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Research papers

Changes in energy balance and total evaporation with age, and between two commercial forestry species in South Africa

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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 $Edun_2$. Results showed that latent energy fluxes dominated the EB in all crops for both summer and winter seasons, indicating a possibility that trees were not limited by plant available water in winter (dry season). 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. Monthly crop factors were derived from FAO ETo and ET for all three crops, providing a convenient and transferable method of estimating ET from meteorological data over a large scale. 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.

1. 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 not spared 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 >19 million ha (Iglesias and Wilstermann, 2009), playing a vital role as a timber source globally (Ouyang et al., 2017). In

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South Africa, *Eucalyptus* plantations comprises 43% of the total commercial forestry area, with *Eucalyptus dunnii* (34%) being the most planted species (Godsmark and Oberholzer, 2017). Eucalypts are mainly grown for dissolving wood pulp products such as high-quality short fine-fibre pulp which is in high demand by the expanding bioeconomy market.

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

Over the past 10 years, areas planted to eucalypts have increased by 10%, while areas planted to *A. mearnsii* have decreased by 21%, owing to the developing bioeconomy markets for dissolving woodpulp (Forestry South Africa, 2018). These markets prefer *Eucalyptus* plantations (Hinchee et al., 2010) over other forest species (such as *A. mearnsii*) due to their high productivity (>35 m^3 ha^{-1} $year^{-1}$), high rates of growth, good properties of wood, and a provision of benefits to the environment such as carbon sequestration (Forrester et al., 2010; Ouyang et al., 2017). As a result, there has been an increase in genus exchange from other forestry species (ie. *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). 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. In addition, there are no available crop factors developed for Two Streams research catchment that can be used to estimate ET using easily accessible automatic weather station data. 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* (Culow 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 compare energy balance and total evaporation of *A. mearnsii* and *E. dunnii.* The specific objectives of the study were to:

1) Compare *A. mearnsii* seasonal energy balance and total evaporation at two-years-old and six-years-old.
2) Compare the seasonal energy balance and total evaporation of a two-year-old *A. mearnsii* against a two-year-old *E. dunnii* from a previous rotation planted on the same site.
3) Derive crop factors from measured total evaporation for the two-year-old *E. dunnii*, two-year-old *A. mearnsii* and six-year-old *A. mearnsii*.

2. Materials and methods

2.1. The description of the 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 (Fig. 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 1. The catchment consists of a very deep soil profile (13 m deep) underlined by a weathered bedrock (saprolite) and fractured basement rock (Clulow et al., 2011; Everson et al., 2014).

2.2. History of the Two Streams catchment

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 × 3 m (1667 trees ha^{-1}). For a newly planted *E. dunnii* crop, ET measurements were conducted when trees were 1.6 years old (October 2019). Trees were subjected to standard afforestation practices such as pruning and thinning, weeding pre-canopy closure and forest litter removal every 5th row to minimise fire risk. The catchment has a north-west orientation, with a slope of approximately 20%. A lattice mast (24 m tall) was constructed in the middle of the plantation to provide a solid point for the installation of different measurement sensors.

The detailed materials and methods used in measuring energy fluxes, ET, 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.

2.3. Micrometeorological measurements

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

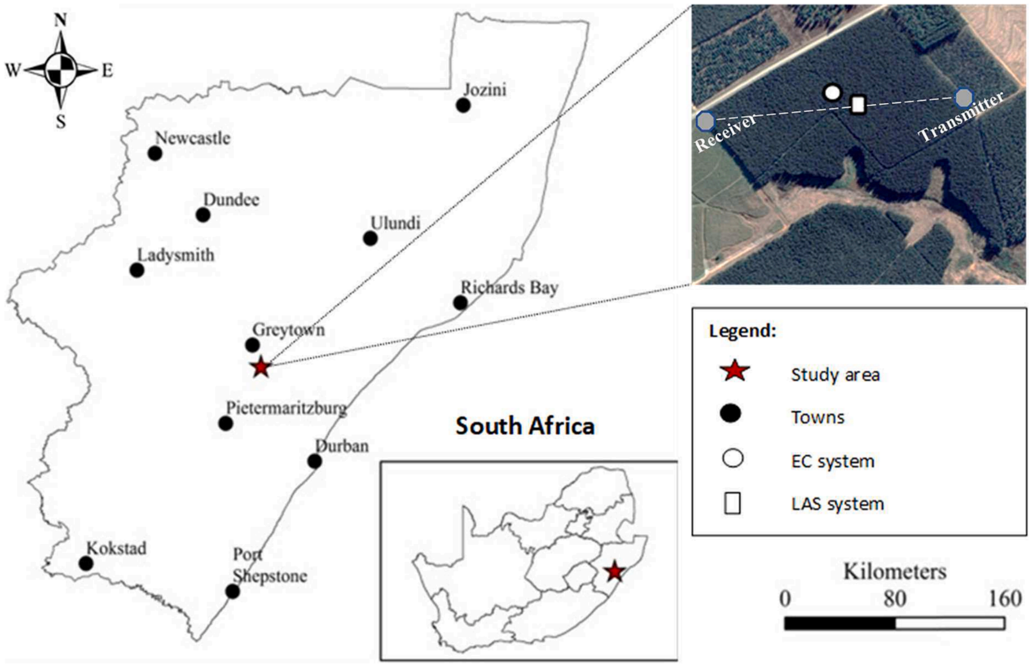

Fig. 1. Location of the study area at Two Streams research catchment. The Google Earth extract (top right) provides aerial view of the catchment (© Google Maps 2022).

Table 1
The general characteristics of the Two Streams research ratchment. The abbreviations MAP and MAT denotes mean annual precipitation and mean annual temperature, respectively (Culow et al., 2011; Everson et al., 2014).

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

2.4. Energy balance and flux measurements

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

$$R_n = H + LE + G + C_s + LE_{adv} + H_{adv} \tag{1}$$

where, R_n is the net irradiance, H is the sensible heat flux, LE is the latent heat flux, G is the ground heat flux, C_s is the canopy-stored heat, LE_{adv} is the LE advection and H_{adv} is the H advection. Units for all terms are in Wm^{-2}. Eq. (1) can be presented as shortened energy balance by neglecting the terms, C_s, LE_{adv} and H_{adv}, since they are deemed negligible (Thom, 1975) and presented as:

$$Rn = G + H + LE \tag{2}$$

Eq. (2) can be rearranged such that LE is the subject of the equation and is equivalent of ET by conversion (Savage et al., 2004).

Eddy covariance (EC) is a technique based on estimation of eddy fluxes and is expressed as:

$$H = \overline{\rho_a} c_p \overline{w' Tair'} \tag{3}$$

Where, ρ_a is the density of dry air (kg m^{-3}), c_p is the specific heat capacity for air at constant pressure (J kg^{-1} K^{-1}), w' is the vertical WS (m.s^{-1}) and T_{air} is the air temperature (°C). The w' and T_{air} are measured using the sonic anemometer and the primes denote fluctuation from a temporal average and the overbar represents a time average. The averaging period of the instantaneous fluctuations of w' and T_{air} should be long enough (30 to 60 min) to capture all the eddies that contribute to the flux and fulfil the assumption of stationarity (Meyers and Baldocchi, 2005). The vertical flux densities of H (ET indirectly derived by Eq. (2)) were estimated by the mean covariance calculation of sensible heat flux (Eq. (3)).

2.4.1. 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 was measured using the large aperture scintillometer (LAS, Kipp and Zonen, Delft, Netherlands) and calculated from the changes in the refractive index of air between a transmitter of monochromatic infrared radiation (at beam wavelength of 880 nm) and receiver along a fixed transect about 1000 m long (Fig. 1) using the following equation (Wang et al., 1978):

$$C_n^2 = 1.12\sigma_{lnI}^2 D^{7/3} L^{-3} \tag{4}$$

where D is the aperture diameter (m) and L is the path length (m). The effective LAS beam height above the canopy was 7.6 m. The middle of the transect where most of the signal originates was dominated by the *Amear*$_2$, and the signal influence of other vegetation types can be considered negligible. A detailed description of LAS measuring technique can be found in Clulow et al (2011). In a second measurement period, October 2012 to September 2013, the *A. mearnsii* trees were between 6.0 and 7.0 years old and are referred to as *Amear*$_6$. During these measurements of the more mature *Amear*$_6$ trees an EC system was used to measure H using a three-dimensional sonic anemometer (CSAT3, Campbell Scientific Inc., Logan, Utah, USA) and measurements of R_n and

G were conducted simultaneously on the study site. The zero plain displacement and roughness layer were determined to be at 12.0 m and 24.2 m, respectively. Therefore, the instrument measurement height was 18 m above tree canopy. For both *Amear*$_2$ and *Amear*$_6$ crops, the energy balance (LE) was calculated as a residual term using Eq. (2) and equated to ET by conversion (Savage et al., 2004).

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

After the harvesting of *A. mearnsii* and planting of the *E. dunnii* trees, H measurements were continued using a three-dimensional CSAT3 sonic anemometer (Campbell Scientific) and an unshielded chromel constantan (Type-E) fine wire thermocouple (0.76 μm TCs) from October 2019 to September 2020 over two-year-old *E. dunnii* trees (*Edun*$_2$). The sonic anemometer was installed above the tree canopy (at a height of 18 m), affixed to a lattice mast and oriented to face the north (predominant wind direction) to minimise air flow distortion by the mast. The zero plain displacement was 7.2 m while the roughness layer was determined to be 16.2 m. Data were recorded on a CR3000 datalogger (Campbell Scientific Inc., Logan, Utah, USA), powered by a 100 Ah deep-cycle lead-acid battery.

2.5. Data processing

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

2.5.1. Eddy covariance system

The half-hourly data were screened according to the following criteria 1) data obtained when the sensor malfunctions were removed from the analysed dataset 2) data on rainy days were excluded due to the negative impact of rainfall on turbulent fluxes as reported by Zhang et al. (2016) 3) incomplete 30-min data were removed, when the missing ratio was >5% in the 30-min raw data 4) night-time data ($R_n < 0$) was removed from the analysis due to potentially large nocturnal influences at night-time (Blanken et al., 1998; Wilson et al., 2001).

2.5.2. Large aperture scintillometer

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

2.6. Ancillary measurements during measurements periods

Soil heat flux was measured using two HFP01-L soil heat flux plates and parallel TCAV-L averaging TCs probes (Campbell Scientific Inc.). 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 to estimate the heat stored in the soil. Soil water content (SWC) was measured using a CS616 volumetric soil water content sensor (Campbell Scientific Inc.) which was placed at 0.06 m depth in the soil to measure SWC during the three measurement periods. These measurements were conducted every 10 s and recorded on a CR3000 datalogger every 30 min. In addition, R_n was measured using a net radiometer (NRLite, Kipp and Zonen) attached to the lattice mast on a horizontal boom 2.5 m away from the lattice mast at a height of 22 m.

2.7. Tree growth measurements

Measurements of diameter at breast height (DBH) were conducted between the period October 2007 to September 2008 and October 2012 to September 2013 using a 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):

$$Dq = \sqrt{\frac{\left(\sum(DBH)^2\right.}{n}} \tag{5}$$

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

The conical over bark volume (v, m^3) for a period, January 2006 to February 2018 was calculated based on data availability, while monthly v was calculated each month for a period September 2019 to August 2021 using Eq. (6) (White et al., 2014):

$$v = \left(\frac{\pi}{12}\right)\left(\frac{Dq}{100}\left(\frac{h}{h-1.3}\right)\right)^2 h \tag{6}$$

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

$$V = \frac{10000}{A}\sum_{i=1}^{n} vi \tag{7}$$

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 and *n* is the total number of trees within a plot.

The leaf area index (LAI) measurements were conducted monthly 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 within the study site for eight months in the year 2020 (March to April, June to September and November to December). For *Amear*$_2$ and *Amear*$_6$ LAI, measurements were conducted periodically by Clulow et al. (2011) in a transect within the study site using the LAI 2000 (Licor Inc.) and LAI 2200 Plant canopy Analyzer (Licor Inc.), respectively. LAI measurements were conducted in year 2007 (October and November), 2008 (April, August and November) and 2009 (February) for *Amear*$_2$, while *Amear*$_6$ LAI measurements were conducted in year 2011 (October), 2012 (January, July and November) and 2013 (March).

2.8. 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.

2.9. FAO Penman-Monteith reference evaporation

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

$$K_c = \mathrm{ET} / ET_o \tag{8}$$

where K_c is a crop factor. The calculated K_c allows for an estimation of ET from standard weather station data. In this study, monthly K_c values were calculated for each measurement period.

2.10. Statistical analysis

Analysis of variance (ANOVA) was used to analyse the differences in energy balance parameters (Rn, H, LE, G), growth parameters (PWP_{WOOD} and LAI), ET and SWC between *Amear₂*, *Amear₆* and *Edun₂* using the R version 3.6.1 statistical package. Variables were transformed as appropriate to meet the assumption of normality. Where the overall F-statistics was significant ($p < 0.05$), treatments means were compared using Fischer's Least Significant Difference at the 5% level of significance ($LSD_{5\%}$).

3. Results

3.1. 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 (Fig. 2). The daily I_s was lowest in June (mean range: 5.1–12 MJ m^{-2}) and most consistent, whereas December and January experienced higher and more variable I_s (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 T_{air} of 38.6° C, 33.8° C and 37.5° C were measured in January 2008, December 2012 and January 2020, respectively, while the lowest measured T_{air} was $-1°$ C in June across all the measurement periods. The lowest average daytime RH across all the measurement periods was measured in September (approximately 30%), while the mean daytime VPD was the highest ($Amear_2 = 2.6$ kPa, $Amear_6 = 2.5$ kPa and $Edun_2 = 3.4$ kPa) during September which is well known for dry, warm Berg winds. The average WS were notably high in July for year 2019′ 20 and in October for 2007′ 08 and 2012′13. The prevailing wind direction was from the north-east and the south for all measurement periods. Most of the rainfall (70%) occurred during summer from September to April of each measurement period (Fig. 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.

3.2. Soil water content

There was a distinct seasonal variation in SWC dynamics for all measurement periods (Fig. 3). The annual rainfall between measurement periods was not significantly different ($p > 0.05$), however, the SWC was generally higher in the *Amear₂* (Fig. 3), followed by *Amear₆* and *Edun₂*. The *Amear₂* SWC was significantly greater during the wet season (maximum: 0.40 m3 m^{-3} compared to 0.25 and 0.28 m3/m^{-3} for *Edun₂* and *Amear₆*, respectively (Fig. 3). Commercial forest plantations are known to have a very deep rooting system and are able to access soil water stored in deep soil layers from previous wet years (Christina et al., 2017). A study by Everson et al. (2014) on the same catchment, reported that the six-year-old *Acacia mearnsii* tree roots were as deep as 8 m into the soil profile. Similar results were reported by Dye (1996) in the Mpumalanga province of South Africa, where three-year-old *Eucalyptus grandis trees* abstracted water down to 8 m below the soil surface. The deep soil profile with the presence of weathered bedrock (saprolite) at the Two Streams research catchment suggests that trees were capable of rooting deep into the soil profile and were probably restricted by the bedrock (grey fine-grained shale). Therefore, there a high possibility in this study that tree roots, even for the young crops, accessed soil water stored deep in the soil profile from previous wet years.

3.3. Flux measurements

The daily R_n 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 R_n was translated through to H and LE, causing these fluxes to be positive during the daytime. The comparison of 30-min averages of R_n, H, LE and G in wet summer (October to March) and cold dry winter (May to August) indicated that there were no statistically ($p > 0.05$) significant differences in R_n in both summer and winter measurement periods (Table 2). However, during summer, energy partitioning of R_n into LE and H in all crops was dominated by LE ($p < 0.05$,

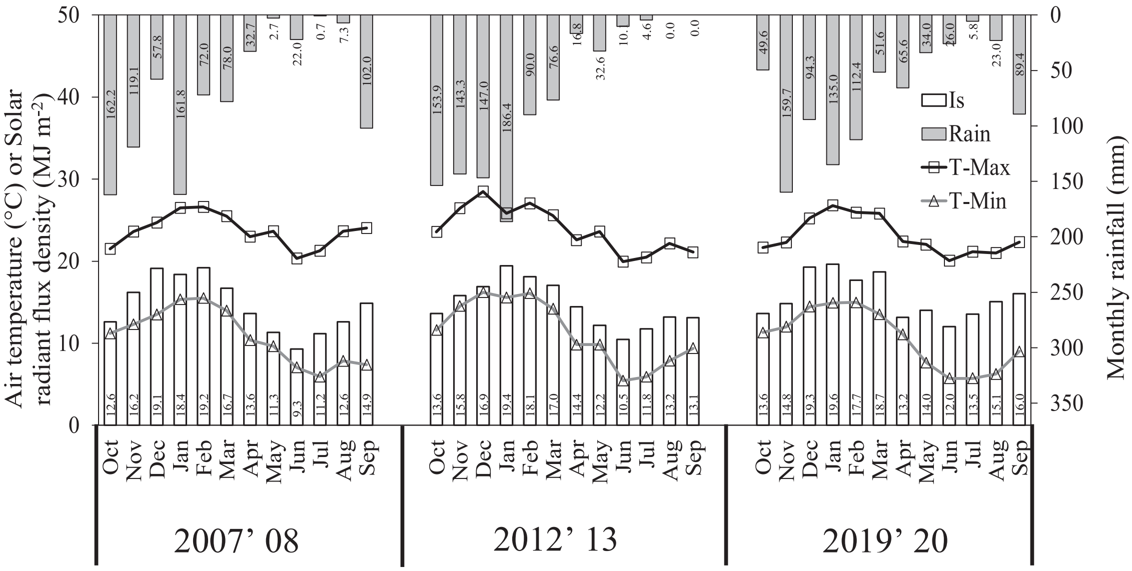

Fig. 2. Monthly values of mean daily radiant flux density (I_s, MJ m^{-2}) maximum (T-Max) and minimum (T-Min) air temperatures (°C) and corresponding total monthly rainfall measured at Two Streams research catchment in 2007′ 08, 2012′ 13 and 2019′ 20 hydrological years.

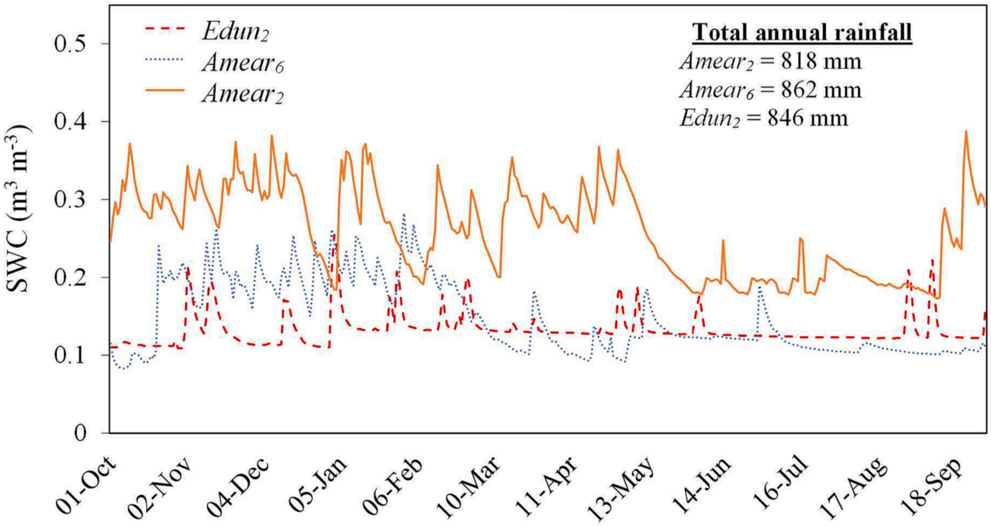

Fig. 3. The daily mean soil water content (SWC, $m^3 m^{-3}$) measured in the top 0.6 m of soil on a study site planted with two-year-old *A. mearnsii* (*Amear*$_2$, October 2007 to September 2008), two-year-old *E. dunnii* (*Edun*$_2$, October 2019 to September 2020) and six-year-old *Acacia mearnsii* (*Amear*$_6$, October 2012 to September 2013).

Table 2
Comparison of the Analysis of variance (ANOVA) results for daily energy fluxes during October to March (wet season) and April to September (dry season) measurement period between the two-year-old *E. dunnii* trees (*Edun*$_2$), two-year-old *A. mearnsii* (*Amear*$_2$) and six-year-old *A. mearnsii* (*Amear*$_6$). Significant mean differences are indicated using different letters at 5% level of significance.

	***Amear*$_2$** (2007′ 08)	***Edun*$_2$** (2019′ 20)	***Amear*$_6$** (2012′ 13)
	October to March measurement period ($W m^{-2}$)		
R_n	577.6	577.2	599.1
H	205.9a	229.9a	289.7b
LE	325.2a	289.2b	319.2a
G	23.1a	10.1b	24.9a
	April to September measurement period ($W m^{-2}$)		
R_n	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

Table 2) accounting for 55%, 61% and 53% of R_n for the *Amear*$_2$, *Amear*$_6$ and *Edun*$_2$, respectively. The peak LE values corresponded with maximum R_n values >900 Wm^{-2} for all crops. The LE fluxes continued to dominate ($p < 0.05$) during the winter season for the *Amear*$_2$ (66%) and *Edun*$_2$ (60%), however, the H and LE fluxes were statistically ($p > 0.05$) similar for the *Amear*$_6$ (LE = 132.3 $W m^{-2}$, H = 117 Wm^{-2}). The smallest portion of available energy (*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 ($p > 0.05$).

3.4. 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 Fig. 4. In early summer (November to January), mean daily ET for young crops ($p = 0.31$) was statistically greater ($p < 0.05$) than the mature crop. In the middle of the dry season (June and July), *Edun*$_2$ ET was significantly ($p < 0.01$) greater than both the *Amear*$_2$ and the *Amear*$_6$, which were not significantly ($p > 0.05$) different from each other. 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 (Fig. 4). The total accumulated rainfall for each measurement year was statistically similar across the three years. The accumulated ET exceeded rainfall for all crops (Fig. 4), with the least margin for *Amear*$_6$ (16.5%), while young crops ET were 27.5% and 30% greater for *Amear*$_2$ and *Edun*$_2$, respectively. FAO ETo varied over the three years, ranging from 918 mm to 1061 mm for the *Edun*$_2$ and *Amear*$_2$ respectively (Fig. 4).

3.5. Crop factors

The K_c was calculated at a daily interval from the ET (ET_{LAS} for the *Amear*$_2$ and ET_{EC} for the *Edun*$_2$ and *Amear*$_6$) and FAO ETo, using Eq. (8), and thereafter averaged for each month of the measurement period for each crop (Fig. 5). When $K_c = 1$, the Two Streams catchment ET equals to FAO ETo. However, a K_c of < 1 or > 1 indicated that the catchment actual ET is less than or greater than the FAO ETo, respectively. Comparison of K_c between our crops indicated that the K_c was between 0.7 and 1.3 throughout the year for all crops, except during a distinct period when the *Amear*$_2$ K_c (September 2008), *Amear*$_6$ K_c (June and July 2013) and *Edun*$_2$ K_c (May and June 2020) were 1.4, 1.4 and 1.6, respectively (Fig. 5). This is an indication that the ET significantly exceeded the FAO ETo during these periods.

3.6. Comparison between the leaf area index

The LAI for the *Edun*$_2$ showed a typical seasonal pattern (Fig. 6), 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 (Fig. 6).

3.7. 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 (Fig. 7).

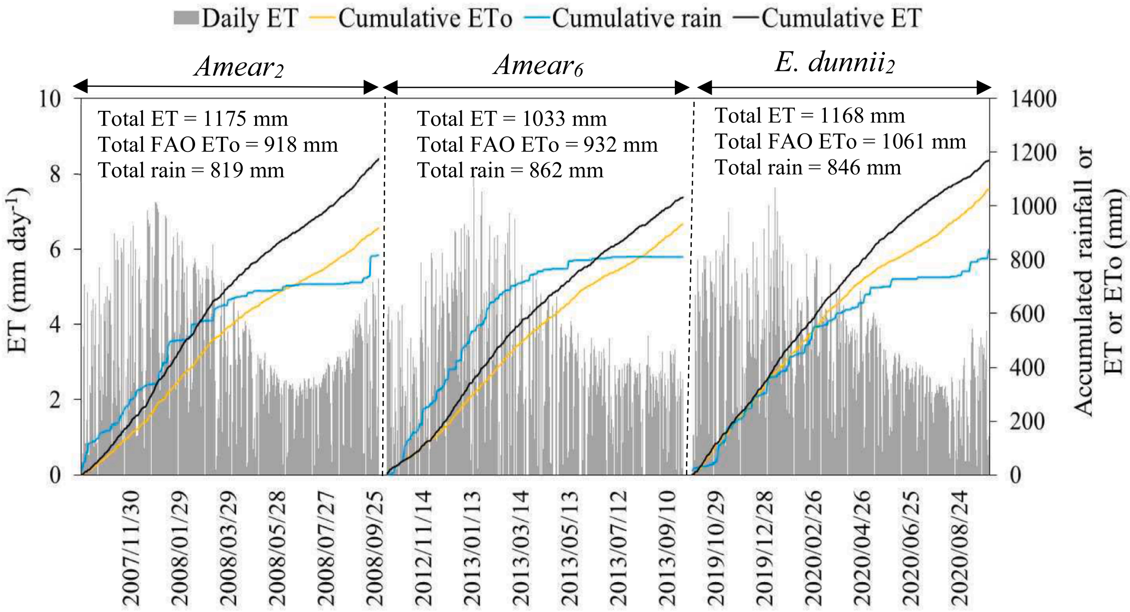

Fig. 4. Comparison between total evaporation (ET) by two-year-old *A. mearnsii* (*Amear*$_2$, measured using large aperture scintillometer from Oct 2007 to Sep 2008), six-year-old *A. mearnsii* (*Amear*$_6$, measured using eddy covariance from Oct 2012 to Sep 2013) and two-year-old *E. dunnii* (*Edun*$_2$, measured using eddy covariance from Oct 2019 to Sep 2020) with corresponding accumulated rainfall, ET and FAO reference evaporation (FAO ETo, mm day^{-1}).

4. 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 total 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 of genus 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 total 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.

4.1. Energy balance components and seasonal influence

The EB for each measurement period was mainly driven by local meteorological variables such as R_n and changes in vegetative characteristics. For example, during the summer wet season when R_n 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).

4.2. Total evaporation comparison between measurement periods

The annual measured ET for *Amear*$_2$, *Edun*$_2$ and *Amear*$_6$ were 30%, 27.5% and 16.5% greater than rainfall, respectively. These results are similar to two previous ET studies conducted on the same catchment; 1) Dye and Jarmain (2004) used Bowen ratio technique on four-year-old *A. mearnsii* and found ET to exceed precipitation by 18%, and 2) Clulow et al. (2011) using LAS on *A. mearnsii* reported 46% greater ET than rainfall. These two studies plus our study indicated a negative water-balance between input and output and suggests that trees sourced water external to the catchment and most likely from regional groundwater or soil water accumulated from fallow periods or unplanted nearby areas. It is common knowledge that post planting, exotic tree species develop a dimorphic root structure (deep tap root and superficial roots) to increase the chances of accessing water near the soil surface as well as in deep soil layers (Kimber, 1974; Sands and Mulligan, 1990). A South African study by Dye (1996) on three-year-old *E. grandis* in South Africa excluded rainfall using plastic sheeting and found that there was no decline in ET as soil water deficit increased. This was attributed to the ability 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

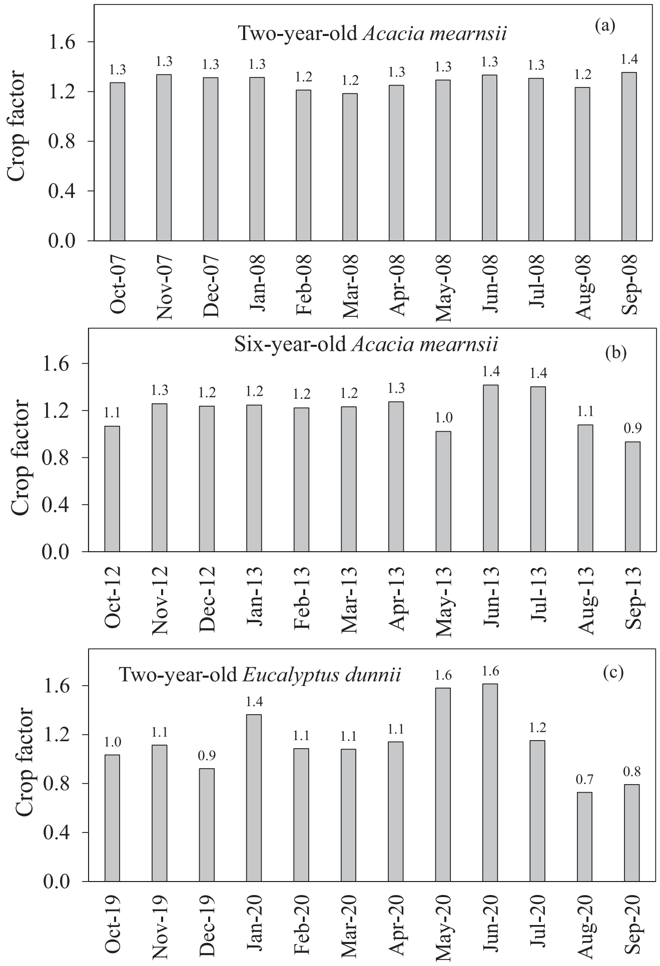

Fig. 5. Monthly crop factors for (a) two-year-old *Acacia mearnsii* (b) six-year-old *Acacia mearnsii* and two-year-old *Eucalyptus dunnii* derived at Two Streams research catchments for 2007′ 08, 2012′ 13 and 2019′ 20 hydrological years, respectively.

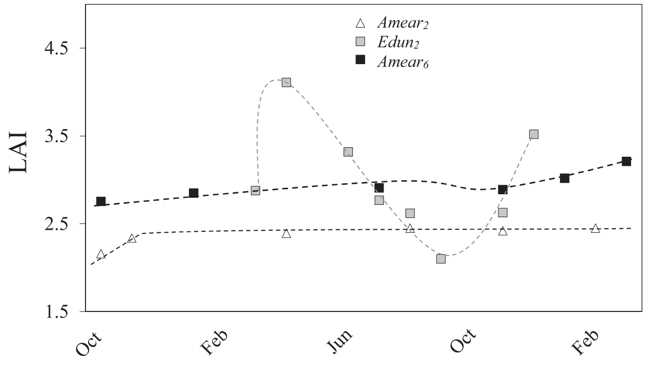

Fig. 6. The leaf area index (LAI) measured at Two Stream research catchment for the two-year-old *Acacia mearnsii* (*Amear*$_2$), two-year-old *Eucalytus dunnii* (*Edun*$_2$) and six-year-old *Acacia mearnsii* (*Amear*$_6$). For *Amear*$_2$, the LAI measurements were conducted in year 2007 (October and November), 2008 (April, August and November) and 2009 (February). In *Amear*$_6$ measurements were conducted in year 2011 (October), 2012 (January, July and November) and year 2009 (January and March). Monthly LAI measurements for *Edun*$_2$ were conducted in 2020 (March and April, June to September and November and December).

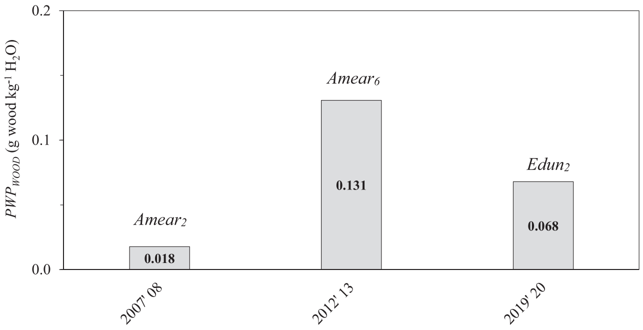

Fig. 7. The plantation water productivity (PWP_{WOOD}) of two-year-old *Acacia mearnsii* (*Amearn*$_2$), six-year-old *Acacia mearnsii* (*Amearn*$_6$) and *Eucalyptus dunnii* (*Edun*$_2$) in 2007′ 08 (September 2007 to October 2008), 2012′ 13 (September 2012 to October 2013) and 2019′ 20 (September 2019 to October 2020), respectively, at Two Streams research catchment.

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. (1997), 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* 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 transpiration 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 (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.

The K_c values ranged from 0.7 to 1.3, an indication that ET was either less than, equal to or greater than FAO ETo, which was expected during the wet summer months for actively growing trees due to higher I_s and fluctuation in SWC. However, higher K_c values during the dry season (May to July), 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. 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.

4.3. Plantation water productivity

Comparison of PWP_{WOOD} for young crops (*Amear*$_2$ and *Edun*$_2$)

indicated that *Edun*$_2$ produced more wood per total water used than the *Amear*$_2$. These results corroborated with other 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 water use efficiency 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}.

4.4. Implication of results on water resources and climate change

Our results in this study indicated that young *Eucalyptus* and *Acacia* crops use more water than the more matured crop and that all crops most likely accessed water stored deep in the soil profile and even the water table through capillary rise. These results are critical in terms of establishment and management of forest plantations by the commercial forestry industry in South Africa, since commercial plantations are largely confined in high rainfall areas (Dye, 2013). These areas are critically important water sources for rivers and streams, and were mostly covered by grassland and Fynbos (*Macchia* shrub), which use water significantly lower than forest plantations, before commercial forest plantations were established. Their replacement by evergreen commercial forest plantations has reduced the catchment water yields (Dye, 2013), with severe negative implications to downstream water users. The reduction in water yield has been exacerbated by the impact of climate change, which results to an increase in air temperature which cause intensification of the hydrological cycle, in turn increasing the total evaporation of plantation forests and high variability in rainfall patterns (Kusangaya et al., 2014). An increase in total tree evaporation will cause plantations forests to rapidly deplete soil water stored in the soil profile. Such challenges require forest producers to consider new approaches that will assist in mitigating the impact of climate change such as breeding tree species that use water more efficiently. Streamflow reduction by commercial forest plantations in commonly modelled in South Africa, our results suggests that hydrological models should accommodate deep-rooted trees accessing water stored deep in the soil profile from previous wet years and even groundwater reserves.

In situ measurements of ET in commercial forest plantation are important for the forestry industry, however, they are complex and expensive for countries such as South Africa with limited resources. The crop coefficients derived in this study will help local forest producers to estimate total evaporation from easily accessible FAO ETo. In addition, data from this study can be used to calibrate and validate future modelling studies in South Africa.

A conclusion based on our results is that commercial forest plantation, despite the stage of development, may use water stored deep in the soil profile and even groundwater reserves. However, measurement of total water balance is recommended and continuation of ET measurements on the *E. dunnii* crop is suggested for a full rotation and be expanded to other commercial forest plantations to fully confirm this finding.

5. Conclusion

This study compared EB and total water use by young exotic tree species (*Edun*$_2$ and *Amear*$_2$) and a mature crop (*Amear*$_6$) using internationally recognised techniques, EC and LAS in the same catchment over different measurement periods. The EB fluxes were dominated by LE during summer for all crops, even during the dry season, which was an indication that these crops were accessing stored soil water or groundwater reserves. Comparison between *Edun*$_2$ and *Amear*$_2$ ET losses indicated similar responses, however, the ET of the mature crop (*Amear*$_6$) was significantly lower than both the *Edun*$_2$ and *Amear*$_2$ crops, which was expected as literature reports that the exotic species reach their peak water-use in the middle of their rotation (~5 years), thereafter decreasing. Recommendations are that measurements on *E. dunnii* are continued for a full rotation and expanded to other commercial forest plantations. The derived K_c values will assist in predicting ET using easily accessible FAO ETo and in verifying data from 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 total water use of *Edun*$_2$ and *Amear*$_2$ was similar, the mature *Amear*$_6$ water-use was lower than the young crops. It was concluded that commercial forest plantation, at any stage of development, have a potential to negatively impact the water yield. It would be beneficial to continue the measurements of ET of the actively growing *E. dunnii* trees at Two Streams for the full rotation. The long-term measurements of *E. dunni* trees will assist in understanding the long-term water balance and in particular the deficit in the water balance repeatedly measured in the catchment.

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CRediT authorship contribution statement

Nkosinathi D. Kaptein: Formal analysis, Writing – original draft, Writing - review & editing. **Colin S. Everson:** Supervision, Conceptualization, Resources, Writing – review & editing. **Alistair D. Clulow:** Supervision, Conceptualization, Resources, Project administration, Writing – review & editing. **Michele L. Toucher:** Supervision, Conceptualization, Resources, Project administration, Funding acquisition, Writing - review & editing. **Ilaria Germishuizen:** Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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