Forest Ecology and Management 466 (2020) 118149

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

# Stocking effects on seasonal tree transpiration and ecosystem water balance in a fast-growing *Eucalyptus* plantation in Brazil

Rodrigo Eiji Hakamada[a,*], Robert M. Hubbard[b], Jose Luiz Stape[c], Walter de Paula Lima[d], Gabriela Gonçalves Moreira[d], Silvio Frosini de Barros Ferraz[d]

[a] *Department of Forest Science, Federal Rural University of Pernambuco, Recife, PE 51.020-240, Brazil*
[b] *USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO 80526, United States*
[c] *UNESP-FCA, Botucatu, SP CEP 18.610-300, Brazil*
[d] *Department of Forest Sciences, University of São Paulo, Piracicaba, SP 13.400-000, Brazil*

ARTICLE INFO

*Keywords:*
Tree spacing
Water use
Planted forests
Planting density
Canopy interception
Soil evaporation

ABSTRACT

High stocking short rotation plantations provide high yields for bioenergy use and have been adopted worldwide, especially in tropical areas. This silvicultural approach might alter ecosystem water balances compared with lower stocking, longer rotation practices. The sensitivity of water balance to stocking might also differ among genotypes. We evaluated the primary components of ecosystem water balance (transpiration - $E_t$, canopy interception - $E_i$, soil evaporation – $E_s$) for two hybrid clones that differ in drought tolerance and productivity (*E. urophylla* × *E. grandis*, Clone B2 and *E.grandis* × *E.camaldulensis,* Clone C3) planted in stockings ranging from 590 to 2,950 tree ha.$^{-1}$ in a tropical region in Brazil. On a monthly time step, all water balance components of the two clones were largely related to the seasonality of rainfall, where the wet season represented 73% of the total rainfall, these processes corresponded on average to 76, 75, 67 and 70% of annual canopy interception, soil evaporation, transpiration and evapotranspiration (*ET*), respectively. For both clones, temperature ($R^2 = 0.32$) and precipitation ($R^2 > 0.76$) explained evapotranspiration responses while adding stocking as a second independent variable slightly improving the model for clone B2 but no improvement was detected for clone C3. When scaling up the monthly data to yearly analyses, all water balance components responded strongly to tree stocking for both clones during the two years of measurements (1.7 to 3.7 years-old). Annual transpiration rose linearly with stocking for the clone B2, rising from 550 mm yr$^{-1}$ up to 1,039 mm yr$^{-1}$, corresponding to 53–100% of precipitation (P). The clone C3 showed a much weaker influence of stocking on transpiration, rising only from 550 mm yr$^{-1}$ at low stocking to 650 mm yr$^{-1}$ at high stocking (53–63% of P). Canopy interception rose from about 230 mm yr$^{-1}$ at low stocking to 300 mm yr$^{-1}$ at high stocking, with little difference between the clones, ranging from 21 to 30% of P. Evaporation from the soil decreased with increased stocking for both clones and represented an average of 20–12% of P from lowest to highest stocking. Total evapotranspiration (*ET* – sum of $E_t$, $E_i$ and $E_s$) was about 1,000 to 1,050 mm yr$^{-1}$ at low-to-moderate stockings of both clones, but the less-drought tolerant clone B2 showed substantially higher total evapotranspiration at high stocking (2,900 mm yr$^{-1}$) compared to the clone C3 (2300 mm yr$^{-1}$). The difference between precipitation and evapotranspiration (the overall ecosystem water balance) declined with increasing stocking, dropping below 0 at stockings higher than 1,030 tree ha$^{-1}$ for both clones. High stocking in highly productive *Eucalyptus* plantations may be less sustainable across multiple rotations, since any deficit in the ecosystem water balance would need to come from longer-term soil water storage. Our results indicate that both genetics and tree stocking can be used as silviculture tools to manage the sustainably of short rotation forest plantations in the face of climate change.

## 1. Introduction

Over the last 25 years, planted forest area in the tropics increased at an average rate of 2.5% per year, reaching approximately 56 million ha (Payn et al. 2015). *Eucalyptus* plantations are one of the most commonly planted species because wood productivity of these forests can exceed 50 m$^3$ ha$^{-1}$ yr$^{-1}$ (Stape et al. 2010, Gonçalves et al., 2013). The high growth rates of forest plantations are the result of research and

---

* Corresponding author.
*E-mail address:* rodrigo.hakamada@ufrpe.br (R.E. Hakamada).

https://doi.org/10.1016/j.foreco.2020.118149
Received 23 March 2020; Received in revised form 3 April 2020; Accepted 7 April 2020

development in silviculture and genetic improvement, that often yields up to a 10-fold increase in volume compared to that obtained by non-plantation forests (Oliveira et al. 2002, Payn et al. 2015, Binkley et al., 2020).

Silvicultural practices including high stocking, short-rotation plantations (e.g., > 3,000 tree $\text{ha}^{-1}$ with harvesting scheduled each 3–4 years) are becoming popular for bioenergy production in the tropics as these systems have been found to produce the same amount of wood biomass in a shorter period of time (Guerra et al., 2014; Eufrade Junior et al., 2016). The implications for ecosystem water balance (EWB) could be important (Whitehead and Beadle, 2004) if these silvicultural systems have higher evapotranspiration than precipitation leading to a long-term decrease in water reserves (Calder et al., 1997, Mendham et al., 2011).

Many forest management decisions have been proven to affect ecosystem water balance from a landscape management perspective, such as the percentage of the landscape coverage by plantations (Ferraz et al., 2019) or the modification of harvesting age (Cornish and Vertessy, 2001, Forrester et al., 2010), to the stand silvicultural prescription, as the stocking or the number of trees per area. Stocking affects water relations from tissue components (Forrester, 2015) to watershed scale (Attia et al., 2019), normally with increasing number of trees in planted forests increasing the water use of the stand (Forrester, 2015). The majority of studies, including non-tropical regions, have studied the effect of stockinǵs influence on water balance through thinning (White et al., 2014, Tsamir et al., 2019), and a few studies control stocking by varying planting spacing (Leite et al., 1999). Remaining trees after thinning differ in many physiological aspects compared to unthinned population, such as transpiration, stem resistance to water transport and leaf area (Whitehead et al., 1984).

High leaf area (often $> 5\ \text{m}^2\ \text{m}^{-2}$) in *Eucalyptus* plantations (Giunti Neto et al., 2015) may lead to both high transpiration rates in trees, and high interception loss of rain retained on leaf surfaces (Benyon and Doody, 2015, Bialkowski and Buttle, 2015). High water use might lead to high vulnerability to water stresses, especially during droughts (McDowell, et al. 2008, White et al. 2009, Allen, et al. 2015, Hakamada et al. 2017) or when Eucalypts are planted on drier sites (Ferraz et al., 2019).

Stocking influences ecosystem water balance (Whitehead et al., 1984, Bréda et al., 1995, Forrester et al., 2012) and Eucalypt species differ in transpiration rates (White et al., 2002; Mugunga et al., 2015). As part of the TECHS Project (Binkley et al. 2017), our aim was to quantify the influence of stocking on ecosystem water balance components for two high-productivity *Eucalyptus* clones growing in a tropical area of Brazil. We selected two hybrids with distinct water stress tolerances; a drought sensitive hybrid of *Eucalyptus grandis* and *E. urophylla* (Clone B2), and a drought tolerant hybrid of *E.grandis* × *E.camaldulensis (*Clone C3) (Gonçalves et al., 2013), and measured key components of evapotranspiration (Table 1) during two hydrological years in the period of peak of tree growth (1.7–3.7 years). We hypothesized that:

i) Evapotranspiration increases with stocking, particularly in the wet season, explained by the tight relationship between rainfall and water use by trees and
ii) The increase in evapotranspiration with stocking will be greater for the drought sensitive clone B2 because of its lower sensitivity of stomatal conductance to water deficit.

**Table 1**
Abbreviations for water balance variables used in this paper.

| Variable | Abbreviation |
|---|---|
| Transpiration (stand scale) | $E_t$ |
| Soil evaporation | $E_s$ |
| Canopy Interception | $E_i$ |
| Precipitation | *P* |
| Throughfall | *TF* |
| Evapotranspiration | *ET* |
| Potential evapotranspiration | *PET* |
| Stemflow | *SF* |
| Ecosystem water balance | *EWB* |

## 2. Materials and methods

### 2.1. Site description

Our study was conducted in an experimental plantation that was planted on 02/21/2012 in Mogi Guacu, state of São Paulo, Brazil (22°20́58́S and 46°58′16́W), at an altitude of 664 m. Local climate (Fig. 1) is humid mesothermal according to Koppen's classification. Mean annual temperature is 22 °C, and mean annual precipitation is 1,200 mm, with 120 rainy days, mostly (82%) concentrated in summer (October to March). Potential evapotranspiration (*PET*) averages 1,170 mm, similar to the *PET* observed during the two hydrological years of our study (1,140 and 1,110 mm). The average aridity index (AI = *PET*/*P*; (Budyko, 1974)), in the region is 0.81, however, during our study, it reached 1.48 and 0.91 during the first and second year respectively. The region typically experiences an annual water deficit of 50 mm, with a soil water storage capacity of 150 mm (Demattê, 2000). The soil in the experimental area is characterized as red oxisol, with a clay content of 39% and a pH in water of 4.3. The soil is very deep, with an effective depth on the order of 20 m.

### 2.2. Experimental design

We took advantage of the TECHS project (Binkley et al., 2017, http://www.ipef.br/techs/en/) experimental design. Each of the plots in the stocking experiment was 0.38 ha, and trees were planted at 3-m intervals within rows, but with a gradient of distances between rows (Fig. 2). This design allowed us to have a wide range of stockings and different genotypes in a relatively small area. We evaluated water balance components at four stockings with 14 trees per plot, and eight of these trees in each plot were selected for sapflow measurements. The four stockings were 2950, 1420, 1030 and 590 trees $\text{ha}^{-1}$ (Fig. 2).

Our unit of observation was the individual tree for evaluating the response of water balance components with increasing stocking. Even though neighboring trees are not spatially independent, they provide a fair estimate of water balance components because any interaction between trees is competitive, leading to increased (rather than decreased) variation in physiology. The design also encompasses realistic competitive interactions that happen in operational plantations. Our experimental site is uniform, but slight differences in soils might have some influence on water balance components; however, the 4-fold range in stocking is likely a much stronger factor on water balance components than any minor variation in soils.

We measured two genotypes differing in drought sensitivity. The clone B2 is a hybrid of *E. urophylla* × *E. grandis* and is drought sensitive (Gonçalves et al., 2013) and the clone C3 (*E.grandis* × *E.camaldulensis*) is more drought tolerant; both differed in canopy structure and leaf area index (Fig. 3). The site was prepared by subsoiling at a depth of 0.60 m, followed by planting operation in February 2012. The level of fertilization was defined to eliminate any nutritional limitation to growth with the use of 70 kg N $\text{ha}^{-1}$, 110 kg P $\text{ha}^{-1}$, and 160 kg K $\text{ha}^{-1}$. Ant control was performed prior to planting and every year afterwards with 0.3% sulfluramide. Weeds were prevented with Glyphosate at 2.88 kg active ingredient $\text{ha}^{-1}$, so, the site was kept without any vegetation but the *Eucalyptus* trees. The entire test site was maintained pest and disease free through visual inspection since saplings were planted and sapling survival was 100%.

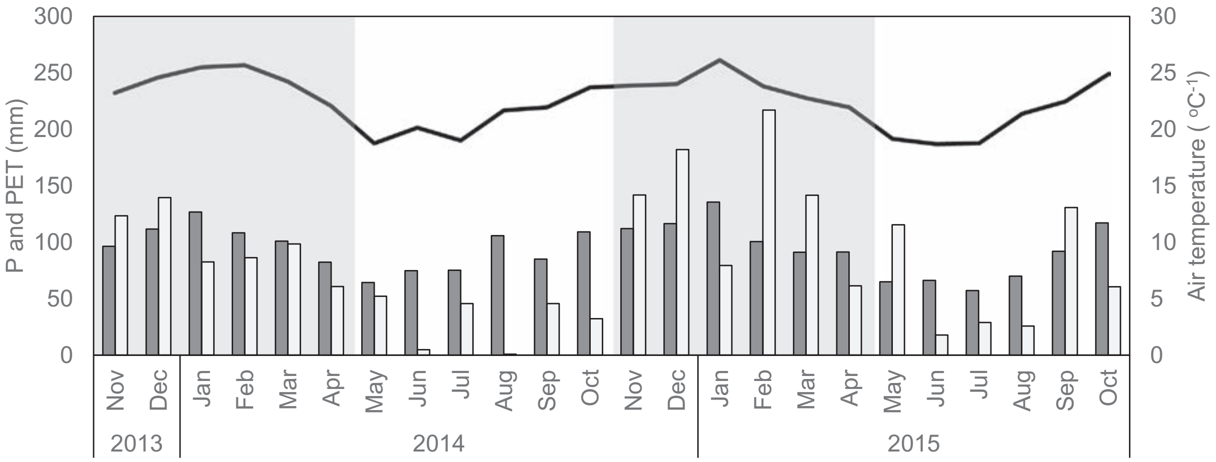

**Fig. 1.** Precipitation (*P*) (light bar), potential evapotranspiration (*PET*) (dark bar) determined by the Penman-Monteith method and air temperature (line) during the 2-year period from November 2013 to October 2015, measured in a weather station 500 m far from the experiment. Grey strips represent wet season that accounted for 73% of precipitation.

## 3. Individual (*tree transpiration*) and stand transpiration ($E_t$) measurements

We used 20 mm Granier-style heat dissipation probes (Granier, 1987) to quantify tree transpiration on 64 individual trees (eight trees × four stockings × two clones) for 24 months, from November 2013 to October 2015, when trees were between 1.7 and 3.7 years old. Data were collected every 15 s, and 15-minute averages recorded via a multiplexer coupled to a data logger (CR1000 and AM 16/32, Campbell Scientific, Inc., Logan, UT). Probes were positioned at each cardinal direction (north, south, east, and west), and the sensors were moved 90° clockwise every three months to minimize differences in circumference over the time span of the experiment (Grime and Sinclair, 1999). Probes were insulated using styrofoam and foil-backed insulation, with transparent plastic bags around the insulation to protect from moisture and stemflow. Sapflow density was calculated using the standard Granier equation (Granier, 1987) but with coefficients derived from a specific *Eucalyptus* calibration (Hubbard et al., 2010). We estimated sapwood area for the measurement trees using allometric equations based on diameter at breast height. For these equations, 15 trees were harvested (of each clone) from the adjacent site with identical stockings. Thin (10–15 mm) disks were cut at breast height and conducting sapwood area was estimated visually by measuring four equally opposed radii of the obvious translucent portion of the disk and calculating area as an ellipse (for details see Otto et al., 2014). Sapwood area in relation to DBH was estimated by power models for each genotype (sapwood = a + b*DBH, $r^2 > 0.78$). Transpiration per tree (L $tree^{-1}$) was estimated as the product of sapflow density and sapwood area. Sapwood thickness averaged between 19 and 22 mm so we expect the sap velocity measured by the probes was representative of the entire sapwood area. Stand transpiration (mm $ha^{-1}$) was estimated using the sum of values for the eight trees per plot.

## 4. Ecosystem water balance (*EWB*)

Solar radiation, temperature, relative humidity, precipitation and wind velocity data were obtained every 5 min from an automated weather station 1 km from the test site. These data were stored every hour using a Campbell CR1000® datalogger.

All water balance components are shown in table 1. *P* was measured

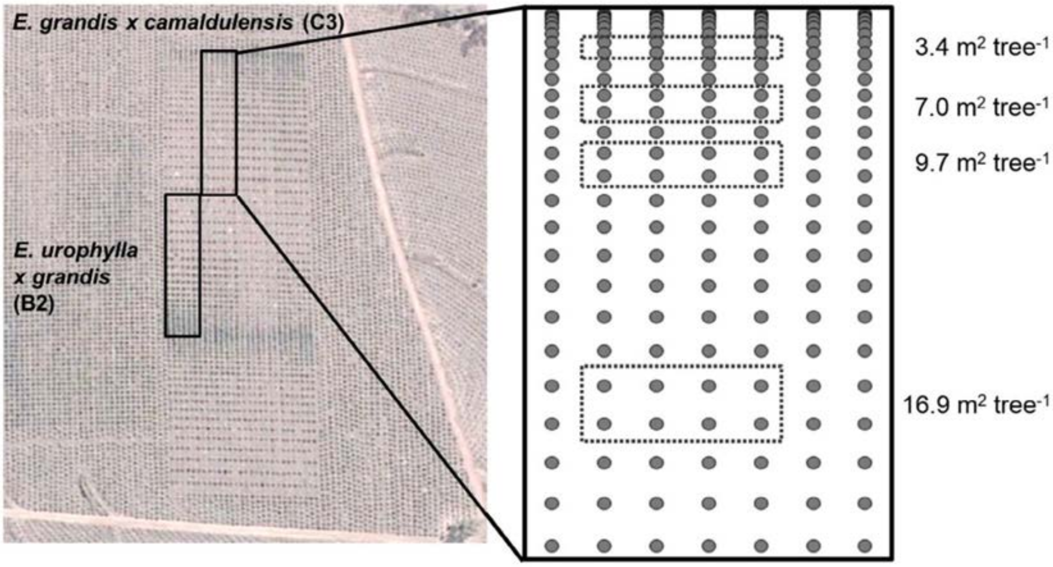

**Fig. 2.** Test site. Left: Photographic image obtained from Google Earth® when trees were 12 months old, solid squares show the location of the two genotypes used in the study. Right: diagram showing the increasing spacing between trees and the plots with different spacings per tree (590, 1030, 1420 and 2950 tree $ha^{-1}$).

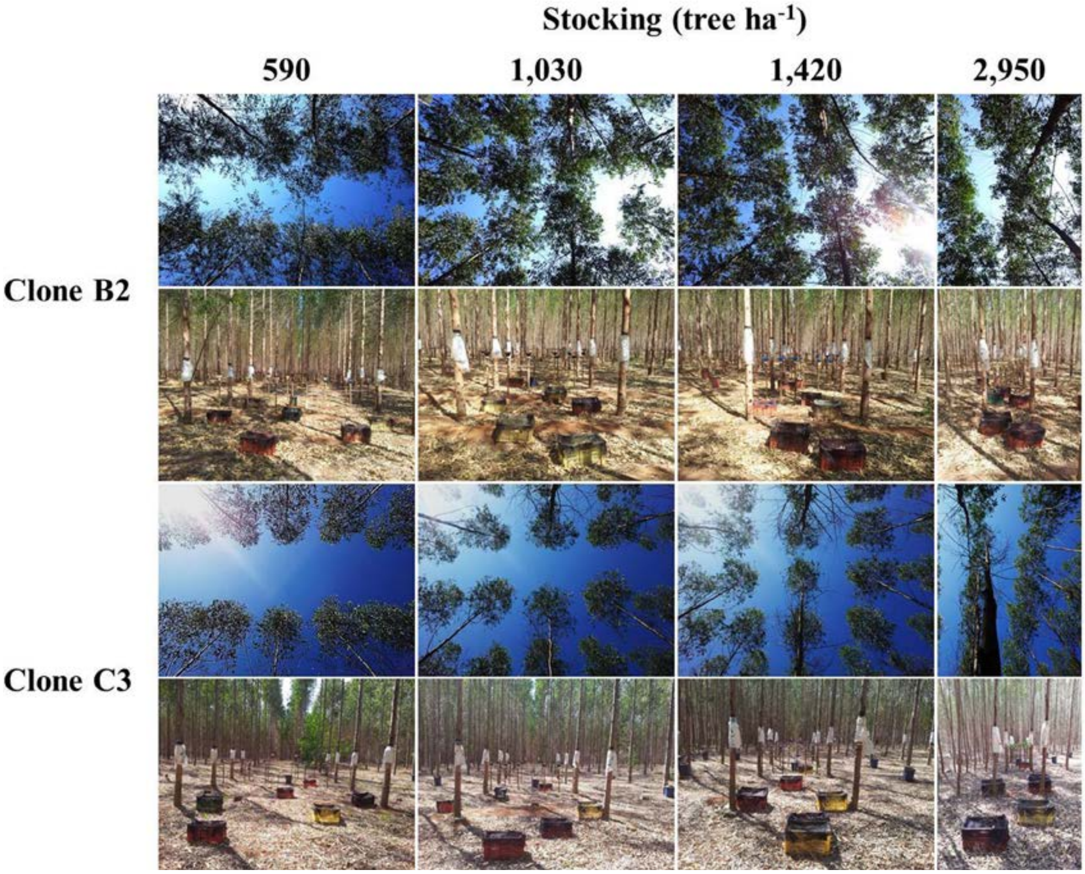

**Fig. 3.** General view of the field experiment, showing clone B2 increasing light interception with increasing stocking at age 3.7, with a higher leaf area index than clone C3 (bottom).

with 12 funnel collectors with an area of 0.026 $m^2$ (0.183 m in diameter) in an open area within 50 m of the plots. *TF*, i.e., the difference between the precipitation outside and inside the canopy, was obtained by placing 12 collectors at each stocking for each clone. Water collected by the 12 funnels in each plot was directed to a reservoir tank and was measured after each precipitation event $>$ 2 mm using a balance. Collectors were distributed across representative areas below the canopies, including within and between rows. An additional group of 12 collectors was installed in an open area adjacent to the research plots.

Soil water evaporation ($E_s$) was estimated according to White et al. (2002). From January to October 2014 and from May to October 2015, when *PET*, estimated using the Penman-Monteith equation (Allen et al., 1998) exceeded precipitation, we assumed a value for $E_s$ of 0.01 mm $h^{-1}$ for 10 h $day^{-1}$. This was the lowest value in a study of $E_s$ from dry soil according to a study in similar latitude by Leuning et al. (1994). When precipitation exceeded potential evapotranspiration, from November to December of 2013 and from November 2014 to April 2015, we used:

$$E_s = E_{eq} = \frac{\Delta}{\Delta + \gamma} R_s \tag{1}$$

where:

$E_s$ = soil water evaporation = $E_{eq}$ = equilibrium evaporation;

$\Delta$ = slope of the relation between saturated vapor pressure and temperature;

$\gamma$ = psychrometric constant;

$R_s$ = net radiation below the canopy (MJ $m^{-2}$).

The slope of the relationship between saturated vapor pressure and temperature was calculated according to Murray (1967), and the psychrometric constant was determined by FAO method (Allen et al., 1998). Net radiation was measured hourly and to estimate the net radiation below canopy, we used the average percentage of radiation measured by a ceptometer below the canopy compared to the open field measurement for each clone and each stocking. Measurements were done every three months and values were interpolated.

Stemflow was estimated with a water-collection system installed on six trees per plot. Water from these stems was weighed on balance at the same time as throughfall measurements. We used the ground area occupied by each tree to extrapolate to a hectare basis. Canopy interception ($E_i$) was calculated with Eq. (2):

$$E_i = P - (TF + SF) \tag{2}$$

Evapotranspiration (*ET*) was calculated as:

$$ET = E_t + E_i + E_s \tag{3}$$

Ecosystem water balance (*EWB*) for each stocking and clone was calculated as proposed by Lee (1980) as:

$$EWB = P - ET \tag{4}$$

Surface runoff was unimportant at this site (slope $<$ 1%). The evaporation from understory was also irrelevant, because the experiment was kept weed free for the duration of our measurements.

### 4.1. Leaf area index

Leaf area index (LAI) was estimated using Beer's law assuming a light extinction coefficient of 0.5 (Almeida et al., 2004), and the difference between photosynthetically active radiation (PAR) values measured outside the forest (simulating a measurement above the canopy) and below the canopy.

We measured PAR in each stocking nine times between November 2013 and October 2015 (approximately every 3 months) using a ceptometer (Decagon Devices Inc., Pullman, WA, USA). Measurements were performed in two transects per plot, with 16 measurements per transect. After measurement in each plot, PAR was measured outside the forest. Measurements were conducted between 11:30 and 13:00 on clear days with no clouds or wind.

### 4.2. Statistical analysis

Results were analyzed at a monthly and yearly time step. The independent variables leaf area index, stemflow, soil evaporation, canopy interception, transpiration, evapotranspiration and ecosystem water balance were correlated to the dependent variable, stocking, through linear and non-linear models. Models were considered significant at $\alpha < 0.05$ and were selected with parsimony based on the least AIC and highest coefficient of determination using CurveExpert version 2.6 (http://www.curveexpert.net/). We evaluated the normality and homogeneity of variance in all models. We tested if models of the two clones differed from each other based on a test of identity as proposed by Leite and Oliveira (2006) where each tree was a unit of observation. However, as a conservative measure, we also analyzed the effect of stocking by pooling all eight trees at each stocking into a single average, giving four observations for testing the effect of stocking. The average trend would be the same in this analysis, but the reduction in degrees of freedom gives a far more conservative test of the effects of stocking than in our basic design that used each tree as a unit of observation. Our plots had 100% survival, promoting uniformity in size of neighboring trees. All the analysis were conducted in Sigma Plot (Systat Software, San Jose, CA, USA) and using an Excel spreadsheet for the test of identity.

Although the individual tree was our sampling unit, our study only assessed water balance components at one site. To support our assumption that results from this site would be relevant to other TECHS sites across Brazil, we examined volume growth for the two clones in this study across all TECHS sites. We reasoned that because of the strong positive relationship between leaf area, water use and growth, changes in tree volume with stocking would support findings from this study.

## 5. Results

### 5.1. Monthly results

All water balance components of the two clones were largely related to the seasonal weather. Water balance components during the wet season averaged 73, 75, 76, 67 and 70% of annual precipitation, canopy interception, soil evaporation, transpiration and evapotranspiration, respectively (Fig. 4A to 4H) (Table S1). Cumulative ecosystem water balance (Fig. 4I, J) after the first year of measurement, which had 30% lower precipitation than the historic average, was negative for all stockings for both clones and became more negative with an increase in stocking. During the second hydrological year, where rainfall was much closer to the historical average (only 11% higher), only the highest stocking treatment was negative.

For both clones, temperature increases from 18 to 24 °C increased *ET*, declining from 24 °C to hotter months (Fig. 5A, 5B). The effect of *P* on *ET* was stronger ($R^2 > 0.76$, $P < 0.0001$) (Fig. 5C, 5D) with a linear behavior for clone B2 and sigmoidal for clone C3, with stabilized *ET* after a *P* of 200 mm $\text{month}^{-1}$. Including stocking as a second independent variable slightly improved the model for clone B2, reducing 7 points in AIC and increasing $R^2$ from 0.67 to 0.70 (Table S2), while no improvement was detected for clone C3 when including stocking (Fig. 5E, 5F).

### 5.2. Yearly results

Increased stocking of trees led to increase in stemflow, canopy interception, transpiration and evapotranspiration, along with decreases in soil evaporation and throughfall (Fig. 6). For the clone B2, stemflow increased from 16 to 40 mm $\text{yr}^{-1}$ as stocking increased from 590 tree $\text{ha}^{-1}$ to 2,950 tree $\text{ha}^{-1}$. *SF* was higher in the clone C3, increasing from 24 to 61 mm $\text{yr}^{-1}$ from the lowest to the highest stocking (Fig. 6A). Soil evaporation decreased with increasing stocking in both genotypes, and remained 50% higher in the clone C3 (Fig. 6B). Canopy interception increased with stocking from an average of 452 to 630 mm (Fig. 6C). These values were, on average, 8% greater in the clone B2, probably because of higher LAI (Fig. 9B). Higher stocking resulted in greater transpiration for both clones, with B2 exceeding C3 by 22% (Fig. 6D). *TF* decreased by 13% with increasing stocking from 1605 to 1397 mm (Fig. 6E). The increases in transpiration and stocking resulted in an increase in *ET* (Fig. 6F). Model equations (Table S3) were all significant with high coefficients of correlation, indicating that water use related strongly to stocking.

Fig. 7 compares the values obtained for each variable with the lowest and higher stocking for both clones. For some variables, the lowest and higher stockings were not the absolute lowest or highest value. However, there were significant increase or decrease for all when modeling the yearly results, so the difference of highest and lowest stocking shows the tendency and magnitude of differences. The highest stocking exhibited *ET* values that were 49% greater for B2 (11% greater for C3) than for the lowest stocking. *SF* was a small component of the overall water balance, and it had the largest relative response to stocking, with the highest stocking showing 240% greater *SF* than the lowest stocking. *TF* and soil evaporation were less responsive to stocking.

Evapotranspiration was dominated by the transpiration component (Fig. 8). The components of soil evaporation and canopy interception showed opposite responses to stocking, leading to a relatively constant contribution of the sum of these two for total *ET*. The ecosystem water balance went from positive at stockings below about 1000 trees $\text{ha}^{-1}$ to negative for higher stockings for both clones.

The mean percentage of incoming photosynthetically active radiation (PAR) absorbed by the canopy at midday increased asymptotically with increasing stocking, ranging from 71–82% for clone B2 and from 40 to 66% for clone C3 (Fig. 9A). The average LAI from nine assessment periods was greater at higher stockings for both genotypes (Fig. 9B), varying from 3.2 to 4.2 for B2 and from 1.6 to 2.8 for C3. Even though there is a clear trend of increasing in LAI, for clone B2 from about 1,000 trees $\text{ha}^{-1}$ the absorbed light kept constant, suggesting intercepted irradiance is becoming saturated.

## 6. Discussion

Our first hypothesis was supported as evapotranspiration increased with stocking for both genotypes, particularly in the wet season. There was not a difference of proportion of *ET* accumulated at wet season for different stockings, representing on average of all stockings 72 and 68% for clones B2 and C3. The responses of *ET* to seasonality is variable and has been reported as higher *ET* (O'Grady et al., 1999), no variation during the year (Eamus et al., 2001) and lower *ET* in dry season (Moreaux et al., 2013, Ouyang et al., 2018). *ET* of forest plantations could be influenced by many factors, as atmospheric conditions like air humidity and temperature, the amount of rainfall and soil water storage (Whitehead and Beadle, 2004). In our case, the lower *ET* in the dry season could be attributed to a decline in stomatal conductance caused by higher evaporative demand as measured in the same clones by Otto et al. (2017) and reported for *Eucalyptus* trees by Moreuax et al. (2013). Also, our results could be explained by a tight relationship between rainfall and water use by trees, as shown by Christina et al. (2017) and Christina et al. (2018). These previous studies were done for only one genotype at one stocking (~1,111 trees $\text{ha}^{-1}$), and ours revealed this behavior occurred for all stockings levels. The increase of *ET* when rainfall increases could be explained by many ecophysiological

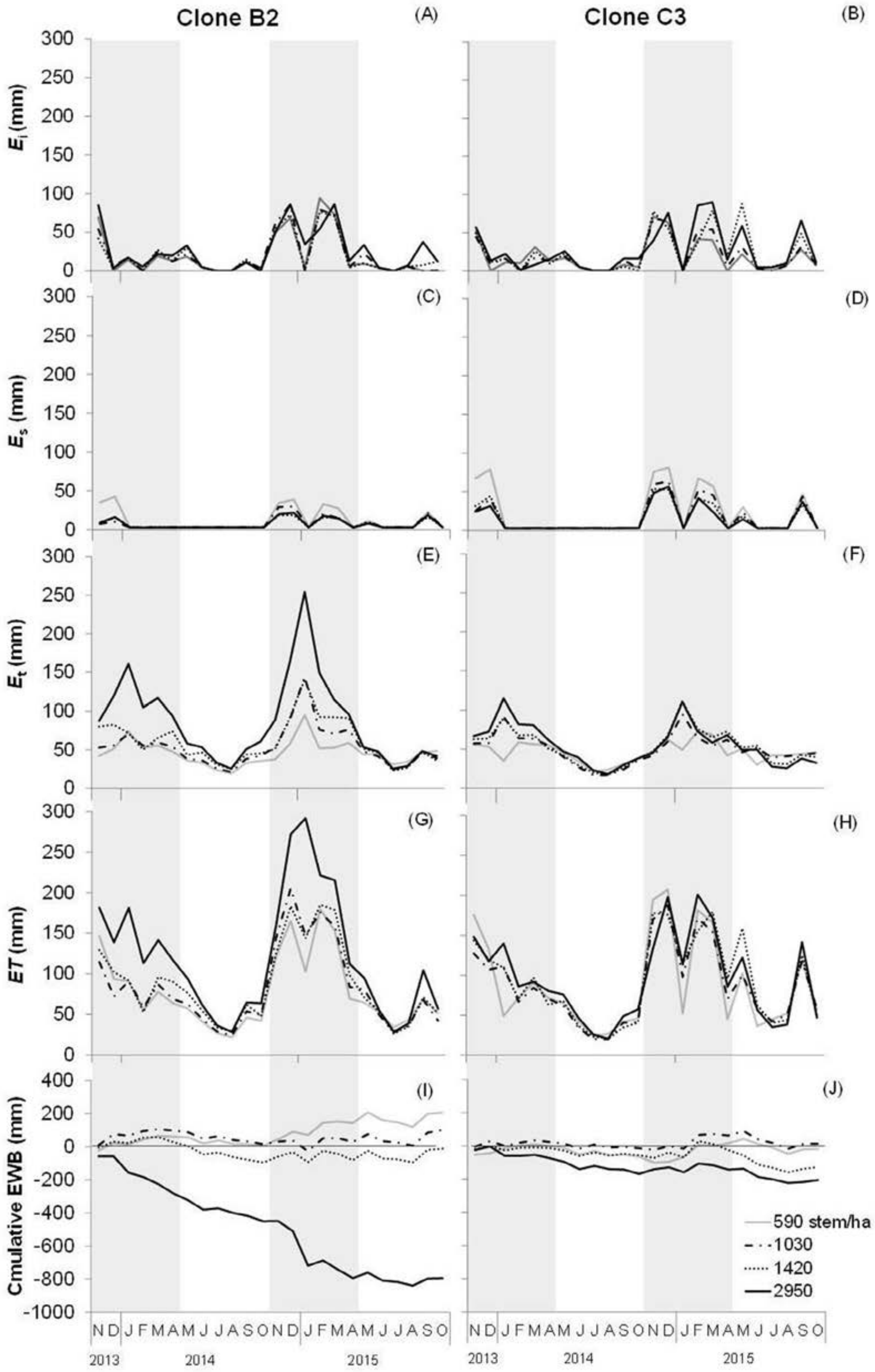

**Fig. 4.** Grey strips represent wet season that accounted for 73% of precipitation. All water balance components of the two clones were largely related to the seasonality of rainfall, with stocking having a significant effect in canopy interception ($E_i$) and soil evaporation ($E_s$) (A to D) but greater effect on transpiration ($E_t$) (E, F) which resulted in an average of 70% of evapotranspiration (*ET*) (G, H) concentrated in wet season. The cumulative ecosystem water balance (*EWB*) was negative for stocking > 1030 trees $ha^{-1}$, with a higher effect on Clone B2, which is more sensitive to drought.

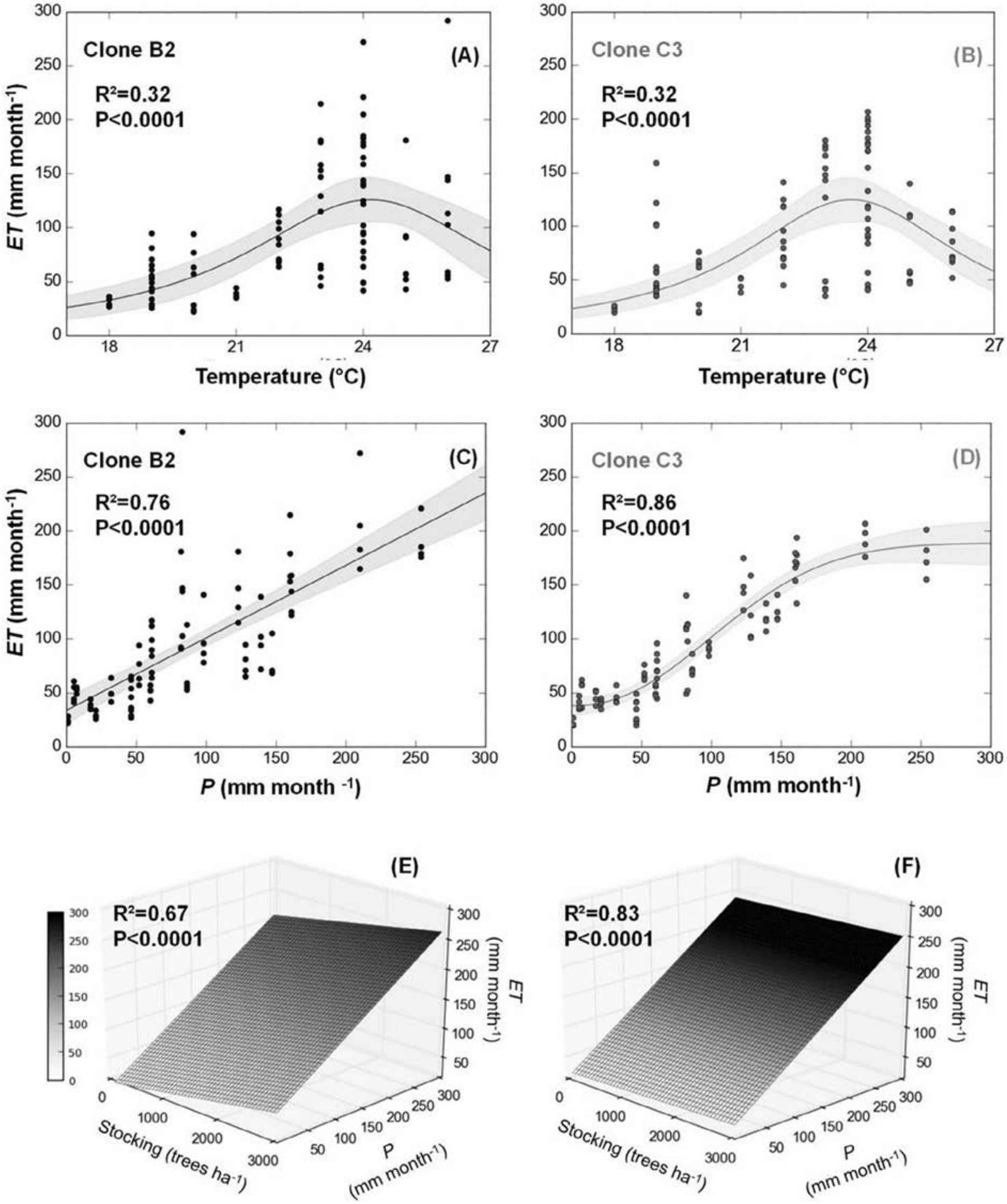

**Fig. 5.** Effect of precipitation on evapotranspiration *(ET)* for clones B2 and C3 (A, B) in a monthly time step was stronger ($R^2 > 0.76$, $P < 0.0001$) than the effect of temperature ($R^2 = 0.32$, $P < 0.0001$) (C, D). Increasing precipitation and stocking also lead to higher evapotranspiration, mainly for clone B2 (E, F).

adaptations of trees according to stocking. Higher stockings in this study had taller trees, which could be interpreted as a deeper root system, because there is a strong relationship between tree height and fine root depth (Christina et al, 2011, Silva et al., 2020), resulting in higher access to deep water reservoirs, and consequently to higher *ET*.

Increasing temperature from 18 to 24 °C increased *ET*, then declined from 24 °C to hotter months. The same limit of temperature was found by Binkley et al. (2020) to wood growth. The authors attribute the relationship to respiration, that is, there is an expenditure of C when the temperature is above 24 °C. We found temperature higher than 24 °C reduced ET, showing that in addition to the increase in respiration, there is probably reduced stomatal conductance and carbon uptake associated with higher air saturation deficit at higher temperatures (Otto et al., 2017).

At a yearly time step higher stockings resulted also in more water use. Average canopy interception values for both clones increased at higher stockings from 20% of precipitation to approximately 29% of precipitation. However, this pattern was compensated by the inverse pattern of soil evaporation, so the primary driver of changes in ecosystem water balance was transpiration. Benyon and Doody (2015)

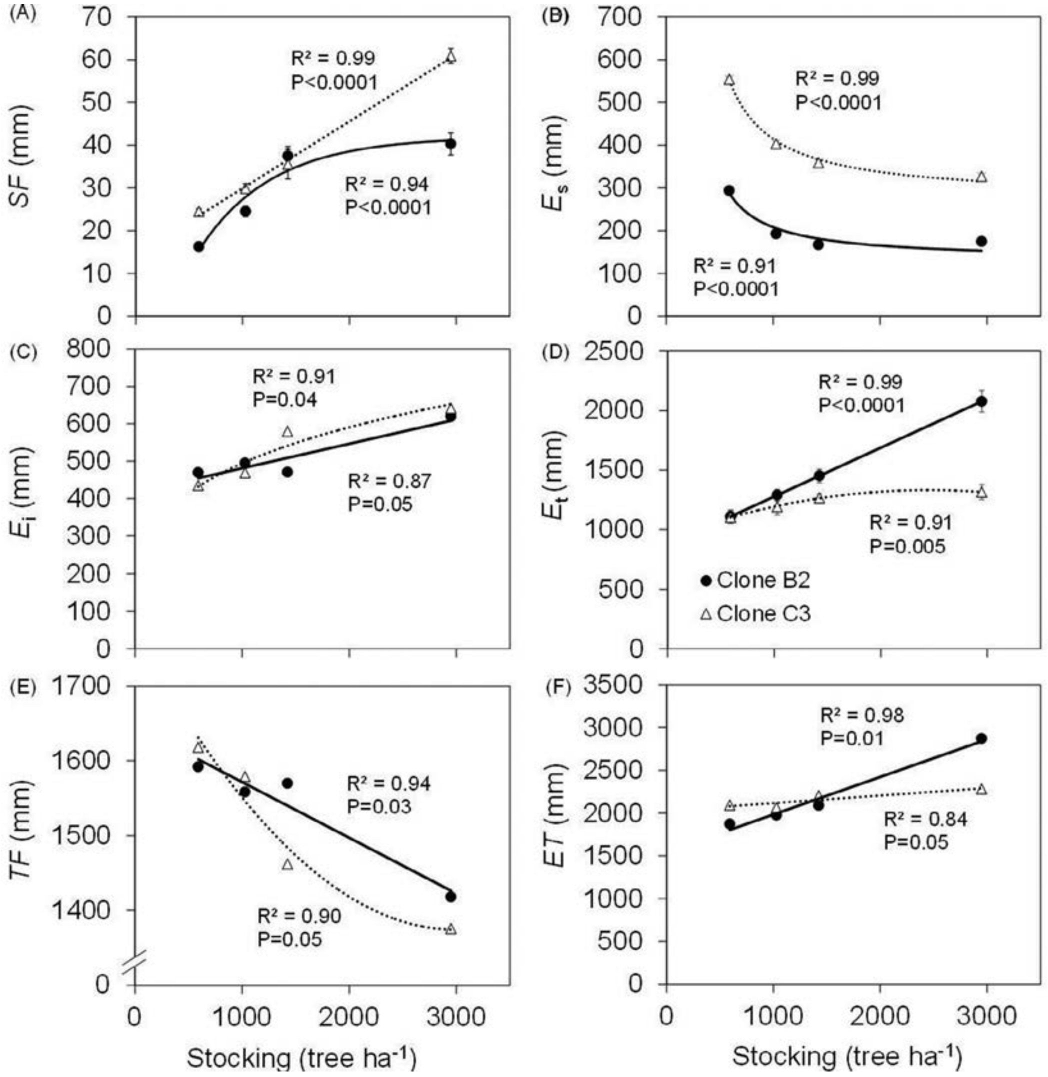

**Fig. 6.** (A) Stemflow, (B) canopy interception, (C) throughfall, (D) soil evaporation, (E) transpiration and (F) evapotranspiration observed in *E. urophylla* × *E. grandis* (B2) and *E. grandis* × *E. camaldulensis* (C3) clones at stockings varying from 590 to 2,950 trees ha$^{-1}$ from 1.7 to 3.7 years. Error bars when present represent standard error.

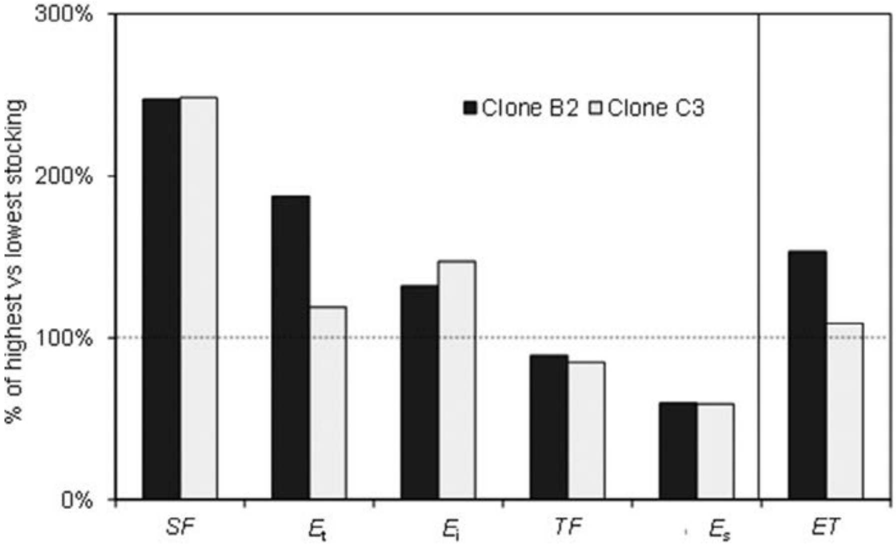

**Fig. 7.** Stemflow (*SF*), transpiration ($E_t$), canopy interception ($E_i$), throughfall (*TF*), soil evaporation ($E_s$) and the resulting evapotranspiration were all affected when comparing the extreme values of higher and lower stockings (2950 in comparison to 590 of stems ha$^{-1}$), represented by the dashed line during the 2-year period of evaluation for each clone.

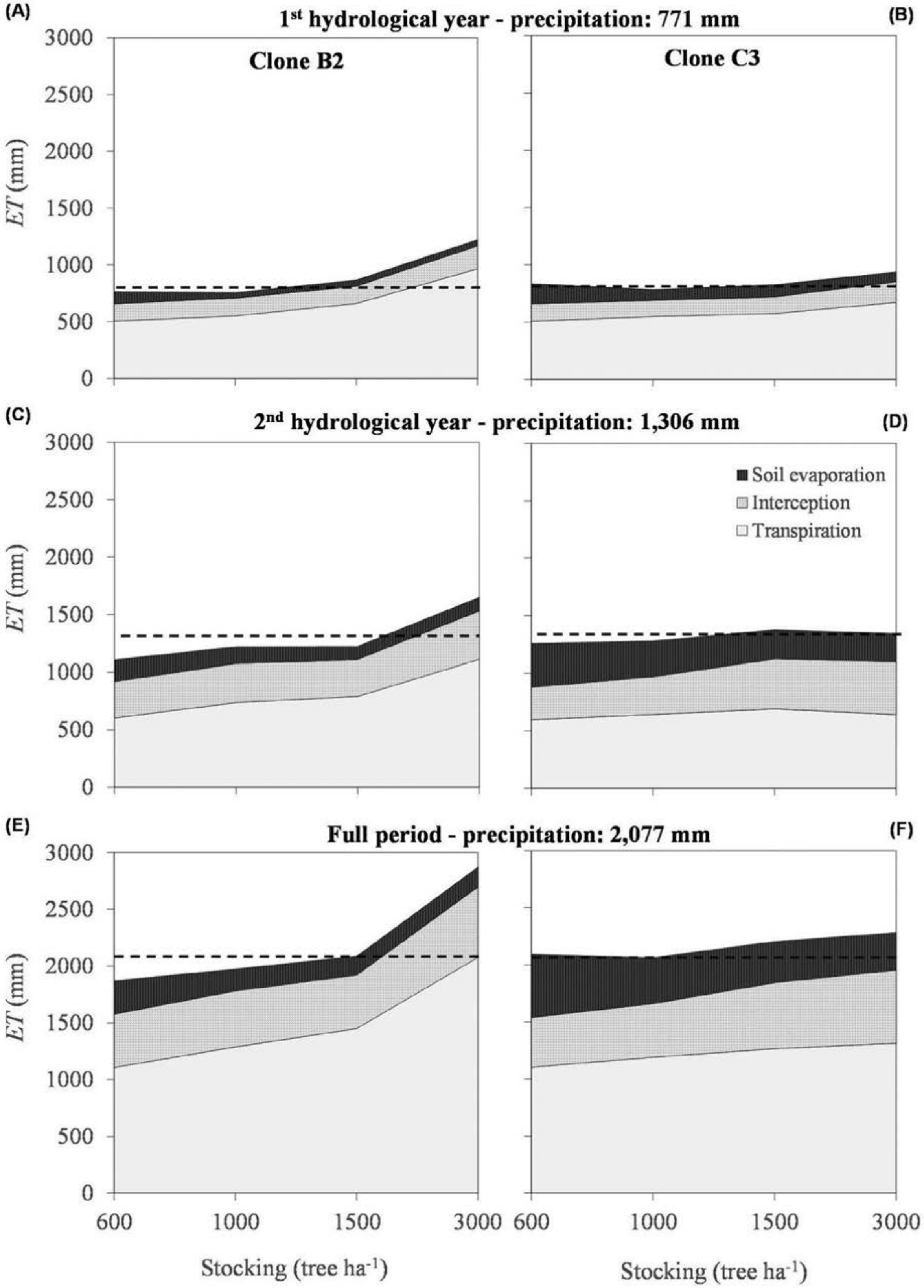

**Fig. 8.** Sum of water fluxes during the 1st and 2nd hydrological years and the full period year in forests of (A, C, E) *E. urophylla* × *E. grandis* (B2) and (B, D, F) *E. grandis* × *E. camaldulensis* (C3) with varying stocking. Dashed line represents the rainfall during the respective period.

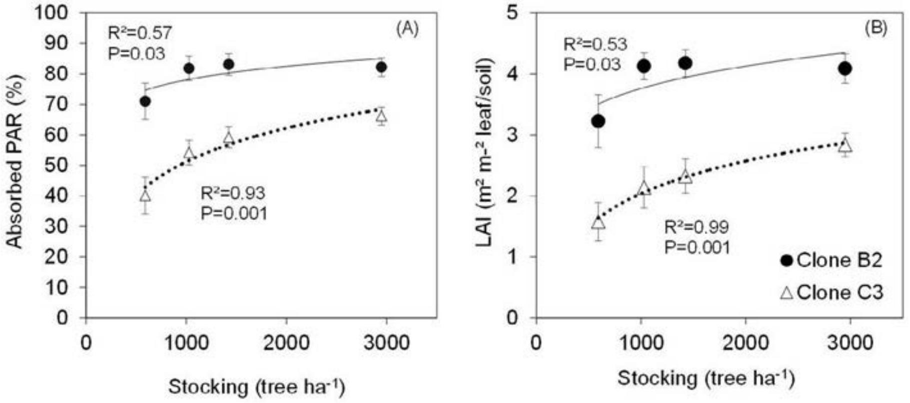

**Fig. 9.** Absorbed PAR (A) and leaf area index (B) increased with stocking but clone B2 stabilized after 1000 trees ha$^{-1}$. Values are averages of nine measurement periods during the 2-year study, and bars are standard error bar among measurements.

reported similar results using *Eucalyptus globulus* and *Pinus radiata*, where higher LAI among *Pinus* species resulted in greater canopy interception, which was compensated by lower soil evaporation resulting in a similar ecosystem water balance between the two species.

Canopy interception is directly related to leaf angle (Crockford and Richardson, 2000) and branch architecture (Bialkowski and Buttle, 2015), which could partly explain an average difference of 11% between the two genotypes. In addition, clone B2 LAI was on average twofold larger than observed in clone C3. Similar results were reported in previous work, where thinning of 50% of the basal area reduced $E_i$ from 14–8% in *Criptomeria Japonica* (Shinohara et al., 2015). In *E.globulus,* the $E_i$ reached 19% for trees at different ages (Benyon and Doody, 2015), and varied between 17% and 25% for *E. regnans* trees in their natural habitat, ranging in age from 30 to 200 years (Haydon et al., 1997). In a region near the current study site, the native vegetation displayed canopy interception of 8% (Cabral et al., 2015), suggesting that replacement of native forests with *Eucalyptus* plantations may impact ecosystem water balance based on canopy interception losses alone.

Stand transpiration was the largest component of total *ET,* with an average of 65% of precipitation (ranging from 53–82% across stockings and clones). Other studies have found that stocking differences either from the initial planting stocking or from later thinning result in alterations in the components of the water balance across different ecosystems. For example, a 50% thinning reduced transpiration from 44–21% in *Chamaecyparis obtusa* and *Cryptomeria japonica* (Tateishi et al., 2015) and in semi-arid regions thinning reduced transpiration of *Pinus halepensis* by 40% (González-Sanchis et al., 2015).

LAI is directly related to transpiration, being one of the reasons we supposed *ET* was higher is higher stocking treatments, as found in this study and others (Whitehead and Beadle, 2004, Sun et al., 2015). Simulated thinning through a reduction of LAI by 20–80% of original levels resulted in an increase in water yield ranging from 3–13% in a simulation applied to the entire US territory (Sun et al., 2015). In *Chamaecyparis obtusa* stocking reduction from 2400 to 1300 trees ha$^{-1}$ increased throughfall by 21% (Nanko et al., 2015).

We did not measure soil water storage in this study but recognize its importance in the constructing an ecosystem water balance. However, the most important contribution of this study in terms of ecosystem water balance is that fast-growing trees planted in tighter spacings presented negative ecosystem water balance and probably used stored soil water (Laclau et al., 2014, Nanko et al., 2015), mainly in the dry season (Xie et al., 2015). High water consumption (*ET* 44% greater than precipitation) resembled what was observed with *E.camaldulensis* at a stocking of 2,500 trees ha$^{-1}$ in India (Calder et al., 1997), where *ET* was 62% greater than PPT, on average. Mendham et al. (2011) reported that, because the depth of the root system of *Eucalyptus globulus*, there was a reduction in groundwater that would probably not be replenished in a following rotation, thus affecting the timber productivity in that site. Fine roots from these clonal *Eucalyptus* trees can go as deep as about 80% of the total tree height, and reached a depth of greater than 15 m in intact and coppice trees (Germon et al., 2019, Silva et al., 2020). Yin et al. (2015) calculated that, among species inhabiting semi-arid environments, up to 45% of the *ET* comes from deep water reservoirs. Lower precipitation also directly affects the ratio *ET* to precipitation (Xie et al., 2015), because *ET* in trees with elevated LAI remains high even with reduced water availability. Christina et al. (2015) identified that after canopy closure (~2-year-old) in *Eucalyptus grandis* and under similar weather conditions to those we observed, approximately 20% of $E_t$ water comes from depths greater than 10 m. Approximately, 1–3% of *ET* comes from the water table after canopy closure. This strategy has been identified in a number of tropical species as an adaptation to water stress (Canadell et al., 1996, Markewitz et al., 2010). The negative ecosystem water balance also reveals a potential impact that could affect the equitable use of water at the catchment scale (Lima et al., 2012), and tree survival (White et al., 2009).

The management of planted forests aims to maximize productivity and profitability at the end of the rotation period. When the productivity expected from tropical sites was lower because of less intensive forestry practices (e.g., fertilization, intensive weed control) and lower requirement for value-added materials ($< 20$ m$^3$ ha$^{-1}$ yr$^{-1}$), the optimum stocking for plantations was higher ($> 1600$ trees ha$^{-1}$) (Balloni and Simões (1980), Bredenkamp, 1987, Schönau and Coetzee, 1989). However, recent studies point to a stocking of 1000–1500 trees per hectare as optimal for volume and profit generation for the industries of energy and cellulose (Bernardo et al., 2004, Stape and Binkley, 2010, Gonçalves et al., 2013). Our study occurred during a two-year period of high water deficit, and only stockings below about 1000 trees ha$^{-1}$ had greater precipitation than *ET*. Higher stocking plantations may face greater stress and risk in response to droughts, and lower stocking plantations might sustain high rates of growth while increasing water yields (White et al., 2009, Gonçalves et al., 2013, Hakamada et al., 2017).

In an old forest of *E.camaldulensis*, Horner et al. (2009) observed that mortality was near zero in stockings between 600 and 1000 trees per hectare, whereas at higher stocking, tree survival was highly impacted after 30 years. Similar results were found in highly productive forests in Brazil, where stockings above 1000 trees per hectare presented high mortality rates at the peak of LAI, at approximately 3 years of age (Hakamada et al., 2015). During the first 12-month study period, the aridity index (*PET/P*) was twofold higher than the historic average of 0.81 which is indicative of the high annual climatic variation that may be impacting forest plantations (Booth, 2013). In areas where the ratio is higher than one, i.e., under water deficit, the degree of change in soil cover impacts more than what is observed in humid areas. Our information on water use in relation to stocking and clones should provide useful information for a risk assessment framework.

The increase in *ET* with stocking was greater for the drought sensitive clone B2 confirming our second hypothesis (For details see Table S1). At the highest stocking we measured, the clone C3 had much lower transpiration and *ET* than the B2 clone. This is consistent with data from the other TECHS sites where B2 routinely succumbed to drought at higher densities while the C3 clone survived. There are several possible explanations for the lack of a proportional increase in transpiration and *ET* with density for the drought tolerant clone. Otto et al. (2017) showed that the C3 clone had a higher sensitivity to VPD than clone B2, so as water stress increased with the high stocking treatment (Hakamada et al., 2017), C3 was able to limit water loss; similar behavior was shown for *E. camaldulensis* compared to *E. pellita* in a dry region in Brazil (Leles et al., 1998). It's also possible that higher leaf area at the 2950 trees ha$^{-1}$ stocking caused significant shading within the steep leaf angled canopy of C3 (Mattos et al., this issue), thereby lowering stomatal conductance. Discerning the mechanisms for the patterns we observed will require more research.

How general would these patterns be for other clones at this site, or for these clones at other sites? We are confident that the water budget trends in relation to stocking are robust, though differences among clones will also be important. Nine other clones planted in this TECHS location behaved similarly to the two intensively studied clones in this paper, showing increased biomass accumulation with increasing stocking. The clones B2 and C3 were included in all the tropical TECHS sites, and they presented very similar growth compared with our site (Binkley et al., this issue). Therefore, we expect the results from this intensive study would likely represent a general response of wood growth and ecosystem water balance to stocking. Risks of drought-induced problems in tree survival and growth may increase above stockings of about 1000 trees ha$^{-1}$, and lower stocking plantations could be a strategy to enhance the balance between sustaining wood production and maintaining ecosystem services in forest landscapes.

## CRediT authorship contribution statement

**Rodrigo Eiji Hakamada:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Resources, Supervision, Writing - original draft, Writing - review & editing. **Robert M. Hubbard:** Conceptualization, Methodology, Resources, Supervision, Writing - review & editing. **Jose Luiz Stape:** Conceptualization, Writing - review & editing. **Walter de Paula Lima:** Writing - review & editing. **Gabriela Gonçalves Moreira:** Data curation, Funding acquisition, Project administration, Resources. **Silvio Frosini de Barros Ferraz:** Supervision, Writing - review & editing.

## Acknowledgments

We are grateful to Dan Binkley for comments that greatly improved the paper. The project was possible only through the coordination provided by Forestry Science and Research Institute (IPEF, ipef.br/techs/en, Directors Luiz Ernesto George Barrichelo and José Otávio Brito). TECHS was funded by the following 26 companies: Anglo American (Andre Machado), Arauco (Rodrigo Coutinho), Arborgen (Gabriela Bassa), ArcelorMittal (Roosevelt Almado), Cenibra (Fernando Leite), CMPC (Elias Araujo),Comigo (Ubirajara Oliveira), Copener (Jacyr Alves), Duratex (Raul Chaves), Eldorado (Vinicius Silva), Fazenda Campo Bom (Jacqueline Pirez), Fibria (Rodolfo Loos), Florestal Itaquari (Admir Mora), Forestal Oriental (Ricardo Methol), Gerdau (Francisco Gomes), GMR (Paulo Leite), International Paper (Cristiane Lemos), Jari (Katia Silva), Klabin (James Stahl), Lwarcel (Marcela Capoani), Montes del Plata (Alejandro Gonzalez), Plantar (David Fernandes), Rigesa (Ricardo Paim), Suzano (Luiz Fabiano and Leandro de Siqueira), Vallourec (Helder Andrade, in memoriam) and Veracel (Helton Lourenço). Several universities and institutes also supported TECHS: University of Sao Paulo, Sao Paulo State University, Federal University of Lavras, Federal University of Rio Grande do Norte, Colorado State University, North Carolina State University, and the USDA Forest Service. This study was supported by a scholarship from CAPES (Coordination for the Improvement of Higher Education Personnel). This study was supported by a scholarship from CAPES (Coordination for the Improvement of Higher Education Personnel).

## Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foreco.2020.118149.

## References

Allen, C.D., Breshears, D.D., Mcdowell, N.G., 2015. On underestimation of global vulnerability to tree mortality and forest die-off from hotter drought in the Anthropocene. Ecosphere 6, 1–55.

Allen, R.G.; Pereira, L.S.; Raes, D.; Smith, M., 1998. Crop evapotranspiration: guidelines for computing crop water requirements. Rome: FAO, 1998. 300 p. (FAO. Irrigation and Drainage Paper, 56).

Almeida, A.C., Landsberg, J.J., Sands, P.J., 2004. Parametrization of 3-PG model for fast growing *Eucalyptus grandis* plantations. For. Ecol. Manage. 193, 179–195.

Attia, A., Nouvellon, Y., Cuadra, S., Cabral, O., Laclau, J.P., Guillemot, J., Campoe, O., Stape, J.L., Galdos, M., Lamparelli, R., le Maire, G., 2019. Modelling carbon and water balance of *Eucalyptus* plantations at regional scale: Effect of climate, soil and genotypes. For. Ecol. Manage. 449, 117460.

Balloni, E.A., Simões, J.W., 1980. O espaçamento de plantio e suas implicações silviculturais. Circular Técnica IPEF 1, 1–16.

Benyon, R.G., Doody, T.M., 2015. Comparison of interception, forest floor evaporation and transpiration in P*inus radiata* and *Eucalyptus globulus* plantations. Hydrol. Process. 29, 1173–1187.

Bernardo, A.L., Reis, M.G.F., Reis, G.G., Harrison, R.B., Firme, D.J., 2004. Effect of density on growth and biomass distribution in *Eucalyptus camaldulensis, E. pellita* and *E. urophylla* plantations in southeastern Brazil. For. Ecol. Manage. 104, 1–13.

Bialkowski, R., Buttle, J.M., 2015. Stemflow and throughfall contributions to soil water recharge under trees with differing branch architectures. Hydrol. Process. 29, 4068–4082.

Binkley, D., Campoe, O.C., Alvares, C.A., Carneiro, R.L., Cegatta, I.R., Stape, J.L., 2017. The interactions of climate, spacing and genetics on clonal *Eucalyptus* plantations across Brazil and Uruguay. For. Ecol. Manage. 405, 271–283.

Binkley, D., Campoe, O.C., Alvares, C.A., Carneiro, R.L., Stape, J.L., 2020. Variation in whole-rotation yield among *Eucalyptus* genotypes in response to water and heat stresses: the TECHS project. Forest Ecol. Manage. https://doi.org/10.1016/j.foreco.2020.117953.

Booth, T.H., 2013. *Eucalyptus* and climate change. For. Ecol. Manage. 301, 28–34.

Bredenkamp, B.V., 1987. Effects of spacing and age on growth of *Eucalyptus grandis* on a dry Zululand site. S Afr. For. J. 140, 24–28.

Bréda, N., Granier, A., Aussenac, G., 1995. Effects of thinning on soil and tree water relations, transpiration and growth in an oak forest (*Quercus petraea* (Matt.) Liebl.). Tree Physiol. 15, 295–306.

Budyko, M.I., 1974. Climate and life. Academic Press, Orlando, pp. 508.

Cabral, O.M.R., Rocha, H.R., Gash, J.H., Freitas, H.C., Ligo, M.A.V., 2015. Water and energy fluxes from a woodland savanna (cerrado) in southeast Brazil. J. Hydrol. Regional Studies 22–40.

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

Christina, M., Laclau, J.P., Gonçalves, J.L.M., Jourdan, C., Nouvellon, Y., Bouillet, J.P., 2011. Almost symmetrical vertical growth rates above and below ground in one of the world's most productive forests. Ecosphere 2 (3), 1–10.

Christina, M., Le Maire, G., Battie-Laclau, P., Nouvellon, Y., Bouillet, J.P., Jourdan, C., Gonçalves, J.L.M., Laclau, J.P., 2015. Measured and modeled interactive effects of potassium deficiency and water deficit on gross primary productivity and light-use efficiency in *Eucalyptus grandis* plantations. Glob. Change Biol. 21, 2022–2039.

Christina, M., le Maire, G., Nouvellon, Y., Vezy, R., Bordon, B., Battie-Laclau, P., Goncalves, J.L.M., Delgado-Rojas, J.S., Bouillet, J.P., Laclau, J.P., 2018. Simulating the effects of different potassium and water supply regimes on soil water content and water table depth over a rotation of a tropical *Eucalyptus grandis* plantation. For. Ecol. Manag. 148, 4–14.

Christina, M., Nouvellon, Y., Laclau, J.P., Stape, J.L., Bouillet, J.P., Lambais, G.R., Le Maire, G., 2017. Importance of deep water uptake in tropical eucalypt forest. Funct. Ecol. 31 (2), 509–519.

Calder, I.R., Rosier, P.T., Prasanna, K.T., Parameswarappa, S., 1997. *Eucalyptus* water use greater than rainfall input-possible explanation from southern India. Hydrol. Earth Syst. Sci. Discuss. 1, 249–256.

Cornish, P.M., Vertessy, R.A., 2001. Forest age-induced changes in evapotranspiration and water yield in a eucalypt forest. J. Hydrol. 242, 43–63.

Crockford, R.H., Richardson, D.P., 2000. Partitioning of rainfall into throughfall, stemflow and interception: effect of forest type, ground cover and climate. Hydrol.

Process. 14, 2903–2920.
Dematté, J., 2000. Levantamento semi-detalhado dos solos da Champion Papel e Celulose. Champion Papel e Celulose, Mogi Guaçu, pp. 85.
Eamus, D., Hutley, L.B., O'Grady, A.P., 2001. Daily and seasonal patterns of carbon and water fluxes above a north Australian savanna. Tree Physiol. 21, 977–988.
Eufrade Junior, H.J., De Melo, R.X., Sartori, M.M.P., Guerra, S.P.S., Ballarin, A.W., 2016. Sustainable use of eucalypt biomass grown on short rotation coppice for bioenergy. Biomass Bioenergy 90, 15–21.
Ferraz, S.F.D.B., Rodrigues, C.B., Garcia, L.G., Alvares, C.A., Lima, W.D.P., 2019. Effects of *Eucalyptus* plantation on streamflow in Brazil: Moving beyond the water use debate. For. Ecol. Manage. 453, 1–10.
Forrester, D.I., 2015. Transpiration and water-use efficiency in mixed-species forests versus monocultures: effects of tree size, stand density and season. Tree Physiol. 35, 289–304.
Forrester, D.I., Collopy, J.J., Beadle, C.L., Warren, C.R., Baker, T.G., 2012. Effect of thinning, pruning and nitrogen fertilizer application on transpiration, photosynthesis and water use efficiency in a young *Eucalyptus nitens* plantation. For. Ecol. Manage. 266, 286–300.
Forrester, D.I., Collopy, J.J., Morris, J.D., 2010. Transpiration along an age series of *Eucalyptus globulus* plantations in southeastern Australia. For. Ecol. Manage. 259, 1754–1760.
Germon, A., Jourdan, C., Bordron, B., Robin, A., Nouvellon, Y., Gonçalves, J.L.M., Chapuis-Lardy, L., Pradier, C., Guerrini, I.A., Laclau, J.-P., 2019. Consequences of clear-cutting and drought on fine roots dynamics down to 17 m in coppice-managed eucalypt plantations. For. Ecol. Manage. 445, 48–59.
Giunti Neto, C., Hakamada, R., Otto, M.S.G., Stape, J.L., Silva, S.R., 2015. Calibração de dois métodos indiretos para estimativa do índice de área foliar em plantações de *Eucalyptus*. Scientia Forestalis 43, 919–930.
González-Sanchis, M., Del Campo, A.D., Molina, A.J., 2015. Modeling adaptive forest management of a semi-arid Mediterranean Aleppo pine plantation. Ecol. Model. 308, 34–44.
Gonçalves, J.L.M., Alvares, C.A., Higa, A.R., Silva, L.D., Alfenas, A.C., Stahl, J., Ferraz, S.F.B., Lima, W.P., Brancalion, P.H.S., Hubner, A., Bouillet, J.P.D., Laclau, J.P., Nouvellon, Y., Epron, D., 2013. Integrating genetic and silvicultural strategies to minimize abiotic and biotic constraints in Brazilian eucalypt plantations. For. Ecol. Manage. 301, 6–27.
Granier, A., 1987. Evaluation of transpiration in a Douglas-fir stand by means of sap flow measurements. Tree Physiol. 3, 309–320.
Grime, V.L., Sinclair, F.L., 1999. Sources of error in stem heat balance sap flow measurements. Agric. For. Meteorol. 94, 103–121.
Guerra, S.P.S., Garcia, E.A., Lanças, K.P., Rezende, M.A., Spinelli, R., 2014. Heating value of eucalypt wood grown on SRC for energy production. Fuel 137, 360–363.
Hakamada, R.E., Lemos, C.C.Z., Silva, R.M.L., Batistuzzo, G., Fonseca, J., Gabriel, J., Almeida, A., 2015. Primeiro relato do efeito do espaçamento de plantio na sobrevivência e crescimento de clones de *Eucalyptus grandis x E.urophylla* em solo arenoso na região Centro Norte do Tocantins. Série Técnica IPEF 20, 36–41.
Hakamada, R.E., Hubbard, R.M., Ferraz, S.F.B., Stape, J.L., Lemos, C.C.Z., 2017. Biomass production and water stress increase with stand density in four highly productive clonal *Eucalyptus* genotypes. Southern Forests 79, 251–257.
Haydon, S.R., Benyon, R.G., Lewis, R., 1997. Variation in sapwood area and throughfall with forest age in mountain ash (*Eucalyptus regnans* F Muell). J. Hydrol. 187, 351–366.
Horner, G.J., Baker, P.J., Mac Nally, R., Cunningham, S.C., Thomson, J.R., Hamilton, F., 2009. Mortality of developing floodplain forests subjected to a drying climate and water extraction. Glob. Change Biol. 15, 2176–2186. https://doi.org/10.1111/j.1365-2486.2009.01915.x.
Hubbard, R.M., Stape, J.L., Ryan, M.G., Almeida, A.C., Rojas, J., 2010. Effects of irrigation on water use and water use efficiency in two fast growing Eucalyptus plantations. For. Ecol. Manage. 259, 1714–1721.
Laclau, J.P., Da Silva, E.A., Lambais, G.R., Bernoux, M., Le Maire, G., Stape, J.L., Nouvellon, Y., 2014. Dynamics of soil exploration by fine roots down to a depth of 10 m throughout the entire rotation in *Eucalyptus grandis* plantations. Front. Plant Sci. 4, 1–12.
Lee, R., 1980. Ecosystem water balance. In: MOONEY, H.A.; GODRON, M. Disturbance and ecosystems. Berlin: Springer. p. 99-116.
Leite, F.P., Barros, N.F., Novais, R.F., Sans, L.M.A., Fabres, A.S., 1999. Relações hídricas em povoamento de eucalipto com diferentes densidades populacionais. Revista Brasileira Ciência do Solo 23, 9–16.
Leite, H.G., Oliveira, F.H.T., 2006. Statistical procedure to test identity between analytical methods. Commun. Soil Sci. Plant Anal. 33, 1105–1118.
Leles, P.D., Reis, G.G., Reis, M.G.F., Morais, E.J., 1998. Relações hídricas e crescimento de árvores de *Eucalyptus camaldulensis* e *Eucalyptus pellita* sob diferentes espaçamentos na região de cerrado. Revista Árvore 22 (1), 41–50.
Leuning, R., Condon, A.G., Dunin, F.X., Zegelin, S., Denmead, O.T., 1994. Rainfall interception and evaporation from soil below a wheat canopy. Agric. For. Meteorol. 67, 221–238.
Lima, W.P., Laprovitera, R., Ferraz, S.F.B., Rodrigues, C.B., Silva, M.M., 2012. Forest plantations and water consumption: a strategy for hydrosolidarity. Int. J. Forest Res. 2012, 1–8.
Markewitz, D., Devine, S., Davidson, E.A., Brando, P., Nepstad, D.C., 2010. Soil moisture depletion under simulated drought in the Amazon: impacts on deep root uptake. New Phytol. 187, 592–607.
Mattos, E.M., Binkley, D., Campoe, O.C., Alvares, C.A., Stape, J.L., 2020. Variation in canopy structure, leaf area, light interception and light use efficiency among *Eucalyptus* clones. For. Ecol. Manage. 463, 118038.
Mendham, D.S., White, D.A., Battaglia, M., Mcgrath, J.F., Short, T.M., Ogden, G.N., Kinal, J., 2011. Soil water depletion and replenishment during first- and early second-rotation *Eucalyptus globulus* plantations with deep soil profiles. Agric. For. Meteorol. 151, 1568–1579.
McDowell, N., Pockman, W.T., Allen, C.D., Breshears, D.D., Cobb, N., Kolb, T., Sperry, J., West, A., Williams, D., Yepez, E.A., 2008. Mechanisms of plant survival and mortality during drought: why do some plants survive while others succumb to drought? Tansley review. New Phytol. 178, 719–739.
Moreaux, V., O' Grady, A. P., Nguyen-The, N., & Loustau, D., 2013. Water use of young maritime pine and Eucalyptus stands in response to climatic drying in south-western France. Plant Ecol. Div., 6, 57-71.
Mugunga, C.P., Kool, D., Van Wijk, M.T., Mohren, G.M.J., Giller, K.E., 2015. Water use by short rotation *Eucalyptus* woodlots in southern Rwanda. Agrofor. Syst. 89, 1119–1139.
Murray, F.W., 1967. On the computation of saturation vapor pressure. J. Appl. Meteor. 6, 203–204. https://doi.org/10.1175/1520-0450(1967)006<0203:OTCOSV>2.0.CO;2.
Nanko, K., Onda, Y., Kato, H., Gomi, T., 2015. Immediate change in throughfall spatial distribution and canopy water balance after heavy thinning in a dense mature Japanese cypress plantation. Ecohydrology 9, 300–314.
O'Grady, A.P., Eamus, D., Hutley., L.B., 1999. Transpiration increases during the dry season: patterns of tree water use in eucalypt open-forests of Northern Australia. Tree Physiol., 19, 591-597.
Oliveira, A.D., Mello, A.A., Scolforo, J.R.S., Resende, J.L.P., Mello, J.M., 2002. Avaliação econômica da regeneração da vegetação de cerrado, sob diferentes regimes de manejo. Revista Árvore 26, 715–726.
Otto, M.S.G., Francisco, J.G., Gonsalez, B.T., de Almeida Calvo, L., de Mattos, E.M., de Almeida, M., de Andrade Moral, R., Demétrio, C.G.B., Stape, J.L., de Oliveira, R.F., 2017. Changes in γ-aminobutyric acid concentration, gas exchange, and leaf anatomy in *Eucalyptus* clones under drought stress and rewatering. Acta Physiol. Plant. 39, 208.
Otto, M.S.G., Hubbard, R., Binkley, D., Stape, J.L., 2014. Dominant clonal *Eucalyptus grandis* × *urophylla* trees use water more efficiently. For. Ecol. Manage. 328, 117–121.
Ouyang, L., Zhao, P., Zhou, G., Zhu, L., Huang, Y., Zhao, X., Ni, G., 2018. Stand-scale transpiration of a *Eucalyptus urophylla* × *Eucalyptus grandis* plantation and its potential hydrological implication. Ecohydrology 11, e1938.
Payn, T., Carnus, J.-M., Freer-Smith, P., Kimberley, M., Kollert, W., Liu, S., Orazio, C., Rodriguez, L., Silva, L.N., Wingfield, M.J., 2015. Changes in planted forests and future global implications. For. Ecol. Manage. 352, 57–67.
Schönau, A.P.G., Coetzee, J., 1989. Initial spacing, stand density and thinning in eucalypt plantations. For. Ecol. Manage. 29 (4), 245–266.
Shinohara, Y., Levia, D.F., Komatsu, H., Nogata, M., Otsuki, K., 2015. Comparative modeling of the effects of intensive thinning on canopy interception loss in a Japanese cedar (*Cryptomeria japonica* D. Don) forest of western Japan. Agric. For. Meteorol. 214, 148–156.
Silva, V., Nogueira, T., Abreu, C., He, Z., Buzetti, S., Laclau, J., Teixeira, M., Grilli, E., Murgia, I., Capra, G., 2020. Influences of edaphoclimatic conditions on deep rooting and soil water availability in Brazilian *Eucalyptus* plantations. For. Ecol. Manage. 455.
Stape, J.L., Binkley, D., 2010. Insights from full-rotation Nelder spacing trials with *Eucalyptus* in São Paulo, Brazil. Southern Forests 72, 91–98.
Stape, J.L., Binkley, D., Ryan, M.G., Fonseca, S., Loos, R., Takahashi, E.N., Silva, C.R., Silva, S., Hakamada, R.E., Ferreira, J.M., Lima, A.M., Gava, J.L., Leite, F.P., Silva, G., Andrade, H., Alves, J.M., 2010. The Brazil *Eucalyptus* potential productivity project: influence of water, nutrients and stand uniformity on wood production. For. Ecol. Manage. 259, 1686–1694.
Sun, G., Caldwell, P.V., McNulty, S.G., 2015. Modelling the potential role of forest thinning in maintaining water supplies under a changing climate across the conterminous United States. Hydrol. Process. 29, 5016–5030.
Tateishi, M., Xiang, Y., Saito, T., Otsuki, K., Kasahara, T., 2015. Changes in canopy transpiration of Japanese cypress and Japanese cedar plantations because of selective thinning. Hydrol. Process. 29, 5088–5097.
Tsamir, M., Gottlieb, S., Preisler, Y., Rotenberg, E., Tatarinov, F., Yakir, D., Tague, C., Klein, T., 2019. Stand density effects on carbon and water fluxes in a semi-arid forest, from leaf to stand-scale. For. Ecol. Manage. 453, 117573.
Yin, L., Zhou, Y., Huang, J., Wenninger, J., Zhang, E., Hou, G., Dong, J., 2015. Interaction between groundwater and trees in an arid site: Potential impacts of climate variation and groundwater abstraction on trees. J. Hydrol. 528, 435–448.
White, D., Dunin, F.X., Turner, N.C., Ward, B.H., Galbraith, J.H., 2002. Water use by contour-planted belts of trees comprised of four *Eucalyptus* species. Agric. Water Manag. 53, 133–152.
White, D.A., Crombie, D.S., Kinal, J., Battaglia, M., Mcgrath, J.F., Mendham, D., Walker, S.N., 2009. Managing productivity and drought risk in *Eucalyptus globulus* plantations in South-Western Australia. For. Ecol. Manage. 259, 33–44.
White, D.A., Mcgrath, J.F., Battaglia, M., Mendham, D., Kinal, J., Downes, G.M., Crombie, D.S., Hunt, M.E., 2014. Managing for water-use efficient wood production in *Eucalyptus globulus* plantations. For. Ecol. Manage. 331, 272–280.
Whitehead, D., Beadle, C.L., 2004. Physiological regulation of productivity and water use in *Eucalyptus*: a review. For. Ecol. Manage. 193, 113–140.
Whitehead, D., Jarvis, P.G., Waring, R.H., 1984. Stomatal conductance, transpiration, and resistance to water uptake in a *Pinus sylvestris* spacing experiment. Can. J. For. Res. 14, 692–700.
Xie, H., Zhu, X., Yuan, D.Y., 2015. Pan evaporation modelling and changing attribution analysis on the Tibetan Plateau (1970–2012). Hydrol. Process. 29, 2164–2177.