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Water use and wood productivity of *Eucalyptus grandis* plantations: effects of management, water supply and soil texture

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Thesis presented to obtain the degree of Doctor in Science. Area: Forest Resources. Option in: Silviculture and Forest Management

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versão revisada de acordo com a resolução CoPGr 6018 de 2011

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1. Uso da água 2. Eficiência do uso da água 3. Fotossíntese 4. Plantações de eucalipto 5.Condutância estomática 6. Condutância estomática I. Título

RESUMO

Uso da água e a produtividade de plantações de *Eucalyptus grandis*: efeito do manejo e das características do solo

A alta produtividade das florestas de *Eucalyptus* sp está diretamente associada aos recursos disponíveis no ambiente como água, nutrientes e luz, como também pelo uso eficiente dos recursos por diferentes genótipos. Diversos trabalhos foram realizados sobre o uso da água das florestas de eucalipto. Pesquisadores e gestores florestais sempre são questionados sobre o uso da água e a eficiência do uso da água pelas florestas de eucalipto. Diversos trabalhos mostraram que o uso da água em florestas de eucalipto podem alcançar 1100 mm a 1300 mm. No entanto, essas estimativas podem variar em função das condições edafoclimáticas e de manejo da floresta O objetivo principal dos estudos atuais é entender a dinâmica do ciclo da água em diferentes escalas da floresta, na folha, a árvore e na escala da bacia hidrografica. Alguns estudos vêm mostrando que a adubação, em particular com potássio, também pode aumentar a demanda de água por parte das árvores.O K propicia aumento de biomassa foliar e IAF das plantas, sugerindo aumento da transpiração das árvores. Estudos na escala da bacia hidrográfica, mostraram que bacias hidrográficas ocupadas por florestas de eucalipto podem reduzir o fluxo superficial dos cursos da água como também o estoque de água nas diferentes camadas do solo, o que pode comprometer a disponibilidade hídrica numa escala local. Por outro lado, alguns trabalhos mostraram que os impactos das florestas plantadas nos recursos hídricos dependem do regime pluviométrico local. Outros fatores podem influenciar o uso da água pelas florestas tais como a capacidade de retenção de água no solo, condições atmosféricas, espaçamento e genótipos. O principal objetivo dos gestores florestais, frequentemente, tem sido a busca por uma técnica de manejo florestal que permita o alcance de altas taxas de produtividade dos genótipos plantados. Atualmente, o manejo florestal não leva em conta a disponibilidade dos recursos ambientais, principalmente a água por meio do regime pluviométrico. Essas estratégias são importantes para aumentar a sustentabilidade das florestas plantadas, principalmente em áreas em que a disponibilidade de água é crítica. A compreensão da dinâmica dos parâmetros fisiológicos pode ajudar os gestores florestais a entenderem as respostas das árvores em função das condições climáticas e planejar estratégias que possam aumentar a sustentabilidade dos plantios florestais de *Eucalyptus* sp.

Palavras-chave: Uso da água; Eficiência do uso da água; Fotossíntese; Plantações de eucalipto; Condutância estomática; Condutância estomática.

ABSTRACT

Water use and wood productivity of *Eucalyptus grandis* plantations: effects of management, water supply and soil texture

Water availability is a strategy resource for forest plantation. Many authorities and researches are concerned about the water use and the impact of forest plantation. Water use and water use efficiency have been measuring in all over the world. High productivity of Eucalyptus sp plantation are depend of environmental resources such water, nutrients, light and also genotype resource efficiency. High water use is also associated with high productivity and water use efficiency. Many reports were published about water use in eucalyptus plantation. Water use might vary among 1100 mm to 1300 mm for eucalyptus plantation. Climate conditions, soil characteristics and forest management might influence water use. Currently, studies aim to understand hydrology cycle at the leaf, trees and on landscape scale. Previous studies showed that K fertilizer increase water demand. Leaf biomass and LAI also increase due to K fertilizer application, which suggest increase in water use. Eucalyptus forest plantation may also decrease water discharge in catchment, which might decrease water availability in local scale. However, transpiration varied within soil moisture, precipitation, temperature, atmosphere conditions, fertilizer application, genotype and latitude. The main objective of forest managers was often find a technique regime which forester may use to achieve the target growth rate. Nowadays, it is important to manage the forest taking to account local resource supply, local climate condition and resource availability. These strategies might increase the sustainability of forest plantation. Measurement of physiological functioning might help forests manager to understand the growth response of our forest as result of climate condition and also planing new strategies to increase forest sustainability.

Keywords: Water use; Water use efficiency; Photosynthesis; Eucalyptus forest management; Water deficit; Stomatal conductance

LIST OF ABREVIATION

MAI – Mean annual increment (m^3 ha^{-1} ano^{-1})

VPD – Vapour pressure déficit (kpa)

LAI – Leaf area index

LMA – Leaf mass area

WUE – Water use efficiency (kg m^{-3})

WUE_{ab} – Water use efficiency for aboveground biomass (kg m^{-3})

WUE_p- Water use efficiency for stemwood (g DM kg^{-1} H_2O)

GPP- Gross primary production

DBH – Diameter at breast height

Et- Evapotranspiration (mm)

ET_{EC} – Evapotranspiration measured by Eddy Covariance (mm)

T_{SF} – Transpiration measured by Sap Flow (mm)

ET_{TDR} – Evapotranspiration measured by Time Domain Reflectometer (mm)

PPFD- Constant photosynthetic photon flux density (µmol m^{-2} s^{-1})

1. INTRODUCTION

Eucalyptus productivity increased by a factor of 4 from 1970 to 2015, due to intensification of management, genetic improvements (Resende et al., 2012) and better silvicultural practices (Gonçalves et al., 2004). Eucalyptus forest plantation are among the most productive forest in the world. In Brazil, the majority plantation are locate on Tropical and Subtropical regions (Flores et al., 2016; Stape et al., 2010). Stem production across tropical region are among 9 to 45 Mg ha^{-1} $year^{-1}$ and 19 to 44 Mg ha^{-1} $year^{-1}$ on subtropical regions (Binkley et al., 2017).

Eucalyptus stands are planted on a short rotation (6-8 years) for pulp and paper and also for biomass (4 years). After the clear-cut, coppice management is common worlwide. Historically, Brazilian Eucalyptus coppice management consisted of three cycle, which one high forest clear cut followed by two coppice clear cuts (Souza, 2001). However, at high quality sites there are also possible to manage the forest for three to four cycles (Gonçalves et al., 2008). Two cycles of coppice management have been considering profitable and also lower establishment cost (Rezende et al., 2005). The silvicultural technology used minimum cultivation methods and high fertilizer rates. Both silvicultural technology guarantees similar wood production volume to those at first rotation (Gonçalves et al., 2008).

High growth rates and high forest productivity are result from genetic improvement and also silvicultural pratice such as site preparation, fertilization, spacing and weed control (Gonçalves et al., 2013). Climate and environmental characteristics influences the growth of planted forest of Eucalyptus. Water, nutrients and light are the main factors which affect forest productivity (Landsberg and Waring, 2014). In particular, water availability might limit tree growth in many tropical regions. A study conducted in the state of Bahia, Brazil, showed that double precipitation to 800 mm year-^{1} to 1600 mm $year^{-1}$ led to a 3-fold increase in wood growth, from 10 Mg ha^{-1} $year^{-1}$ to 30 Mg ha^{-1} $year^{-1}$ (Stape et al., 2004a). Suplemental water within sites increases Eucalyptus wood growth by 20-80% (Ryan et al., 2010; Stape, 2010). Hence, environmental changes in the future will determine the high rates of Eucalyptus growth. Water availability and annual precipitation regime may alter gross primary production and wood production by one-third to one-half (Stape et al., 2008). Regional changes in climate might change regional production (Binkley et al., 2017).

The main objective of forest management was often to maximizing forest productivity by manipulating resource supply, capture and resource use by the forest. The selection of the best genetic materials takes into account biotic and abiotic resistance and wood quality of materials (Mafia, 2016). Silvicultural researches improved our understanding about the responses of tree growth and wood quality to soil quality, fertilizers, spacing, weed control and soil preparation, which result high rate of growth for Eucalyptus plantation (Gonçalves et al., 2004).

Many sites currently used for Eucalyptus production were selected based on their ability to sustain forest productivity. The effect of silvicultural practices on physiological processes have been widely studied, especially the relationship between tree growth and environmental resource seasonality (Battie-Laclau et al., 2016; Binkley and Stape, 2004; Stape et al., 2010). Water, nutrients and light are the main factors that limit forest productivity. All these factors have a strong effect on tree physiological functions and forest productivity.

Water is important to physiology of plants and its also crucial role in all physiological process. It is responsible to transport carbohydrates, nutrients and phytohormones which are required for growth. Plants require a vast quantity of water. Aproximately 90% of N, P and K are absorbed and 10% to 70% of photosynthetically fixed carbon into new tissues. Water retained on biomass are less than 1%. The remainder is lost by transpiration (Lambers, 1998; Landsberg, 1999; Taiz and Zeiger, 2013).

Water is an important factor affecting forest productivity. Fast growth species, generally have high water use, which raises questions regarding both the ecological impacts of plantations and sustainability of wood production

(Lima, 2011). These questions are important for forest sector. Quantifying both the water use and water use efficiency of fast-growing plantations in contrasting environmental contexts and management is thus a major research goal. Water use efficiency quantify the productivity of forest per amount of used water. It is therefore a good indicator of tree performance (King et al., 2013; Lévesque et al., 2014). Water use efficiency has been shown to vary across environmental conditions. It may be estimated at various spatial and temporal scales (Binkley and Stape, 2004).

Fast growth rates are commonly associated to high water use. Measurement of rainfall was correlated with mean annual increment (MAI), suggesting that water availability controls productivity in tropical regions. Many studies recognized the role of water in the control of forest productivity (Gonçalves et al., 2004; Santana et al., 2000; Stape et al., 2004b) but research quantifying water use and how it vary at different climate condition and contrasted soil texture are still unknown.

Water use by an Eucalyptus plantation in Southern Brazil has been shown to be 587 mm year^{-1}, 1397 mm year^{-1}, 1597 mm year^{-1}, 1491 mm year^{-1} and 1081 mm year^{-1} in the first 5 years after planting (Christina et al., 2016). Similar results were also reported in other experiments in Brazil such as 1371 mm year^{-1} (Battie-Laclau et al., 2016; Stape, 2010). Different results were also obtained in other studies in different environmental conditions (Forrester et al., 2010b; Hubbard et al., 2010, 2004). Vapour pressure deficit (VPD) and leaf area index (LAI) influence transpiration rate. VPD is the evaporative demand which determine evaporative rates from the forest canopies. It is also depend from energy balance, wind speed and radiant energy flow rates across the foiliage. Transpiration will be faster from forest canopies with large amounts of foliage (Landsberg and Waring, 2014) .

Large amounts of fertilizer are applied in Eucalyptus commercial plantations to reach high productivity (Battie-Laclau et al., 2016). In particular, potassium showed increase LAI (Stape, 2002), photosynthesis, stomatal regulation and transpiration (Battie-Laclau et al., 2014b, 2014a; Taiz and Zeiger, 2013; Whitehead and Beadle, 2004a) and also to change leaf water potential (Battie-Laclau et al., 2016). Potassium supply may also change nutrient use efficiency, light use efficiency (Christina et al., 2015; Stape et al., 2004b) and water use efficiency (WUE) (Battie-Laclau et al., 2016, 2014b, 2013; Laclau et al., 2009). Wood production, gross primary productivity (GPP) and photosynthetic capacity was also increase by potassium fertilization (Battie-Laclau et al., 2014a).

Potassium supply increased canopy transpiration and water use efficiency for stemwood production by 1.7 and 60%, respectively, 2 year after planting in a Eucalyptus plantation of Southern Brazil (Battie-Laclau et al., 2016). Water use efficiency results have shown ranged 1.1 to 1.9 stemwood m^{-3} of water transpired for potassium fertilizer. These results were corroborated by other experiments (Stape et al., 2004b). Resource use efficiency have been shown positively correlate with growth rate in tropical Eucalyptus forest plantations. Breeding programs have tried to select trees with high growth rates, which may have in turn led to select trees with high water use efficiency for stemwood production (Battie-Laclau et al., 2016).

A growing body of evidences suggest that intensive management practices aiming to increase the productivity of Eucalyptus plantations also increase resource use efficiency, including light use efficiency (Binkley and Stape, 2004; Campoe et al., 2012), water use efficiency and nitrogen use efficiency (Binkley and Stape, 2004). However, it remains clear that the total amount of ressource use by trees also increases with forest productivity (Battie-Laclau et al., 2014b).

Many authorities are concerned with the high rate of water use by eucalyptus plantation. Some strategies have been discussed to improve land-use management at the watershed scale with the objective to decrease total water use (Lima, 2011). Forest plantations and water resource are at the center of political concerns due to the potential strong impact of Eucalyptus plantations on water resource at regional scale (Lima, 2011). The impact of Eucalyptus plantations on water resource has however to be apreciated in the light of local environemental context.

Many strategies have been proposed to reduce the envionmental impact of fast-growing forest plantations, including the creation of reserves for native habitats, mosaics of natural and exotic vegetation, longer rotation length and management for multiple use on land use planning (Gonçalves et al., 2017). At the stand level it has been proposed alternative genetic materials and lower stocking density (Ferraz et al., 2013; Hakamada et al., 2017). Researchers have recommended to revisiting the management of Eucalyptus plantations, taking into account the characteristics of local area to reach the best trade-off among ecosystem services and wood production.

In the future, sustaining eucalyptus forest productivity under climate change will be the main challenge of practitioners. Research on climate change have predicted reduction in rainfall in most tropical regions, where forest Eucalyptus plantation are concentrated (IPCC, 2013). More intense and frequent drought periods will affect these plantations, which might reduce tree growth and pattern of water use (Wu et al., 2011). Drought events might reduce Eucalyptus plantation yield by as much as one third over the six to seven year of a commercial rotation in Brazil (Almeida et al., 2010). In addition to this, Eucalyptus plantations might be exposed to higher fire hazard and pest infestation. Elevated temperature and CO_2 concentration will also have independent impacts on Eucalyptus trees physiology (Booth, 2013). However, the interacting impacts of these various factors on forest productivity remain unknown. Adaptive strategies should be adopted by forest managers to overcome the challenges brought by climate change for sustainable wood production (Booth, 2013).

There are some gaps about the relationship of water use and water use efficiency in two contrasted soil texture and also physiological studies about Eucalyptus coppice management. It is defined two chapters on this thesis. In the first chapter, the objective is to evaluate the effect of soil texture (clayish and sand soil) on stand characteristics, water use and water use efficiency and comparison between Sap Flow measurements, Time Domain Reflectometer and Eddy Covariance system. The second chapter will address stand characteristics, water use and water use efficiency for stemwood production, photossynthetic rates, transpiration and intrisic water use efficiency on Eucalyptus plantation manage for coppice. The chapter are:

1) Effects of soil texture on transpiration and water use efficiency for stemwood production in a commercial Eucalyptus plantation.
2) Effect of potassium and water supply on productivity and water use in *Eucalyptus grandis* plantation managed as coppice.

With these two chapters, I expect to partially discuss the gaps of knowledge about the relationship of water, use and soil texture in commercial Eucalyptus stands and analyze the effect of potassium fertilizer applycation on psysiological parameter on Eucalyptus manage for coppice.

2. CONCLUSIONS

Chapter 1: Effects of soil texture on transpiration and water use efficiency for stemwood production in a commercial Eucalyptus plantation.

Water use and water use efficiency at the clayish and sandy soil was similar. Soil texture between the sites was not sufficient to modify the transpiration at the tree scale. Volume, Abouveground biomasss, Sapwood area, sapwood increment, leaf area index was also similar between clayish and sandy soil;

Sap flow and Time Domain Reflectometer underestimate transpiration and evapotranspiration compare to Eddy Covariance System. Sap Flow is subject to some errors such as electrical supply. Electrical supply has to be well dimensioned. This technique is useful to estimate water use and to understand physiological response at the stands from the environment. Time Domain Reflectometer is also limited and might be subject to some errors based on infiltration and deep drainage and dependent of the type of soil. Eddy covariance has the capacity to measure evapotranspiration of eucalyptus forest plantation. This technique might adequately quantify water use and reduce uncertainties.

Water use efficiency and water use are important for forest planning at the land scale. There are few information about the water use and water use efficiency in different climate and species of *Eucalyptus* sp. Information about water use and water use efficiency are important to understand the relation of forest growth, resource use and resource use efficiency.

Chapter 2: Effect of potassium and water supply on productivity and water use in *Eucalyptus grandis* plantation managed as coppice.

Our study did not find different result between forest manage for coppice and seed-origin-plantation. Both type of management showed the same magnitude of stemwood, annual net primary productivity and leaf net primary productivity at 1 to 2 years after clear-cut. These results suggest that root system development in deep soil layer might be an advantage for water and nutrient absorption in the initial regeneration. Tree carbon allocation in forest manage for coppice might be partioning in leaf, branches and on stemwood production. However, carbon allocation in seedling forest stand might be partionining among below and aboveground biomass. Potassium fertilized application improve production of aboveground biomass. Throughtfall exclusion did not affected significantly aboveground production. Potassium fertilized plot with throughfall exclusion (K-W) produce less aboveground biomass than K fertilized plot without throughtfall exclusion (K+W).

Stand water use was highest for all K fertilized application in forest manage for coppice. However, water use was less than forest stand seedling measured in the previous study. Water use efficiency for stemwood was similar on the initial growth phase of forest manage for coppice. The difference above water use among forest management is due to tree diameter and stock density on forest manage for coppice. Not all stumps regenerated even in K fertilized plot. The dominate sprout on the stump was left to regrowth. In addition to this, the sprouts was not uniform for all plot. Forest manage for coppice use less water than seedling forest stands, approximately 18% less water use than seedling forest stand. Our estimation of transpiration might be understimate due to electrical problems. Hence, the first hypothese of this study was not confirmed.

Leaf water potential in dry season range -2.1 and -2.4 MPa in K fertilized plot and was more pronunced at the throughfall exclusion on dry season. This result was similar to the previous study. Both treatment on K fertilized plot showed highest leaf water potential than control plot, suggesting that potassium fertilizer application might increase water stress and water demand by the tree. The second hypotheses was confirmed.

Stand water use was higher on both plot fertilized by K application, suggesting that K fertilized increase water demand by the trees. This result was similar to the previous studies. The results have shown that water use were less K fertilizer plot with water exclusion than on K fertilized without water exclusion. Troughfall exclusion might decrease water availability for water absorption. Leaf water potential reached -2.4 MPa on dry season, suggesting that both treatments with potassium fertilizer have shown increase in water demand by fertilization. Hence, the third hypothese was not confirmed in this study.

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