Comparative water-use by fast-growing *E. grandis* x *E. nitens* clonal hybrid and *Pinus elliottii* near the Two Streams Research Catchment, South Africa

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15 **Abstract.** Pine plantations are the dominant specie currently planted within the South African commercial forestry industry.
Improvements in bioeconomy markets for dissolving wood pulp products have seen an expansion in fast-growing *Eucalyptus*
plantations due to their higher productivity rates and better pulping properties than pine. This has raised concerns regarding
the expansion of *Eucalyptus* plantations and how they will affect water resources as they have been reported to have higher
transpiration (T) and total evaporation rates (ET) than pine. We compared T (mm), diameter at breast height (DBH, cm) and

20 leaf area index (LAI) of an eight-year-old *Eucalyptus grandis* x *Eucalyptus nitens* clonal hybrid (*GN*) with twenty-year-old
Pinus elliottii. Transpiration was measured for two consecutive seasons (2019' 20 and 2020' 21) using a heat ratio sap-flow
method. The ET was calculated using published values of soil evaporation and rainfall canopy interception to quantify the
impact of each species on water resources. In 2019' 20 season, annual T for *P. elliottii* exceeded *GN* by 28%, while 2020' 21
season showed no significant differences. This was associated with 17 and 21% greater LAI for *P. elliottii* than *GN* in 2019'

25 20 and 2020' 21 season, respectively. Dq increments were statistically similar ($p > 0.05$) in 2019' 20 season, whereas the 2020'
21 season produced significant differences ($p < 0.05$). Transpiration for *P. elliottii* showed a strong ($R^2 > 0.70$) linear
relationship with solar radiation, LAI and shallow soil matric potential, while *GN* had a good ($R^2 > 0.70$) relationship with
solar radiation only. The soil water potential was very low at the *GN* site, indicating that the site was water stressed, with trees
competing for water as soon as it becomes available to sustain T, causing a rapid soil water depletion after rainfall, while *P.*

30 *elliottii* used water more gradually. *P. elliottii* estimated ET was 18% greater than *GN* in 2019' 2020, with no significant
differences in 2020' 21 season. Results from this study indicated that on water limited sites, T and ET between *GN* and *P.*
elliottii may not be different, however, in subtropical regions, *GN* T and ET have the potential to exceed *P. elliottii*, causing

soil water depletion. Long-term total soil water balance studies in the same region would be beneficial to understand the impact of long-term commercial forestry on water resources.

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1 Introduction

The expansion of new areas of commercial afforestation in South Africa have generally slowed in recent years in favour of the composition of existing plantations changing. This decrease has been attributed to political, environmental and climate change influences (Nambiar, 2019). Pine plantations are still the dominant species in South Africa occupying approximately 49.6%

40 of total commercial forest plantation areas (Forestry South Africa, 2018). These plantations are mainly grown for sawlog (74.7%) and coarse-fibre pulpwood (24.9%). Over the years, there has been an improvement in the bioeconomy market for dissolving wood pulp products such as short fine-fibre pulp. Fast-growing *Eucalyptus* species are now being considered an alternative to pine due to their superior fibre and pulping properties (Dougherty and Wright, 2012), short rotation (8-12 years) and high productivity rates (Albaugh et al., 2013). *Eucalyptus* plantation productivity can be as high as 35 m^3 ha^{-1} $year^{-1}$ on

45 highly productive sites compared to 25-27 m^3 ha^{-1} $year^{-1}$ of pine (Fox et al., 2007). As a result, over the past 10 years, the areas planted to pine in South Africa have decreased by 2% while *Eucalyptus* increased by 10% (Forestry South Africa, 2018). There are now plans to replace as many as 300 000 ha of pine with *Eucalyptus* over the next 20 years (Forestry South Africa, 2018). The potential for an increase in planting *Eucalyptus* species in South Africa may present several environmental considerations including a potential impact to biodiversity (Callaham et al., 2013) and high rates of transpiration (T) and total evaporation

50 (ET) (Stanturf et al., 2013). There is a wide body of knowledge indicating that *Eucalyptus* species T is greater than pine (Scott and Lesch, 1997; Albaugh et al., 2013) and can reduce off-site water yield (Calder, 2002). Given the imminent increase in *Eucalyptus* plantations in the near future, it is vital to make a direct comparison of T by pine and *Eucalyptus*. A *Eucalyptus grandis* versus *Pinus patula* comparison by Scott and Lesch (1997) on very deep soils, found that *E. grandis* used up to 100 mm more water per year than *P. patula* using streamflow measurements. In contrast, White et al. (2021), reported no annual

55 differences between T and ET of *E. globulus* and *P. radiata* in central Chile.

Pinus elliottii and *E. grandis* x *Eucalyptus nitens* clonal hybrid (*GN*) are the second and fourth most planted species in South Africa, respectively. There is no existing literature that quantifies and compares T and ET by these two species in South Africa and mixed reports in the international literature. The objective of this study was therefore to compare T and ET by *GN* versus *P. elliottii* plantations and the impact posed by each species on plantation water yield. For fair comparison, both species were

60 in the same stage of development, therefore, the *P. elliottii* plantation (age 20 years old) was 12 years older than *GN* (8 years old).

2 Methods

2.1 Description of study area

65 The study area was located on the Mistley Canema estate (29°12'19.78"S, 30°39'3.78"E) in the KwaZulu-Natal midlands of South Africa, which is about 70 km north-east of Pietermaritzburg (Fig. 1). The area is generally hilly with rolling landscapes and a high percentage of arable land (Everson et al., 2014). It is dominated by forb-rich, tall, sour *Themeda triandra* grasslands of which only a few patches remain due to invasion of native *Aristida junciformis*. Soils in this area are highly leached with apedal and plinthic soil forms, mostly derived from the Ecca group with dolerite dykes and sills. Area is commonly covered

70 in heavy mist which significantly contributes to precipitation (Mucina and Rutherford, 2006). Weather events such as moderate frost, droughts, hail, and berg winds are frequent in the area.

2.2 Site description

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

75 planted to *GN* in August of 2013. Study site 2 (3.5 km away from the catchment) was established in August 2001 and planted to *Pinus elliottii.* Basic characteristics for both study sites are presented in Table 1. Study sites were 4 km away from each other with the automatic weather station located approximately equidistant between the two sites. Both *GN* and *P. elliottii* were planted at a spacing of 2 x 3 m (1667 trees ha^{-1}). The *GN* trees were established using cuttings, while for *P. elliottii*, seedlings were used. Both study sites were subjected to standard afforestation practices such as pruning and thinning, weeding pre-

80 canopy closure and slash removal every 5th row to minimise fire risk.

2.3 Environmental monitoring

An automatic weather station was installed on a flat uniform grassland area in the middle of the two study sites to provide supporting meteorological measurements. Measurements of air temperature (Tair) (HMP 60, Vaisala Inc., Helsinki, Finland), the relative humidity (RH) (HMP60, Vaisala Inc., Helsinki, Finland), the wind speed and direction (Model 03003, R.M. Young,

85 Traverse City, Michigan, USA), the solar radiation (I$_s$) (Kipp and Zonen CMP3) and rainfall (TE525, Texas Electronics Inc., Dallas, Tx, USA) were conducted every 10 s and output hourly. The sensors were installed according to recommendations of the World Meteorological Organisation (WMO, 2010) with the rain gauge orifice at 1.2 m and the remaining sensors at 2 m above the ground surface. The sensor outputs were recorded on a CR1000 datalogger. The datalogger (Campbell Scientific Inc., Logan, Utah, USA) recorded 5-min outputs and was programmed to calculate the Vapour Pressure Deficit (VPD) using

90 Tair and RH measurements according to Savage et al. (1997).

2.4 Transpiration flux measurements

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

95 The heat ratio method of a heat pulse velocity system (HPV) (Burgess et al., 2001) was used to estimate sap-flow at various depths across the sap-wood of each selected tree for the 2019' 20 (October 2019 to October 2020) and 2020' 21 season (October 2020 to October 2021). The HPV system consisted of a line heater probe (4 cm long and of 0.18 cm outside diameter brass tubing) with enclosed constantan filament that provides a heat source for 0.5 s when powered and a pair of type T copper-constantan thermocouples to measure the heat ratio. For *Pinus elliottii* trees, slightly longer heater probes (6 cm) were used

100 due to the xylem being situated deeper in coniferous trees when compared to angiosperm trees. Prior to probe installation, thickness of the bark was measured, and suitable sensor insertion depth was identified using an increment borer and Methyl Orange staining. 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

105 the sap-flow direction. Probes were installed at various depths (Table 2) within a tree. Hourly measurements were executed and recorded using a CR1000 datalogger (Campbell Scientific Inc.) powered by a single 55-amp hour lead acid deep cycle battery. Thermocouples were connected to an AM 16/32 multiplexer (Campbell Scientific Inc.), which was in turn connected to a CR1000 datalogger to allow for 32 measurements at various sap-wood depths across the four instrumented trees. Data were remotely downloaded using a GSM modem (Maestro Wireless Solutions Ltd. Hong Kong, China)

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

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

Where k is a thermal diffusivity of fresh wood (a nominal value of 2.5 x 10^{-3} cm^2 s^1), x is the distance of each temperature

115 probe from heater probe (cm), and V_1 and V_2 are temperature increases in upstream and downstream probe (°C) at equidistant points.

A slight probe misalignment may occur during the drilling process even when a drill guide is used. This was assessed by checking for inconsistencies in the zero flux values in periods where sap-flow was expected to be zero, such as over pre-dawn,

120 during rainfall events, or in high RH and low SWC conditions. The sap-flow values during these times were adjusted to zero and an offset calculated from an average of these values and applied to the whole dataset. For probes used in this study, the offset was < 5% of the midday sap-flow rates.

Wounding or non-sap conducting area around the thermocouples was accounted for using wound correction coefficients described by Burgess et al. (2001). Thereafter, sap velocities were calculated accounting for moisture fraction and wood density

125 as described by Burgess et al. (2001). Finally, sap velocities were converted to T rates (mm day^{-1}) by summing products of sap velocity and cross-sectional area for individual stems. The T rates were then weighted as per individual tree contribution to provide a measure of whole stand T.

2.5 Soil water content and soil water potential

At both sites, soil water content (SWC) was measured in the upper 60 cm of the soil profile (20, 40 and 60 cm depth) using

130 CS616 sensors (Campbell Scientific Inc.). Measurements were taken hourly to coincide with the sap-flow measurements and recorded on the CR1000 datalogger. SWC values were converted to matric potential using water retention relationship curves. This was achieved using a HyProp unit (MeterGroup) and WP4C (MeterGroup).

2.6 Heat ratio technique calibration

The HPV method is an internationally recognised and reliable technique for measuring individual tree T in uniform stands

135 (Hatton and Wu, 1995; Meiresonne et al., 1995; Crosbie et al., 2007). There are however difficulties, bringing uncertainty to the accuracy of the absolute sap-flow results, such as the anisotropic sap-wood properties (Vandegehuchte et al., 2012), radial patterns of the sap-flow (Cermák and Nadezhdina, 1998), tree symmetry (Vertessy et al., 1997) and changes in spatial patterns of T (Traver et al., 2010). Some studies have indicated that the technique underestimates sap-flow in *Eucalyptus* by as much as 45% (Maier et al., 2017; Fuchs et al., 2017), whereas pine may be overestimated by as much as 49% (Dye et al., 1996b).

140 This necessitated a calibration experiment to validate the field measurements.

The calibration experiment was conducted in an open area at the Institute for Commercial Forestry Research nursery, located at the University of KwaZulu-Natal, Pietermaritzburg for a period of 30 days as illustrated in Figure 2. Two-year-old *GN* and four-year-old *Pinus elliottii* trees grown in 25-L plastic containers (diameter=36 cm, height = 42 cm) filled with vermiculite

145 were sourced from Mondi Mountain Home Estate nursery (Hilton, South Africa). The containers had holes at the base (to allow for drainage) and were placed on a rubber mat with slots to prevent root contact with soil and to allow water to drain away from the container. Twenty-four hours before starting the experiment, both trees were well watered, and each container was insulated using plastic at the tree base to prevent soil evaporation and induce water loss solely through T. Tree diameters at the start of an experiment were 4.2 and 3.6 cm for *GN* an *P. elliottii*, respectively. Each tree was instrumented with HPV

150 sensors to measure hourly sap-flow (as discussed in section 2.4) and summed from sunrise to sunset to make up daily tree T (L day^{-1}). Concurrently, each soil container was weighed in the morning and afternoon, using a lysimeter (resolution=0.001g, placed on a flat concrete surface to ensure it remains level during the experiment) to determine daily changes in container weight (kg, where 1 kg was assumed to be equivalent to 1 L) as a measure of T. This process was repeated for five days to get a calibration over a range of plant available water values, whereafter trees were again well-watered (achieved by removing

155 insulation plastic) and allowed to drain completely before restarting measurements. Sapwood area and wounding was accounted for according to Burgess et al. (2001) to derive daily T. A simple regression was conducted between daily T and daily change in tree mass.

2.7 Growth measurements

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

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

where; d is the DBH (cm) of an individual tree and n is the total number of trees. Tree heights for the 48 trees were measured
165 simultaneously using a hypsometer (Vertex Laser VL402, Haglof, Sweden). Monthly measurements of leaf area index (LAI) were conducted using a LAI-2200 Plant Canopy Analyzer (Licor Inc., Lincoln, New York, USA) on a 0.6 ha transect that was identified through the middle of each study site from October 2019 to October 2021.

2.8 Statistical analysis

Analysis of variance (ANOVA) was used to analyse species differences in stand characteristics (T, Dq, tree heights and LAI)
170 using the R version 3.6.1 statistical package. Variables were transformed as appropriate to meet the assumptions of normality. Where the overall F-statistic was significant ($p < 0.05$), treatment means were compared using Fischer's Least Significant Difference at the 5% level of significance (LSD$_{5\%}$). Statistical parameters that were used included the regression co-efficient (R^2), root mean square error (RMSE), standard error of a regression slope (SE slope), standard error of the intercept (SE intercept) and a ratio of variance of y-intercept to x-intercept (F).

175 ## 3 Results

3.1 Automatic weather station

The minimum and maximum daily Tair were typical of the 30-year average of Mistley Canema. Maximum recorded Tair was 36.5 and 37.5°C for 2019' 20 and 2020' 21 seasons, respectively. There were several days where Tair were below freezing between May and July for both seasons (Fig. 3a). Rainfall between 01 October 2019 and 30 September 2020 amounted to 857
180 mm and 825 mm for 01 October 2020 to September 2021. Majority of this rainfall (70%) fell during summer months (November to March) for both seasons (Fig. 3d). By comparison, ETo totals calculated using hourly AWS data and the FAO56 method (Allen et al., 1998) amounted to 1100 mm and 1056 mm for 2019' 20 and 2020' 21 seasons, respectively. Daily maximum VPD was 3.08 kPa for 2019' 20 increasing to 3.53 kPa for 2020' 21 season during hot summer months (Fig. 3c).

Monthly average wind speed ranged from 2.2 to 7.7 m. s^{-1} over the two seasons with maximum wind speeds up to 37 m.s^{-1} in
185   August/ September. The RH reached 100% during the night, decreasing to as low as 20% during the day on hot summer
months. Average I_s for 2019' 20 and 2020' 21 season was 15.5 and 16 MJ m^{-2} day^{-1}, respectively, while both seasons
experienced a maximum I_s of 30 MJ m^{-2} in summer for both measuring seasons (Fig. 3b).

3.2 Soil matric potential

There was a high temporal variation in soil matric potential for all measuring sensors. Peak (wet conditions) plant available
190   water (*PAW*) for the *P. elliottii* site during the wet summer months was -37, -110 and -60 kPa for 20, 40 and 60 cm sensors,
respectively. The 60 cm sensor was consistently wetter than the 40 cm sensor. Matric potential decreased (getting drier) to a
minimum of -350 kPa in the winter season (June to August) (Fig. 4a). The *GN* site was generally much drier than the *P. elliottii*
site with the 40 and 60 cm sensor measuring *PAW* beyond -1500 kPa in most instances, except during rainfall events (Figure
4b). The lowest *PAW* measured during the study period was -5000 and -12200 kPa for the 40 cm and 60 cm sensors,
195   respectively, indicating exceptionally dry soil conditions and beyond the accurate measuring range of the sensors. The 20 cm
sensor recorded its highest *PAW* of -52 kPa after rainfall during the study period. After a rainfall event, *PAW* for the *GN* site
was depleted rapidly, within hours. This contrasts with the *P. elliottii* site, where water was depleted more gradually, lasting
for a few days post rainfall. There was a linear relationship between daily T and matric potential for the top 20 cm of soil on
both sites (Fig. 5). This relationship was good (R^2=0.72) for the *P. elliottii* and weak (R^2=0.41) for the *GN* site, with a slightly
200   higher RMSE for the *P. elliottii* site.

3.3 Heat ratio calibration

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

$$GN = 0.54x^2 + 0.24x + 0.32 \tag{3}$$
$$P.\ elliottii = 0.58x^2 - 0.10x + 0.37 \tag{4}$$

3.4 Transpiration rates

210   The T followed typical seasonal and diurnal pattern for both sites in both 2019' 20 and 2020' 21 seasons (Fig. 7). *Pinus elliottii*
had significantly ($p < 0.01$) higher mean daily T compared to *GN* (Fig. 7) except for the winter of 2021 (May to August) where
GN was statistically (p=0.012) greater. Mean daily T values in summer of 2019' 20 season for *Pinus elliottii* and *GN* were 2.5
mm and 1.9 mm, respectively. By comparison, summer mean T values of 2020' 21 season were 2.6 mm for *P. elliottii* and 2.1
mm for *GN* ($p < 0.05$). After a significant rainfall event (~10 mm), T for *GN* momentarily exceeded *P. elliottii* for a few days,

215   thereafter, falling below *P. elliottii*. The maximum T for *GN* was 5.2 mm and 3.8 mm for 2019' 20 and 2020' 21 seasons, respectively, versus 5.6 mm for *P. elliottii* in both seasons. During 2019' 20 season, *GN* reached peak T rates early in summer (late December 2019) compared to *P. elliottii*, where peak T rates were measured in late January to early February of 2020 (Fig. 7). However, maximum T rates were reached mid-January for the 2020' 21 season by both crops, which coincided with high I_s, Tair and VPD. During winter months (June to July) of both the 2019' 20 and 2020' 21 seasons no T could be detected

220   by probes on *GN* trees on several days, despite clear weather conditions. This corresponded with low soil water potential of -360 kPa for the 20 cm and very low matric potential of < -1500 kPa for the 40 cm and 60 cm deep sensors. By comparison, T could be measured in *P. elliottii* trees where the soil was less dry in winter, however at very low T rates (~0.33 mm day^{-1}). Following rainfall, the *P. elliottii* response to *PAW* lagged behind the *GN* trees. While *GN* T increased almost immediately, *P. elliottii* T only responded a few days later (Fig. 8).

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   The differences in seasonal patterns of T are better illustrated using daily accumulated T as presented in Fig. 9. Over the 2019' 20 season, the total accumulated daily T for *P. elliottii* was 30% greater than *GN*, while the total accumulated rainfall exceeded *P. elliottii* and *GN* T by 21 mm and 258 mm, respectively (Fig. 9). In comparison, the total accumulated T rates in 2020' 21 season were statistically similar *(p > 0.05)* throughout the season with accumulated rainfall 18 and 20% greater than T for *P.*

230   *elliottii* and *GN*, respectively. The accumulated ETo exceeded rainfall by 22% in both seasons. Total annual T rates for *GN* were slightly higher in 2020' 21 than 2019' 20 season by 6%, while *P. elliottii* T rates reduced by 19% during the same period (Fig. 9).

3.5 Response to climatic variables

   Tree T for each species was compared by multiple regression analysis to micrometeorological parameters including I_s, VPD,

235   rainfall, RH, wind speed and Tair to determine individual and combined drivers of T. The most responsive variable was I_s for both tree species, where an increase in I_s resulted to an increase in T ($R^2 > 0.75$), except in winter of 2019' 20 season for *GN* and 2020' 21 season for *P. elliottii* (Table 3). VPD significantly influenced *GN* T only in the summer months for both seasons, where a 2nd order polynomial relationship was produced ($R^2 > 0.62$). Transpiration increased with an increase in VPD, up to a threshold of approximately 2.8 mm day^{-1}, thereafter remaining constant (data not shown). In addition, there was hysteresis in

240   *GN*, where at similar VPD, T was greater in the morning than in the afternoon. By comparison, *P. elliottii* showed no significant response to VPD on both measuring seasons (Table 3). Tree T was also highly correlated with RH in *P. elliottii*, where T increased with decrease in RH, reaching a peak of 2.5 mm (RH=21%) and 5.6 mm (RH=23%) in 2019' 20 (winter) and 2020' 21 (summer), respectively. Rainfall, wind speed and Tair did not significantly influence T of both species.

3.6 Tree growth

245   At the beginning of the study, *P. elliottii* trees were larger in diameter than *GN*. There was a seasonal pattern in Dq increment by both species (Fig. 10), with no significant (*p > 0.05*) differences in 2019' 20 season, while 2020' 21 season produced

significantly ($p < 0.05$) greater growth increment in *P. elliottii* than *GN*. Interestingly, a negative growth increment was measured during the winter of 2019' 20 season for *GN*, which was probably caused by soil water deficit.

3.7 Leaf area index

250   The mean summer LAI for *P. elliottii* was 17% greater than *GN* (*P. elliottii*=2.5 vs *GN*=2.05, $p < 0.05$) in 2019' 20 increasing to 21% (*P. elliottii*=3.1 vs *GN*=2.4, $p < 0.05$) in 2020' 21 season. Winter LAI decreased to 1.31 and 1.76 for *P. elliottii* and *GN*, respectively. Total monthly T was linearly related to monthly LAI of both *P. elliottii* and *GN* (Fig. 11), with statistical differences in the regression ($p < 0.05$). However, there was a greater RMSE, SE intercept and SE slope in *P. elliotti* than in *GN*.

4 Discussion
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4.1 Daily T

The *P. elliottii* mean daily T exceeded *GN* by about 24% over the 2019'20 and by 19% in 2020'21 seasons, mainly influenced by I_s and RH. Differences in T between *GN* and *P. elliottii* could be attributed to the following reasons: 1) trees in the *GN* site were water stressed, this was observed through the extremely low *PAW* throughout the monitoring period, shrinking of tree

260   diameters in winter, zero rates of T on some days during winter months and a significant decrease in LAI over winter and 2) sap-wood for *P. elliottii* was nearly twice the sap-wood area of *GN* due to species age difference. The *GN* mean T range of 0.9–5.2 mm and 0.5–3.8 for 2019' 20 and 2020' 21 seasons, respectively, measured in this study agreed with *Eucalyptus* studies in relatively low rainfall areas with trees of the same age. For example, a study by Forrester et al. (2010) on seven-year-old *E. globulus* in Australia measured a T range of 0.4–1.9 mm day^{-1} (MAP=708 mm). David et al. (1997) measured daily

265   T of 0.5–3.64 mm at a *E. globulus* site in Portugal with a MAP of 600 mm. A South African study by Dye et al. (1996a) on nine-year-old *E. grandis* in Mpumalanga, South Africa measured T of 2.0–7.5 mm day^{-1} with the potential to exceed 8.0 mm day^{-1} under high VPD (Dye et al., 2013), however, this study was conducted in a high rainfall area (MAP=1459), with almost double the MAP of the current study. For *P. elliottii*, peak T of 5.6 mm day^{-1} in this study agreed with other studies, such as Hatton and Vertessy (1990) who measured a maximum T of 5 mm day^{-1} in *P. radiata* in new South Wales, Australia.

270   During summer *GN* T peaked earlier than the *P. elliottii* (more distinct in 2019' 20 season) and then decreased swiftly, so that it was less than the *P. elliottii* T in the late summer to early autumn. In addition, the *GN* T increased sharply after the rainfall events and thereafter decreased as *PAW* was rapidly depleted, while *P. elliottii* responded more gradually. This suggests that *GN* trees have a different growth and water use strategy to *P. elliottii,* that involves using available water rapidly. A similar observation was reported by White et al. (2021) from *E. globulus* in central Chile. This implies that *GN* trees compete for

275   water and use it more rapidly when it becomes available, and this strategy can expose them to extreme water stress if soil water deficit conditions persist as reported by Mitchell et al. (2013). *P. elliottii* had a greater T at stem sizes similar to the *GN* (ie. Dq for smallest *P. elliottii* tree versus Dq for largest *GN* tree). This may be attributed to a markedly smaller heartwood in *P.*

elliottii than *GN*. However, it should be noted that pine trees consist of several latewood rings in which no sap movement occurs (Dye et al., 2001). Diurnal changes in T typically lagged behind VPD, creating a pattern of hysteresis, where at similar

280 VPD, T was greater in the morning than in the afternoon for *GN*. Studies by O'Grady et al. (1999) and Maier et al. (2017) attributed this to low soil hydraulic conductivity or the use of stored stem water for T in the first portion of the day. Further analysis in our study indicated that *GN* T was significantly influenced by VPD only in summer, suggesting that very low *PAW* may have affected water uptake to a greater extent in winter.

4.2 Annual T

285 On an annual basis, *P. elliottii* trees transpired 28% more water (836 mm) than *GN* (599 mm) in the 2019' 20 season, while the 2020' 21 season saw no significant differences between the two species (*P. elliottii*=678 mm vs. *GN*=639 mm). The low rates of T in winter months (May to August) of 2021 of the *P. elliotti* site (Fig. 7), which were probably caused by low *PAW*, resulted in the similar annual T rates in the 2020' 21 season by both species. Studies (Moran et al., 2017; Samuelson et al., 2019) reported that the first reaction by pine species to a decrease in *PAW* is a significant reduction in stomatal aperture,

290 causing a decrease or cessation of T. By comparison, *GN* indicated a different response, where T continued (even when *PAW* was marginally limiting) to a point where it was below detection by our HPV system and this trait makes eucalypts vulnerable during extended or severe drought periods. Similar findings were reported by White et al., (1999) and Eksteen et al., (2013) in *E. nitens*, where trees utilised *PAW* till permanent wilting point, which seems to be well beyond the -1500 kPa typically cited in literature for many plants (Santra et al., 2018).

295 There are contrasting results in some annual comparative studies of T between *Eucalyptus* and *Pinus* species. In an eight-year-old *E. benthamii* vs *P. taeda* comparative water use study in the United States (Maier et al., 2017), annual T of 1077 and 733 mm year^{-1} for *E. benthamii* and *P. taeda*, respectively, were measured. In a South African study (tree water use estimated using water balance), *Eucalyptus grandis* used 100 mm more water per year than *Pinus patula* (Scott and Lesch, 1997). Notwithstanding these findings, another study in southeastern Australia, Benyon and Doody (2015) found no significant

300 differences between annual water use (only T was measured) between *E. globulus* and *P. radiata*, with or without access to groundwater. Like other studies (Whitehead and Beadle, 2004; Samuelson et al., 2008), a strong correlation between T and LAI was observed in this study, with *P. elliottii* having a greater T rate than *GN* at a similar LAI. This good correlation may present a modelling opportunity to estimate T using site measurements of LAI or remote sensing estimates of LAI.

4.3 Species differences in estimated total evaporation

305 Water loss from I (canopy interception) and E_s (soil evaporation) were estimated in this study due to their value when evaluating the stand water balance and species impact on catchment water yield. Maier et al. (2017) reported that I and E_s may account for up to 45% of stand water balance. Canopy interception differs vastly and depends on rainfall, the LAI and canopy architecture (Cannell, 1999). These factors may be very variable, making it difficult to generalise, however, it is commonly accepted that pine have a greater I than *Eucalyptus* (Maier et al., 2017). Canopy interception was estimated using published

310   data, with *Eucalyptus* (Soares and Almeida, 2001; Benyon and Doody, 2015) losing 19% through I, and pine 31% of total annual rainfall (Sun et al., 2010; Bulcock et al., 2014; Benyon and Doody, 2015). Using these values, annual I for our study was estimated at 162 mm for *GN* and 266 for *P. elliottii* in 2019' 20 season, while 2020' 21 season experienced 157 and 256 mm for *GN* and *P. elliottii*, respectively. The E_s was likely to be higher for *GN* than *P. elliottii*, as per the LAI at the pine site being significantly higher (17%) than at the *GN* site, resulting in shading. A study by Benyon and Doody (2015) compared I

315   and E_s across 18 plantations of *E. globulus* and *P. radiata* and reported an average E_s of 15% for *P. radiata* and 29% for *E. globulus* of annual rainfall. Annual E_s estimates using these values amounts to 249 mm for *GN* and 129 mm for *P. elliottii* in 2019' 20 season, while 2020' 21 season estimates were 124 and 240 mm for *P. elliottii* and *GN*, respectively. The annual estimated ET for *P. elliottii* (1231 mm) in 2019' 20 season was 18% greater than *GN* (1010 mm), while there were no significant differences between species ET in the 2020' 21 season (*GN*=1036 mm vs. *P. elliottii*=1058 mm), based on a rainfall

320   of 857 and 825 mm for 2019' 20 and 2020' 21 season, respectively. It is evident from these estimated values and measured data that both study sites experienced water stress due to ET exceeding the rainfall. *Eucalyptus* species are known to root deeper than pine (Canadell et al., 1996) and can rely on groundwater to drive T (Morris and Collopy, 1999). However, in our study there is clear evidence that *GN* trees did not have access to underground water reserves due to shrinking of tree diameters and T rates below detection by our HPV system in the dry season.

325   **4.4 Implications on catchment water yield**

Our results indicated that *P. elliottii* ET was significantly greater than *GN* in 2019' 20, while 2020' 21 ET patterns were statistically similar. These results were influenced by *PAW* and physiological response by each specie to soil water deficit. It is most likely that *GN* trees would have used more water than *P. elliottii* if *PAW* was not limiting or if trees had been able to exploit groundwater reserves. This conjecture is supported by studies conducted by Calder (1992), Dye et al. (1996a) and

330   O'Grady et al. (1999), where *Eucalyptus* T was higher during the dry season than during the wet season, largely due to exploitation of groundwater reserves.

These implications are significant in local planning by the commercial forestry industry, since current markets favour replacement of longer rotation pine with shorter rotation *Eucalyptus* plantations. However, without comprehensive knowledge of long-term total water balance measurements, the implications cannot be quantified. Studies have reported a negative effect

335   of *Eucalyptus* to catchment water yield (Almeida et al., 2007), whereas others have reported no significant impacts (Lane et al., 2004; White et al., 2021). A conclusion based on our results, is that species conversion from *P. elliottii* to *GN* in moderate to low rainfall areas and where groundwater resources are inaccessible, for example where these resources are too deep for roots to reach, may not adversely affect the water yield, however, in subtropical regions where the water table can be shallow, the impact could be severe. Due to climate variability, long-term studies under non-stressed and stressed conditions are needed

340   in this region to quantify the total water balance (ET, surface runoff, soil water storage and how water partitioning responds to climate change and afforestation over time).

5 Conclusions

This paper presents a study in South Africa comparing T, estimated ET and tree growth of *P. elliottii* and *GN*, which are the second and fourth most planted species by the commercial forestry industry in South Africa, respectively. *P. elliottii* T and
345   estimated ET were significantly higher than *GN* in 2019' 20 season with similar trends for LAI and Dq, while 2020' 21 showed statistically similar T and ET by both crops. These results contrast with some previous pine and eucalypts comparative studies conducted in South Africa and internationally, which reported that *Eucalyptus* species are heavy water users compared to pine. In our study, the lower water use of *GN* was most likely due to extreme soil water deficit (even during summer) and inaccessible groundwater resources. We conclude that on sites with limited water availability, water use (ET and T) between pine and
350   *Eucalyptus* species may not be apparent. However, in subtropical regions (where water is not limiting), *Eucalyptus* species water use has the potential to exceed pine. This was observed in this study, where, after a high rainfall event, *GN* T exceeded *P. elliottii*, decreasing thereafter as soil water got depleted within the profile. However, it is important to note that the ET values in this study were calculated from I and E_s estimates based on the published data and it would be beneficial to continue this study with confirmed measurements of total soil water balance over a long-term for results verification. A good linear
355   relationship observed between T vs LAI and T vs *PAW* at the soil surface, may be useful in future modelling studies where T could be estimated at a wide scale through rapid assessment of LAI.

6 Data availability

Due to the high-frequency data used for this paper, all data with linked figures and tables have been uploaded to the central database at the Centre for Water Resources Research (CWRR) at the University of KwaZulu-Natal in Pietermaritzburg. The
360   author, Nkosinathi David Kaptein, can be contacted for these data at kapteinnd@gmail.com.

7 Author contribution

MLT and ADC were responsible for funding acquisition, resources and project administration. MLT, ADC and CSE conceptualised the study and conceived the methodology. NDK was a student who collected the data, analysed, interpreted, and wrote the original draft of the paper. ADC, MLT, CSE, SBD and IG provided student supervision, discussed the results,
365   and contributed to the final version of the paper.

8 Competing interests

The contact author has declared that none of the authors has any competing interests.

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Figure 1. Location of the study area next to Two Streams Research catchment. The © Google Earth Pro extract (above) provides location of the two study sites, *E. grandis* x *E. nitens* (*GN*), *Pinus elliottii* and the automatic weather station.
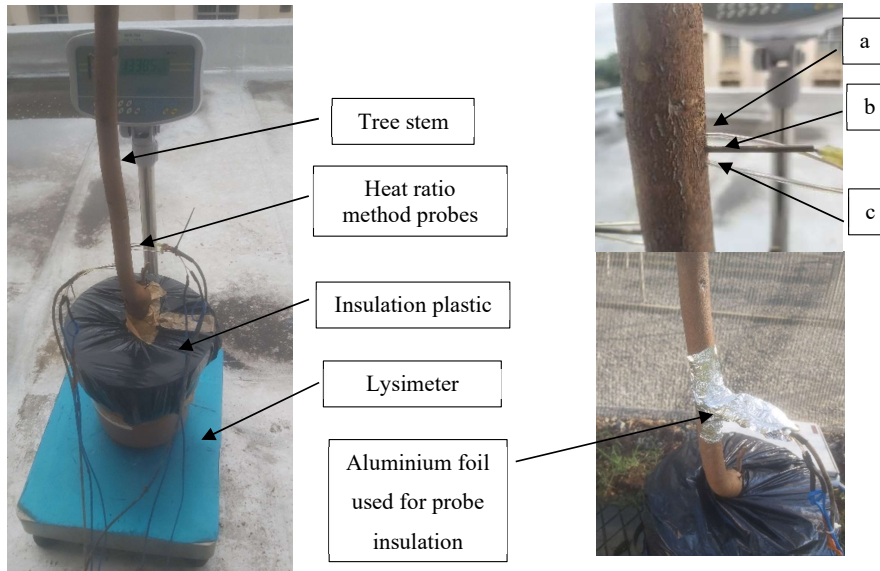
Figure 2. An illustration of a calibration experiment setup showing a tree installed with the heat ratio probes, placed in a lysimeter. Insert: a= downstream probe, b= heater probe, c= upstream probe with aluminium foil used for insulation.

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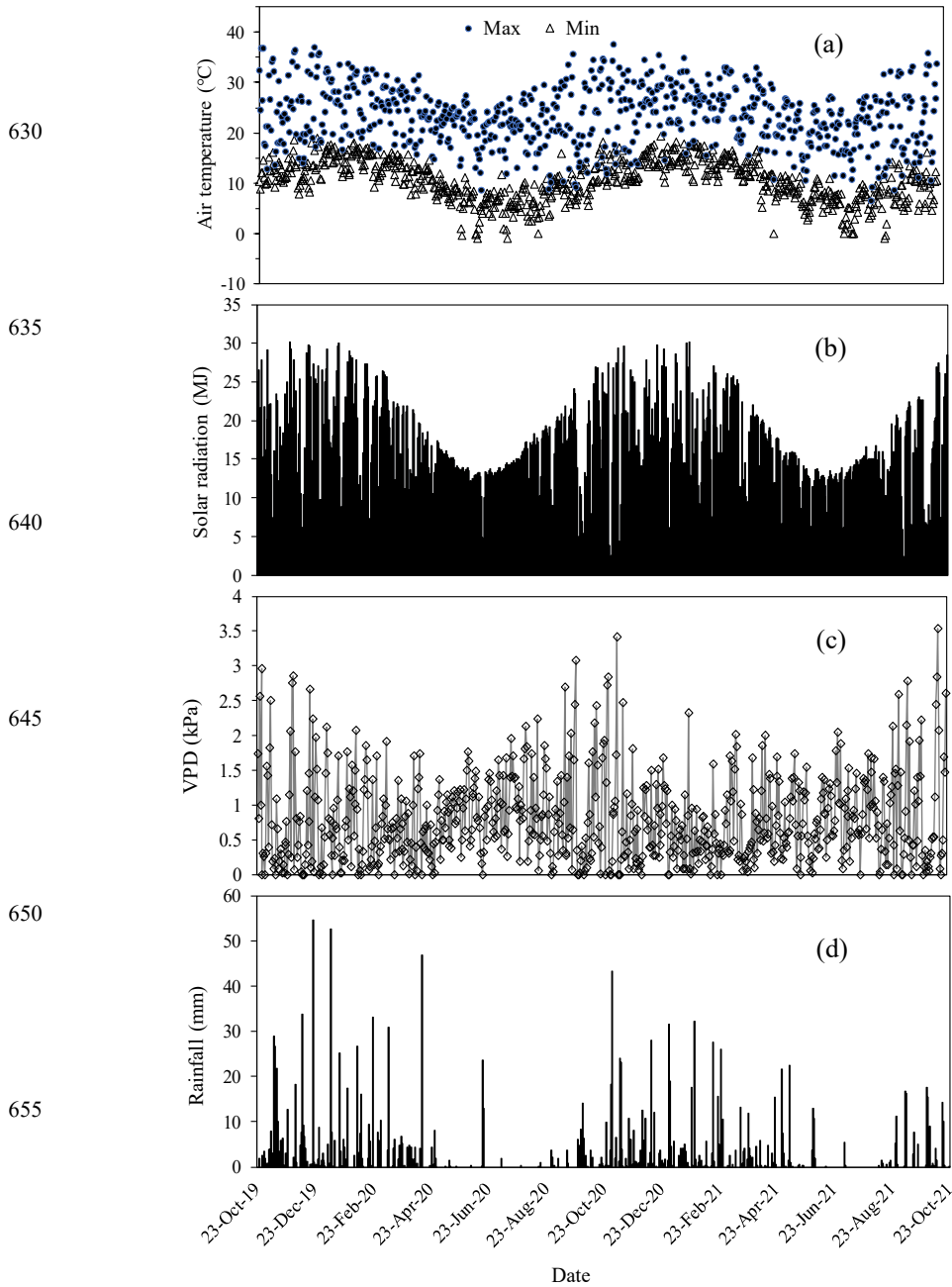


Figure 3. (a) the daily minimum (Min) and maximum (Max) air temperature (°C) (b) daily total solar irradiance (MJ) (c) daily mean vapour pressure deficit (VPD, kPa) and (d) total daily rainfall (mm) for a duration October 2019 to October 2021.

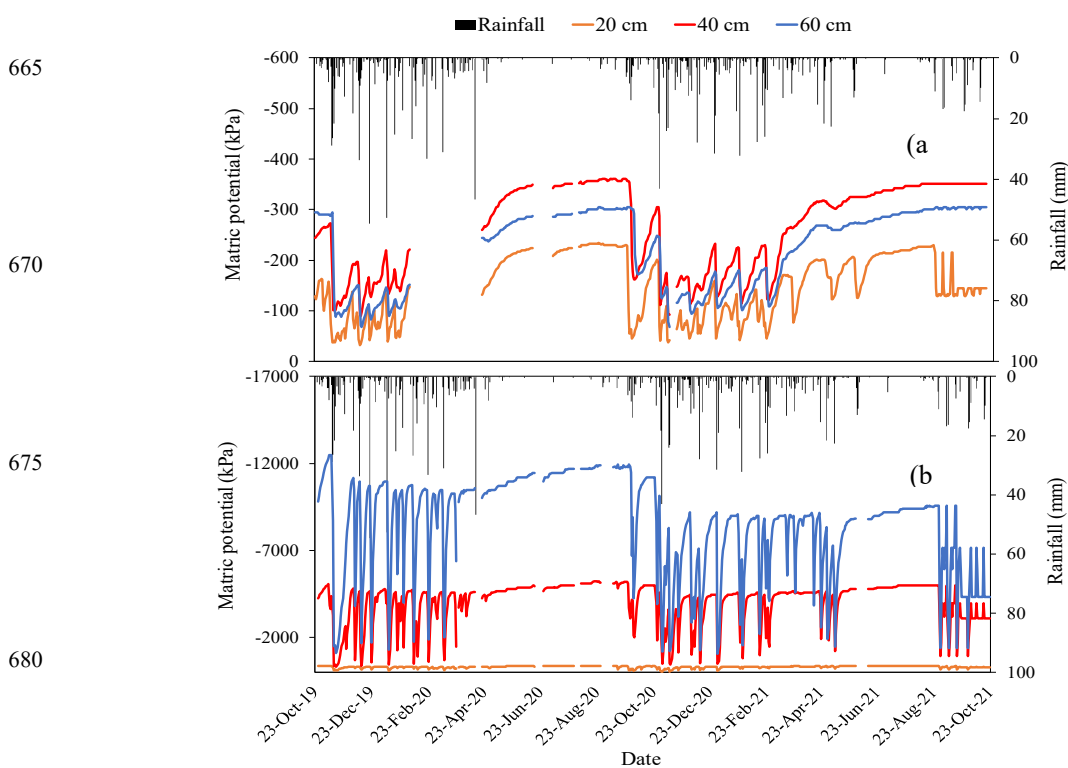



Figure 4. Dynamics of plant available soil water (matric potential) at various depths in the root zone of (a) *Pinus elliottii* and (b) *E. grandis* x *E. nitens* clonal hybrid in response to rainfall events during the period October 2019 to October 2021. A gap in graphs indicates a missing data.

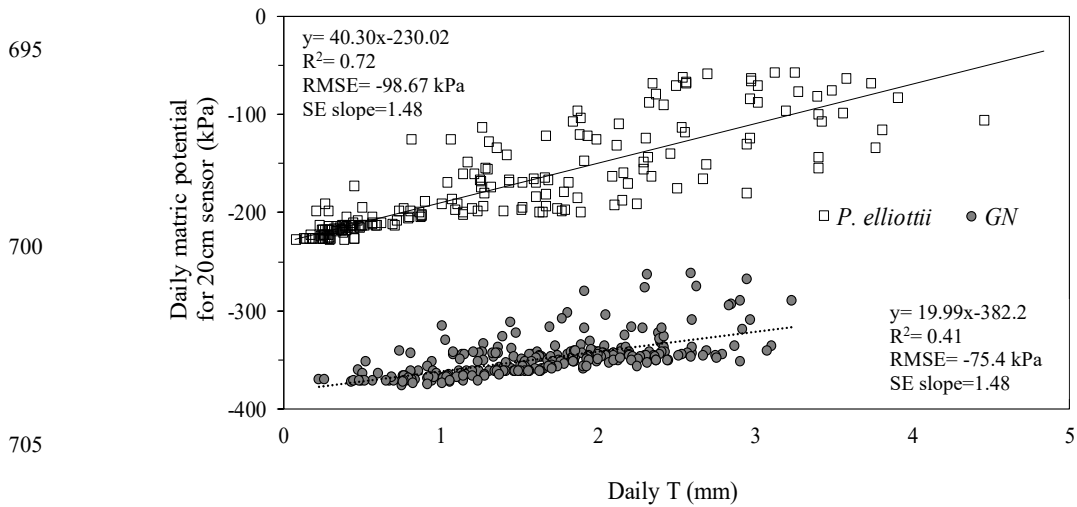



Figure 5. Relationship between daily transpiration (T, mm) and daily 20 cm matric potential sensor (kPa) for *Pinus elliottii* and *E. grandis* x *E. nitens* clonal hybrid (*GN*). The equation of the regression line, regression coefficient (R^2), root mean square error (RMSE) and the standard error of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

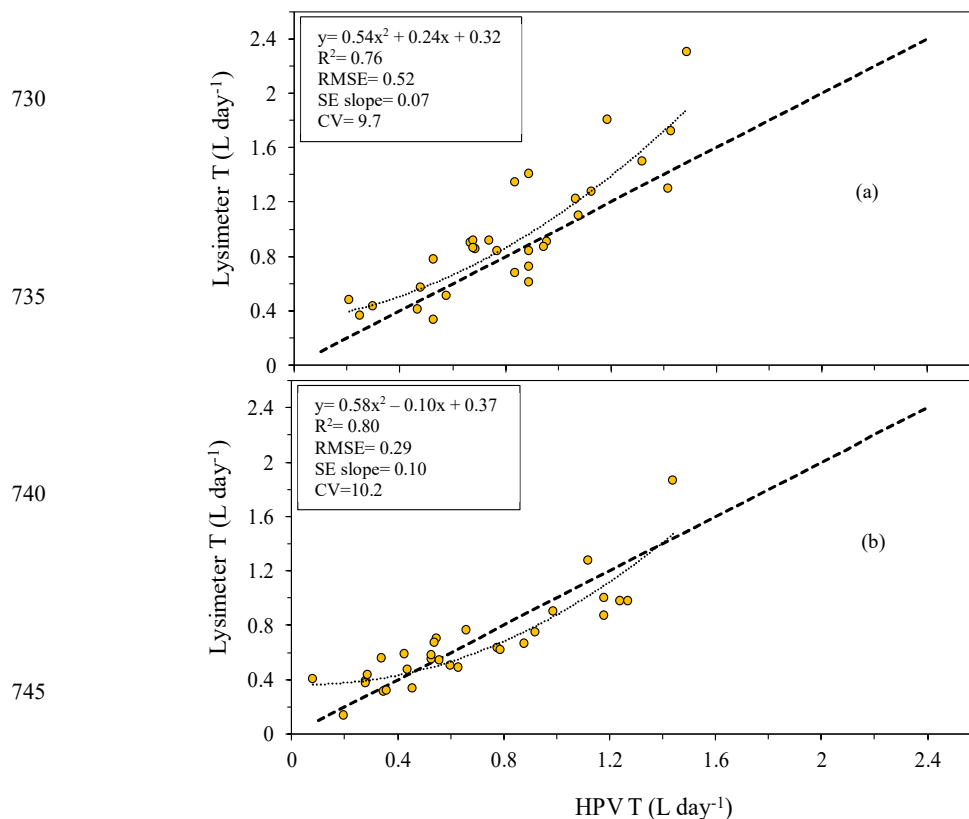
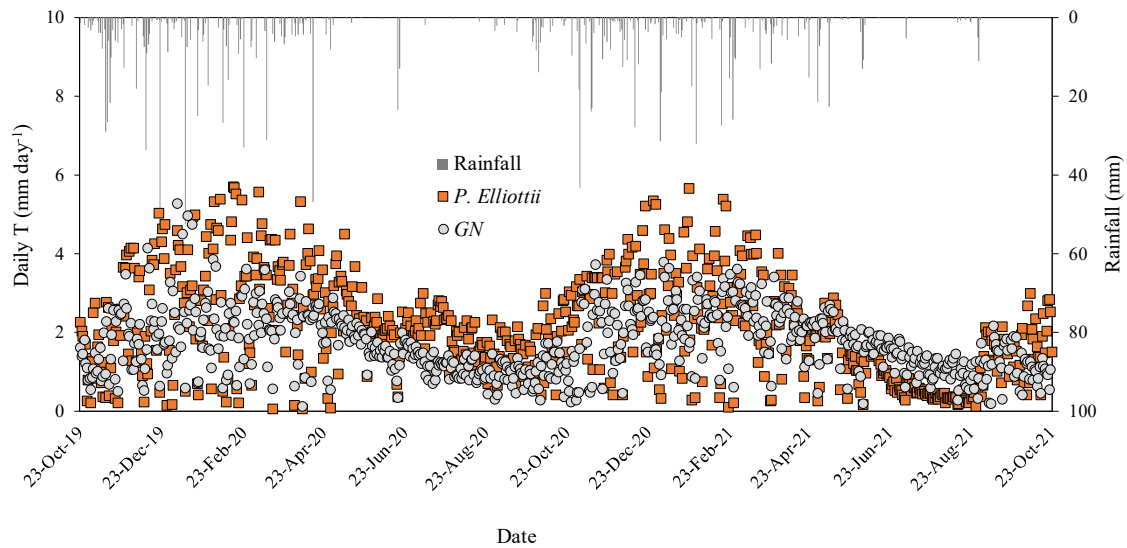



Figure 6. Relationship between daily transpiration (T) measured using a heat ratio technique (HPV, L day^{-1}) and the T measured using a lysimeter (through a change in mass, L day^{-1}) for (a) two-year-old *Eucalyptus grandis* x *Eucalyptus nitens* clonal hybrid and (b) three-year-old *Pinus elliottii*. The equation of the regression line, regression coefficient (R^2), root mean square error (RMSE), standard error of the regression slope (SE slope) and coefficient of variation (CV) for each specie is presented. The dashed line is the 1:1 line.

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

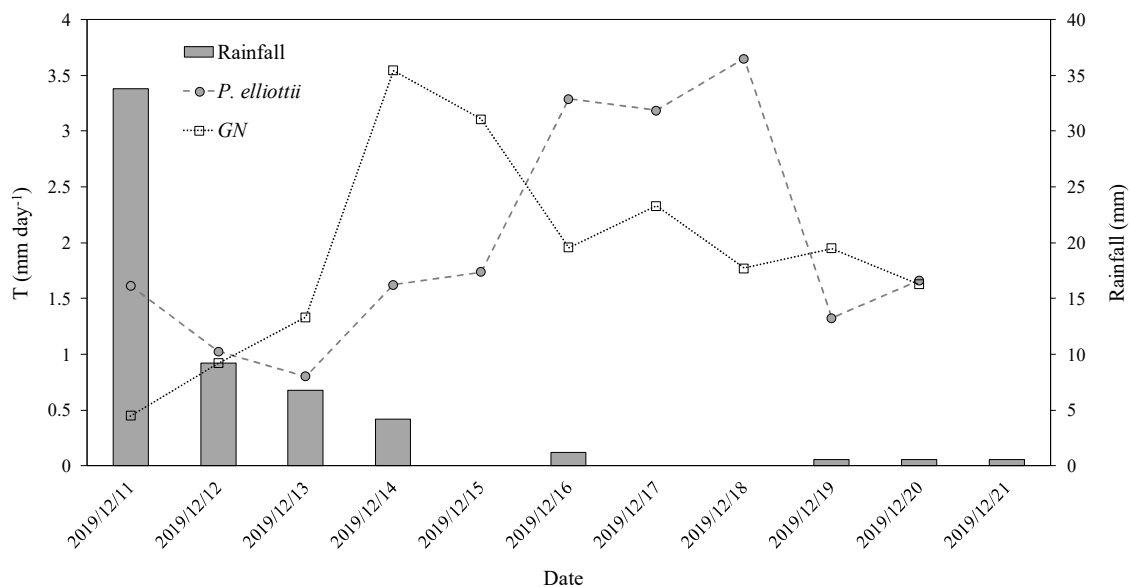



Figure 8. Ten-day daily transpiration (T, mm day^{-1}) for 20-year-old *P. elliottii* and 8-year-old *Eucalyptus grandis* x *Eucalyptus nitens* clonal hybrid (*GN*) with corresponding rainfall (mm) showing T response by each specie to rainfall.

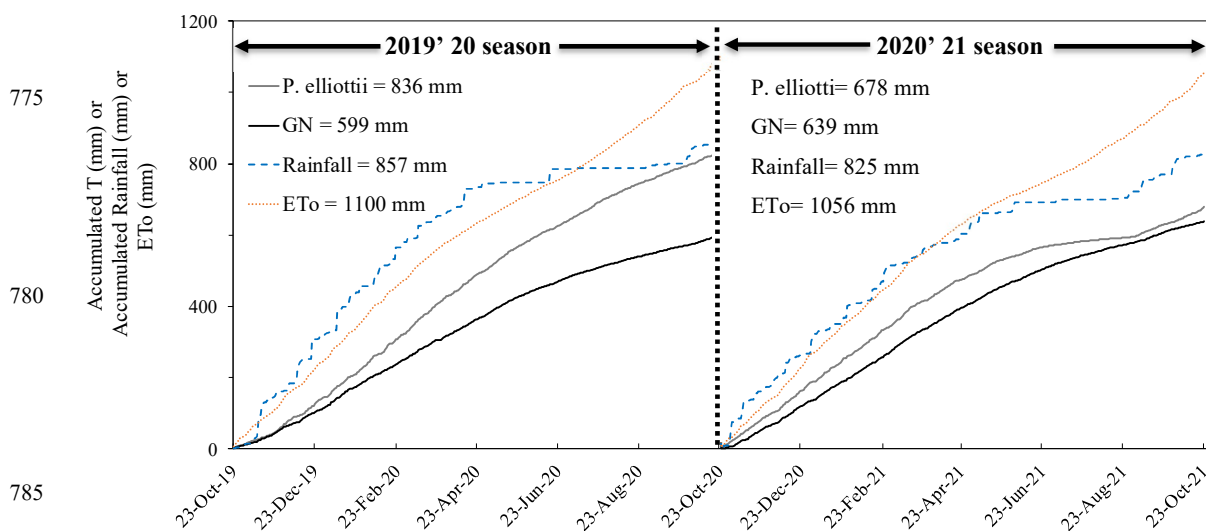
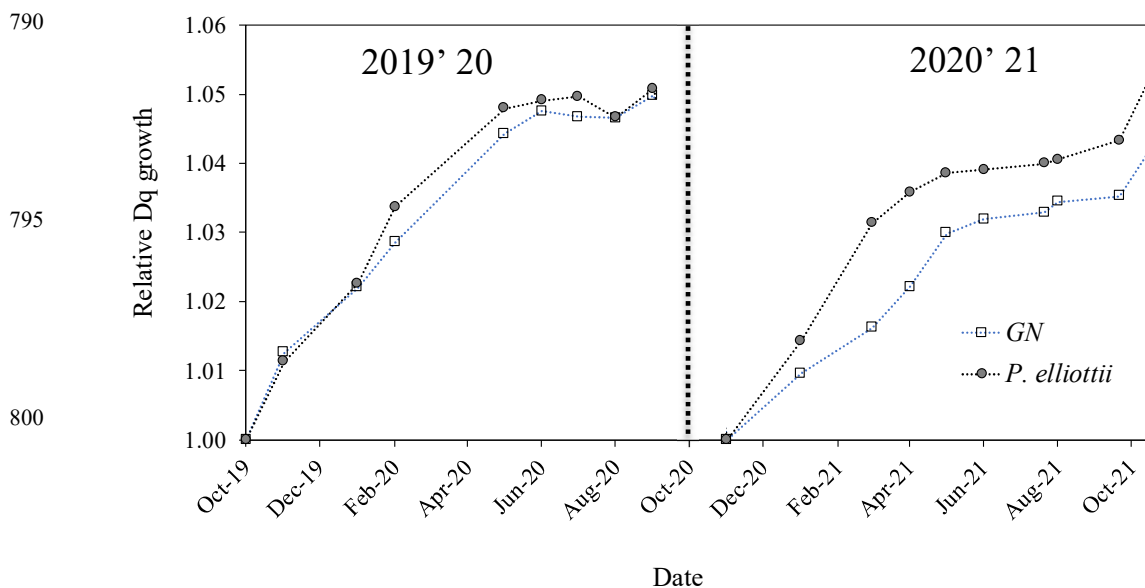



Figure 9. The accumulated transpiration (T, mm), rainfall (mm) and FAO reference evaporation (ETo, mm) for 2019' 20 season (Oct 2019 to Oct 2020) and 2020' 21 season (Oct 2020 to Oct 2021).

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

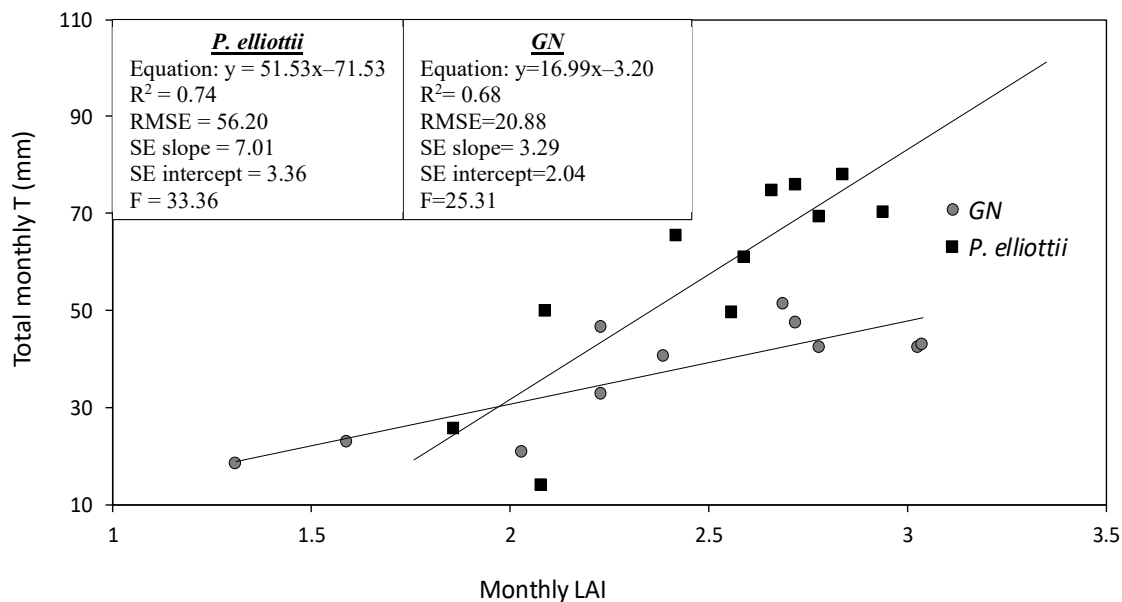



Figure 11. A linear relationship between total monthly transpiration (T, mm) and monthly measured leaf area index (LAI) for *E. grandis* x *E. nitens* clonal hybrid (*GN*) and *P. elliottii*. The equation of the regression line, regression coefficient (R^2), root mean square error (RMSE), the standard error of the regression slope (SE slope), the standard error of the y- intercept (SE intercept) and the ratio of variance (F) for each specie is presented.

Table 1. The general characteristics of the two study sites at Mistley Canema. The abbreviations MAP and MAT denotes mean annual precipitation and mean annual temperature, respectively.

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

Table 2. Detailed description of trees monitored on *Pinus elliottii* and *E. grandis* x *E. nitens* clonal hybrid (*GN*) study sites.

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

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Table 3. Statistical significance (*p*-values derived ANOVA tests) of the *Eucalyptus grandis* x *E. nitens* (*GN*) *and Pinus elliottii* hourly mean transpiration over 2019' 20 and 2020' 21 season (summer = November to February and winter = June to July) versus the mean hourly climatic variables (I_s= solar radiation, VPD=vapour pressure deficit, RH=relative humidity, WS=wind speed and Tair=air temperature). Statistically significant ($p < 0.05$) values are shown in bold type.

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

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