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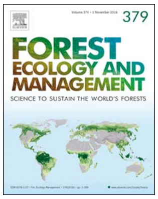

Simulating the effects of different potassium and water supply regimes on soil water content and water table depth over a rotation of a tropical *Eucalyptus grandis* plantation

M. Christina[a,b,c,*], G. le Maire[a,b,d], Y. Nouvellon[a,b,e], R. Vezy[a,f], B. Bordon[g], P. Battie-Laclau[a,b,h], J.L.M. Gonçalves[g], J.S. Delgado-Rojas[g], J.-P. Bouillet[a,b,g], J.-P. Laclau[a,b,g,i]

[a] *CIRAD, UMR Eco&Sols, F-34398 Montpellier, France*
[b] *Eco&Sols, Univ Montpellier, CIRAD, INRA, IRD, Montpellier SupAgro, Montpellier, France*
[c] *CIRAD, UR 115 AIDA, F-34398 Montpellier, France*
[d] *NIPE, UNICAMP, CEP 13083-970 Campinas, SP, Brazil*
[e] *Universidade de São Paulo, Departamento de Ciencias Atmosfericas, CEP 05508-900 São Paulo, SP, Brazil*
[f] *INRA, UMR 1391 ISPA, F-33140 Villenave d'Ornon, France*
[g] *Universidade de São Paulo, ESALQ, CEP 13418-900 Piracicaba, SP, Brazil*
[h] *Universidade de São Paulo, CENA, CEP 13400-970 Piracicaba, SP, Brazil*
[i] *Universidade Estadual Paulista 'Júlio de Mesquita Filho', Departamento de Solos e Recursos Ambientais, CEP 18610-300 Botucatu, SP, Brazil*

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ABSTRACT

Although large amounts of potassium (K) are applied in tropical crops and planted forests, little is known about the interaction between K nutrition and water supply regimes on water resources in tropical regions. This interaction is a major issue because climate change is expected to increase the length of drought periods in many tropical regions and soil water availability in deep soil layers is likely to have a major influence on tree growth during dry periods in tropical planted forests. A process-based model (MAESPA) was parameterized in a throughfall exclusion experiment in Brazil to gain insight into the combined effects of K deficiency and rainfall reduction (37% throughfall exclusion) on the water used by the trees, soil water storage and water table fluctuations over the first 4.5 years after planting *Eucalyptus grandis* trees. A comparison of canopy transpiration in each plot with the values predicted for the same soil with the water content maintained at field capacity, made it possible to calculate a soil-driven tree water stress index for each treatment. Compared to K-fertilized trees with undisturbed rainfall (+K+W), canopy transpiration was 40% lower for K deficiency (−K+W), 20% lower for W deficit (+K−W) and 36% lower for combined K deficiency and W deficit (−K−W) on average. Water was withdrawn in deeper soil layers for −W than for +W, particularly over dry seasons. Under contrasted K availability, water withdrawal was more superficial for −K than for +K. Mean soil water content down to 18 m below surface (mbs) was 24% higher for −K+W than for +K+W from 2 years after planting (after canopy closure), while it was 24% lower for +K−W and 12% lower for −K−W than for +K+W. The soil-driven tree water stress index was 166% higher over the first 4.5 years after planting for −W than for +W, 76% lower for −K than for +K, and 14% lower for −K−W than for +K+W. Over the study period, deep seepage was higher by 371 mm yr^{-1} (+122%) for −K than for +K and lower by 200 mm yr^{-1} (−66%) for −W than for +W. Deep seepage was lower by 44% for −K−W than for +K+W. At the end of the study period, the model predicted a higher water table for −K (10 mbs for −K+W and 16 mbs for −K−W) than for +K (16 mbs for +K+W and 18 mbs for +K−W). Our study suggests that flexible fertilization regimes could contribute to adjusting the local trade-off between wood production and demand for soil water resources in planted forests.

1. Introduction

Planted forests provided 46% of the wood consumption worldwide in 2012, and 65% in tropical and subtropical regions (Payn et al., 2015). In tropical and subtropical regions, the growth of these highly productive planted forests is largely dependent on fertilization regimes (e.g. Smethurst, 2010) and their contribution to satisfying the global wood demand should increase in the future (Paquette and Messier,

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[*] Corresponding author at: UPR AIDA, CIRAD, 2 Avenue Agropolis, 34398 Montpellier Cedex 5, France.
E-mail address: mathias.christina@cirad.fr (M. Christina).

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2010). However, climate change is expected to exacerbate the intensity and frequency of droughts in tropical and subtropical regions (Allison et al., 2009; IPCC, 2013; Solomon et al., 2009). Fast-growing tropical plantations are particularly vulnerable to drought and changes in rainfall patterns (Allen, 2009). Consequently, the sustainability of fast-growing planted forests in a future with extended dry periods in many tropical regions will probably require a revision of management strategies to improve tree tolerance to drought (Battie-Laclau et al., 2014a, 2016; Carter and White, 2009).

Water storage in deep soil layers is likely to have a major effect on tree functioning in tropical regions (Malhi et al., 2008). Indeed, water uptake by deep roots is generally considered as an efficient adaptation to drought in tropical forests to maintain transpiration rates during dry periods by withdrawing water from soil deeper than 8 to 10 m below surface (mbs) (Christina et al., 2017; Markewitz et al., 2010; Nepstad et al., 1994). Water uptake in the capillary fringe above the water table is likely to account for a substantial proportion of tree water use in eucalypt forests (Dawson and Pate, 1996; Zolfaghar et al., 2014; Eamus et al., 2015), even under relatively high rainfall regimes (approx. 1500 mm yr^{-1}) for water tables at 10 mbs–18 mbs (Christina et al., 2017). Recent studies have shown that tree water stress and mortality are dependent on the amount of water stored in deep soil layers in Australian eucalypt forests (Harper et al., 2009; Brouwers er al., 2013; Zolfaghar et al., 2014), in the Amazonian Forest (da Costa et al., 2010; Malhi et al., 2009) and in the Brazilian savanna (Jackson et al., 1999; Oliveira et al., 2005). In consequence, modifications to current management practices in drought-prone planted forests have been proposed to decrease tree water stress during dry periods. The most common silvicultural adaptations proposed are: (i) to plant species and hybrids selected by breeding programs for their high tolerance to drought (Dutkowski et al., 2012; Rojas et al., 2017), (ii) to decrease the stocking densities (Mendham et al., 2011; White et al. 2009) or rotation periods, to restore soil water storage after clear-cutting (Harper et al., 2014), (iii) to reduce the amounts of fertilizer applied (Forrester et al., 2013; Battie-Laclau et al., 2014a; White et al., 2009), and (iv) to concentrate future afforestation programs on deep soils (Harper et al., 2014; Battie-Laclau et al., 2016).

Although it is well established that an adequate nutritional status helps plant tolerance to abiotic stresses (Cakmak, 2005; Reddy et al., 2004), carbon partitioning to wood production (Litton et al., 2007; Epron et al., 2012), and water-use efficiency (White et al., 2014; Battie-Laclau et al., 2016), some studies have shown that fertilization is likely to increase tree water stress during dry periods (Linder et al., 1987; White et al., 2009), for example by increasing leaf area. Measurements (Battie-Laclau et al., 2014a, 2016) as well as modeling approaches (Christina et al., 2015) in a field experiment manipulating throughfall and potassium (K) supply showed that a decrease in K fertilizer relative to current practices in commercial eucalypt plantations might help reduce tree water stress during drought through lower water use and increased water storage in deep soil layers during rainy seasons.

Concerns have been raised since the new millennium about the impact of highly productive eucalypt plantations on groundwater resources and stream flow in tropical regions (Cossalter and Pye-Smith, 2003; Farley et al., 2005). In a future drier climate, management practices should be adapted to maintain wood production while limiting adverse consequences on groundwater resources. Our study aimed to gain insight into the effects of contrasting K nutrition and water supply regimes on tree water use and water seepage under highly productive *Eucalyptus* plantations in tropical soils. We hypothesized that: (i) a decrease in rainfall reduces tree water use and groundwater recharge, but increases tree water stress and the depth of water uptake in the soil and (ii) a decrease in K fertilization could mitigate the adverse consequences of low precipitation on tree water stress and soil water resources.

2. Material and methods

2.1. Site description

The experiment was conducted at the Itatinga Experimental Station of the University of São Paulo in Brazil (23° 020S; 48° 380 W). From 2010 to 2014, the mean annual precipitation was 1578 mm yr^{-1}, with a drier year in 2014 (1189 mm yr^{-1}) at this site. The dry season lasted from June to September with a mean monthly temperature of 15 °C, and the rainy season was from October to May, with a mean monthly temperature of 25 °C and higher overall PAR. The experiment was located on a hilltop (slope $<$ 3%) at an altitude of 850 MASL. The soils were very deep Ferralsols ($>$ 15 m; Christina et al., 2011) developed on Cretaceous sandstone, with clay content ranging from 14% in the top soil to 23% in deep soil layers (Laclau et al., 2010).

The experiment was described in detail by -Laclau et al. (2014a). A split-plot experimental design was set up in June 2010 with a highly productive *Eucalyptus grandis* clone used in commercial plantations by the Suzano Company (São Paulo, Brazil). Two K fertilization regimes ($+/-$K) and two water supply regimes ($+/-$W) were applied in three blocks. The area of the individual plots was 864 m^2 (144 trees per plot). The four treatments were:

- $+$K$+$W: K fertilization (0.45 mol K m^{-2} applied as KCl) and no throughfall exclusion,
- $-$K$+$W: no K fertilization and no throughfall exclusion,
- $+$K$-$W: K fertilization and about 37% throughfall exclusion,
- $-$K$-$W: no K fertilization and about 37% throughfall exclusion.

K fertilizer was applied 3 months after planting and the amount was calculated to be a non-limiting factor at our study site (Almeida et al., 2010). Before fertilization, mean exchangeable K was ranging from 0.02 cmolc kg^{-1} in the upper soil layer and $<$ 0.01 cmolc kg^{-1} between 0.05 mbs and 15 mbs (Laclau et al., 2010). Other amendments (3.3 g P m^{-2}, 200 g m^{-2} of dolomitic lime and trace elements) were applied at planting for all treatments and at 3 months after planting (12 g N m^{-2}); this was not limiting for tree growth at this study site (Laclau et al., 2009). Manual weeding was done in the first months after planting and then glyphosate was applied before canopy closure to totally eliminate weeds in the experiment. Leaf cutting ants were controlled before planting using sulfluramide based baits. A manual hole was made for planting. Throughfall was excluded using panels made of clear, PAR-transmitting greenhouse plastic sheets mounted on wooden frames at a height of 1.6 m–0.5 m. Plastic sheets (37 cm in width) were set up in the throughfall exclusion plots to cover 37% of the area, and the throughfall exclusion amounted to $\sim$450 mm y^{-1}. Photographs of the design can be found in Battie-Laclau et al. (2014a,b).

Meteorological data were obtained from June 2010 to December 2014 using an automatic weather station placed at the top of a 21 m high tower located at 50 m from the experiment at a half-hourly time step. The following data were used as inputs to the MAESPA model: incident total short-wave radiation (RAD, W m^{-2}), air temperature (Tair, °C), relative humidity (RH, %), atmospheric pressure (Press, Pa), wind speed above the canopy (Wind, m s^{-1}) and precipitation (PPT, mm). Annual precipitations were 1834, 1622, 1714 and 1103 mm yr^{-1} in 2011, 2012, 2013 and 2014 (an exceptionally dry year), respectively.

Measured canopy transpiration was estimated using sap flow measurements at tree scale (see Battie-Laclau et al. 2016 for details) to be compared with model simulation. The sap flow density was measured from July 2011 to June 2013 in 10 to 13 trees, throughout the range of cross-sectional area in each treatment, at a 30-min time step, using a calibration equation determined in a preliminary study (Delgado-Rojas et al., 2010, slope = 0.97 and R^2 = 0.94 between predicted and measured values of tree transpiration). In each treatment, a linear regression was performed between the daily sap flow of each tree and the circumference at breast height (CBH). These regressions were then used