Forest Ecology and Management xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Forest Ecology and Management

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

Combining *Eucalyptus* wood production with the recovery of native tree diversity in mixed plantings: Implications for water use and availability

Nino Tavares Amazonas[a,*], David I. Forrester[b], Rafael Silva Oliveira[c], Pedro H.S. Brancalion[a]

[a] *Universidade de São Paulo, Escola Superior de Agricultura Luiz de Queiroz, Departamento de Ciências Florestais, Laboratório de Silvicultura Tropical, Avenida Pádua Dias, 11. CEP 13.418-900, Piracicaba, SP, Brazil*

[b] *Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Birmensdorf, Switzerland*

[c] *Department of Plant Biology, Institute of Biologia, University of Campinas, Caixa Postal 6109, CEP 13.083-970, Campinas, SP Brazil*

A R T I C L E I N F O

Keywords:
Atlantic Forest Restoration Pact
Ecophysiology
High diversity mixed plantation
Leaf water potential
Soil volumetric water content
Stomatal conductance

A B S T R A C T

Mixed forest plantations now emerge as an alternative to traditional plantations in the tropics and represent ecological gains associated with production, wood quality and nutrient cycling. Mixed plantations with higher diversity may also be advantageous concerning their use of soil water. To shed light onto water-related issues of mixing *Eucalyptus* and a high diversity of tropical native trees, we explored the following questions: What is the impact of high diversity mixed plantations of *Eucalyptus* intercropped with native trees on soil water? How does the mixture affect the physiology of water use in native trees? Firstly, we tested the hypothesis that stands of *Eucalyptus* mixed with a high diversity of native trees consume less water compared to *Eucalyptus* monocultures, by measuring the temporal dynamics of soil water. Secondly, we tested how mixing with *Eucalyptus* affects the hydraulic performance of fast- and slow-growing native species in these forestry systems. This is the first time a large experiment has been implemented to compare the effects of monospecific *Eucalyptus* plantations, native species mixtures and mixed plantations of *Eucalyptus* and native species on soil water dynamics under controlled conditions in terms of site, age, soil type, topography and climate. We found that high diversity mixed plantations of *Eucalyptus* and native trees use less soil water, than *Eucalyptus* monocultures. However, the soil under the mixtures was drier than in native species stands. The mixing with *Eucalyptus* affected the hydraulic performance of native species by decreasing the leaf water potential and stomatal conductance of the fast-growing species, suggesting that fast-growing species performance may be especially constrained by competition for water from *Eucalyptus*. These findings have important implications for forest management and ecological restoration in the tropics. They will help to further develop silvicultural options to adapt to climate change and improve plantation forestry by using mixed plantations for production purposes or rehabilitation of degraded lands.

1. Introduction

New silvicultural systems have been developed to meet the growing demand for forests of multiple uses (Lamb, 2005), including the emergent need to achieve environmental benefits allied to production (Stanturf et al., 2014). Mixed forest plantations now emerge as an alternative to traditional silviculture in the tropics, conferring ecological gains associated with production, wood quality, nutrient cycling and water use efficiency (Bouillet et al., 2013; Forrester, 2015; Forrester et al., 2006; Kelty, 2006; Piotto, 2008). These systems are more resilient and aggregate benefits associated with carbon-pool stability and other ecosystem services (Hulvey et al., 2013), but are often only preferred when their productivity is higher than that of monocultures. Higher productivity in mixtures is often achieved by combining a nitrogen fixing tree (e.g. *Acacia* species) with non-legume trees used for wood production, to take advantage of the higher nutrient inputs supplied (Bouillet et al., 2013). However, two-species mixed plantations designed for wood production make minimal contributions to biodiversity conservation. This may be increased with the offer of economic incentives associated with the additional values of these systems, such as payments for ecosystem services like biodiversity conservation, carbon storage, or water regulation, to compensate for lower yields (Brancalion et al., 2012).

The high productivity of *Eucalyptus* plantations, the most important commercial genera in the tropics (Del Lungo et al., 2006), is associated with a high demand for water (Whitehead and Beadle, 2004). Water

* Corresponding author.
E-mail addresses: namazonas@gmail.com (N.T. Amazonas), david.forrester@wsl.ch (D.I. Forrester), rafaelsoliv@gmail.com (R.S. Oliveira), pedrob@usp.br (P.H.S. Brancalion).

https://doi.org/10.1016/j.foreco.2017.12.006
Received 1 July 2017; Received in revised form 15 November 2017; Accepted 2 December 2017

Please cite this article as: Tavares Amazonas, N., Forest Ecology and Management (2017), https://doi.org/10.1016/j.foreco.2017.12.006

supply is a key resource determining the productivity of *Eucalyptus* plantations in some regions (Stape et al., 2010) and climate change may negatively affect the hydraulic performance of trees and plantations in regions where it increases temperatures, decreases precipitation and causes soil moisture drought (IPCC, 2015), ultimately compromising wood production and increasing the susceptibility of these forests to die-off (Allen et al., 2010). *Eucalyptus* can obtain water from deep soil layers (Christina et al., 2017) from the early stages of stand development, but may depend on precipitation and moisture of superficial soil layers at the end of the rotation when deep soil layers have dried out (Nouvellon et al., 2011). Other species have different ecological strategies and demand less water. Increasing species diversity in plantations could thus lead to complementary resource use by trees and a decrease in water demand at the stand level, reducing vulnerability to droughts caused by climate change and resulting in more sustainable wood production.

To examine how the water use and physiological performance of native species are affected by mixing with *Eucalyptus* or a high diversity of tropical native trees, we explored the following questions: What is the impact of high diversity mixed plantations of *Eucalyptus* intercropped with native trees on soil water? How does the mixture affect the physiology of water use in native trees? We tested two hypotheses related to the water use strategies of trees in the tropics, with implications for forest management and restoration. Firstly, we tested the hypothesis that stands of *Eucalyptus* mixed with a high diversity of native trees consume less water compared to *Eucalyptus* monocultures, by measuring the temporal dynamics of soil water. We expected intermediate values of soil water content in mixtures compared to *Eucalyptus* monocultures (drier soils) and native species stands (wetter soils). Secondly, we examined whether the mixing with *Eucalyptus* affects the hydraulic performance of fast- and slow-growing native species, by assessing the leaf water potential and the stomatal conductance of model species. We expected to find a decreased hydraulic performance of native trees. There is a widespread concern in society about the impact of *Eucalyptus* monoculture plantations on the conservation of water resources, and natural forests that grow more slowly are believed to have smaller impacts. Reliable information on water use by native and exotic trees derived from controlled experiments is, however, limited. This is the first time a large experiment has been implemented to compare the effects of monospecific *Eucalyptus* plantations, native species mixtures and mixed plantations of *Eucalyptus* and native species on soil water dynamics under controlled conditions in terms of site, age, soil type, topography and climate.

2. Material and methods

2.1. Study site

The experimental site is located in Aracruz, ES, Brazil, (19°49′12″S, 40°16′22″W), within the Atlantic Forest region, managed by Fibria Celulose S.A. The site has a flat relief with a typical Yellow Argisol (Ultisol) presenting a sandy/medium/clayey texture. The region has a tropical climate with a dry winter (Aw) (Köppen, 1936) and a hot wet summer, with annual average temperature of 23.4 °C and annual average rainfall of 1,412 mm (Alvares et al., 2013). Historically, the region experiences a water deficit from February to September (Sentelhas et al., 2013). Precipitation was markedly lower during the period we measured soil moisture compared to historical averages (Supplementary Fig. 1). The weather data from the meteorological station of the seedling nursery located approximately 12 km from the experimental site is shown in Supplementary Fig. 2.

2.2. Experimental design and characteristics of the forests

The experiment had a randomized block design, with three treatments and five blocks (15 plots). Each plot consisted of 10 rows of 24 trees, including two outer rows as borders. Each effective plot measured 18 m × 60 m (1080 m^2) and included six rows of 20 trees. The three treatments included a *Eucalyptus* monoculture (hereafter EUC); a mixed plantation of *Eucalyptus* intercropped with 30 native tree species, in alternating single rows (hereafter MIX); and native species plots consisting of 10 native pioneer species (instead of *Eucalyptus*) intercropped with the same 30 native tree species, in alternating single rows (hereafter NAT). In the mixture or native species treatments, half of the seedlings were *Eucalyptus* or 10 native pioneers, and the other half were seedlings from 30 native tree species (diversity group) common to both treatments. The site was planted in July 2011 using a 3 m × 3 m spacing at a density of 1,111 trees ha^{-1}. The *Eucalyptus* used was a clone of *E. grandis* x *E. urophylla*. All seedlings were planted at the same time using the same silvicultural techniques that are commonly used in *Eucalyptus* plantations in the region (fertilization according to the nutritional demands of *Eucalyptus* to local soil conditions, weed control using glyphosate spraying, and ant control using insecticide baits). All treatments had the same spacing in between rows and trees within rows. To control for the variability of neighborhood effects, each native species was planted in the same position within all plots. The list of species used in each treatment is shown in Supplementary Table 1. We used inventory data to estimate aboveground woody biomass as a proxy for production. At 57 months after plantation, we measured the diameter at breast height (DBH) at 1.3 m and total height of all live trees. For multi-stemmed individual trees, we measured the largest five stems. To estimate the aboveground biomass of native trees, we used equations published for native species growing in restoration sites of similar age (Ferez et al., 2015). For *Eucalyptus* biomass, we used equations developed by Rocha (2014). *Eucalyptus* monocultures produced the greatest biomass (93.2 Mg ha^{-1}), followed by mixtures (85.2 Mg ha^{-1}; 81.6 from *Eucalyptus* and 3.6 from native trees in the diversity group) and native species plots (9.3 Mg ha^{-1}; 5.6 from pioneers and 3.7 from trees in the diversity group).

2.3. Soil volumetric water content

Soil volumetric water content was measured weekly for one year (from May 2015 through June 2016) in 30 positions, two in each plot, including the three treatments and covering all seasons. We installed tubes and used a portable device (Diviner 2000, Sentek) to measure soil volumetric water content (Sentek Pty Ltd., 2009) for every 10-cm soil layer down to 1.3 m.

2.4. Xylem water potential and stomatal regulation

Two native species with contrasting growth rates were chosen as model species for the ecophysiological traits, each of which had high survival rates and equal numbers of individuals (only one native tree missing). We chose two Fabaceae to reduce the effect of genetic distance on physiological behavior. *Paubrasilia echinata* Lam. is a slow-growing, late-successional species, while *Mimosa artemisiana* Heringer & Paula is a fast-growing species with traits common to early-successional tree species. We measured two individuals per plot (20 trees of each species). *Eucalyptus* trees were too tall to measure using the resources available for this study. We measured the DBH of all individuals of these species used for the measurement of ecophysiological traits at age 47 months to relate DBH differences between treatments (mixing effect) to differences in hydraulic performance. We compared xylem water potential (Ψ_{xylem}) and stomatal conductance (g_s) of the model species intercropped with *Eucalyptus* with trees in native species plots. We estimated xylem water potential (MPa) using a pressure chamber (model 600, PMS Instrument Company), by measuring the water potential of leaves detached from small branches (< 2 cm diameter) in the outer part of the middle third of the crown, facing south and shaded. Leaf water potential tends to vary considerably within complex canopies because of contrasting light conditions, so our leaf sampling was