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Research paper

Water use and potential hydrological implications of fast-growing *Eucalyptus grandis* x *Eucalyptus urophylla* hybrid in northern Zululand, South Africa

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We measured the tree transpiration of 9-year-old, *Eucalyptus grandis* x *Eucalyptus urophylla* clonal hybrid (GU) trees in the commercial forestry area of northern KwaZulu-Natal, South Africa. Transpiration was measured using the heat ratio method over two consecutive hydrological years (2019/20 and 2020/21) and up-scaled to a stand level. Leaf area index (LAI), quadratic mean diameter, and soil water content (SWC) were measured over the same period using an LAI 2200 plant canopy analyser, manual dendrometers and CS616 sensors, respectively. The depth to groundwater was estimated to be approx. 28 m, using a borehole next to our study site. Results showed that transpiration followed a seasonal pattern, with daily mean of 2.3 mm·tree^{-1}·day^{-1} (range: 0.18 to 4.55 mm·tree^{-1}·day^{-1}) and 3.3 mm·tree^{-1}·day^{-1} (range: 0.06 to 6.6 mm·tree^{-1}·day^{-1}) for 2019/20 and 2020/21, respectively. Annual GU transpiration was higher than that found by international studies under similar conditions, but was within the same transpiration range as *Eucalyptus* genotypes in the KwaMbonambi area. Plantation water productivity, calculated as a ratio of stand volume to transpiration, was higher than for other published studies, which was attributed to a very high productive potential of the study site. Multiple regression using the random forests predictive model indicated that solar radiation, SWC and air temperature highly influence transpiration. There is a high possibility that our GU tree rooting system extracted water in the unsaturated zone during the dry season. Due to the use of short-term results in this study, the impact of GU on water resources could not be quantified; however, previous long-term paired catchment studies in South Africa concluded that *Eucalyptus* has a negative impact on water resources. Further research is suggested with long-term measurements of transpiration and total evaporation and an isotope study to confirm the use of water by GU trees in the unsaturated zone.

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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; Benyon et al., 2006; Scott and Prinsloo, 2008; Vanclay, 2009; Chevesich et al., 2017; Doody et al., 2023). 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 1 100 to 1 200 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 systems enabling them to access deep water reserves, especially during drier months (Van Dijk and Keenan, 2007; Doody et al., 2015). Kimber (1974) reported that eucalypts may develop a dimorphic root structure to increase their chances of accessing water in the soil surface as well as in deep soil layers. A study by Doody et al. (2015) showed that during the wet season *Eucalyptus camaldulensis* produced dense fine roots at the soil surface to maximise water uptake, while during the dry season trees relied on the water stored deep in the soil profile.

Some studies have provided evidence that well-managed *Eucalyptus* plantations provide benefits to the environment (Casson, 1997). For example, commercial forests improve soil infiltration (Van Dijk and Keeenan, 2007), significantly reduce surface runoff (soil erosion) and minimise soil evaporation from forest compartments (Wichert et al., 2018). However, studies in South Africa (Dye, 1996), India (Calder et al., 1992), southern China (Morris et al., 2004) and Australia (Benyon et al., 2006; Doody et al., 2015; Chevesich et al., 2017; Doody et al., 2023) indicated that, with limited water resources, the management and location of *Eucalyptus* trees must be carefully considered to minimise competition with other water users.

Expansion of knowledge of *Eucalyptus* water use (particularly the genetically improved clonal hybrids produced by forest breeding programmes) is vital to understand the impact these species have on the environment and to inform management 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), Brazil (Hubbard et al., 2010; Smethurst et al., 2015; Hakamada et al., 2020), Australia (Myers et al., 1996; Benyon et al., 1999; 2011; O'Grady et al., 1999; Doody and Benyon, 2011; Doody et al., 2022; 2023) and central Chile (White et al., 2021) have 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 2019, the South African Department of Environment, Forestry and Fisheries (DEFF) reported that the subtropical regions (northern KwaZulu-Natal coast, South Africa) were planted with 66 800 ha of *Eucalyptus* plantations, which account for 6% of the total commercial forestry area in South Africa, playing a crucial role in the economy of this region (Stats SA, 2019). The most planted forest genotype in this region is *Eucalyptus grandis* x *Eucalyptus urophylla* clonal hybrid (GU) due to its high tolerance to fungi 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 these high-water-use eucalypts may contribute to a reduction in underground water reserves (Dye et al., 1997) in this area. The only tree water use study previously conducted in the region investigated *E. grandis* (Dye et al., 1997, Everson et al., 2019) and *E. grandis* x *E. camaldulensis* clonal hybrid (Dye et al., 2004). To our knowledge, there has been no previous work on water use by GU. The objective of this study was to quantify the water use (referred to as transpiration) and tree water productivity of the 9-year-old GU stand in KwaMbonambi, northern KwaZulu-Natal, South Africa, to evaluate their impact on soil and groundwater resources, in order to maximize productivity without compromising water resources. In addition, the relationship between transpiration and micrometeorological variables was established to enable the estimation of tranpiration from ‘easy-to-measure’ micrometeorological data.

MATERIALS AND METHODS

Study site

The site was located in the Zululand coastal plains, near KwaMbonambi, northern KwaZulu-Natal, South Africa (Fig. 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 9-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 are typical of subtropical humid conditions as detailed in Table 1. The GU trees were planted in October 2011 with a spacing of 3 m x 2 m (1 667 trees·ha^{-1}) using clonal cuttings. The study site was subjected to standard afforestation practices such as weeding pre-canopy-closure.

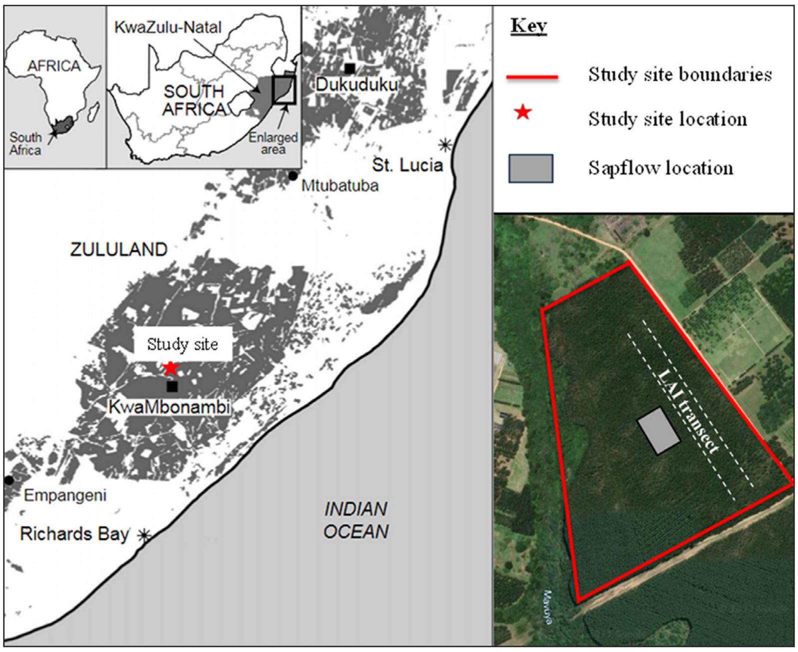

Figure 1. Location of KwaMbonambi study site in the north-eastern area of KwaZulu-Natal. Grey areas indicate the distribution of commercial forestry areas. The Google Earth Pro extract (bottom right) provides an aerial view of the study site planted with *Eucalyptus grandis* x *E. urophylla*, showing the placement of the transpiration-measuring equipment and the transect used to measure the leaf area index (LAI).

Table 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)	1 260
Mean annual temperature (°C)	21.9
Altitude (m amsl)	24

**South African Taxonomic System*

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 rain gauge which was at 1.2 m. Hourly and daily data for air temperature ($Temp_{air}$, °C) (HMP 60, Vaisala Inc., Helsinki, Finland), relative humidity (RH, %) (HMP 60, Vaisala Inc., Helsinki, Finland), solar radiation (I_s, MJ·m^{-2}) (Kipp and Zonen, CMP3), wind speed (WS, m·s^{-1}) (model 03003, R.M. Young, Traverse City, Michigan, USA), rainfall (mm) (TE525, Texas Electronics Inc., Dallas, Tx, USA), calculated vapour pressure deficit (VPD) (using $Temp_{air}$ and RH measurements according to Savage et al., 1997) and FAO reference evaporation (mm) (FAO ETo) were downloaded from: https://sasri.sasa.org.za/rtwd/524/index.html.

Transpiration measurements

A heat pulse velocity system (HPV) of the heat ratio technique (Burgess et al., 2001) is an internationally recognised and reliable technique (Steppe et al., 2010; Forster, 2017) for measuring tree transpiration in commercial forest plantation stands and has been used by several researchers (Dye, 1996; Dye et al., 1997; 2004; Forester et al., 2010; Doody and Benyon, 2011; Drake et al., 2012; Hakamada et al., 2020). Due to the high cost associated with purchasing the HPV system, most of the above-mentioned studies conducted measurements on 4 healthy representative trees that were selected based on diameter stratification. In this study, 4 healthy representative trees were selected from 48 trees. 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 4 size classes; small, medium, medium-large and large.

Transpiration was estimated 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 laboratory constructed 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. 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 (referred to as transpiration in this document) direction. Four probes were installed per tree at various sapwood depths (as described in detail in Table 2) (Nadezhdina et al., 2007; Ford et al., 2004). Hourly measurements were executed and recorded on a datalogger (CR1000, Campbell Scientific Inc., Logan, Utah, USA), which was powered by a single 55 Ah lead acid deep cycle battery. Thermocouples were connected to a multiplexer (AM 16/32, Campbell Scientific Inc.), which was in turn connected to the datalogger to allow for 32 thermocouple measurements at various sapwood depths across the 4 instrumented trees. Measurements were conducted at different sapwood depths due to radial differences in sapflow at different depths in the sapwood (Nadezhdina et al., 2007; Ford et al., 2004). Data were remotely downloaded using a GSM modem (Maestro Wireless Solutions Ltd. Hong Kong, China). The hourly measurement sequence included measuring each thermocouple 10 times for accurate initial temperatures. Following a heat pulse, the downstream and upstream temperatures were measured approximately 40 times between 60 and 100 s. Thereafter, sapflow (V_h, cm·h^{-1}) was calculated using Burgess et al. (2001),

$$V_h = \frac{k}{x}\ln\left(\frac{V_1}{V_2}\right)3600 \quad (1)$$

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

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 transpiration was expected to be zero, such as over pre-dawn, during rainfall events, or in high RH and low SWC conditions. The transpiration values during these times may be adjusted to zero and an offset may be calculated from an average of these values and applied to the whole dataset. It is important to note that values less than zero (negative values) can be measured in deep-rooted trees such as *Eucalyptus* due to hydraulic redistribution (Scholz et al., 2002); however, these values have been reported to be negligible. For probes used in this study, the offset was <5% of the midday transpiration 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 transpiration rates were then up-scaled from sample trees to the entire forest stand using the transpiration distribution in DBH classes – this method is described in detail by Cermak et al. (2004).

Soil water content

Soil water content (SWC, m^3·m^{-3}) was measured in the upper 0.60 cm of the soil profile (0.2, 0.4 and 0.6 m depth) using CS616 soil water content measuring sensors (Campbell Scientific Inc.). The CS616 SWC sensor consists of two 30 cm long stainless-steel rods and uses the time domain reflectometer method to measure the SWC. The sensor circuitry generates an electromagnetic

Table 2. Detailed description of 4 trees selected for instrumentation with heat pulse velocity technique in KwaMbonambi study area

Tree no.	Overbark diameter (cm)	Bark thickness (cm)	Sapwood depth (mm)	Probe depth (mm)			
Tree 1	10.3	0.7	4.7	0.8	1.5	2.5	3.5
Tree 2	19.8	1.2	5.5	0.8	1.5	2.5	3.5
Tree 3	16.2	1.1	4.5	0.8	1.5	2.5	3.5
Tree 4	15.1	0.9	4.2	0.8	1.5	2.5	3.5

pulse, from which an elapsed pulse travel time and reflection are measured and then used to calculate the SWC. The CS616 SWC sensors were placed adjacent to the HPV system, with a single sensor per depth, and each sensor interpreted separately. Previous *Eucalyptus* root studies (Christina et al., 2016) indicated that the majority of large and fine roots are located in the top 0.6 m of the soil profile, hence SWC measurements in this study were conducted in the top 0.6 m of the soil profile and ran concurrently with the sap-flow measurements and were recorded on the CR1000 datalogger. However, *Eucalyptus* trees are known to root very deeply, with the possibility to access groundwater. Depth to groundwater was not measured in this study but estimated to be at approximately 28 m, using depth to groundwater level measured in the borehole next to our study site.

Growth measurements

Measurements of DBH (cm) for 48 trees were conducted for a period of 24 months (once every 2 months, producing 12 measurement points) using manual dendrometer bands (D1, UMS, Muchin, Germany) permanently attached to a tree, with an accuracy of 0.1 mm. Tree heights (h, cm) for the 48 DBH trees were measured simultaneously with DBH measurements, using a hypsometer (Vertex Laser VL402, Haglof, Sweden).

The conical overbark volume (v, m^3) was calculated every 2 months using White et al. (2014):

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

where: h is tree height, π is pi with a value of 3.14 and Dq is the quadratic mean diameter, calculated as (Curtis and Marshall, 2000):

$$\mathrm{Dq} = \sqrt{\frac{(\sum(\mathrm{DBH})^2)}{n}} \quad (3)$$

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

$$V = \frac{10\,000}{A}\sum_{i=1}^{n} v_i \quad (4)$$

where: v_i was the productive volume of the ith tree, A was the total area (m^2) of the plot where measurements were conducted, n is the total number of trees within a plot and 10 000 represents 1 ha (equivalent to 10 000 m^2). The stand volume was converted to mass (m, grams) using:

$$\mathrm{p} = \frac{m}{v} \quad (5)$$

where: γ is the density of trees within our measurement plot; γ was determined by randomly collecting 10 fresh representative wood samples from trees within the measurement plot. The fresh wood samples were submerged in deionised water for 48 h, thereafter weighed using a mass balance. The wood samples were then oven-dried at 105°C for 48 h and again weighed. The wood density for each sample was calculated as a ratio of oven-dried wood sample mass to fresh wood sample mass, and samples averaged to a single wood density value.

Leaf area index was measured once every 2 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 to avoid the impact of the edge effect on LAI measurements (Woodgate et al., 2015). The transect was 10 m wide and 250 m in length and measurements were conducted every 5 m, producing a total of 50 LAI measurements, which were thereafter averaged to a single LAI.

Annual plantation water productivity (PWP_{WOOD}), expressed in g wood per kg water was calculated for GU as a ratio of V to transpiration for the 2019/20 (October 2019 to September 2020) and 2020/21 (October 2020 to September 2021) hydrological years, as described in detail by Kaptein et al. (2023a).

Statistical analysis

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

RESULTS

Weather data

Solar irradiance followed the seasonal trends expected in the northern KwaZulu-Natal area, with the same pattern for both measurement years (Fig. 2). The maximum daily I_s on clear days in winter (May to July) was approximately 14 $MJ \cdot m^{-2} \cdot day^{-1}$, (November to February), 31.5 $MJ \cdot m^{-2} \cdot day^{-1}$ for 2019/20 and 30.6 $MJ \cdot m^{-2} \cdot day^{-1}$ for 2020/21. In both years, there were noticeably more cloudy days in summer, with cloud dominating until late morning on many days. Maximum daily $Temp_{air}$ in summer for both years was 38.8°C. Minimum daily $Temp_{air}$ in summer was as high as 24°C, decreasing to 2.7 and −0.1°C in the winters of 2019/20 and 2020/21, respectively. Daily mean VPD was not as seasonal as $Temp_{air}$ and I_s, although it tended to be slightly higher in summer and slightly lower in winter. The average VPD for 2019/20 was 0.73 vs. 0.62 kPa in 2020/21, reaching maximum values in summer of 2.69 and 1.79 kPa for 2019/20 and 2020/21,

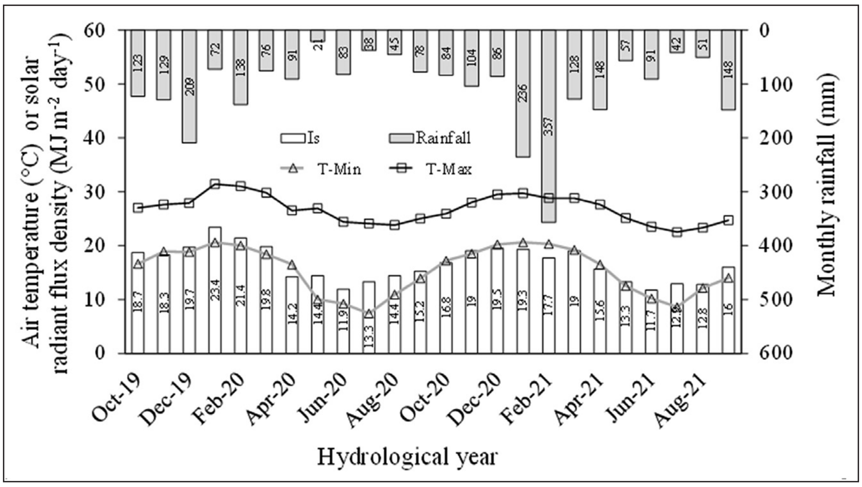

Figure 2. Monthly values of mean daily maximum (T-Max) and minimum (T-Min) air temperatures (°C), mean daily radiant flux density (MJ·m⁻²·day⁻¹) and corresponding total monthly rainfall (mm) measured near KwaMbonambi from October 2019 to September 2021

Table 3. 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	July	Aug	Sep	Totals
2019/20	120	117	129	162	134	123	77	66	54	62	79	91	1 213.4
2020/21	113	123	135	134	103	114	84	60	45	56	69	92	1 128.0

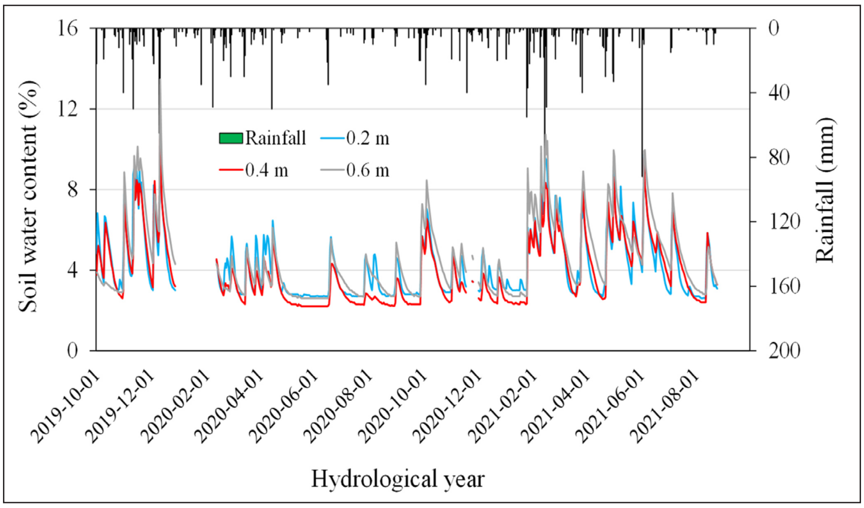

Figure 3. The mean daily soil water content (%) measured at different soil depths (0.2 m, 0.4 m and 0.6 m) with corresponding rainfall over a duration of October 2019 to September 2021. Missing data typically occurred due to instrument failure or power interruption.

respectively. Rainfall occurred throughout the year with the majority (60%) falling in the summer period (October to March) (Fig. 2). Total measured rainfall in 2019/20 was 1 104.4 mm, whereas 2020/21 experienced 28% more rainfall (1 532.8 mm). By comparison, FAO ETo totals calculated using hourly AWS data and the FAO56 method (Allen et al., 1998) amounted to 1 213.4 and 1 128.0 mm for 2019/20 and 2020/21, respectively, following seasonal trends (Table 3). Monthly average WS were variable (range: 1.3 to 10.7 m·s⁻¹) over the 2 years with maximum WS of 39.4 m·s⁻¹ in February 2021.

Soil water content

All SWC sensors responded to rainfall events, except when precipitation was small (< 3 mm) (Fig. 3). The SWC was generally low, between 3 and 10% (Fig. 3), indicating low water retention properties by 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 water was abstracted by trees and some drained through the sandy soil.

Eucalyptus trees are known to have a very deep rooting system and are capable of accessing soil water in deeper soil water reserves (Christina et al., 2016). A study by Dye (1996) in the Mpumalanga Province of South Africa reported that *Eucalyptus grandis* trees abstracted water down to 8 m below the soil surface. Soils in our study site were reported to be very deep (> 30 m) and free draining. There is, therefore, a high possibility that tree roots in this study accessed soil water stored deeper in the soil profile from previous wet years. The depth to groundwater was estimated to be at approximately 28 m, using data from a nearby borehole.

Tree transpiration

The transpiration rates typically followed seasonal trends for both measuring years (Fig. 4). Mean daily transpiration values in summer (October to March) of 2019/20 and 2020/21 were 2.7 mm·tree⁻¹·day⁻¹ (15.5 L·tree⁻¹·day⁻¹) and 3.3 mm tree⁻¹ day⁻¹ (19.7 L·tree⁻¹·day⁻¹), respectively. Daily peak summer transpiration of 6.5 mm·tree⁻¹·day⁻¹ (38.3 L·tree⁻¹·day⁻¹) in 2019/20, increasing to 6.8 mm·tree⁻¹·day⁻¹ (41 L·tree⁻¹·day⁻¹) in 2020/21, were measured in the middle of October for both years, which coincided with high values of I_s and $Temp_{air}$. During the winter months (May to August), transpiration measurements were between 0.6 and 1.6 mm·tree⁻¹·day⁻¹ (3.6–9.0 L·tree⁻¹·day⁻¹) in 2019/20, while 2020/21 experienced 2.4–3.1 mm·tree⁻¹·day⁻¹ (14.2–18.5 L·tree⁻¹·day⁻¹). Mean daily transpiration for large overbark diameter trees (Tree 2 = 5.8 mm·tree⁻¹·day⁻¹ and Tree 3 = 4.6 mm·tree⁻¹·day⁻¹) were found to be 35 to 48% greater than the smaller diameter tree (Tree 1 = 3.0 mm·tree⁻¹·day⁻¹).

The differences in seasonal patterns of transpiration are best illustrated using daily accumulated transpiration over each year (Fig. 5). Rainfall varied from one year to the next with 2020/21 having almost 28% more rain than 2019/20. FAO ETo responded to the higher rainfall in 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 transpiration responded to the increased rainfall in the 2020/21, increasing by 242 mm or nearly 20%.

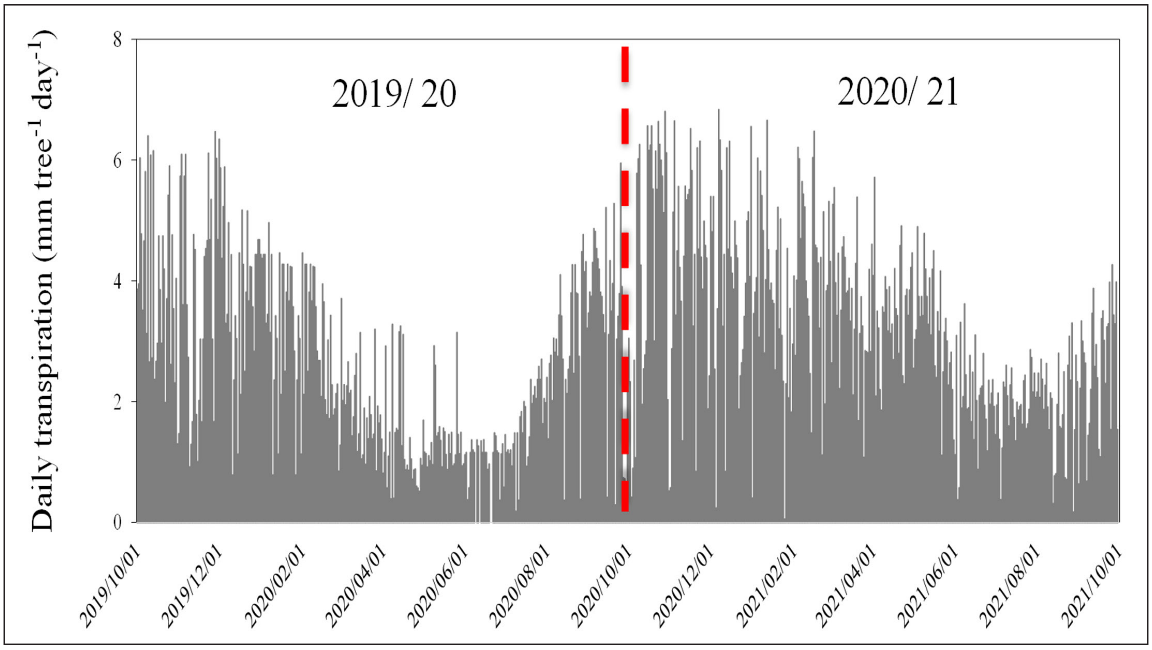

Figure 4. Daily transpiration (mm·tree⁻¹·day⁻¹) of a 9-year-old *Eucalyptus grandis* x *Eucalyptus urophylla* clonal hybrid over 2019/20 (October 2019 to September 2020) and 2020/21 (October 2020 to September 2021) hydrological years. The red vertical line separates the hydrological measurement years.

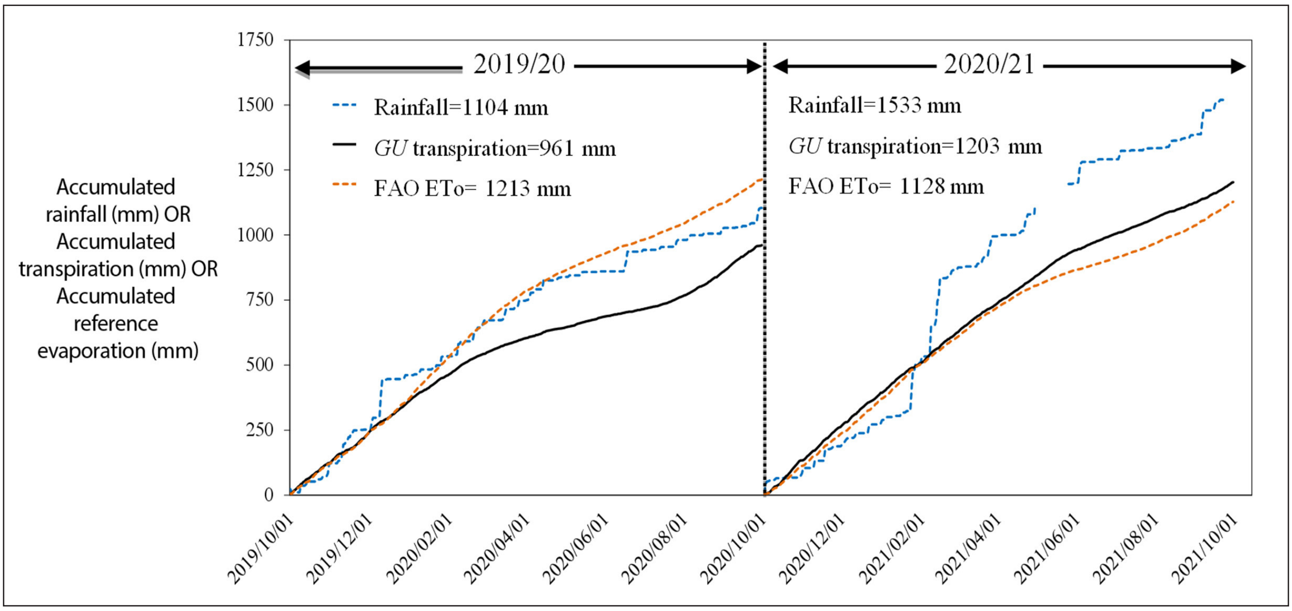

Figure 5. The accumulated transpiration (mm), rainfall (mm) and FAO reference evaporation (ETo, mm) for 2019/20 (October 2019 to September 2020) and 2020/21 (October 2020 to September 2021) hydrological years.

A regression was conducted between monthly transpiration and growth parameters (Dq, *h* and LAI) and it was found that the relationships between these were poor, with coefficients of determination ranging from 0.21 to 0.30 (data not shown). The results of the RF multiple regression predictive model rated meteorological variables, I_s, SWC at 0.6 m, $Temp_{air}$ and WS as the most important predictors of transpiration, in descending order of importance (Fig. 6), with an R^2 of 0.61, mean squared error of 1.42 and mean of squared residual of 1.77. By comparison, RH and rainfall were the least important variables in the model, with 45% variance. Overall, the model showed that transpiration is influenced by micrometeorological variables with different degrees of influence.

Tree growth, volume and leaf area index

Stand volume and Dq followed seasonal patterns as expected. Average summer (October to March) stand volume increased (every 2 months) by 16 $m^3 \cdot ha^{-1}$ in 2019/20 and 30 $m^3 \cdot ha^{-1}$ in 2020/21 ($p < 0.05$) (Fig. 7). During the dry season, stand volume in 2020/21 (20 $m^3 \cdot ha^{-1}$) was statistically ($p < 0.05$) higher than in 2019/20 (11 $m^3 \cdot ha^{-1}$) and likely the result of 28% greater rainfall in 2020/21 (1 533 mm) than in 2019/20 (1 104 mm).

Leaf area index displayed seasonal patterns (Fig. 8) with peak LAI measured during high rainfall months (October to December). Low LAI was measured in the dry season (May to September), a period where GU trees were observed to drop leaves in response to soil water deficit.

Plantation water productivity

The PWP_{WOOD} was calculated as the ratio of stand volume to tree transpiration. The mean annual GU PWP_{WOOD} was 4.17 g wood per kg water in 2019/20, decreasing by 20% in 2020/21 to 3.32 g wood per kg water. This decrease was attributed to a transpiration in 2020/21 that was significantly ($p < 0.05$) greater than 2019/20 (2019/20 = 961 mm vs. 2020/21 = 1 203 mm).

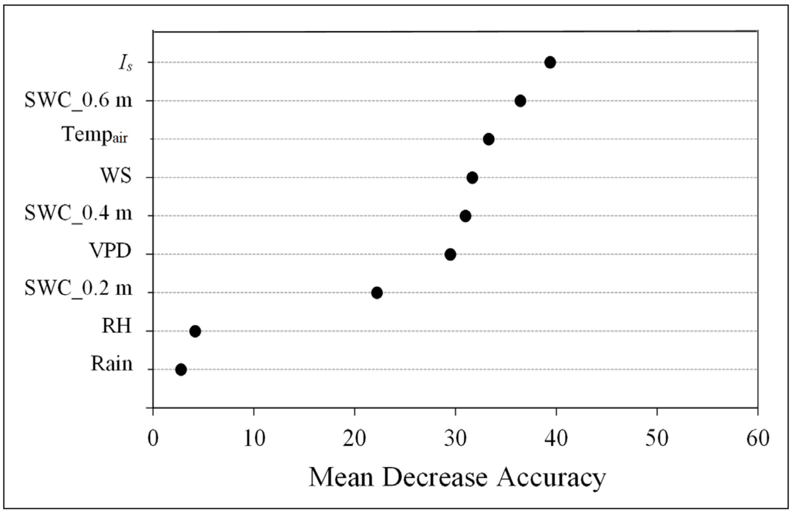

Figure 6. Variable importance plot from the random forest model where transpiration was made a response variable and meteorological data, solar radiation (I_s), air temperature ($Temp_{air}$), vapour pressure deficit (VPD), wind speed (WS), relative humidity (RH) and soil water content (SWC) at a soil depth of 0.2-, 0.4- and 0.6 m, predictor variables. Mean decrease accuracy (MDA) is a measure of how much the model error increases when a particular variable is randomly permuted. The high MDA indicates that a variable is a good predictor.

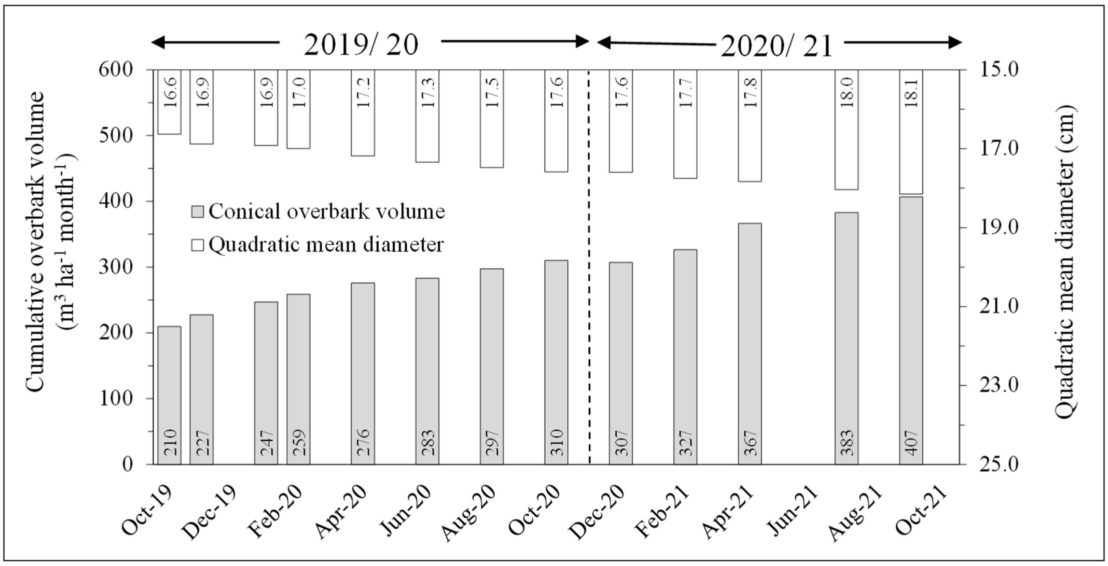

Figure 7. Cumulative overbark stand volume ($m^3 \cdot ha^{-1}$) and quadratic mean diameter (cm) of *Eucalyptus grandis* x *E. urophylla* clonal hybrid in KwaMbonambi over two consecutive hydrological years, 2019/20 (October 2019 to September 2020) and 2020/21 (October 2020 to September 2021). The dashed vertical line separates the hydrological years.

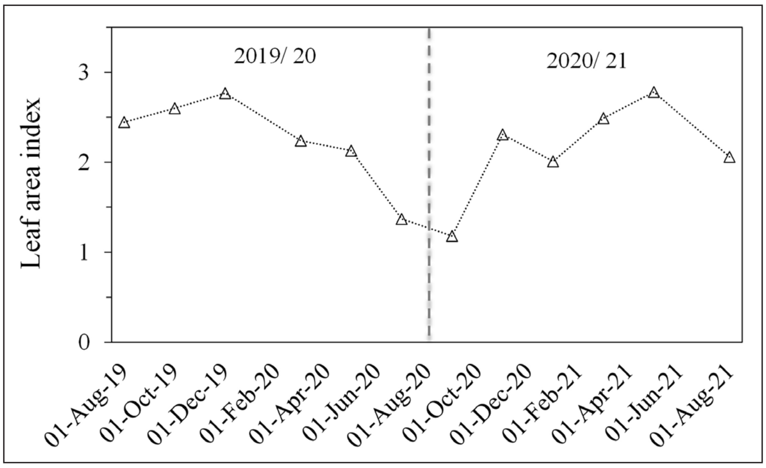

Figure 8. Leaf area index of *Eucalyptus grandis* x *Eucalyptus urophylla* clonal hybrid measured in KwaMbonambi from August 2019 to August 2021

Table 4. Annual transpiration of *Eucalyptus* species in experiments conducted in different parts of the world. A hyphen (–) indicates that the data were not provided.

Study	Tree age (years)	Location	Species	Annual rainfall (mm)	Annual Transpiration (mm)
Our study	9	South Africa, KwaMbonambi	*E. grandis x E. urophylla*	1 104 and 1 533	961 and 1203
Dye et al. (1997)	7	South Africa, KwaMbonambi	*E. grandis clones*	1 107	601, 608, 740, 777, 1 412, 1 423
Almeida et al. (2007)	8	Brazil	*E. grandis*	1 147	885
Lane et al. (2004)	9	China	*E. urophylla*	1 525–2 226	498–548
Engel et al. (2005)	10	Argentine	*E. camaldulensis*	803	348–817
Benyon et al. (2006)	5	Australia	*E. globulus* Labill	630	847–1 343
Macfarlane et al. (2010)	6–12	Australia	*E. marginata*	1 135–1 235	231–505
Silveira et al. (2016)	8	Uruguay	*E. globulus*	792–2 523	–

DISCUSSION

Weather

The Zululand area is well-known to experience variable mean annual precipitation (MAP), with periods of extended drought conditions and periods of high rainfall, and with some years receiving as little as 427 mm and others as much as 1 689 mm (Scott-Shaw et al., 2016). The meteorological data during the study period were 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 1 104.4 mm and 1 532.8 mm were in the middle to upper range of MAP, respectively. Air temperature, RH, I_s and WS were all as expected, with no unusual weather conditions over the study period.

Transpiration

Daily transpiration

Results from this study agreed with other studies of *Eucalyptus* species of a similar age in the northern Zululand region of South Africa. For example, a study by Dye et al. (1997) in KwaMbonambi on 8-year-old *E. grandis* measured a transpiration range of 15–34 L·tree^{-1}·day^{-1} on less productive sites, increasing to 30–64 L·tree^{-1}·day^{-1} on highly productive sites. Everson et al. (2019) reported summer mean transpiration of 18.04 L·tree^{-1}·day^{-1} decreasing to 7.76 L·tree^{-1}·day^{-1} in winter 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 transpiration of 13.9 L·tree^{-1}·day^{-1} with a peak of 49 L·tree^{-1}·day^{-1}. A comparison of results from our study with local (adjacent to our study site, Dye et al., 1997) and international studies conducted under similar conditions (Almeida et al., 2007) suggest that the transpiration of the genetically improved GU is statistically similar to pure species parents (*E. grandis* or *E. urophylla*).

Annual transpiration

The annual transpiration rates in our study were much higher than transpiration measurements across other regions of the world (Table 4), with the exception of a South African (KwaMbonambi area) study by Dye et al. (1997) and a south-eastern Australian study (Benyon et al., 2006). In both these studies (Dye et al., 1997; Benyon et al. 2006), *Eucalyptus* trees were reported to have access to groundwater. There was a surplus in the water balance between inputs (water supply by precipitation) and transpiration losses of 143 mm (13% of rainfall) and 330 mm (22% of rainfall) in 2019/20 and 2020/21, respectively. In this surplus, water losses from soil evaporation and canopy interception were not included since they were not measured in this study. Measurements of SWC in the top 0.6 m of the soil profile indicated that SWC was very low, particularly in winter (a peak of 7.5% in 2019/20 and 13% in 2020/21), showing that the sandy soils (closer to the surface) were dry and had poor water-holding capabilities. However, GU trees did not show any visible signs of water stress throughout the monitoring period. This is a strong indication that GU trees accessed soil water from elsewhere than at the soil surface.

Eucalyptus trees are known to develop a dimorphic root structure (deep tap root and superficial lateral roots) to increase the chances of accessing water near the soil surface as well as in deep soil layers (Jacobs, 1955; Kimber et al., 1974) and even the water table (Benyon and Doody, 2006; Doody et al., 2009, Doody et al., 2023). However, penetration may be restricted by soil or regolith layers (Ngubo et al., 2022). *Eucalyptus* tap roots have been reported to reach depths of 28 m (Dye, 1996), and even greater than 60 m, as observed in one recorded case (Stone and Kalisz, 1991).

In our study, the depth to water table was not physically measured; however, there was a borehole nearby (approximately 300 m from our study site) where depth to groundwater was measured at 28 m during borehole installation in year 2016. A study by Calder et al. (1997) in southern India reported an average root extension of approximately 2.5 m per year in *E. camaldulensis*. Based on a constant annual root depth growth rate of 2.5 m in 9 years, which was highly possible in deep, free-draining Zululand sandy soils, roots for our GU trees would be approx. 22 m deep during the study period. Given the maximum reported capillary fringe of 0.5 m in sandy soils (Shen et al., 2013), direct groundwater uptake by our GU tree roots would be possible up to 22.5 m deep. Using the depth to water table for the borehole next to our study area as a reference, there is a high possibility that the unconfined and semi-confined aquifers were too deep for the roots of our GU crop. Evidence of a lack of contact with groundwater was corroborated with a significant decrease in transpiration, DBH and LAI of our GU crop during the dry season, which increased during the wet season when significant rainfall returned. With the SWC very low at the soil surface and the water table too deep for access by GU trees, the only available water that could be extracted by trees is water that occured within the unsaturated zone or the perched aquifers, or from water reservoirs that can occur within the soil profile (Scott and Prinsloo, 2008). Similar results were reported by Kok (1976) and most recently by Ngubo et al. (2022), where groundwater recharge was reduced after afforestation due to water extraction through increased transpiration from the unsaturated zone. However, in our study, the potential access by our trees to alternative water sources was not quantified.

Relationship between transpiration and micrometeorological variables

Transpiration in *Eucalyptus* has been described to have a strong relationship with atmospheric micrometeorological conditions (Forrester et al., 2010; Albaugh et al., 2013, Kaptein et al., 2023b) and readily available water in the rooting area (Azlan et al., 2012). In our study, random forest variable importance measures indicated that I_s, SWC (measured at a depth of 0.6 m) and $Temp_{air}$ were the most influential variables in the model. Similar results have been documented in other *Eucalyptus* studies (Taylor et al., 2001; Ouyang et al., 2017; Perez et al., 2021). For example, Ouyang et al. (2017) reported a very good relationship between transpiration and VPD (R^2 > 0.80). Perez et al. (2021) concluded that climatic variables are a good predictor of stand transpiration. 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). A study by Calder (1998) indicated that total evaporation in evergreen forests, unlike shorter vegetation which is highly influenced by the supply of I_s, is highly influenced by advection energy greater than I_s. This suggests that I_s on its own can not be used to estimate tree transpiration in commercial forests.

Leaf area index responded to rainfall and SWC, with LAI increasing in the wet season and decreasing 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 (Whitehead and Beadle, 2004; Saadaoui et al., 2017; Salvi et al., 2021). Trees with larger DBH produced significantly greater transpiration than the smaller diameter trees, which is partly attributed to a larger sap-conducting area than the small trees. Similar results were reported by Otto et al. (2014) in a Brazilian *Eucalyptus* potential productivity study where larger trees not only transpired more than smaller trees but 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.

Potential impact of eucalypts on water resources

Forest plantation water-use studies and their potential impact on water resources are complex and require comprehensive long-term measurements of groundwater and hydrological parameters to be conclusive. There have been several long-term paired catchment studies conducted in South Africa (Van Lill et al., 1980; Smith and Scott, 1992; Scott and Lesch, 1997; Scott and Smith, 1997; Scott et al., 2000) that quantified the impact of eucalypts on water resources, particularly streamflow. A study by Scott and Lesch (1997) in Mokobulaan experimental catchment indicated that eucalypts cause a faster reduction in streamflow (90–100%). These results were verified by Scott et al. (2000) where peak reductions in streamflow were reported between 5 and 10 years after establishing *Eucalyptus*. Another South African study by Smith and Scott (1992), investigated the impact of *Eucalyptus* on low flows in various paired catchments located in different regions of South Africa (Westfali, Cathedral Peak, Jonkershoek, Mokobulaan). Results from this study showed that afforestation with *Eucalyptus* has a negative impact on low flows in all paired catchments, with low flows reducing by 100% in certain cases.

Many studies around the world (George et al., 1999; Benyon and Doody, 2004; Benyon et al., 2006; Doody et al., 2009; Christina et al., 2016) have quantified the impact of *Eucalyptus* plantations on groundwater reserves. These studies provided strong evidence that when the water table is shallow, *Eucalyptus* trees most likely extract groundwater reserves. In south-eastern Australia (Benyon et al., 2006), *Eucalyptus* trees were found to use more groundwater annually (>50%) than the annual rainfall to meet evaporative demands when the water table was less than 6 m from the surface. The groundwater used by *Eucalyptus grandis* and *Eucalyptus globulus* was quantified to be 435 mm·year^{-1} (range: 108–670 mm·year^{-1}). In Argentina, Jobbagy and Jackson (2004) indicated that a *Eucalyptus* plantation reduced groundwater recharge and reduced the water table level by an average of 38 cm compared to adjacent grassland. A study by Bari et al. (1996) in Western Australia found that after clearfelling *E. marginata*, groundwater levels significantly increased, leading to increase in the flow of adjacent streams.

There is no solid evidence in our study that GU trees reduced the streamflow and directly accessed groundwater as tree roots were shallow; however, tree transpiration continued in the dry season (in low quantities) regardless of very low SWC at the soil surface. This suggested that GU trees most likely accessed water stored in the unsaturated zone or from water reservoirs that can occur within the soil profile. However, this suggestion is not conclusive as more detailed measurements of groundwater and soil water within the soil profile are needed.

Plantation water productivity

The annual PWP_{WOOD} calculated in our study, of 4.17 and 3.32 g wood per kg water for 2019/20 and 2020/21, respectively, was categorised as very productive (based on a typical PWP_{WOOD} range of 0.3 to 3.1 g wood per kg water (White et al., 2014, 2015).

There are few studies that have quantified PWP_{WOOD} in South Africa and internationally with which to compare these results. However, Forrester et al. (2010) calculated PWP_{WOOD} of approximately 0.6 g wood per kg water in Australia, for a 14-year-old *Eucalyptus globulus*. The PWP_{WOOD} values in our study were greater than those for unmanaged coppice (range: 0.2 to 3.1 g wood per kg 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). High PWP_{WOOD} values in our study were not surprising as soils in northern Zululand have been reported to have a very high growth potential (Dye et al., 2004) and the rainfall is high in comparison with other areas where eucalypts are planted. In addition, a study by Dovey et al. (2011) adjacent to our study site reported that atmospheric nutrient deposition (compounds primarily from industrial pollution, biomass burning, lightning and coastal wind-blown sea-spray or mist) may provide trees with adequate nutrients, which may have influenced the high PWP_{WOOD} in our study.

CONCLUSIONS

This study has quantified the seasonal variation of water use by a 9-year-old GU plantation in a remote study site in KwaMbonambi, in northern KwaZulu-Natal, using the most advanced transpiration measuring technique, the HPV. Results showed that annual water use by GU was higher than that recorded in international studies conducted under similar conditions, but within the range of water use studies conducted in the KwaMbonambi area. Although these results well-reflected the northern region of Zululand, it is recommended that water use measurements are replicated at other adjacent sites on different clonal hybrids to improve the confidence limits of our water use results. There is a high possibility that our GU tree rooting systems accessed water stored in the unsaturated zone during the dry season to maintain transpiration, as roots were most likely too shallow to access the water table. Using water from the unsaturated zone to maintain transpiration may negatively impact groundwater resources, as this water is ultimately responsible for recharging the water table. However, to quantify the impact of GU on groundwater reserves requires long-term measurements of total tree water use and accurate measurements of depth to groundwater. Due to the short-term nature of the measurements in this study, the impact of GU on water resources can not be quantified, but previous long-term paired catchment studies in South Africa and abroad showed conclusive evidence that commercial afforestation has a negative impact on water resources. The RF model used in this study indicated that I_s, SWC at 60 cm soil depth and $Temp_{air}$ highly influence transpiration. Results from this model provide a good baseline for future modelling studies where difficult water use measurements can be estimated from 'easy-to-measure' weather variables.

In conclusion: (i) water use by GU is not different from other genotypes, based on results from local (adjacent to the study site) studies; (ii) the 9-year-old GU has a potential to use water stored deeper within the soil profile; and (iii) the GU in this study had higher PWP_{WOOD} than that found in other studies, which was likely influenced by the high production potential of our study site. Further long-term measurements of total evaporation and isotope research is suggested to quantify the water sources of GU trees.

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