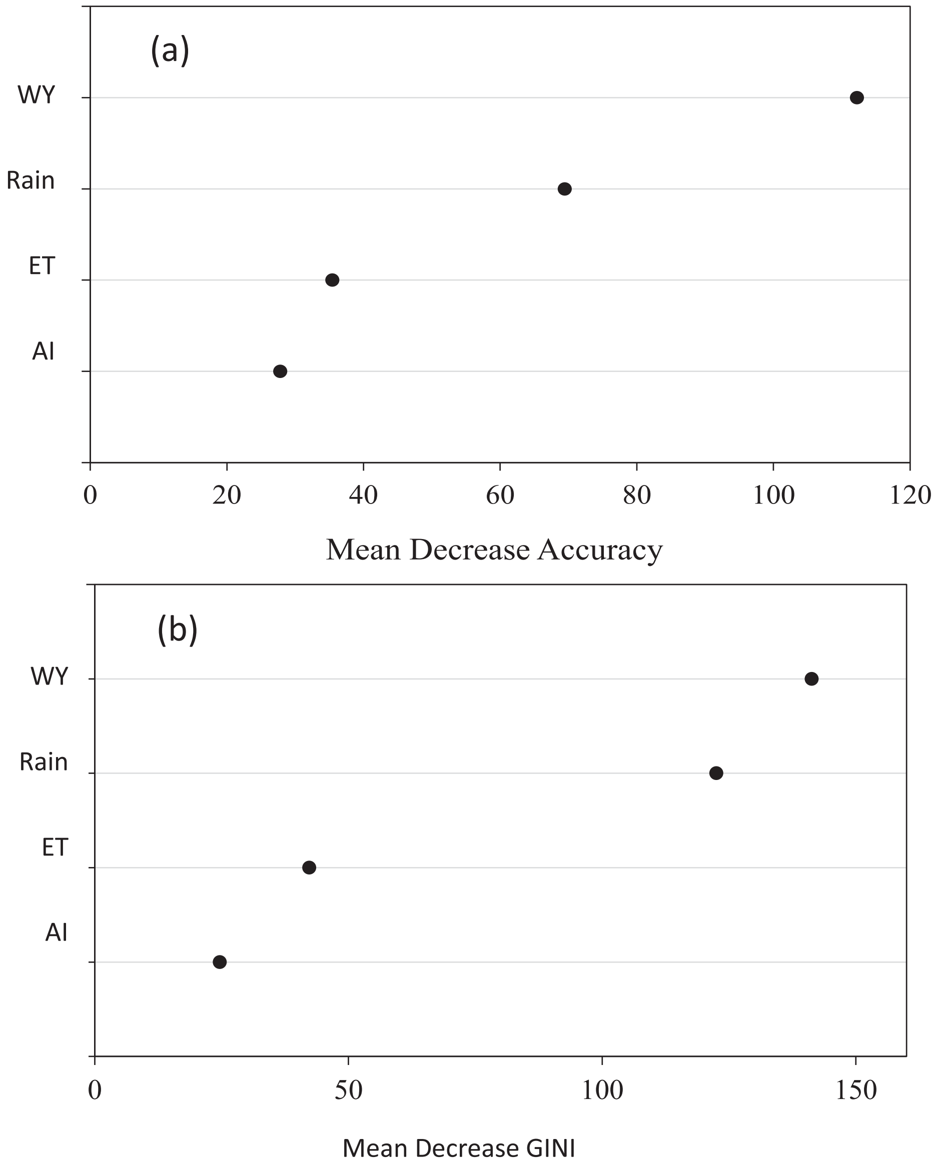


**Figure 6-9: Measures of relative importance of predictive variables based on (a) Mean Decrease Accuracy (MDA) and (b) Mean Decrease GINI (MDG). The MDA is a measure of the rate of error when predictive variable value is permuted randomly. The MDG is computed by summing up all decreases in GINI impurity when a predictive variable is used to form a split at the node.**

### 6.6.7 Two Streams catchment water budget

The change in catchment water balance for all measurement years indicated a negative balance in catchment storage, except for 2013, which coincided with a very low ET (Table 6.2). The measurement periods with the greatest decline in catchment water storage were year 2010, 2014, 2015, 2020 and 2021. The reduction in storage was expected in years 2010, 2014 and 2015 as they experienced El Niño conditions, whereas 2020 and 2021 had the highest ET after the *E. dunnii* crop was planted in 2018. The annual direct runoff was highest in year 2007, 2008, 2020 and 2021 with values of 52.1 mm, -65.9 mm, -74.4 mm and -61.5 mm, respectively. This coincides with the periods when the trees were relatively young (one to two years old) and were less likely to have an impact on the total runoff. Direct runoff decreased with larger canopies in subsequent years (Table 6.2). The ET was the highest contributor to water loss from the catchment contributing on average 96%.

**Table 6.2: The annual water balance for the Two Streams research catchment for a duration 2001 to 2021 hydrological years. The "*" denotes that data were not available. The negative number in the table indicates water loss.**

| Year | Crop | Crop age (years) | Rainfall (mm) | Actual ET (mm) | Direct runoff (mm) | Baseflow (mm) | Change in catchment storage (mm) |
|---|---|---|---|---|---|---|---|
| 2007 | *A. mearnsii* | 1 | 689 | -842 | -52.1 | -41.9 | -247 |
| 2008 | | 2 | 819 | -849 | -65.9 | -27.5 | -123.4 |
| 2009 | | 3 | 775 | -803 | -44.7 | -26.7 | -99.4 |
| 2010 | | 4 | 533 | -893 | -20.4 | -11.5 | -391.9 |
| 2011 | | 5 | 855 | -872 | -15.9 | -17.5 | -50.4 |
| 2012 | | 6 | 846 | -850 | -25.09 | -18.6 | -47.7 |
| 2013 | | 7 | 862 | -692 | -44.7 | -28.3 | 97 |
| 2014 | | 8 | 632 | -828 | -22.2 | -19.9 | -238.1 |
| 2015 | | 9 | 490 | -678 | -18.7 | -24.1 | -230.8 |
| 2016 | | 10 | 592 | -747 | -18.8 | -19.9 | -193.7 |
| 2017 | | 11 | 663 | -769 | -19.8 | -22 | -147.8 |
| 2018 | | 12 | 757 | * | * | * | * |
| 2019 | *E. Dunnii* | 1 | 748 | * | * | * | * |
| 2020 | | 2 | 846 | -1222 | -74.4 | * | -450.4 |
| 2021 | | 3 | 839 | -1118 | -61.5 | * | -340.5 |
| **Average** | | | **793** | **-859** | **-10.8** | **-23.4** | **-189.5** |

*Baseflow values adopted from Ngubo et al., 2022.*

## 6.7 Discussion

Previous studies (Zhang et al., 2011; Petrone et al., 2010; Smethurst et al., 2015) reported that Q is highly influenced by precipitation distribution and intensity, terrain and topography, crop water use, the soil water holding capability, plant canopy interception, soil hydraulic conductivity and the soil water holding capacity. In this study, after clearing of the riparian areas, WY significantly increased (42%), which was partly influenced by rainfall which was 25% greater than the MAP during this period. These results are similar to two South African Q studies; first, Prinsloo and Scott (1999) in the Western Cape province found that after clearing of riparian areas, Q increased by 10.4 $m^3$ per day per ha cleared, second, Dye and Poulter (1995) reported a 120% increase in Q (equivalent to 30.5 $m^3$ per day) post clearing of the riparian areas. A conclusion from these studies was that riparian areas should be kept under short indigenous vegetation, for example grass and fynbos, to sustain Q over a long term, a conclusion supported by our study.

### 6.7.1 Catchment water yield

Water yield was high (0.08-0.09) at the beginning of the *A. mearnsii* and *E. dunnii* rotation (when trees were two years old) and decreased as *A. mearnsii* trees grew (0.06), reaching the lowest threshold of 0.02 in 2011 (when trees were five years old). This WY decline, coincided with El Niño events experienced in 2010, which may have influenced this significant decrease. The SWC followed a similar decreasing pattern between 2008 to 2012, suggesting that a lack of rainfall was most likely the cause of WY decline during this period. Despite the low SWC, the annual ET rates remained relatively high throughout the study period, and very high for the young *E. dunnii crop*, suggesting that trees probably sourced water external to the catchment and most likely from regional groundwater or soil water accumulated from fallow periods or unplanted nearby areas, which will potential impact baseflow negatively, hence the WY. Notwithstanding the probable impact of drought on WY, international studies (Kuczera, 1987; Ferraz et al., 2013; Ferraz et al., 2019) reported that WY may be influenced by tree age. For example, WY is generally high at the beginning of the rotation, decreasing as trees grow, reaching a low threshold in the middle of the rotation (~ 5-7 years). There is a likelihood in our study that WY was partly influenced by tree age.

### 6.7.2 The impact of catchment afforestation on streamflow

There was evidence in this study suggesting that afforestation in the catchment has a direct influence on Q and WY. For example, the relationship between Q and LAI in *E. dunnii*, where LAI increased with an increase in Q up to a threshold of 2.92, thereafter, decreasing. This suggested that at LAI greater than 2.92, trees possibly intercepted rainfall resulting in reduced runoff. These results are supported by studies from Zhang et al. (2017), Bian et al. (2020) and Igder et al. (2022). A study by Farley et al. (2005) analysed 26 catchment datasets with 504 observations 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. Similarly, a study in China by Bian et al. (2020) reported that dense vegetation (high LAI) in commercial forestry resulted in high rainfall interception during summer months, which caused a significant reduction in runoff into the stream. The *A. mearnsii* trees are reported (Bulcock and Jewitt, 2012) to have a higher rainfall interception (~28%) than *Eucalyptus* (~15%) although this was not evident in the relationship between Q and LAI in our study.

### 6.7.3 The effect of trees on groundwater resources

Results from AI indicated that ET significantly exceeded rainfall by 20% throughout the monitoring period of 15 years (*A. mearnsii*: 11 years and *E. dunnii*: 4 years). These results are reflected in the catchment water balance, which indicates negative values for catchment change in storage, mainly due to ET being greater than rainfall, except for the year 2013. In addition, ET was the main contributor to water loss in the catchment (96%). 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 rainfall. These two studies plus our new study indicates a negative balance between input and output and suggests that trees source water in the soil water storage from previous wet years held deep in the soil profile or water from lateral flows from surrounding areas.

Tree roots have been shown to penetrate as deep into the soil as is needed to reach the available water, unless restricted by soil or regolith characteristics (Stone and Kalisz, 1991; Stone and Comerford, 1994). A mature *A. mearnsii* tree roots have been recorded to reach a depth of 35 m (Scott and Le Maitre, 1998). Six years after *A. mearnsii* was planted (October 2012), drilling in the catchment revealed live roots up to 5 metres depth (Everson et al., 2014). Based on a same rate of growth by roots of approximately 5 m in 6 years, by 2018, roots could be approximately 10 m deep. In the current study, groundwater in the centre borehole was measured to be ~22 m, which was probably too deep for roots to come into direct contact with groundwater resources. However, it was shown by Clulow et al. (2011), at the same study site, that the soil profile beyond 1.5 m started to increase in plant available water with depth and roots could be in contact with groundwater through capillary rise. A recent study by Ngubo et al. (2022) using isotope methods to determine the impact of *A. mearnsii* on groundwater reserves found that trees can access groundwater within the unsaturated zone, reducing the quantity of rainfall that reaches the aquifers and eventually discharge to the stream as baseflow.

### 6.7.4 Predicting streamflow from micrometeorological variables

Streamflow has been described to have a relationship with micrometeorological variables such as SWC, rainfall, ET, groundwater storage, WY and AI (Shi et al., 2012; Ferraz et al., 2019). In this study, RF predictive model indicated that WY and rainfall were the most important predictors of Q. Other studies (Petrone et al., 2010, Ferraz et al., 2019) have shown similar good relationship between Q and P and WY. For example, Chauluka et al. (2021) in southern Malawi found a very strong linear relationship between Q and P. The developed model in this study will allow for prediction of Q changes over time from an easily accessible WY and rainfall data.

## 6.8 Conclusion

This study investigated hydrological processes and the long-term impact of *A. mearnsii* and *E. dunnii* (in the early stages of growth) on the Q within the Two Stream experimental catchment, located in KwaZulu-Natal midlands of South Africa. Results from this study showed that groundwater was too deep for tree roots to make direct contact, however, roots could be in contact with the ground water through capillary rise. Total evaporation by both crops exceeded rainfall, causing a negative long-term catchment water balance, thus reducing groundwater and in turn baseflow to the stream. The high rates of ET (even during the wet season) produced high LAI, which probably increased rainfall interception minimising surface runoff to the stream even further. The reduction in WY throughout the *A. mearnsii* rotation may not be only attributed to a single driver such as the El Niño event, but in parallel with other factors such as tree age. The developed predictive model will enable Q to be predicted from easily accessible WY and rainfall dataset. Based on these results we conclude that *A. mearnsii* and young *E. dunnii* trees have the potential to negatively impact the Q at any stage of growth. Future research is suggested to confirm if trees are using underground water reserves through partitioning the water use by trees into rainfall and groundwater reserves using isotopes. In addition, a continuation of ET, Q and groundwater reserve measurements on the currently planted *E. dunnii* crop throughout the rotation is suggested to quantify the impact of *E. dunnii* on Q throughout the rotation.

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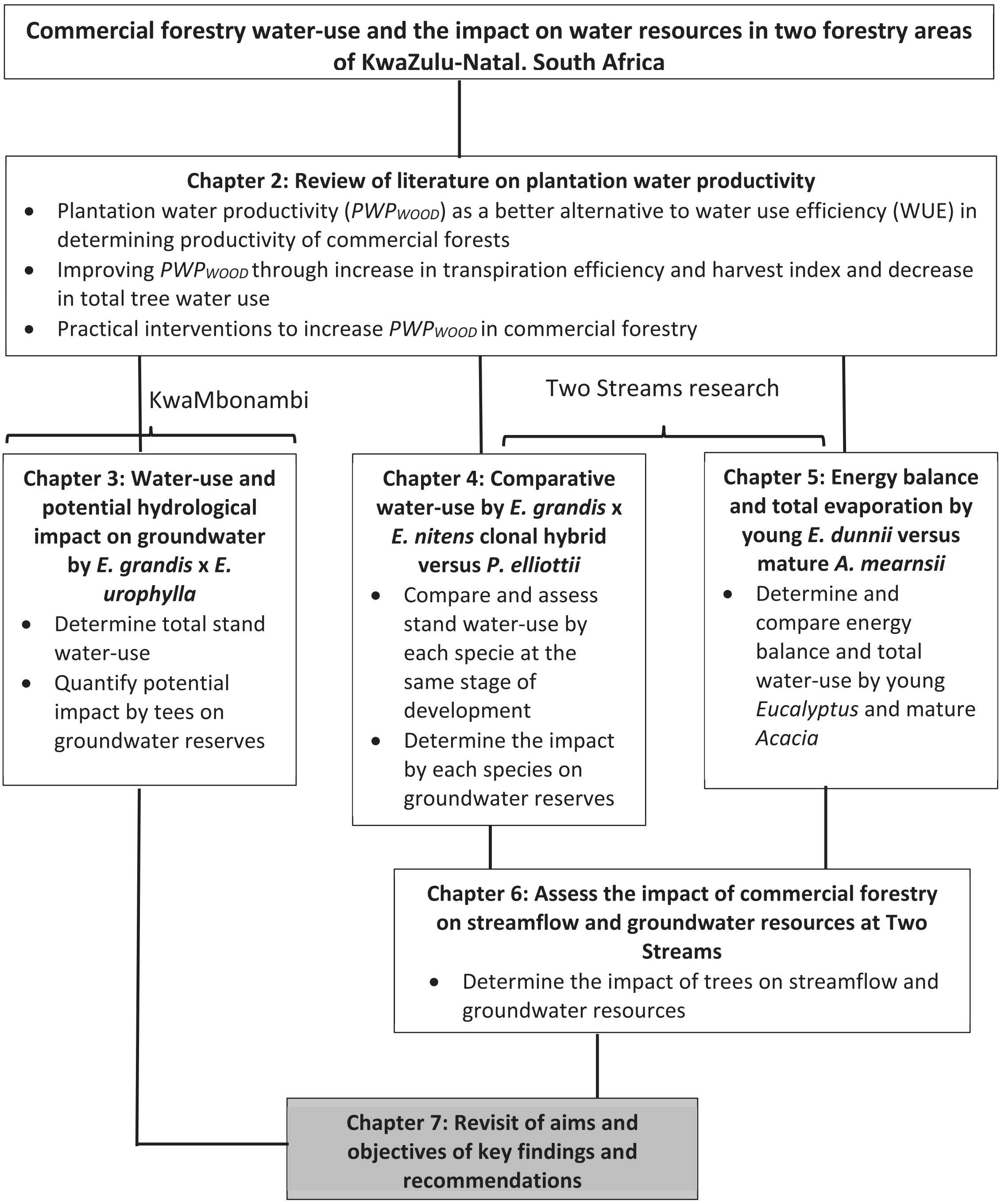
## 6.11 Supplementary information

**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: The centre borehole level measured using the P107 dip meter at Two Streams research catchment.**

**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 groundwater resources 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, employment (Bennett, 2011) and improve soil infiltration rates (Van Dijk and Keenan, 2007), minimising soil evaporation and surface runoff (Wichert et al., 2018). 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. elliottii* 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 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 on groundwater reserves. To achieve this, complex micrometeorological techniques as well as sap flow techniques were used to measure commercial forestry stand water use, quantify the potential impact by each species on groundwater resources and establish genus exchange ratios for converting from one genus to the other 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 specie 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 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 specie and clonal hybrids on water resources was quantified. The quantity and quality of data produced through this research provides a baseline for future hydrological and modelling studies.

## 7.2 Revisiting aims and objectives and contribution to new knowledge

The overall aim of this research was to create new knowledge and advance our understanding of total water use of SFRA's in South Africa, with particular attention on differences between species. The specific aims were to:

1. To expand the knowledge of the estimates of water use of different clones and hybrids of eucalypt, wattle and pine species (e.g. clones/hybrids most commonly used, clones/hybrids planted in optimal sites).
2. To address shortcomings in the availability of leaf area index information for different SFRA species, clones and hybrids.
3. To improve existing tools used for the estimation of the impacts of SFRA through the inclusion of improved soils data and baseline land cover data, as well as the inclusion of the latest process results related to water use (i.e. evapotranspiration) of SFRA clones, hybrids and species.

The outcomes, findings and products of the project are comprised of two final reports. This document details the research undertaken to address Aim 1, which focuses on the improved water use estimation of SFRA species, while the other deliverable speaks to Aims 2 and 3 and documents the SFRA Utility.

The specific objectives of this research, dealt with a chapter at a time, 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) Determine and compare 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 groundwater resources and 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 contributions to new knowledge of this research 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.

## 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 (including a monthly transpiration crop factor) 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 specie in the northern Zululand of South Africa

## 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 showed that the perception that *Eucalyptus* water-use exceeds pine is not always the case and that site specific differences, even in close proximity to each other climatically, can have a significant influence on 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. It was shown that that the water use of young *A. mearnsii* and *E. dunnii* were 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

- Enhanced the understanding of the impact of *A. mearnsii* and young *E. dunnii* crop on streamflow and groundwater resources at Two Streams research catchment. The research conducted in this study showed the potential negative impact of afforesting the catchment with both the *A. mearnsii* and young *E. dunnii* crops. 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.
- Quantified the total water balance of Two Streams research catchment, with all major components measured, showing total evaporation by trees being a significant contributor to water loss in the catchment.

- Developed a relationship between streamflow and micrometeorological variables, producing a very good relationship, which can be used to estimated streamflow from micrometeorological variables adding value in future water balance modelling studies.

## 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), cell phone 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 an *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.

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