University of São Paulo
“Luiz de Queiroz” College of Agriculture

Climate and forest plantation: the carbon storage and energy biomass production in Southern Brazil

Felipe Schwerz

Thesis presented to obtain the degree of Doctor in Science. Area: Crop Science

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CONTENTS

RESUMO

Clima e plantios florestais: o armazenamento de carbono e a produção de biomassa para energia no sul do Brasil

A busca por fontes alternativas de energia tem se mostrado uma demanda global. Motivado pela preocupação com as mudanças climáticas e pelo esgotamento dos recursos naturais, o mercado mundial tem despertado interesse no estudo e adoção de fontes alternativas renováveis de energia. Uma das alternativas possíveis é o uso da biomassa florestal. Neste contexto, surge a necessidade da realização de estudos que busquem avaliar o crescimento e produtividade de diferentes espécies florestais cultivadas em diferentes espaçamentos de plantio. Desse modo, os objetivos deste estudo são: (i) avaliar a produção de biomassa para energia; (ii) determinar a estocagem e partição de carbono no sistema florestal (biomassa florestal + solo); (iii) determinar a eficiência do uso da radiação solar da espécie *Eucalyptus grandis*; and (iv) caracterizar a composição elementar e as propriedades de quatro espécies florestais *Eucalyptus grandis*, *Mimosa scabrella*, *Ateleia glazioviana* e *Acacia mearnsii* cultivadas em quatro espaçamentos de plantio no sul do Brasil. Um experimento de campo foi realizado de setembro de 2008 a setembro de 2018 na cidade de Frederico Westphalen, Brasil. A biomassa florestal foi determinada pelo método destrutivo. Também foram avaliados o poder calorífico, composição elementar, análise química imediata, eficiência do uso da radiação, coeficiente de extinção luminosa, a interceptação da radiação solar, o índice de área foliar, o particionamento de biomassa, o armazenamento de carbono e o rendimento energético potencial. As informações geradas neste estudo são relevantes e fornecem informações importantes para empresas interessadas na geração de eletricidade a partir de biomassa florestal e produtores florestais, uma vez que auxiliam no planejamento da escolha do espaçamento ótimo a ser utilisado para produção de biomassa para energia. A maior produção de biomassa, armazenamento de carbono e eficiência de uso de radiação foi obtida para a espécie *Eucalyptus grandis* cultivada no espaçamento de plantio (2,0×1,5 m), que resultou em maior quantidade de biomassa para produção de energia. Para as demais espécies florestais, o espaçamento ótimo de plantio para produzir biomassa para energia foi (2,0×1,0 m). Portanto, o uso de espaçamento reduzido de árvores deve ser priorizado e recomendado para futuras explorações de plantações de energia florestal.

Palavras-chave: Biomassa florestal; Carbono; Energia; Espaçamento de plantio

ABSTRACT

Climate and forest plantation: the carbon storage and energy biomass production in Southern Brazil

The search for alternative sources of energy has shown to be a global demand. Motivated by concern about climate change and the depletion of natural resources, the world market has attracted interest in the study and adoption of alternative renewable sources of energy. One possible alternative is the use of forest biomass. In this context, it is necessary to carry out studies that seek to evaluate the growth and yield of different forest species cultivated at different planting spacings. The aim of this study were: (i) to evaluate the production of biomass for energy; (ii) to determine carbon storage and partitioning in the forest system (above-belowground biomass + soil); (iii) to determine the radiation use efficiency of *Eucalyptus grandis*; and (iv) to characterize the elemental composition and properties of four forest species *Eucalyptus grandis*, *Mimosa scabrella*, *Ateleia glazioviana*, and *Acacia mearnsii* grown in four planting spacings in Southern Brazil. A field experiment was conducted from September 2008 to September 2018 in the city of Frederico Westphalen, Brazil. The forest biomass was determined by destructive method. Also, the calorific value, elemental composition, immediate chemical analysis, radiation use efficiency, light extinction coefficient, solar radiation interception, leaf area index, biomass yield and partitioning, carbon storage and potential energy yield were evaluated. Information generated in this study is relevant and provides information for companies interested in electricity generation from forest biomass and forest producers thereby assisting in the planning of optimal spacing to be used for biomass production for energy. The highest biomass production, carbon storage, and radiation use efficiency were obtained in the planting spacing (2.0×1.5 m) for the *Eucalyptus grandis,* which resulted in a higher amount of biomass for energy production. For the other forest species, the optimal planting spacing to produce biomass for energy was the (2.0×1.0 m). Therefore, the use of reduced planting spacing should be prioritized and recommended for future exploitation of forest energy plantations.

Keywords: Forest biomass; Carbon; Energy; Planting spacing

1. INTRODUCTION

The use of renewable energy sources is becoming increasingly necessary, if we are to achieve the changes required to address the impacts of global change and increase the environment protection. Of the renewable energy sources, forest biomass appears to be the most important in terms of technical and economic feasibility in the coming decades (HALL; HOUSE, 1994; BHATTACHARYA et al., 2003; MOLA-YUDEGO et al., 2017; WELFLE, 2017; FERREIRA et al., 2018; HAMMAR et al., 2019).

Forest biomass is one of the most promising strategies for the generation of renewable energy in Brazil (FAÉ GOMES et al., 2013; LOPES et al., 2016; FERREIRA et al., 2018). In this context, new studies involving forest species that present an energetic potential, such as *Eucalyptus grandis*, *Mimosa scabrella*, *Ateleia glazioviana*, and *Acacia mearnsii* are important for the Brazilian energy chain. Currently much attention has been focused on identifying and characterizing suitable forest biomass species and its essential characteristics, regarding ecological, silvicultural and structural factors, and those related to the energy potential of forest biomass in order to provide high-energy outputs, to replace conventional fossil fuel energy sources.

In this context an important question arises: When fossil fuels are depleted, will forest biomass converted to energy-fuel for several needs be enough to provide the energy needs of future generations? Certainly, forest biomass alone will not meet all the energy demand, however, together with different kinds of bioenergy (ESEN; YUKSEL, 2013; OH et al., 2010 et al., 2017; JHA; PUPPALA, 2017; SHUBA; KIFLE, 2018; MENDOZA MARTINEZ et al., 2019) that have been deeply investigated, produced and used in the last years, can provide a large amount of energy-fuel worldwide. According to GUO et al. (2015), bioenergy will provide 30% of the world's energy demand by 2050. The contribution of renewable resources in the Brazilian energy chain is among the highest worldwide, which corresponds to 43.5% of total energy demands in 2016 (EPE, 2017). Brazil have been conducted research for large-scale production of energy derived from wood, investing in fast-growing forest plantations dedicated to the production of wood for energy (forest energy plantations).

The concept of forest energy plantations was introduced in the 1980s to define forest plantations with a large number of trees per hectare in a short-rotation cycle, whose purpose is to produce the largest volume of biomass per unit area and time (COUTO; MÜLLER, 2008). Moreover, forest energy plantations play an essential role in the carbon (C) storage, from the capture and storage of this gas in the form of forest biomass. According to LACLAU (2003), fast-growing forest plantations are considered highly efficient carbon sinks capable of contributing to the mitigation of the increase of CO_2 levels in the atmosphere. Forest biomass for energy generation is considered nearly carbon neutral (KUMAR et al. 2006; THAKUR et al., 2014) because the amount of CO_2 released during combustion is nearly the same as taken up by the tree during growth.

The use of woody biomass as energy-fuel source provides substantial benefits as far as the environment is concerned (DEMIRBAS, 2004; VASSILEV et al., 2010). Biomass absorbs carbon dioxide during growth and emits it during combustion offering the advantage of a renewable and CO_2-neutral fuel. Therefore, biomass helps the atmospheric carbon dioxide recycling and does not contribute to the greenhouse effect (DEMIRBAS, 2004). The characterization of composition, properties and quality of a given biomass source is the initial and most important step during the study and application of this feedstock for energy generation. For example, data from structural, gross calorific value, proximate and ultimate analyses have been used to characterize biomass sources (VAN LOO; KOPPEJAN, 2008; SAIDUR et al., 2011).

Forest energy plantations can be considered as an important sink of C of the atmosphere. Moreover, forest plantations are capable of storing large amounts of CO_2 in a relatively short period of time. This is related especially with the forest species capacity to store carbon in their structure (wood, branches, leaves, roots). Carbon storage in forest plantations involves numerous components including biomass C and soil C. Management systems that maintain a continuous canopy cover are likely to achieve the best combination of high wood yield and C storage (THORNLEY; CANNELL, 2000; LAL, 2005). In this context, it is important to understand and quantify the carbon stored and partitioned in the system as a whole, i. e., soil stocks and forest biomass, including roots biomass, of the different forest species studied. Moreover, there is a lack of information about the carbon storage and partitioning in forest energy plantations.

In order to meet global energy demand and enhancing sinks for carbon storage to mitigate the climate change, new research is needed to study forest energy plantations, considering different forest species growing on different planting spacings in order to evaluate the potential for carbon storage and forest biomass production. According to COUTO; MÜLLER (2008) and WELFLE (2017), the forest management aimed the production of biomass for energy, basically consists of choosing the appropriate species, managing the tree density and planting spacing and the rotation time of the forest plantations.

The planting spacing is a primary factor in the production of forest biomass. The most used spacing for biomass production for energy are those that provide a useful area varying from 3 m² to 9 m² (COUTO et al., 2002). The use of reduced planting spacing is being extensively studied and disseminated due to the benefits provided (NJAKOU DJOMO et al., 2015; EISENBIES et al., 2017). The tendency of reduce the planting spacings for biomass production is highlighted by the need to reduce the crop cycle, resulting in gains in productivity, time and cost with forest management (GONÇALVES et al., 2004; GUERRA, 2012).

Forest management for wood production is carried out mainly by companies and rural producers. The basically management regime adopted by them is planting with spacing of 3 × 2 m and shallow-cut between the 6^{th} and 8^{th} year (STAPE et al., 2001; GONÇALVES et al., 2013). In this context, the authors proposed in this study to evaluate the feasibility of the use of reduced planting spacings (greater number of trees per unit of area), whereas trees grown in these spacings can maximize the solar radiation interception, carbon storage and increase the biomass production for energy. Forest managers can accelerate growth and increase the production of forest biomass by manipulating available natural resources, especially solar radiation, using adequate planting spacing.

Climate conditions have a great influence on tree growth and yield. There is great interest in how plants interactions in different spacings change along spatial gradients in resource availability, especially in solar radiation interception and radiation use efficiency. In a forest production system, the tree growth happens as a function of accumulated biomass through photosynthesis. The biomass yield in plants depends especially upon the quantity of absorbed radiation by leaves, and the efficiency by which can convert and assimilate the light through photosynthesis (LARCHER, 2003).

Incident solar radiation can be a limiting factor for plant growth and development, which affect photosynthetic biomass accumulation according to the planting spacing. Thus, the conversion of the intercepted photosynthetically active radiation into biomass shows the solar radiation use efficiency of the plant (εb) (MONTEITH; MOSS, 1977). The conversion of solar radiation into biomass is also affected by the leaf area index, which can change according to the plant distribution in the field (SANQUETTA et al., 2014b). Plant biomass accumulation is dependent on the intercepted photosynthetically active radiation and efficiency of the conversion of solar radiation into photoassimilates (BEHLING et al., 2015). Therefore, spacing can affect the ability of trees to acquire available resources, especially the amount of solar radiation intercepted by the plants, determining the forest yield.

In this context, the radiation use efficiency can be assessed by measuring the intercepted photosynthetically active radiation (PARi) that is converted into biomass (MONTEITH; MOSS, 1977). According PRETZSCH and BIBER (2016), little attention has been given to the radiation use efficiency in order to improve forest yields. Recently, there had been increasing focus in obtain ecological information, such as photosynthesis–light relationships in trees, from the meteorological data use, especially solar radiation and forest growth data such as leaf area index. When related the radiation use efficiency with the planting spacing, closer spacing promotes faster development of the leaf area index, which increases light interception and photosynthesis (GONÇALVES et al., 2013), and thus, the radiation use efficiency by plants can be improved.

In this study, we hypothesized that: (i) forest planting spacing affects the biomass yield, carbon storage, properties and radiation use efficiency, which the use of reduced planting spacings can maximize the solar radiation interception and increase the biomass production for energy generation; and (ii) climatic conditions modify the growth and yield of the forest species studied according the planting spacing. Therefore, the objectives of this research were: (i) to evaluate the production of biomass for energy; (ii) to determine carbon storage and partitioning in the forest system (above-belowground biomass + soil); (iii) to determine the radiation use efficiency of *Eucalyptus grandis*; and (iv) to characterize the elemental composition and properties of four forest species *Eucalyptus grandis*, *Mimosa scabrella*, *Ateleia glazioviana*, and *Acacia mearnsii* grown in four planting spacings in Southern Brazil.

2. LITERATURE REVIEW

2.1 Forest energy plantations and biomass production

Developing energy systems that are less dependent on fossil fuels is a major challenge faced worldwide to reduce negative impacts on the environment. The concept of energy forests arose in this context; it was introduced in the 1980s to define forest plantations with large number of trees per hectare and short rotation cycle, which are intended for producing high volume of biomass per area under a short time (COUTO; MÜLLER, 2008). The basic differences between energy forests and traditional forests are the shorter cutting cycle, and smaller spacing between trees, which are usually 2×2 m, i. e., more than 2,500 trees per hectare (COUTO; MÜLLER, 2008).

Considering the increasing world population, energy demand, and degradation of available natural resources, the use of biomass energy is a potential alternative to mitigate these demands. Moreover, the study and adoption of alternative renewable sources of energy have increased due to the growing concern about climate change. Therefore, forest biomass is one of the most important renewable energy sources in terms of technical and economic viability for the coming decades (HALL; HOUSE, 1994; BHATTACHARYA et al., 2003; MOLA-YUDEGO et al., 2017).

Considering that biomass can provide energy of low-carbon cost, bioenergy options have been included in many countries to provide energy with lower greenhouse gas emissions than fossil fuels (WELFLE et al., 2017). In addition, energy forests are important for carbon storage by capturing and storing CO_2 as biomass. According to LACLAU (2003), fast-growing forest plantations and secondary forests are highly efficient carbon sinks that contribute to mitigating CO_2 levels in the atmosphere.

Researches have been carried out in Brazil for large-scale energy production from wood, and invests have been made on fast-growing forest plantations to produce wood for energy. The Brazilian government have promoted the diversification of the national energy matrix through the National Energy Plan (PNE), the National Energy Efficiency Plan (PNEf), the Incentive Program for Alternative Energy Sources (PROINFA). In addition, the Law project 3,529/2012 established the national policy for electric energy production from biomass, with mandatory inclusion of bioenergy in the composition of the national electricity production (ABRAF, 2013). These government programs confirm the importance of using alternative sources of energy, including forest biomass.

Biomass energy currently represents approximately 10% of the global energy supply; two thirds of this bioenergy is produced in developing countries (IEA Bioenergy, 2013). According to the Renewable Energy Policy and Measure Database (IEA/IRENA, 2017), more than 60 countries currently have national targets or policies to support renewable energy production. Recent energy policies have made Europe the main market for biomass energy trading (IEA Bioenergy, 2012). The demand for forest biomass is expected to increase threefold by 2020, as governments provide subsidies for renewable energy production (BOTTCHER et al., 2012). In this context, Brazil presents adequate environmental and soil conditions to produce larguer amounts of forest biomass and become a major producer and exporter of forest biomass for energy worldwide.

However, new studies on energy forests considering different forest species and planting spacings are needed to evaluate the potential for carbon storages and forest biomass production to meet the global energy demand. According to COUTO; MÜLLER (2008) and WELFLE et al. (2017), forest management for biomass production for energy consists in choosing appropriate species, controlling planting density-spacing, and rotation time of the forest plantations.

2.2 Carbon in the forest plantation

Carbon is one of the most abundant elements on the planet and can be found both in the organic form, present in organisms, and in the inorganic form, present in rocks. The cycle of this element in nature is notably known as one of the most important biogeochemical cycles, influencing the regulation of carbon dioxide (CO_2) concentration in the atmosphere, which is one of the greenhouse gases (GHG) together with nitrous oxide (N_2O) and methane gas (CH_4).

Forests connect to this cycle through photosynthesis, respiration, and decomposition, playing an important role in the cycle regulation by storing carbon in large quantities (BROWN et al., 2002; RYAN et al., 2010). Plant biomass and soil are responsible for the storage of two-thirds of the total carbon present in nature, and only plants store approximately 13% of this total (YU, 2004). Below are represented the main components that involve carbon in the system as a whole (Figure 1).

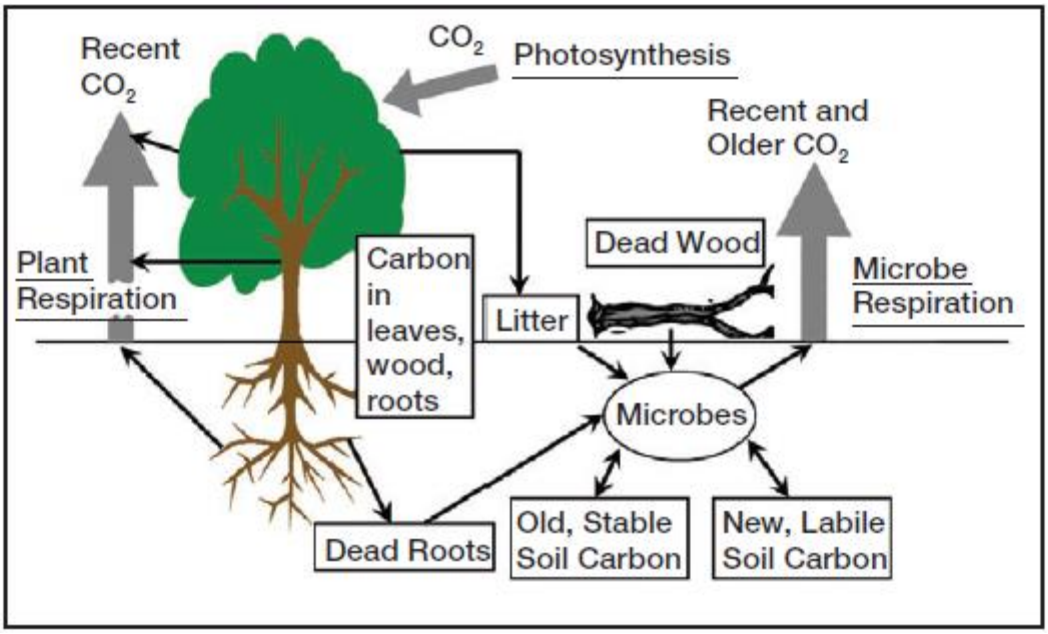

Figure 1. Carbon flows from the atmosphere to the forest and back. Carbon is stored mostly in live and dead forest components as forests grow.
Source: RYAN et al., 2010.

Globally, forests could capture about 12−15% of carbon emitted by fossil fuels (BROWN et al., 2001). Forest plantations and reforestation are extremely efficient in carbon sequestration. According to SILVER et al. (2004) over a period of up to 50 years these forests can stock from 52 to 104 Mg C ha^{-1}, where of the most significant accumulation occurring in the first 20 years, 70% of the areas with this potential are located in tropical regions.

The stock potential of tropical regions according to BROWN et al. (2001) is approximately 80%, with 16 Gt C being stored by reforestation and forest platations, 6.3 Gt C through agroforestry systems, 20 Gt C by forest regeneration and around 16 Gt C with actions that prevent deforestation.

Assessing the growth of exotic trees in Costa Rica REDONDO-BRENES; MONTAGNINI, (2006), found rates of carbon accumulation in the order of 2 to 7 Mg C ha^{-1} per year. In the same case, biomass accumulated at the end of 13 years ranged from 50 to 160 Mg ha^{-1}; WATZLAWICK et al. (2013), reported 90.58 Mg ha^{-1} up to 273.34 Mg ha^{-1} of biomass accumulated in *Pinus taeda* L. at the end of 20 years in the south of Brazil.

Analyzing the carbon stock in the biomass and the soil of native forests in Italy GASPARINI; DI COSMO, (2015) found between 20 and 110 Mg ha^{-1} of carbon stored at the biomass and between 70 and 90 Mg ha^{-1} of carbon stored at the soil, these data corroborate with the studies of LACLAU (2003) that found levels between 80 and 100 Mg ha^{-1} of carbon in the soils. These data show the importance of soil in storing carbon in the systems. Carbon sequestration in forest systems is generally high and the net C balance positive (LAL, 2005). Although afforestation of pasture and agricultural systems can increase soil C sequestration, studies have shown wide variation in magnitude, timing and direction of soil C dynamics, depending on site conditions, management practices, and previous land use (LAGANIÈRE et al., 2010).

According to the International Panel on Climate Change (IPCC, 2007), the change in land use with deforestation and mainly the burning of fossil fuels, among other factors, has accelerated the global warming process, which already causes ecological disturbances and climate. In this context, the use of forest energy plantation plays a key role in the carbon stock and in the production of renewable energy (EISENTRAUT; BROWN, 2012; IIYAMA et al., 2014).

Areas that undergone forest conversion to annual crops had a 59% loss of carbon stored in the soil, with the largest losses being between 30 and 60 cm of soil. While conversion of annual crops to planted forests and forest regeneration increased carbon stocks in the soil by 18 and 53% respectively (GUO; GIFFORD, 2002).

Considering the approach of C in forest energy plantations, one important question arises: Store the C in the forest plantations in order to mitigate the CO_2 emissions or use the forest biomass to produce energy and meet global energy demand? One thing is certain, the two possibilities are valid and relevant considering all the factors involved. An increasing concern for climate change has made many countries consider biofuel and other forms of bioenergy as an important alternative to fossil energy. The carbon stored in the forest is highest when there is little or no harvest from the forest. Increasing the harvest from a forest, in order to produce more bioenergy, may thus conflict with the direct benefit of the forest as a carbon sink. According to LACLAU (2003), fast-growing forest plantations are considered highly efficient carbon sinks capable of contributing to the mitigation of the increase of CO_2 levels in the atmosphere. Moreover, forest biomass for energy generation is considered nearly carbon neutral (KUMAR et al., 2006; THAKUR et al., 2014) because the amount of CO_2 released during combustion is nearly the same as taken up by the tree during growth. In this context, the use of short-rotation cycle of forest energy plantantions are important in both cases, produces biomass for energy and also store carbon in forest biomass.

2.3 Forest species characterization

This thesis proposes the study of four forest species: (i) *Eucalyptus grandis* W. Hill ex Maiden, (ii) *Acacia mearnsii* De Wild, (iii) *Mimosa scabrella* Benth, and *Ateleia glazoviana* Baill. The main characteristics of each species are presented below.

i) Eucalyptus

Eucalyptus grandis (Myrtaceae) is native to Australia. Trees of this species form dense forest masses, reaching 55 m in height and 1.2 to 1.8 m in diameter at breast height (DBH), and present relatively short cycle, and good adaptation to different edaphoclimatic conditions (SCHUMACHER; POGGIANI, 1999; FLORES et al., 2016).

Eucalyptus is the most grown reforestation species in Brazil, covering 72% (5.6 million hectares) of the total planted area in the country (IBA, 2016). The wood from this species is mainly intended for energy production, since it is one of the best options to produce charcoal, cellulose, and paper. The average yield of *Eucalyptus* plantations in Brazil is 36 m^3 ha^{-1} $year^{-1}$ (IBA, 2016).

ii) Black wattle

Acacia mearnsii (Fabaceae) is native to the Southeast of Australia. Trees of this species can reach 5 to 15 m in height, and 10 to 35 cm in DBH at the adult stage (BROWN; KO, 1997), present rounded crown and dark brown bark, and are rich in tannin. They are multipurpose, fast-growing trees that present good adaptation to diverse edaphoclimatic conditions, and are grown in many tropical and subtropical countries of South Asia, Africa, Oceania, and South America (BROWN; KO, 1997). *Acacia mearnsii* is grown in Brazil for tannin extraction, and energy, cellulose, and paper production (GRIFFIN et al., 2011). In addition, the use of this species has great potential for soil quality improvement, contributing to nitrogen fixation and soil organic matter accumulation (SCHUMACHER et al., 2003).

The rotation cycle of *Acacia mearnsii* plantations is 6 to 8 years (FOELKEL, 2008), with an average yield of 15.1 to 30.3 m^3 ha^{-1} $year^{-1}$ in Brazil (STEIN; TONIETTO, 1997). Moreover, the increasing use of mixed plantations composed of nitrogen fixing species (*Acacia mearnsii* or other leguminous species) and Eucalyptus has increased the adoption of these leguminous species to compose forest plantations, which are presenting good perspectives and challenges for future plantations (FORRESTER et al., 2010).

iii) Bracatinga

Mimosa Scabrella Bentham (Fabaceae) is native to Araucaria moist forests (mixed ombrophilous forests) of Brazil. The occurrence of this species is concentrated in the southern and southeastern Brazil, mainly in the states of Rio Grande do Sul, Santa Catarina, and Paraná, between the coordinates 23°S to 29°S and 48°W to 54°W, with altitudes between 500 and 1200 m, and average annual temperatures of 13 to 23 °C (SOMARRIBA; KASS, 2001). Trees of this species have a fast growth and can reach heights of up to 20 m and DBH of up to 40 cm (REITZ et al., 1978).

Mimosa scabrella is grown in Brazil mainly as energy forests (MAZUCHOWSKI et al., 2014) and has drawn the attention worldwide for its use in the production of pharmaceutical compounds (SERAGLIO et al., 2017). It is also a leguminous species that contributes to nitrogen fixation and has been used to compose agroforestry systems.

iv) Timbó

Ateleia glazioviana Baill (Fabaceae) is native to the extreme northeast of Argentina, and southern and southeastern Brazil, as secondary vegetation of deciduous seasonal forests, mainly in the Uruguay River and Paraguay River basins (CARVALHO, 2003). Trees of this species are deciduous and have medium size, with heights of 5 to 15 m and DBH of 20 to 30 cm, presenting an average yield of 9.8 m^3 ha^{-1} $year^{-1}$ (CARVALHO, 2003).

Ateleia glazioviana is grown mainly for recovering degraded areas, intending to produce sawn, and round wood for energy, cellulose, and paper (CARVALHO, 2003). It is also a leguminous species that contributes to nitrogen fixation, and can be used as green manure due to its deciduous leaves in a certain period of the year.

2.4 Planting spacing

The uniform development of fast-growing species during 7 to 9-year rotation cycle is dependent on three factors: selection of appropriate forest species, adequate planting spacing and climatic conditions during the production cycle. One of the main production factors to consider when planning an energy forest system is the planting spacing. The appropriate space between trees is important to fit the better number of trees in a given area, and obtain satisfactory growth levels and yield.

In forest energy plantations the planting spacing can be considered as a primary factor in the production of forest biomass. The maximum stand density for a tree species on a given site is an essential piece of information for assessing site yield, modelling stand dynamics, and the adoption of different silvicultural practices, such as the tree spacing (PRETZSCH; BIBER, 2016). In forest plantations, differences in PARi, radiation use effciency and biomass partitioning can all account for significant proportions of growth responses to increasing resource availabilities (GONÇALVES et al., 2008; RYAN et al., 2010). One way to improve the forest growth and increase the production of forest biomass is manipulating PARi and radiation use effciciency, this is possible using adequate tree spacing. The plant arrangement within the forest stands determines the ability of intraspecific competition of plants by available natural resources. Among the main available resources, solar radiation is the most important in the tree photosynthetic processes, since the different planting spacings can modify the solar radiation dynamics within the forest stands.

The most used spacing between trees intended to biomass production for energy are those that result in an area of 3 m² to 9 m² per tree (COUTO et al., 2002). Techniques for plant densification are being studied and reported due to their benefits (NJAKOU DJOMO et al., 2015; EISENBIES et al., 2017). The use of denser forest plantations for biomass production is a trend because of the need for reducing the production cycle to increase gains in yield, time, and costs of management (GUERRA, 2012).

In this context, studying the growth and yield of different forest species and plant spacing is important to determine the adequate spacing for the conduction of energy forests to produce larguer amounts of forest biomass and to identify possible strategies to improve them and meet the global demand for energy, as well as substitute the fossil fuels and improve C sequestration.

3. MATERIAL AND METHODS

3.1 Study area and experimental design

A field study was conducted from September 2008 to September 2018 in the city of Frederico Westphalen in the state of Rio Grande do Sul, Brazil, at the coordinates 27º22'S, 53º25'W and an altitude of 480 m (Figure 2). The climate is characterized as Cfa, i.e., humid subtropical with mean annual temperatures of 19.1°C, varying with maximum of 38ºC and minimum of 0°C, according Köppen’s climates classification (ALVARES et al., 2013). The soil was classified as Oxisol typical, clayey texture, deep and well-drained. Fertilization was performed before the experiment establishment and consisted on the use of 150 grams of formulated fertilizer for each seedling. Forest seedlings were manually transplanted in the field in September 2008.

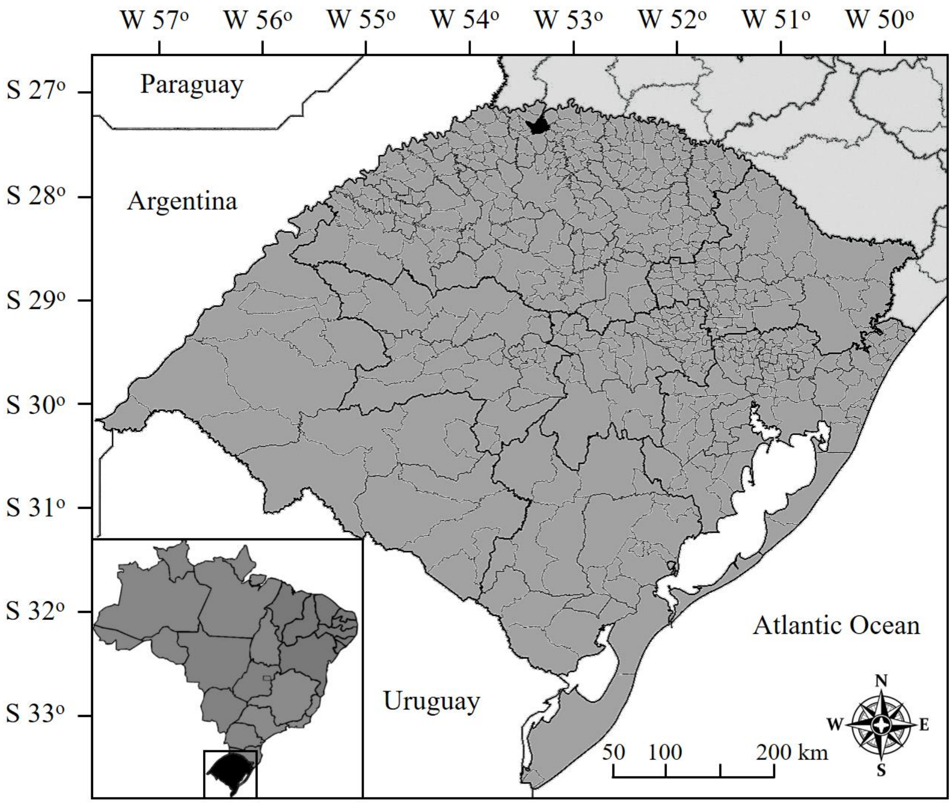

Figure 2. Geographical location of the experiment. The state of Rio Grande do Sul is highlighted in black on the bottom map, while the city of Frederico Westphalen is demonstrated in black on the main map.

The experimental design was a randomized complete block, characterized by a factorial arrangement of 4×4, with four forest species (*Eucalyptus grandis*, *Mimosa scabrella*, *Ateleia glazoviana*, and *Acacia mearnsii*), and four planting spacings (2.0×1.0; 2.0×1.5; 3.0×1.0 and 3.0×1.5 m), with three replications. Each block contemplated 16 experimental units, which was allocated the four levels of planting spacings. A sketch of an experimental unit can be seen in Figure 3.

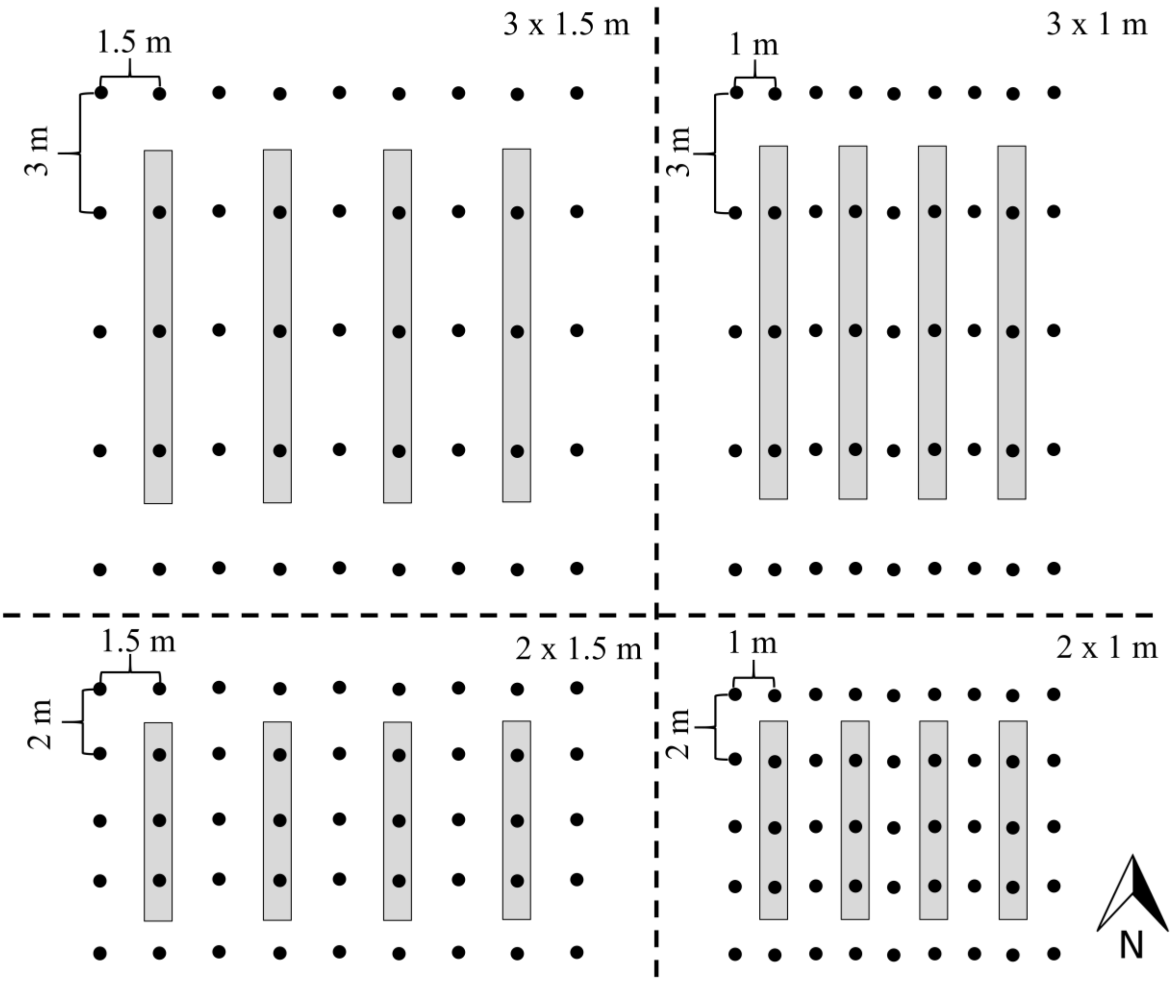

Figure 3. A representation of an experimental unit of each planting spacings (2.0×1.0; 2.0×1.5; 3.0×1.0 and 3.0×1.5 m). Each experimental unit was composed of 45 trees, allocated in five lines. Black circles represent forest trees and rectangles in gray the assessment plots.

3.2 Forest species studied and traits

This thesis proposes the evaluation of four forest species: eucalyptus (*Eucalyptus grandis* W. Hill ex Maiden), bracatinga (*Mimosa scabrella* Benth), timbó (*Ateleia glazoviana* Baill) and Black wattle (*Acacia mearnsii* De Wildeman). The main growth and yield chacarteristics and purpose of each forest species are presented below.

Eucalyptus is originally from Australia, belonging to the Myrtaceae family. Its height can reach 55 m and the diameter at breast height (DBH) of 1.2 to 1.8 m, and has a relatively short cutting cycle and wide adaptation to different climate conditions (FLORES et al., 2016). Eucalyptus is the most cultivated species in Brazil, representing 72.0% of the total area of forest plantations in the country, which corresponds to 5.6 million hectares (IBA, 2016). The average productivity of eucalyptus plantations in Brazil is 36 m^3 ha^{-1} $year^{-1}$ (IBA, 2016). Bracatinga from the Fabaceae family, is originally from the Araucaria Forest (mixed ombrophylous forest) of Brazil. Its height can reach 20 m and DBH up to 0.4 m (REITZ et al., 1978). Additionally, because it is a leguminous species, it has an important contribution in fixing N and have been used to compose agroforestry systems. Timbó belongs to the Fabaceae family. It is characterized by being a deciduous tree. Its height can reach 5 to 15 m and DBH up to 0.20 to 0.30 m, presents an average productivity of 9.8 m^3 ha^{-1} $year^{-1}$ (CARVALHO, 2003). Black wattle, presents high biomass production and gross calorific value, and thus, can be considered as a sustainable source of energy production. STEIN and TONIETTO (1977) reported an average wood production at seven years old from 90 to 180m^3 ha^{-1} and bark yield of 15–30 m^3 ha^{-1}. These species were chosen because of the lack of information related to the energy potential and carbon storage that they present, especially Black wattle, Bratinga and Timbó species, since *Eucalyptus* is the most studied forest species worldwide.

Forest species growth characteristics such as total height (H), diameter at breast height (DBH), volume, basal area (BA), and final tree stand at seven years old (Density) were demonstrated in Table 1. For this study we observed an average reduction of 11% on the final tree stand for the forest species *Eucalyptus grandis*, *Mimosa scabrella*, and *Ateleia glazioviana* while for the *Acacia mearnsii* specie we observed a reduction of 18% on the final tree stand for the planting spacing studied. These reduction in forest stand are related with the mortality of the trees, caused mainly by diseases and pests.

Table 1. Forest species traits grown on four planting spacing at seven years old.

Species	Planting spacing (m)	Tree variables				
		H (m)	DBH (cm)	Volume (m^3 ha^{-1})	BA (m^2 ha^{-1})	Density (tree ha^{-1})
Eucalyptus grandis	2.0×1.0	24.11	54.96	658.42	1069.78	4450
	2.0×1.5	27.54	66.00	679.58	1029.53	2967
	3.0×1.0	23.52	53.86	417.10	692.61	2967
	3.0×1.5	28.17	67.78	468.32	717.17	1978
Mimosa scabrella	2.0×1.0	12.95	33.93	332.86	409.89	4450
	2.0×1.5	12.86	36.53	255.04	318.99	2967
	3.0×1.0	12.05	35.57	216.13	300.03	2967
	3.0×1.5	11.03	31.22	112.84	157.53	1978
Ateleia glazioviana	2.0×1.0	8.60	19.92	90.33	142.99	4450
	2.0×1.5	8.76	21.53	71.14	110.51	2967
	3.0×1.0	9.08	21.58	94.92	126.72	2967
	3.0×1.5	8.90	24.16	58.32	91.94	1978
Acacia mearnsii	2.0×1.0	14.91	45.51	413.42	894.32	4105
	2.0×1.5	13.34	47.86	380.56	490.43	2733
	3.0×1.0	11.65	43.24	318.45	401.32	2733
	3.0×1.5	13.75	52.78	283.63	296.25	1822

Planting spacing had little effect on height growth (Table 1). For instance, the average total height at seven years for *Eucalyptus grandis* was 25.8 m, *Mimosa scabrella* 12.2 m, *Ateleia glazioviana* 8.8 m, and for *Acacia mearnsii* 13.4 m. On the other hand, for the diameter at breast height, volume and basal area we observed variations according with the planting spacing. This demonstrate that the planting spacing had effect on these traits.

3.3 Tree destructive sampling and leaf area assessment

The destructive assessment to determine the biomass yield and potential energy yield of the forest species was carried out in September 2015 (7^{th} year) after planting the experiment. For each planting spacing, nine trees were evaluated, resulting in a total of 36 trees per forest species in the 7^{th} year of the short-rotation cycle. Each tree assessed was considered as an observation unit.

Forest biomass data were obtained from strict cubing. Each tree compartment was assessed using direct method, which consist on cutting and weighing the different tree compartments (SANQUETTA, 2002). Under field conditions the total fresh biomass of sampled trees was assessed. In laboratory the moisture content was determined by the samples from each compartment. Destructive assessments represented by strict cubing, tree weighing, volume determination, and sample collecting are shown in Figure 4.

Figure 4. Destructive assessments represented by strict cubing (A, B, and C), trunk weighing using dynamometer balance (D), volume determination in the laboratory (E) and leaf removal for leaf area determination (F and G).

For the determination of gross calorific value (i), proximate and ultimate analysis (ii), and carbon storage (iii) destructive samples were collected through strict cubing. The samples were collected along the trunk, in the following sections: 0% (basis), 1.30 m (diameter at breast height - DBH), 25%, 50%, 75% and 100% of the total height. For trunk was collected discs with two centimeters thick while for branches and leaves were collected by a stratified way, including lower, middle and upper tree canopy stratum. The samples were allocated into a forced circulation oven at 103±2 °C until reach a constant mass. Thereafter, the collected samples were macerated into a slicer and the fraction retained on the 270-mesh sieve was used.

From the destructive assessments, the samples obtained were used to determine the characteristics: gross calorific value (i), proximate and ultimate analysis (ii), and carbon storage (iii). The collected samples were evaluated in the Forest Biomass Energy Laboratory of the Department of Forestry Engineering and Technology of the Federal University of Paraná (UFPR).

The leaf area was determinated for the *Eucalyptus grandis*, *Mimosa scabrella*, and *Acacia mearnsii* species. For the *Ateleia glazioviana* specie was not possible to quantify the leaf area because this specie presents deciduous characteristics, so, at time of tree assessments, the leaves were not computed. For the other forest species, the leaf area was determined using a leaf area integrator (model LI−3000C). To determine the leaf area, three samples of 300 g were collected from different points at the tree canopy. The samples were gathered and placed in pre-identified individual paper sacks, which were allocated into a forced circulation oven at 60 °C until reach a constant mass. Lastly, the samples were weighed on a precision balance.

Thus, the leaf area of the tree was calculated as equation: LA= (LB × Las) /DBs, where: LA=leaf area in m^2; LB=leaf biomass in kg; Las = leaf area of the sample in m^2; DBs=dry weight of leaf sample in kg.

The leaf area index (LAI) was determined from the total leaf area of each tree and the useful soil area using the following equation: LAI = LA/USA Where: LAI = leaf area index; LA = total leaf area of the tree (m^2); USA = usefull area utilized by the tree (m^2).

3.4 Gross calorific value and potential for energy production

The gross calorific value was assessed for the four forest species and four planting spacing. The gross calorific value was determined using a digital bomb calorimeter, C5000 Cooling System model, according to the technical standard NBR 8633 (ABNT, 1984).

The potential energy yield was estimated for the four forest species studied in a short-rotation cycle, i. e., the forest species were seven years old at time of assessments. The potential energy yield from forest biomass was estimated using biomass data of each tree compartment and gross calorific value of the assessed samples. In order to estimate the amount of energy per hectare, expressed in kW.h ha^{-1}, the biomass of each compartment was multiplied by the gross calorific value of each planting spacing, given by the following equation (BRAND et al., 2010): PEY = (BIO x HCV)/860. Where: PEY = Potential energy yield (kW.h ha^{-1}); BIO = biomass (Mg ha^{-1}); GCV = Gross calorific value (kcal kg^{-1}); and conversion factor = 860 (kcal to KW.h).

3.5 Proximate and ultimate analysis of forest species

The proximate and ultimate analysis were assessed for the four forest species. Ash content (Ash), volatile matter (VM) and fixed carbon (FC) were considered as proximate analysis and they were determined on weight percent in dry basis (wt.% in dry basis). The proximate analysis was performed according to the technical standard NBR 8112 (ABNT, 1986). While for Carbon (C), hydrogen (H), oxygen (O), nitrogen (N), and sulfur (S) contents were considered as ultimate analysis. They also were determined using weight percent in dry basis (wt.% in dry basis). For assessing the elemental composition, a universal Elementar analyzer (Model–Vario micro cube) was used. The oxygen content was obtained by subtracting from 100% the sum of (C, H, N, S and Ash) contents in percentage.

3.6 Above-belowground carbon storage and soil carbon determination

The aboveground biomass sampling was performed using the same methodology, as mentioned in the item 3.3. The carbon content of the forest species studied was performed using a universal Elementar analyzer (Model–Vario micro cube).

The belowground carbon storage determination was performed in September 2018, according to the methodology proposed by SANQUETTA (2002). This evaluation was performed for the *Eucalyptus grandis*, *Mimosa scabrella*, and *Ateleia glazioviana* forest species. The cycle of *Acacia mearnsii* ended in 2015. The root biomass was quantified using the direct method (destructive sampling). The method used is based on root excavation, cleaning, weighing and sample collection in a stratified way, including fine, medium and gross roots (RATUCHNE et al., 2016). Under field conditions the root biomass of sampled trees was assessed (Figure 5). The sampling area changed according to the planting spacing. The useful area collected of each planting spacing were: (1.0×0.5, 1.0×0.75, 1.5×0.5, and 1.5×0.75 m) for the following planting spacings: (2.0×1.0, 2.0×1.5, 3.0×1.0, and 3.0×1.5 m), respectively, using fixed depth of one meter (SANQUETTA et al., 2004). Twenty-four sample trees were evaluated, being eight trees per forest species, two of each planting spacing.

Figure 5. Roots assessments to determine belowground biomass and carbon storage.

Soil carbon content and stock across two soil depths (0–20 and 20–40 cm) for the *Eucalyptus grandis*, *Mimosa scabrella*, and *Ateleia glazioviana* forest species grown on four planting spacings were evaluated in September 2017. For this, volumetric rings were used to collect samples to determine carbon content and soil density in order to quantify the carbon storaged. The soil samples were collected randomly within the plot in order to collect representative and homogeneous samples (Figure 6). Moreover, was collected samples of the forest litter existent above the soil. For this, was used a useful area of one m^{-2}. Representative samples were collected within each plot in order to determine the carbon storage of the litter of forest species at different spacings.

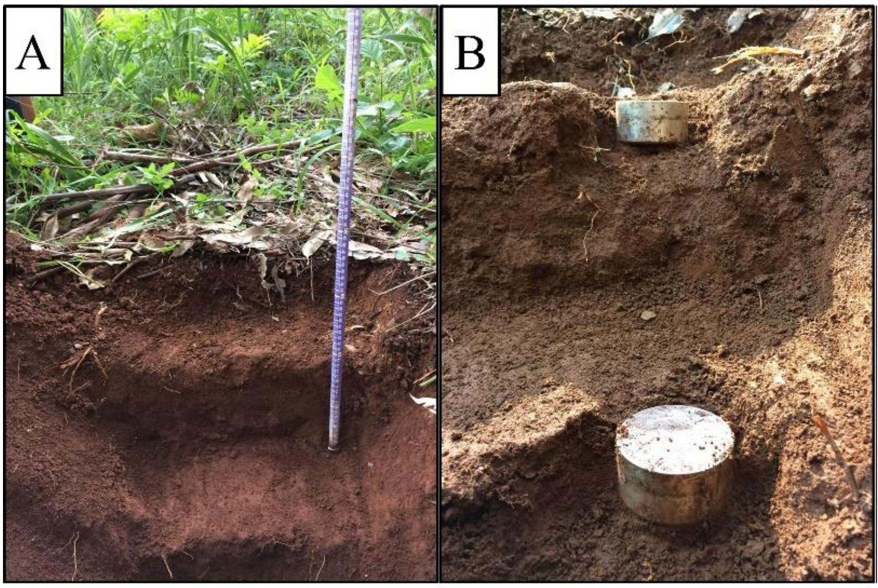

Figure 6. Soil sampling at two depths 0−20 and 20-40 cm to quantify the soil carbon storage (A and B).

The soil carbon content was determined by the dry combustion method (CHNS/O), using an elemental analyzer, Perkin Elmer model, PE−2400 Series II, which is based on the quantification of CO_2 by means of infrared, where CO_2 is formed by the oxidation of the organic constituents at a temperature close to 1500ºC. The soil samples collected were evaluated in the Forest Biomass Energy Laboratory of the Department of Forestry Engineering and Technology of the Federal University of Paraná (UFPR).

The soil carbon stocks were calculated considering the soil density and the layer thickness according the following equation: $SOC_{stock} = C \times SD \times \rho/10$. Where: SOC_{stock} = soil carbon stock (Mg ha^{-1}); C = soil carbon content (g kg^{-1} [soil]); SD = soil density in the layer (g cm^{-3}); ρ= soil layer thickness (cm).

3.7 Climate conditions

The climatic data during the experiment were obtained from a Climatological Station of the National Institute of Meteorology (INMET) linked to the Agroclimatology Laboratory (UFSM) located about 800 m from the study site at coordinates 27° 39'S and 53° 43'W. Climatic values were computed for each season of the year. The sum of the values for incident solar radiation (RAD, MJ m^{-2}) and rainfall (RAIN, mm) were recorded, while values for the minimum air temperature (TMIN, °C), maximum air temperature (TMAX, °C) and average air temperature (TAVE, °C) were computed using the average values for each season of the year.

The average monthly minimum, average, and maximum air temperatures and accumulated solar radiation, and accumulated rainfall obtained during the experiment (September 2008 to September 2017) are shown in Figure 7. The air temperature during the years of the experiment ranged from −2.2 ºC to 37.9ºC, with an average temperature of 18.8ºC. The flux of global solar radiation was 17.35 MJ m^{-2} day^{-1} on average, with a variation of 0.49 to 38.46 MJ m^{-2} day^{-1} (Figure 7). The rain values showed a great variability during the experiment, in overall was observed a monthly average of 182.8 mm. We can highlight also that the water avaibility during the tree growth was enough and this condition was adequate for the trees. Maximum and minimum temperatures and rainfall were, in general, within the average for the region, according to the seasons of the year.

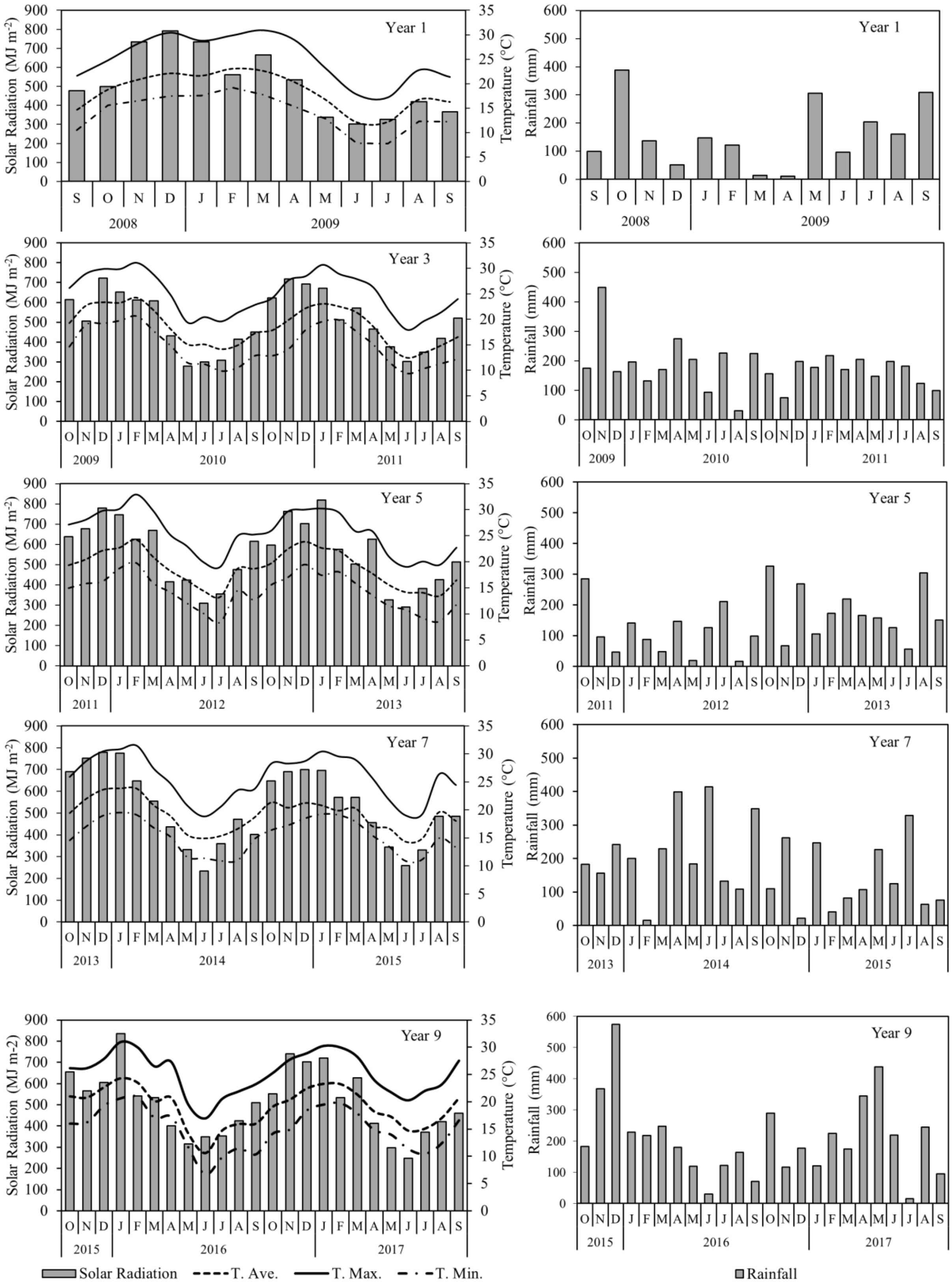

Figure 7. Average monthly values for minimum, maximum and average temperature (T.Max, T.Min and T.Ave), accumulated incident solar radiation, and accumulated rainfall during the experimental period.

3.8 Solar radiation interception and radiation use efficiency

The values for solar radiation interception (SRI) were measured annually, where the solar radiation intercepted was measured above and under the tree arrangement using a portable sensor pyranometer (LICOR PY32164) coupled to a Datalogger (LICOR 1400), which recorded measurements in the period from 10 to 12h. The sample points within each plot in three different directions were systematically established, one located within the row (1), another between each row (2), and the third at a 45° angle between points 1 and 2. The values of intercepted global radiation were obtained according to the following equation: % Intercepted = [100 - (Rn × 100 / Rt)]. Where: Rn = incident radiation under the canopy; Rt = incident radiation above the canopy.

The biomass data and leaf area of the *Eucalyptus grandis* trees for radiation use efficiency evaluation were collected in September in five different periods: 1st year (2009), 3rd year (2011), 5th year (2013), 7th year (2015), and 9th year (2017) after planting seedlings. For each planting spacing, nine trees were evaluated, resulting in a total of 36 trees per evaluation period, totaling 180 trees evaluated during the five periods. In the evaluations the direct method was used, which constituted the cutting and weighing of the different compartments of the trees (SANQUETTA, 2002).

The values of incident global solar radiation were obtained from the meteorological station of the National Meteorology Institute, situated roughly 800 m from the experiment. The values of photosynthetically active radiation were estimated to be 45% of global solar radiation. This fraction follows the average values found by Assis and Mendez (1989). The estimation of accumulated photosynthetically active radiation was based on the methods by MONTEITH and MOSS (1977) and VARLET-GRANCHER et al. (1989). Therefore, the intercepted photosynthetically active radiation was determined based on VARLET-GRANCHER et al. (1989): $PARi = 0.95 \times (PARinc) \times (1- e^{(-k \times LAI)})$, where: PARi = intercepted photosynthetically active radiation (MJ m^{-2} day^{-1}); PARinc = incident irradiant photosynthetically active radiation (MJ m^{-2} day^{-1}); k = extinction coefficient, the values obtained in the present study for each tree spacing were utilized; LAI = leaf area index.

The light extinction coefficient (k) was calculated using the following equation: $k = -\ln (Rn/Rt)/LAI$. Where k = extinction coefficient; Rn = incident radiation under tree canopy (MJ m^{-2} day^{-1}); Rt = incident radiation above the canopy (MJ m^{-2} day^{-1}) and LAI = leaf area index.

The radiation use efficiency was calculated for the *Eucalyptus grandis* on four planting spacing. Production of dry matter was based on the model proposed by (MONTEITH; MOSS, 1977), whereby the dry matter production was calculated from intercepted photosynthetically active radiation (PARi) multiplied by the radiation use efficiency. The εb was calculated by the relation between the average production of accumulated TDM and the PARi involved in the production of biomass according to the following expression: BIO = εb × PARi, where BIO = biomass (kg m^{-2}); εb is the radiation use efficiency (kg MJ^{-1}); and PARi = intercepted photosynthetically active solar radiation (MJ m^{-2} h^{-1}).

The value of radiation use efficiency given by the angular coefficient represents the quantity of accumulated biomass for each energy unit intercepted. Values for radiation use efficiency were evaluated according the total biomass, for each compartment (bole and canopy), where bole represents (trunk+bark) and canopy (branches+leaves), and for each planting spacing. The radiation use efficiency was performed only for the *Eucalyptus* trees in order to observe and understang the high biomass yield obtained in the planting spacing 2.0×1.5 m.

3.9 Statistical analysis

The data were statistically analyzed with the software “Statistical Analysis System” (SAS, 2002), and the results were obtained through the analysis of variance, F test and Tukey test ($p<0.05$). The Bartlett test was used to verify the homogeneity of variances, while the normality distribution of all data was checked using Shapiro–Wilk test.

Also, for the statistical analysis we used multivariate approach. To identify major patterns of variation and ordination of the elemental composition and properties of the different tree compartments we used principal component analysis. This technique is based on a change of the dimensional plane of the prospected data into a new data set that is representative of the original set whilst being smaller in terms of dimensionality.

The treatment evaluated in this study were coded as follows: W (wood), BA (bark), BR (branch), and L (leaf). For the first principal component analysis (PCA), regarding the proximate analysis, we analyze four planting spacing which were coded as follows: 1 (2.0×1.0 m), 2 (2.0×1.5 m), 3 (3.0×1.0 m), and 4 (3.0×1.5 m). For the second PCA, regarding the ultimate analysis, we analyze three assessment years 1 (2009), 2 (2011) and 3 (2013). For understand the Growth×Yield×Climate interactions we used PCA and discriminant analysis.

The growth traits were: H, DBH, LAI and MAI; yield traits: VOL, BIO and ENER; and climate traits: SRI and k. The forest species were coded as follows: *Eucalyptus grandis* (E), *Mimosa scabrella* (M), *Ateleia glazioviana* (A), and *Acacia mearnsii* (AC).

The data used for the PCA were standardized by dividing the difference between each data point and the arithmetic mean of the variable of interest by the standard deviation of the variable. Two principal component vectors were used for the PCA analysis. The normality distribution of all data was checked using the Shapiro–Wilk test. Additionally, paired variables with apparent collinearity were excluded from the PCA analysis. The principal components and biplot graphic were obtained by using the PROC PRINCOMP procedure (SAS, 2002).

4. RESULTS AND DISCUSSION

4.1 Biomass, partitioning and energy yield of the forest species

The biomass yield for the short-rotation cycle of the four forest species studied grown on four planting spacing are showed in Figure 8. We observed a significant difference for the biomass yield for the forest species grown on different planting spacings. For the *Eucalyptus grandis*, the higher biomass yield was observed for the 2.0×1.5 m spacing, which was 21.6, 19.2 e 36.6% higher than the other spacings 2.0×1.0, 3.0×1.0, and 3.0×1.5 m, respectively. Moreover, the widest planting spacing was responsible for the lower production of biomass for all forest species in the short-rotation cycle.

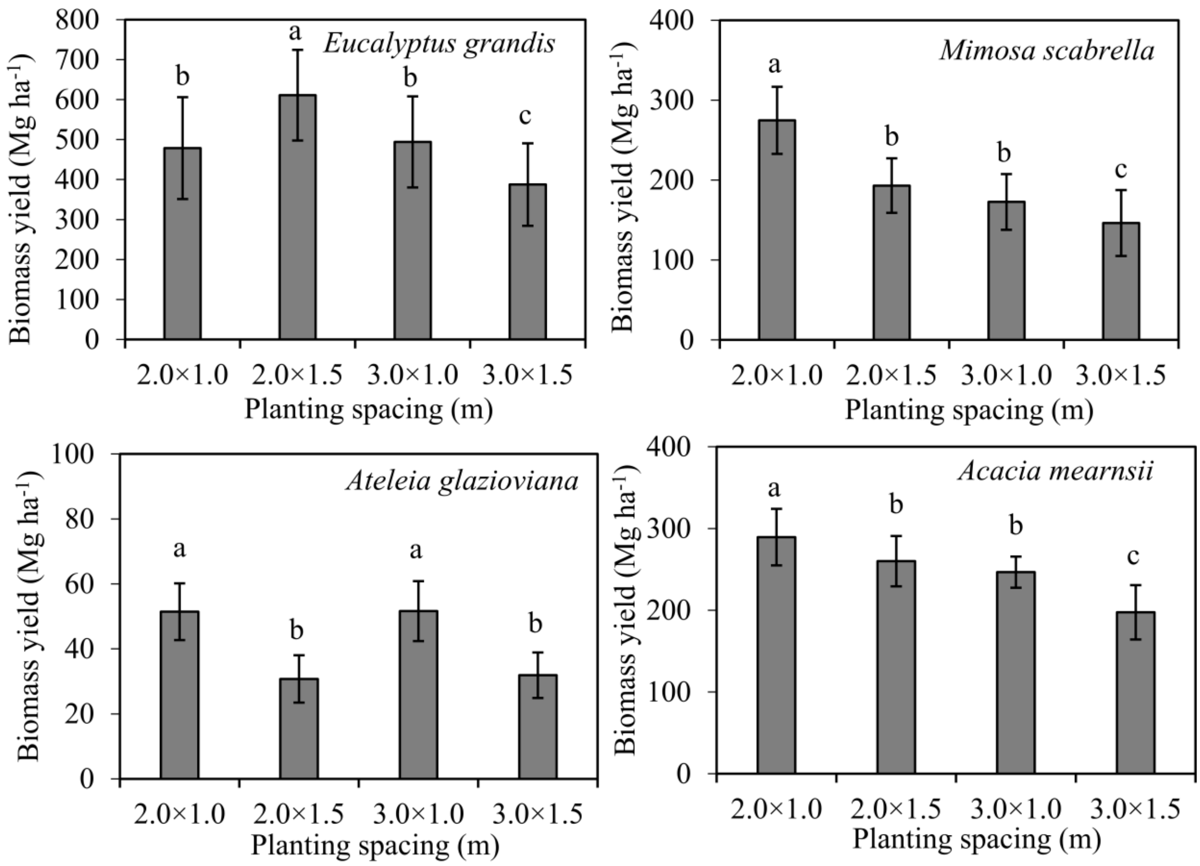

Figure 8. Biomass yield in a short-rotation cycle of *Eucalyptus grandis*, *Mimosa scabrella*, *Ateleia glazioviana*, and *Acacia mearnsii* grown on four planting spacings. Different small letters indicate significant differences (p<0.05) by Tukey test among planting spacings.

Regarding the other forest species, we observed higher biomass yield in the 2.0×1.0 m spacing, with a subsequent decrease in biomass production as planting spacing increased. Only for the *Ateleia glazioviana* it was observed that the spacings 2.0×1.0 and 3.0×1.0 m did not differ significantly. Therefore, for the forest species *Mimosa scabrella* and *Acacia mearnsii* the 2.0×1.0 m spacing was responsible for the higher biomass yield.

Though the sizes of trees are important from a harvesting and relative value perspective, the most important component of value for most forest energy plantations is the amount of biomass yield per hectare. It can be seen that the individual relative biomass yield of trees is greater at the widest spacing levels (3.0×1.5 m), probably due to higher availability of soil, moisture and light resources. However, since the density of planting ranged from 1978 trees ha^{-1} at the 3.0×1.5 m to 4450 trees ha^{-1} at the 2.0×1.0 m spacing level, the overall biomass yield of a unit area of land can be quite different than the average tree size considered alone. In this context, the number of plants per unit area becomes an essential factor for the production of biomass for energy. In this study it was possible to confirm that for the production of *Eucalyptus* the optimal spacing to produce biomass was 2.0×1.5 m and for the other forest species it was 2.0×1.0 m.

The higher biomass production for *Eucalyptus* grown in 2.0×1.5 m spacing can be related to the greater use efficiency of the available natural resources, especially solar radiation, since *Eucalyptus* trees grown in this spacing presented greater radiation use efficiency (Figure 19). Moreover, this study demonstrated that when *Eucalyptus* trees were grown in spaced more densified, that is, smaller than 2.0×1.5 m resulted in the reduction of the total biomass to produce energy. This can be related to the increase in intra-interspecific competition for resources, i. e., the number of trees suppressed was higher.

For the other forest species studied this response was not verified, as the greatest biomass production occurred in the reduced planting spacing. This response can be related to the genetic and silvicultural characteristics of each species (height, dbh, fast growth, genetic improvement, environmental adaptability, among others), as well as the biomass production capacity per unit area. Moreover, intraspecific competition among plants of these species was not sufficient to reduce the forest biomass yield. Therefore, we can highlight that for the production of biomass for energy the use of reduced spacing should be prioritized.

Reduced forest plantation spacing is considered a favorable advantage not only because of the higher biomass yield for energy generation, but also because the canopy closes sooner, resulting in lower maintenance costs with weed control (HAUK et al., 2014). In other hand, with reduced spacings, the costs of establishing plantation are higher, and the harvest cost, which is a main cost of the forest management, tend to increase due to the higher tree density. Recently, new technologies such as modified foragers represent a cost-effective option for harvesting high-density short-rotation energy plantations (GUERRA et al., 2016). Therefore, a proper economic evaluation is needed (STRAUSS et al., 1988).

Another relevant point that we can highlight is the difference among the forest species into produce forest biomass. Although this was not the aim of this study, to compare the forest species, but only to characterize and evaluate the potential of each one, it was possible verify that the *Eucalyptus grandis* was the forest species with the greatest potential for biomass production for energy. Moreover, the forest species that showed the higher biomass yield potential were *Acacia mearnsii*, *Mimosa scabrella* and *Ateleia glazioviana*, in that order.

The huge difference in biomass yield among forest species studied was basically related to the ability of each forest specie into acquire available resources and the efficiency of resource conversion into biomass. Also, the investment in genetic improvement that each species received is one important factor that results in a difference in the potential of biomass production. The *Ateleia glazioviana*, *Mimosa scabrella* and *Acacia mearnsii* species have aroused less interest among breeders when compared to *Eucalyptus* species. The overall choice among the players involved (industries and forest producers) with *Eucalyptus* plantation forestry is based on the number and variety of species within the genus; the potential for adaptation to soil and climatic conditions which vary widely throughout Brazil (STAPE et al., 2010); the ready availability of genetically-improved seed and material for vegetative propagation; and the availability of knowledge about silvicultural treatments and techniques (GONÇALVES et al., 2004, 2008; STAPE et al., 2010).

One of the main factors related to the productivity of forest energy plantations under high plant densities is related to the uniformity of the plants within the area. Due to the large number of trees competing for space and resources, it is possible to have dominant and dominated plants within the forest stand (STAPE et al., 2010). This resuts was observed in this study, mainly for the species *Mimosa scabrella*, *Aleteia glazioviana*, and *Acacia mearnsii*, where it was observed high heterogeneity in the forest stand. Different from that observed for *Eucalyptus grandis*, which showed higher homogeneity, even under high plant density. The results found in this study agree with that reported by RESENDE et al. (2018), who related that the major determinants factors of productivity in forest plantations include the site productive capacity, local environmental uniformity, and the tree genetics, which impact their growth potential and competitiveness. Also, this author emphasize taht heterogeneity within forest plantations is likely to result from at least three factors; i) heterogeneity of environmental conditions within the plantation (SCHUME et al., 2004;

BOYDEN et al., 2012); ii) competitiveness of individuals towards their neighbors, in terms of the strength of the relationships between individual tree growth and neighboring tree growth (RESENDE et al., 2016); and iii) variability in the size and health of the cuttings or seedlings from the nursery.

According with RYAN et al. (2010b) and ASPINWALL et al. (2011), the uniformity achieved through intensive exploitation of forest energy plantations may be limited by the spatial variability of resources (water, nutrients and solar radiation), which leads to heterogeneity in tree growth and reductions in productivity at stand level. In this contex, STAPE et al. (2010) found that plantations with moderate to high heterogeneity of tree sizes (with uniform genetics, silviculture and spacing) yielded 5–20% less wood growth per hectare than highly uniform stands. The reduction in productivity was attributed to a high dominance in heterogeneous populations, because the efficiency of resource use declined for non-dominant trees (BOYDEN et al., 2008; BINKLEY et al., 2010).

This result was also highlighted by BINKLEY and STAPE, (2004), who reported that the productivity of a forest plantation can be represented quantitatively as a function of the availability of resources (notably water, nutrients and solar radiation) and the resource use rate and efficiency from which trees produce wood and non-woody tissue (CANNELL, 1989). Over time, the growth of individual trees changes in response to competition-related differences in resource acquisition and efficiency of resource use (BINKLEY; STAPE, 2004; DOI, 2010). The size of a tree affects its ability to acquire available resources, the efficiency of resource conversion into biomass, and the partitioning of biomass into wood growth. Thus, the huge difference in biomass yield among the different forest species studied can be related with the ability of each forest specie into acquire available resources and the efficiency of resource conversion into biomass.

Although there are a lot of studies on biomass potential already available, their results vary widely, because several factors are related such as ecological, silvicultural, environmental, technological, and management techniques. Some studies estimate potentials close to zero, while others come up with huge potentials satisfying multiple times the world energy demand. In this study, we highlihgted that the use of short-rotation intensive culture systems was an efficient way to produce biomass for energy. According THARAKAN et al. (2003) and NJAKOU DJOMO et al. (2015), this intensive system involves the establishment of plantations using genetically improved materials, vegetative propagated materials and high plantation densities (1,500 to 28,000 plants ha^{-1}).

Short rotation forestry systems are extremely important for the supply of biomass for energy production in short periods of time. However, another important point is related with the exportation of nutrients. This point of view needs to be highlighted and considered in the management strategies. Short cutting cycles with high amounts of biomass produced result in large quantities of nutrients being removed (HEILMAN; NORBY, 1998; JUG et al., 1999; RYTTER, 2002; HYTÖNEN, 2018). Special attention should be directed at the nutrient status of soil when practicing short-rotation forestry (HEILMAN; NORBY, 1998). This is related with the frequent repetition of nutrient drains, which could result in the nutrient impoverishment of the site. An important focus of research in programmes developing forest biomass plantations is to establish fertilization regimes optimizing growth with minimal adverse environmental consequences (HYTÖNEN, 1996; HEILMAN; NORBY, 1998). In this context, a correct fertilization regime, with respect to timing and rates, is one of the most important ways to improve forest energy production and maintain the quality of the site.

The pattern of biomass accumulation in the trunk, branches, leaves, and roots of the *Eucalyptus grandis*, *Mimosa scabrella*, *Ateleia glazioviana*, and *Acacia mearnsii* grown on four planting spacing are showed in Figure 9. The general pattern of biomass partitioning of the forest species was not affected by the planting spacing. Of this accumulated biomass, most of it was allocated into wood production (secondary growth). For the *Eucalyptus grandis*, an average partitioning of 81, 4.1, 3.1, and 11.9% of the biomass accumulated in the respective trunk, branches, leaves and roots components was observed (Figure 9a). It is important to highlight a higher production of root biomass in the 3.0×1.0 m spacing, which represented 15.9% of the total biomass of the trees, being above the average values observed in the literature for this forest species.

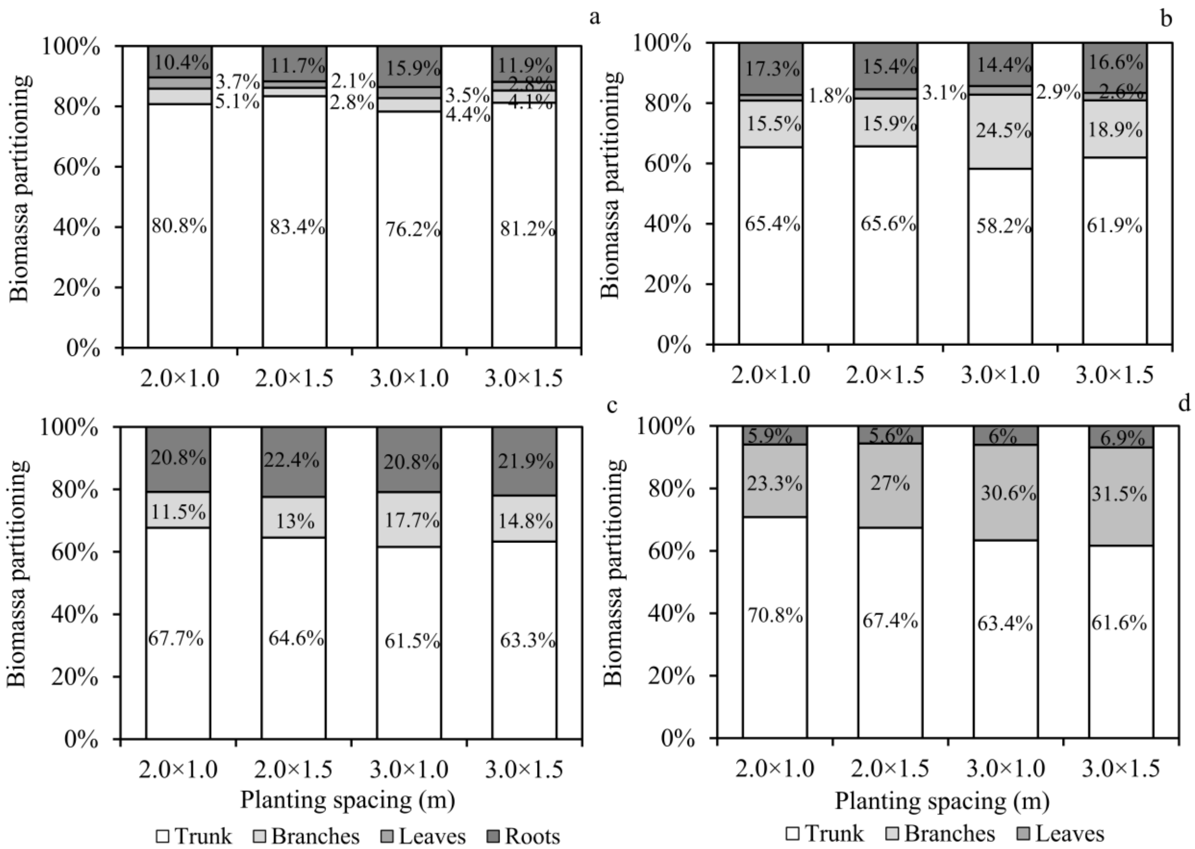

Figure 9. Biomass partitioning in a short-rotation cycle of *Eucalyptus grandis* (a), *Mimosa scabrella* (b), *Ateleia glazioviana* (c), and *Acacia mearnsii* (d) grown on four planting spacings.

The higher root biomass observed for the 3.0×1.0 m spacing can be related with the availability of soil to be explored and lower root competition for water and nutrients when compared to 2.0×1.0 m spacing, for example. However, this condition can not be confirmed because the 3.0×1.5 m spacing did not show the same trend, since it was observed similar root biomass production than the other spacings. According BERNARDO et al. (1998), when planted at increased spacing levels, forest trees will respond by allocating more proportional growth to root systems and foliage, thereby reducing the amount of material allocated to large woody structures, in particular the bole, but also the taproot.

Regarding the *Mimosa scabrella* species, it was possible to observe an average partitioning of the total biomass at 62.8, 18.7, 2.6, and 15.9% for trunk, branches, leaves and roots. While for *Ateleia glazioviana* species, it was not possible to account the dry biomass of leaves, because it is a deciduous species. So, the biomass partitioning was the following 64.3, 14.2, and 21.5% for the trunk, branches and roots, respectively. For the *Acacia mearnsii* the roots assessment was not performed. Therefore, an average partitioning of 65.8, 28.1, and 6.1% for the trunk, branches and leaves was observed, respectively.

Evaluating the forest biomass partitioning, RIBEIRO et al. (2015) reported that the trunk is the compartment that contributed highly to the aboveground tree biomass (82%), followed by the bark (8%), branches (7%) and leaves (3%) for the *Eucalyptus grandis* species. The pattern of allocation observed in this study was similar with that found by CAMPOE et al. (2012), who reported an average partitioning of the total biomass stored in *Eucalyptus grandis* for the different compartments of 82.8, 10.7, 3.6, and 3.0%, for the trunk, roots, branches, and leaves.

This study reported some divergence between our results and those from other studies. PAIXÃO et al. (2006) in a 6-year old *Eucalyptus grandis* plantation in Brazil obtained biomass proportions similar to ours results (trunk = 81.8%, bark = 8.1%, branches = 7.7% and leaves = 2.6%). However, ASSIS (1999) and FEREIRA (1984), reported different biomass proportions for Brazilian stands of *Eucalyptus grandis* and *Eucalyptus urophylla* (4-7 years): 70.4% for the trunk, 11.8% for bark, 10.6% for branches and 7.2% for leaves. We believe that the divergence in the proportion of biomass allocation between the studies and ours can be associated with different site characteristics, species, age and stand management practices.

Moreover, the difference in the biomass partitioning among the forest species can be related with the ability and capacity of the forest species into produce biomass. CAMPOE et al. (2012) highlighted that the accumulated biomass partitioning is related to the tree's ability to produce biomass which is related with the radiation use efficiency by the forest species. A similar pattern of productivity-dependent biomass allocation was observed in other studies dealing with water and nutrient manipulations in forest plantations (GIARDINA et al., 2003; MAIER et al., 2004; STAPE et al., 2008; RYAN et al., 2010; ALMEIDA et al., 2010; EPRON et al., 2012).

Another relevant point that we can highlight is the difference among the forest species into allocate forest biomass in the different compartments. For example, for the trunk compartment, which is the main feedstock used for the industries, the *Eucalyptus grandis* allocate 81% of the total biomass produced while for the other species was observed an average of 64.3%. This difference can be related with the capacity of *Eucalyptus* into produce and storage carbon in the trunk when compared with the other forest species, which allocate more quantity of biomass in branches and leaves. These components are important for the tree growth, but considering the energy generation, the biomass partitioned for the trunk is more desirable.

When related with the results of biomass yield observed previously and taking into account that spacing is one of the factors most influencing biomass and energy production, it is necessary to seek plantation spacings that favor high concentration of biomass in the parts that are to be utilized (wood and branches), instead leaves. The use of branches and leaves biomass shows a disadvantage when compared to wood biomass in the combustion process (TENORIO et al., 2016). This happens because the branch biomass has lower calorific value, higher moisture and content of ashes, therefore its potential for energy is lower than wood. However, these feedstocks (branches and leaves) can be compared to that of other short-rotation crops currently used in some countries (PLEGUEZUELO et al., 2015).

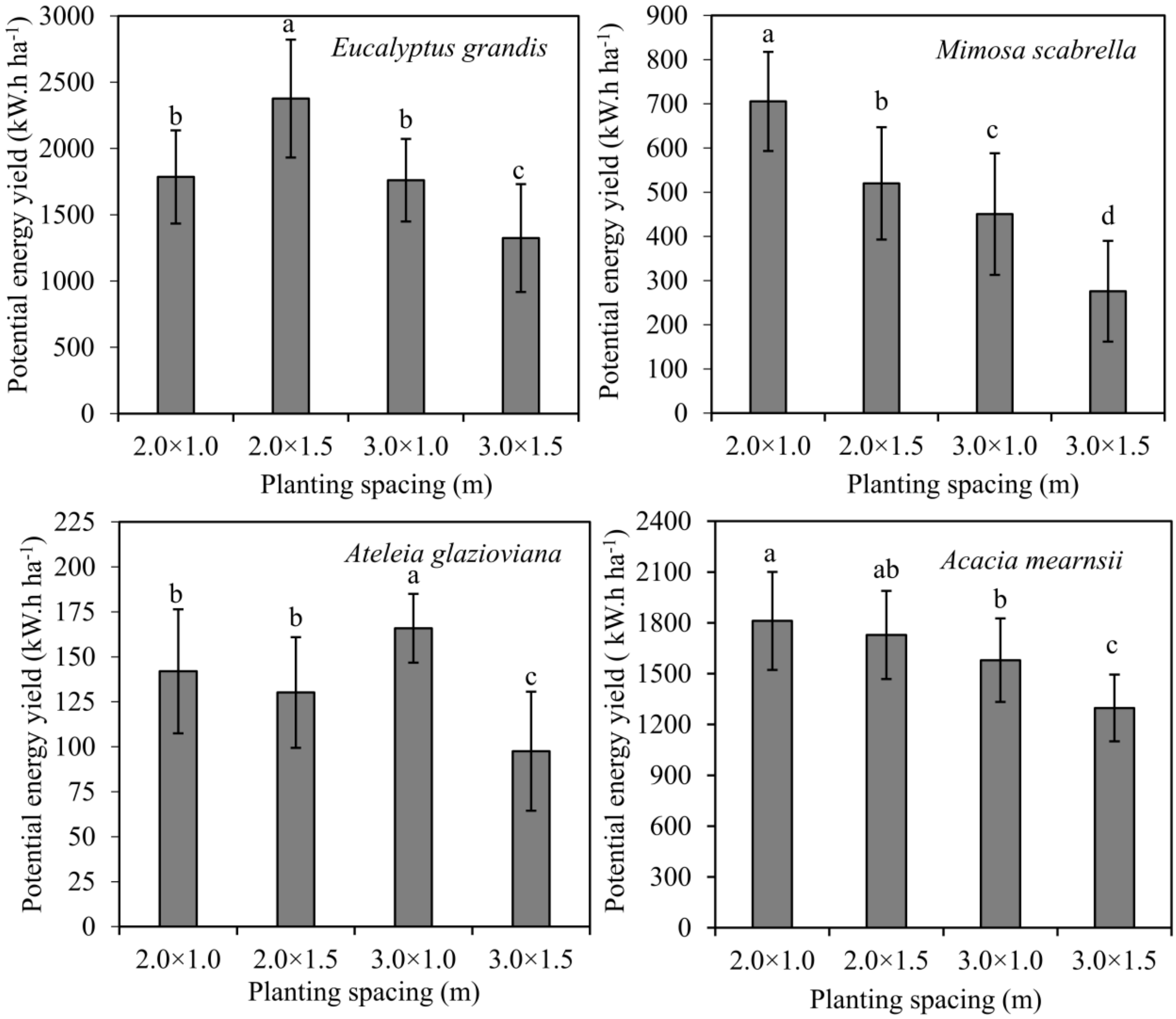

Figure 10. Potential energy yield in a short-rotation cycle *Eucalyptus grandis*, *Mimosa scabrella*, *Ateleia glazioviana*, and *Acacia mearnsii* grown on four planting spacings. Different small letters indicate significant differences (p<0.05) by Tukey test among planting spacings.

The potential energy yield showed the same trend of that observed for the biomass yield. The higher potential energy yield of *Eucalyptus grandis* was observed for the 2.0×1.5 m spacing while for the *Mimosa scabrella* and *Acacia mearnsii* was the 2.0×1.0 m spacing and for the *Ateleia glazioviana* 3.0×1.0 m spacing (Figure 10). In addition, we can highlight that the widest planting spacing 3.0×1.5 m, which is commonly used by forest industries and producers in forest plantations in Brazil, presented the lowest potential energy yield compared to the other spacings studied.

The results obtained in this study are relevant and aid the forest producers to use the optimal planting spacing to produce forest biomass for energy generation. Therefore, the use of reduced spacings should be recommended for future exploitation of forest energy plantations when the final aim is the production of biomass for energy. Changing, in this way, the planting spacing pattern (3.0×1.5 m) used by the majority of forest industries and producers.

The higher potential energy yield of the forest species obtained in the reduced planting spacing can be explained by the greater biomass yield, since the energy potential is directly related with the biomass yield, the higher the biomass produced, the higher the energy potential. The potential energy yield is a variable which depends on the total biomass per hectare, and on the gross calorific value of the biomass. As a consequence, the significant differences in energy yield were caused mainly by differences in biomass yield.

Biomass has a great potential as a renewable feedstock for producing various energy forms. Moreover, biomass is a versatile fuel that can produce biogas, liquid fuels and electricity (KOPETZ, 2007; SAIDUR et al., 2011). Biomass is a renewable energy source because its supplies are not limited. We can always cultivate trees even the waste with transportation, processing and other losses will always exist. In this context, sustainable use of this short-rotation plantations is expected to make a major contribution to economic development in Brazil and to the protection of the native forest resource (LAÉRCIO et al., 2011). However, in order to compete with fossil energy sources, efficient conversion technologies need to be utilized. According WELFLE et al. (2017), Brazil can be categorized as a global giant in terms of its productivity of biofuel feedstocks, especially biomass for energy and pellet production.

According PARRIS (2004), forest biomass has the potential to help meet the growing energy and raw material needs of society in a sustainable manner. This can include, for example, lowering greenhouse gas (GHG) emissions, and bringing benefits to soil and water quality and biodiversity (WELFLE et al. 2017). Forest biomass can only be considered sustainable if it is economically efficient and profitable, provides a net benefit to improving environmental aspect, and is compatible with policy goals for the wider context of energy chain.

Studies have been done evaluating the energy use and GHG emissions for harvesting, processing, and transporting forest biomass in the United Kingdom (WHITTAKER et al., 2011), Finland (WIHERSAARI, 2005), and Sweden (FORSBERG, 2000). The finding of all these studies, was related with the forest biomass can provide an almost carbon neutral energy source that has lower GHG emissions than fossil fuels and requires very little energy for processing and growth compared to what is produced.

Here we are supposing a hypothetical example of the use of forest biomass for energy generation. For this purpose, we used data from *Eucalyptus grandis* forest species cultivated in 2.0×1.5 m spacing obtained in this study (2,762 Gcal ha^{-1}) and population information for Frederico Westphalen (IBGE, 2019). The following question will be answered: What is the forest energy plantation area to meet the energetic power demand of the city of Frederico Westphalen for one year?

The data contained in this example was used exclusively to hypothetically simulate one situation: Average energy consumption per inhabitant = 157 kW.h $month^{-1}$; Population of Frederico Westphalen = 31,120; Conversion efficiency = 45%; and Conversion Gcal to kW.h = 1162.22.

The total area can be calculated following the steps below:

i) Total consumption of energy = 157 × 12 months = 1884 kW.h yr^{-1}

ii) Total consumption of energy for Frederico Westphalen = 1884 kW.h yr^{-1} × 31,120 population = 58,630,080 kW.h yr^{-1}

iii) Energy generation= 2,762 Gcal ha^{-1} / 7 years (short-rotation cycle) = 394.6 Gcal ha^{-1} yr^{-1}

iv) Considering a conversion efficiency of 45% = 394.6 Gcal ha^{-1} yr^{-1} × 0.45 = 177.6 Gcal ha^{-1} yr^{-1}.

v) Converting Gcal ha^{-1} yr^{-1} to kW.h ha^{-1} yr^{-1} = 177.6 Gcal ha^{-1} yr^{-1} × 1162.22 = 206,410.30 kW.h ha^{-1} yr^{-1}

vi) Total area = 58,630,080 kW.h ha^{-1} yr^{-1} / 206,410.30 kW.h ha^{-1} yr^{-1} = 284 ha

In conclusion, the total area required to meet the energy demand of the city of Frederico Westphalen for one year is 284 hectares. This example is hypothetical; however, it shows us the energy potential that the forest energy plantations presents and highlight the need of study new efficient ways of converting biomass to energy.

BRAND et al. (2014), evaluating the biomass produced in commercial plantations of *Pinus taeda*, at different ages and management systems, aiming the generation of energy in cogeneration systems, found that with the productive capacity of biomass (95 Mg ha^{-1}), the potential of electric power would be sufficient to supply 216 residences per month with average consumption of 200 kW.h $month^{-1}$ or, therefore, 155,455 residences during one hour, through the combustion of biomass for generation of electricity in a cogeneration system. These results support the feasibility of the electric power generation from forest biomass.

One of the main challenges to be overcome for a widespread adoption of this forest energy plantation system is related to the efficiency in the conversion of forest biomass to energy. The conversion of biomass into energy can be achieved in a number of ways (SAIDUR et al., 2011). To provide a fuel suitable for direct use in spark ignition gas engines, the fuel must be provided in either a gaseous, or a liquid form (PETER, 2002). Production of a gaseous fuel from biomass can be achieved by the application of a number of technologies, each with its specific requirements, advantages and disadvantages. However, Brazil forestry chain assumes a privileged position as one of the few countries in the world with the appropriate climate and technological conditions for forest energy production (STAPE et al., 2001; GONÇALVES et al., 2008).

The Brazilian forest industry faces important challenges in silviculture, tree improvement, and pests and diseases managemnt, which require further research and collaboration among the few players involved. Information generated in this study is relevant and provides information for companies interested in electricity generation from forest biomass and forest producers thereby assisting in the planning of optimal spacing to be used, as well as confirms the feasibility of the forest trees plantations, especially *Eucalyptus grandis* and *Acacia mearnsii*, for biomass production for energy.

4.2 Growth traits and solar radiation interception by forest plantations

The values of leaf area index for the short-rotation cycle of the forest species are showed in Figure 11. We observed a significant difference for the leaf area index in the different planting spacings. For the *Eucalyptus grandis*, the higher leaf area index was observed for the 2.0×1.0, 2.0×1.5, and 3.0×1.5 m spacing, which were higher than 3.0×1.0 m spacing. Regarding the other forest species, we observed higher leaf area index in the 2.0×1.0 m spacing, with a subsequent decrease in the leaf area index as planting spacing increased. For the *Ateleia glazioviana* specie was not possible to quantify the leaf area index because this specie presents deciduous characteristics, so, at time of tree assessments, the leaves were not computed.

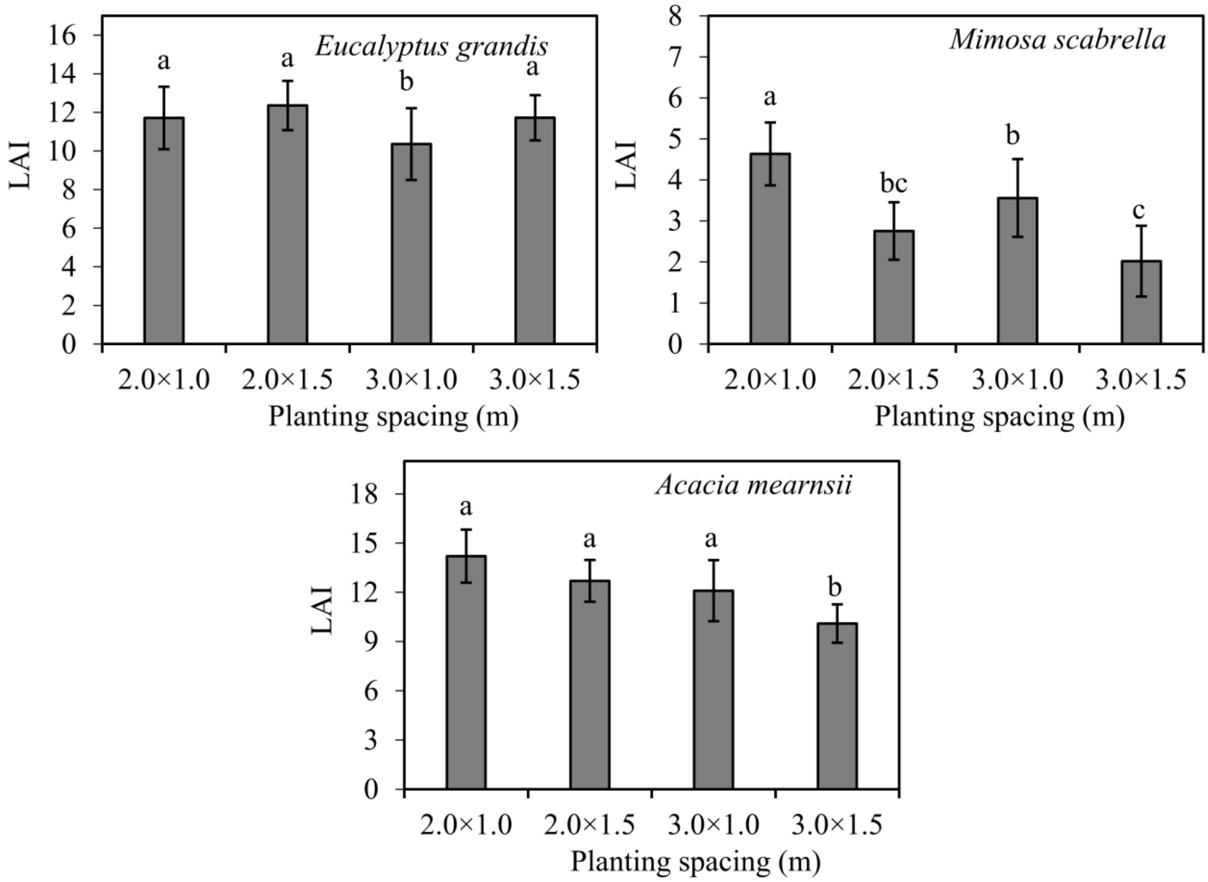

Figure 11. Leaf area index (LAI) in a short-rotation cycle of *Eucalyptus grandis*, *Mimosa scabrella*, and *Acacia mearnsii* grown on four planting spacings. Different small letters indicate significant differences (p<0.05) by Tukey test among planting spacings.

The values of leaf area index observed in this study are higher than that observed in the literature. Changes in the leaf area index can results in some interactions, especially with the solar radiation interception. A tree with high leaf area index might be expected to intercept less solar radiation per unit of leaf area (MJ m^{-2}) because of self-shading by leaves within the same canopy (BINKLEY et al., 2010). Similarly, small trees might be expected to intercept less solar radiation per unit of leaf area because shading by larger trees substantially reduces incident solar radiation. These expectations depend of several factors including sites, treatments, and sampling periods. The amount of leaves per unit of area and its temporal variation, leaf anatomy and canopy architecture are amongst the most important

(WHITEHEAD; BEADLE, 2004). The amount of leaves directly influences the magnitude of gas exchange due to increased transpiration (WHITE et al., 2009) and increased rainfall canopy interception (BENYON; DOODY, 2015). The highest leaf area generally provides greater assimilation of carbon.

In this context, the management of planting density through the spacing is one of the most important silvicultural decisions for the establishment of a forest plantation. It determines the amount of natural resources available for each tree growth. Closer spacing promotes faster development of the leaf area index, which increases solar radiation interception and photosynthesis (LANDSBERG; WARING, 1997). Species with denser crowns, are more responsive to spacing variations than those with less dense crowns (GONÇALVES; MELLO, 2004). This behaviour is directly associated with the intraspecific capacity of species to compete for solar radiation, water and nutrients (GONÇALVES; MELLO, 2004).

The solar radiation interception showed significant difference for the different assessed years (Figure 12). During the assessment years was observed a similar response for the different planting spacing. We observed a significant difference for the planting spacing 3.0×1.0 m for the *Eucalyptus grandis*, which intercepted a smaller amount of solar radiation. This response may be related to the lower values of leaf area index (Figure 11). Considering an average of the forest species, we can highlight that during the forest growth the trees intercepted between 75-85% of the solar radiation incident. The highest variations were observed for the species *Ateleia glazioviana*, which intercepted a smaller amount of solar radiation during the rotation cycle. This result can be related to the genetic (deciduous trees) and silvicultural characteristics of the species.

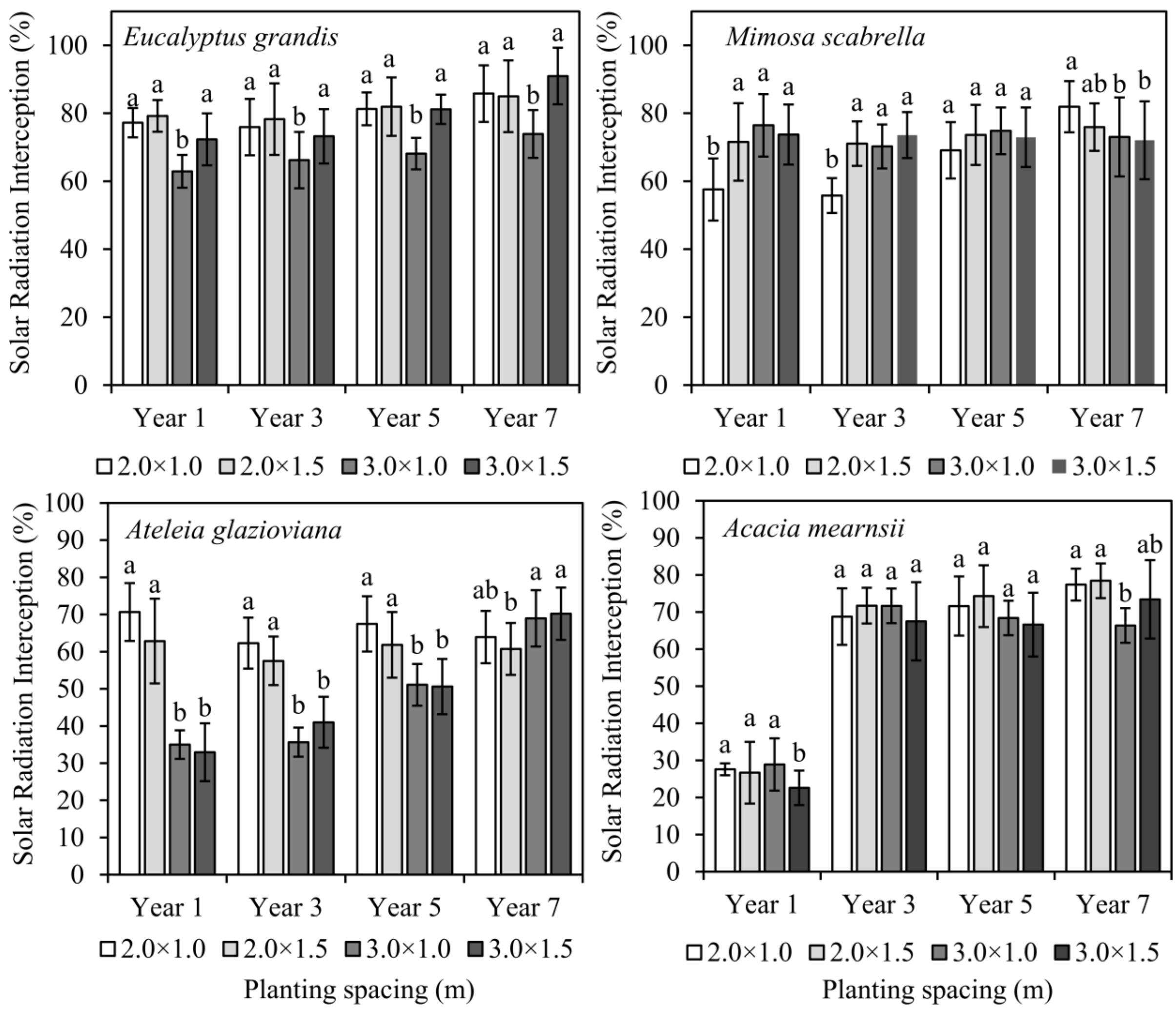

Figure 12. Solar radiation interception during the short-rotation cycle of the different forest species grown on four planting spacings. Different small letters indicate significant differences (p<0.05) by Tukey test among planting spacings.

Differences in solar radiation interception between large and small trees may be important, even when dominance is not strongly developed in a stand (FERNÁNDEZ; GYENGE, 2009). These authors suggested that changes in efficiency of resource use could follow differences in rates of acquisition of resource by individual trees; declines in efficiency of resource use may result from declines in acquisition of resources. In our study, the only changes in solar radiation interception would have resulted from competition from neighbors, so the patterns in resource use were not related to changes in resource supply rates at a stand level. Trees that intercepted more solar radiation used it more efficiently, consistent with general trends reported at the stand level by BINKLEY et al. (2002; 2004). Results that were confirmed in this study.

Several studies with different forest species have found a positive linear relationship between leaf area and solar radiation absorption. BINKLEY et al. (2010) found the relationship in clonal plantations of *Eucalyptus* in Brazil at mid-rotation (1.5–2.5 years old) and late-rotation (5.5–6.5 years old). FORRESTER et al. (2013) studying young (3.2 years) *Eucalyptus nitens* plantations in Australia, reported a linear slope, but it was different for thinned versus unthinned and pruned versus unpruned trees. In all of these studies, large trees with more leaf area did not experience significant self-shading, as additional leaf area was displayed on crowns with a wider radius (BINKLEY et al., 2013). This may be a general pattern among species, stand age, and silvicultural management.

The mean annual increment showed the same trend of that observed for the biomass yield. The higher mean annual increment of *Eucalyptus grandis* was observed for the 2.0×1.5 spacing while for the *Mimosa scabrella* and *Acacia mearnsii* was the 2.0×1.0 m spacing and for the *Ateleia glazioviana* 3.0×1.0 m spacing (Figure 13). In addition, we can highlight that the widest planting spacing 3.0×1.5 m presented the lowest mean annual increment compared to the other spacings studied.

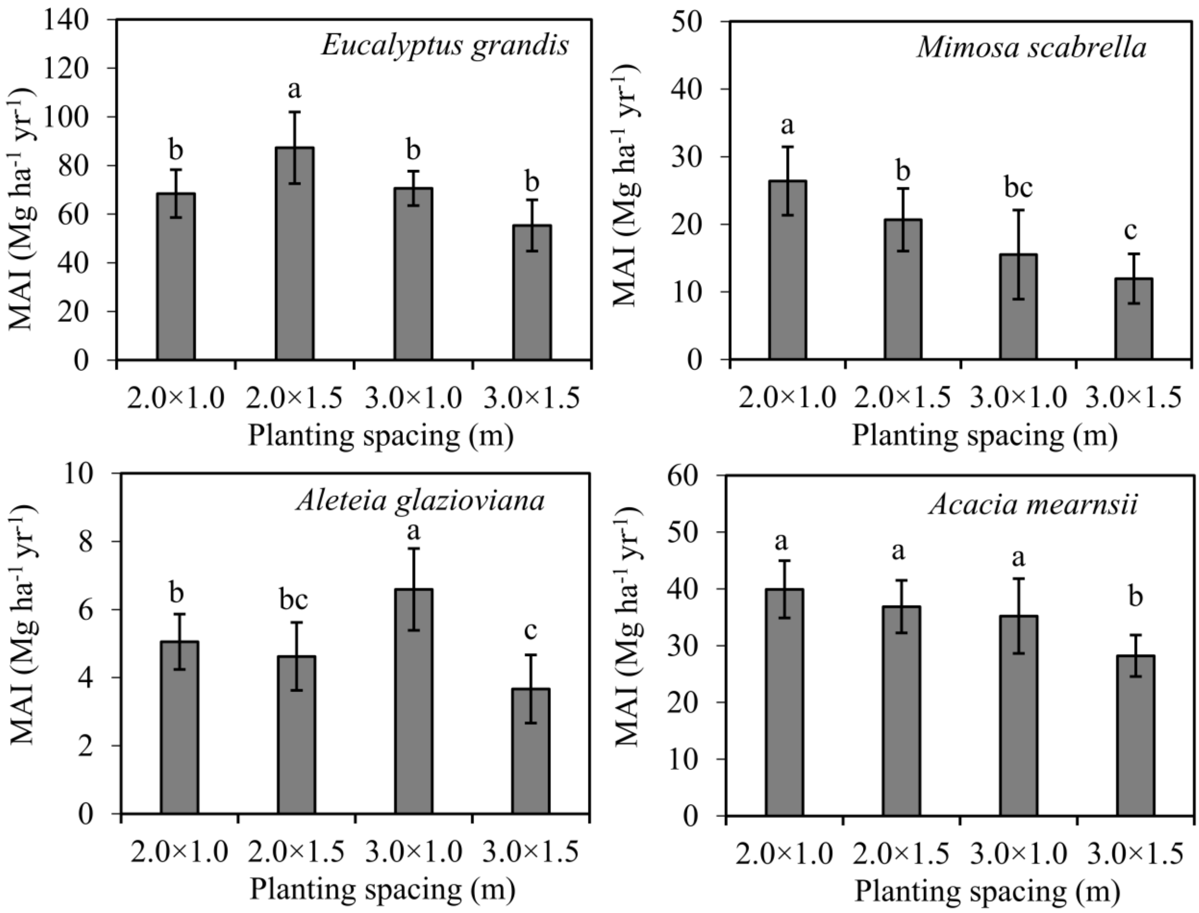

Figure 13. Mean annual increment (MAI) in a short-rotation cycle of *Eucalyptus grandis*, *Mimosa scabrella*, *Ateleia glazioviana*, and *Acacia mearnsii* grown on four planting spacings. Different small letters indicate significant differences (p<0.05) by Tukey test among planting spacings.

We observed a mean annual increment considering all planting spacing for each forest specie of 70.4, 18.6, 5.1 and 35.1 Mg ha^{-1} yr^{-1} for *Eucalyptus grandis*, *Mimosa scabrella*, *Ateleia glazioviana* and *Acacia mearnsii*, respectively. These values of mean annual increment are higher than those reported in the literature. This response is related with the overall biomass yield of a unit area of land. In this context, the number of plants per unit area becomes an essential factor for the rates of growth increment. Therefore, forest plantations conducted at reduced planting spacings result in higher growth rates, and consequently, higher biomass accumulated for energy generation.

According BINKLEY et al. (2017), Brazilian *Eucalyptus* plantations are some of the most productive forest plantations in the world, sustaining mean growth rates of 25 Mg ha^{-1} yr^{-1} (50 m^3 ha^{-1} yr^{-1}). In study conducted by BINKLEY et al. (2017) with several *Eucalyptus* clones they reported that the clones differed strongly in response to temperature, precipitation, and overall patterns of stem production varied as strongly among clones within sites as across the geographic gradient of sites. Moreover, the clones differed greatly in the deployment of leaf area, and in the ability of leaves to grow wood. For instance, the most productive clone showed a mean annual increment of 46 Mg ha^{-1} yr^{-1}, being 45.6% above the average increment observed in the study, which is 25 Mg ha^{-1} yr^{-1}. This response demonstrates the great variation between the response of different forest species when submitted to different conditions of climate, soil and management.

Although many parameters are important determinants of the suitability of a tree species grown for short-rotation forest (SENELWA, 1997), total biomass yield (in terms of tonnes of above ground dry matter per hectare per year), is considered to be the most important as it indicates the ability to produce actual marketable fuelwood product. In this context, mean annual increment vary with species, age of root stock, population density, length of rotation and time of harvest (SIMS et al., 2001; BINKLEY et al., 2017).

4.3 Biomass and soil carbon storage and partitioning in forest plantations

The carbon stock of the forest plantations was evaluated considering the carbon stored in the aboveground (trunk, branches and leaves) and belowground (roots) parts of the trees. Only for the *Acacia mearnsii* species the roots assessments and soil carbon content were not performed because the cycle of this species ended in 2015. Thus, we quantified only the aboveground C stored for this species. The values of carbon stock for the short-rotation cycle of the forest species are showed in Figure 14.

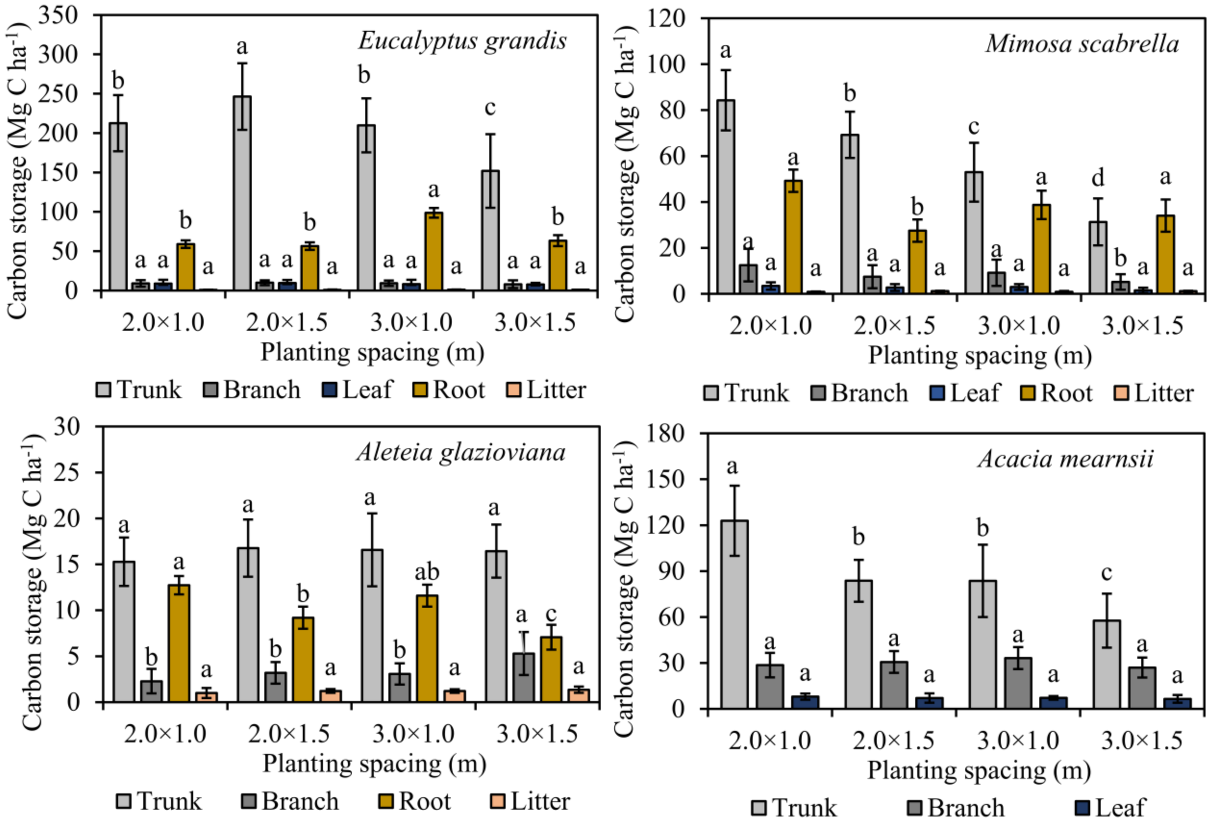

Figure 14. Carbon storage aboveground and belowground in a short-rotation cycle of *Eucalyptus grandis*, *Mimosa scabrella*, *Ateleia glazioviana*, and *Acacia mearnsii* grown on four planting spacings. Different small letters indicate significant differences (p<0.05) by Tukey test among planting spacings.

The average carbon content of the four forest species studied for the different tree compartments following the pattern: leaves (47.16%), followed by the trunk (45.31%), branches (44.38%), and roots (42.54). The results obtained in this study agree with that observed for RIBEIRO et al. (2015), who reported for the *Eucalyptus grandis* species showed and average carbon content for the leaves (46.10%), trunk (44.61%), branches (42.89%), and roots (37.8). These results demonstrated that exist differences in carbon content between the different tree compartments. Several studies use a biomass conversion factor (C=0.50), as average carbon content of the forest species (BROWN et al., 1986). Therefore, we recommend caution in the use of this conversion factor, since there may be overestimation or underestimation depending on the compartment of the tree as well as the species studied. IPCC (2006) recommends that in the absence of specific carbon content values, a default carbon content of 47% should be used to estimate the carbon fraction in the aboveground forest biomass.

The carbon stock above-belowground of the forest species are related with the potential of the forest produce biomass (Figure 8) and the carbon content of each tree compartment. Thus, was possible to verify similar pattern in the carbon stock with the biomass yield. The largest amount of carbon stored for the studied forest species and planting spacings was verified for *Eucalyptus grandis* at 2.0×1.5 m spacing, which was 327.1 Mg [C] ha^{-1}. Since of this total 76.22% refers to the trunk, 3.1% branch, 2.98% leaf, 0.26% litter and 17.45% roots. For the other species was observed lower values of carbon stock. All the forest species showed higher values of the carbon storage in the following pattern: trunk > roots > branches > leaves > litter. The average amount of carbon stored for the other forest species and planting spacings were 109.1 Mg C ha^{-1} for *Mimosa scabrella*, 31.1 Mg C ha^{-1} for *Ateleia glazioviana* and 124.1 Mg C ha^{-1} for *Acacia mearnsii*. While the average amount of carbon stored for *Eucalyptus grandis* was 293.2 Mg C ha^{-1}.

According with the results obtained in this study, we can emphasize that the higher carbon storage observed in the reduced planting spacing is related with the capacity of the trees to convert more efficiently the solar radiation in assimilates and storing in its structural composition. In this context, the larger the amount of biomass produced, the greater the amount of carbon stored. Similar results were found by (SANQUETTA et al., 2014a), who reported that the trunk represents 79.46%, branches 16.62% and leaves 3.92% of the carbon storage in the aboveground of forest species. Moreover, STAPE et al. (2008) verified that the leaves of *E. grandis* x *urophylla* stored 8.8% of the total C of the trees, the branches 7.8% and the trunk 83.4% in plantations located in the South of Bahia.

The same pattern of C storage in the different tree compartments was reported by RIBEIRO et al. (2015), who found that the contribution of each tree compartment in the aboveground biomass, the carbon stock for the stem, bark, branches and leaves accounted for 52.12, 5.09, 4.45 and 1.91 Mg C ha^{-1}, respectively. The belowground carbon stock on the stand level was 9.81 Mg C ha^{-1}. Moreover, reported that the total stand carbon stock in the *Eucalyptus* plantation was estimated to be 73.38 Mg C ha^{-1}. From this total, the above and the belowground carbon stock represented 87% and 13%, respectively.

Regarding the carbon stored aboveground and belowground, we observed an average partition of 76.2 and 23.8%, respectively, for the *Eucalyptus grandis*; 64.58 and 35.42% for the *Mimosa scabrela*; and 67.47 and 32.53 for the *Ateleia glazioviana* species. The results found in this study agree with that obtained by RIBEIRO et al. (2015), who reported that the tree carbon stock in the stand level for the above-belowground parts were 64.2% and 35.8%, respectively. These values are within the carbon stock range for *Eucalyptus* plantations. For instance, in a stand of *Eucalyptus* in Brazil, PAIXÃO et al. (2006) found an aboveground carbon stock of 76.4% and a belowground 23.6%.

The carbon stock in the aboveground biomass of different types of vegetation around the world is very variable, reaching values close to: 120 Mg ha^{-1} in tropical forests, 64 Mg ha^{-1} in boreal forests, 55 Mg ha^{-1} in temperate forests, Mg ha^{-1} in tropical savannas, and 4 Mg ha^{-1} in agricultural lands (IPCC, 2000). SCHROEDER (1992), also mentions that the average carbon stock in some planted tropical forests varies considerably with species, age, and as a consequence of the site's growth and productive capacity. The carbon stock in *Pinus caribaea* stands reaches 59 Mg ha^{-1} at age 15; 72 Mg ha^{-1} in *Pinus patula* at age 20; and 57 Mg ha^{-1} in *Cumpressus lusitanica* at age 20.

The difference in the carbon stored on belowground can be related with the ability of each forest species into produce and partitioning the photoassimilates for the roots and use the availability resources in the soil. There are a number of attributes of tree roots that influence the ability of the tree to compete for soil resources in regions of low availability of water and nutrients. The attributes include the structure of the root system, the distribution of fine roots, the seasonality of growth, and the physiological ability to take up water and nutrients. The root structure and growth are important attributes under genetic control (GONÇALVES et al., 2013).

In this context, we can highlight the importance of the forest energy plantation in store carbon in the forest biomass, and the greater amount of carbon stored were obtained in the reduced planting spacing. Moreover, we need consider the contribution of the soil in storing carbon. Soil plays an important role in carbon storing worldwide.

The soil carbon stock obtained in this study for the two depths evaluated ranged from 37.6 Mg C ha^{-1} up to 46.7 Mg ha^{-1} (10−20 cm) and 30.8 Mg C ha^{-1} up to 39.3 Mg ha^{-1} (20−40 cm), considering all forest species and plantantig spacing. This result demonstrating high vertical variability (Table 2). As the soil carbon stock was computed per layer (0−20 and 20−40), we obtained a relation indicating that the deeper the layer, the lower the carbon stock, meaning that superficial layers contain the largest carbon stock. The soil carbon content, in turn, followed a decaying trend of its value with the increasing of the soil depth, such as observed by (JOBBÁGY; JACKSON, 2000; SALTON et al., 2011; SHEIKH et al., 2009; ZINN et al., 2012; MORAIS et al., 2017).

Table 2. Soil carbon storage for the different forest species grown on four planting spacings at nine years old.

Species	Spacing (m)	Depth (cm)	Soil carbon stock (Mg C ha^{-1})
Eucalyptus grandis	3.0×1.5	0−20	45.860
		20−40	39.294
	3.0×1.0	0−20	41.837
		20−40	32.220
	2.0×1.5	0−20	41.474
		20−40	34.620
	2.0×1.0	0−20	46.154
		20−40	33.235
Mimosa scabrella	3.0×1.5	0−20	37.623
		20−40	31.280
	3.0×1.0	0−20	45.642
		20−40	34.280
	2.0×1.5	0−20	44.466
		20−40	36.806
	2.0×1.0	0−20	43.359
		20−40	31.066
Ateleia glazioviana	3.0×1.5	0−20	41.451
		20−40	33.171
	3.0×1.0	0−20	40.456
		20−40	30.813
	2.0×1.5	0−20	45.789
		20−40	35.369
	2.0×1.0	0−20	46.729
		20−40	35.927

Considering an average in the soil carbon stock for all forest species and planting spacing, we observed values of 43.4 Mg C ha^{-1} (10−20 cm) and 34 Mg C ha^{-1} (20−40 cm), i. e., a reduction in 21.7% of the C stored between the layers. The average accumulated soil carbon stock for the forest species was 77.4 Mg C ha^{-1} (0−40 cm). GASPARINI and DI COSMO, (2015) studying the carbon stock in the biomass and the soil of native forests in Italy found values between 20 and 110 Mg ha^{-1} of carbon stored at the biomass and between 70 and 90 Mg ha^{-1} of carbon stored at the soil, these data corroborate with the studies of LACLAU (2003) that found levels between 80 and 100 Mg ha^{-1} of carbon in the soils. These results emphasize the importance of soil in storing carbon in the forest systems. Carbon sequestration in forest systems is generally high and the net C balance positive (LAL, 2005).

For PULROLNIK (2009), 92% of the soil carbon stock in the *Eucalyptus* forest is concentrated up to one meter deep, and only 8% in the litter. So, CHRISTIE and SCHOLES, (1995) reported that forests do not always store more carbon in the soil than field areas, despite accounting for a significant carbon stock on the surface due to litter. Similar results were observed in other studies. SCHUMACHER and WITSCHORECK (2004), report that there are differences in depth carbon stock in the soil of *Eucalyptus* plantations in Rio Grande do Sul. This reduction of carbon in depth was also cited by ANTUNES (2007) in eucalyptus forest with 4, 5 and 20 years in Dystrophic Red Argisol. The same was verified in *Pinus taeda*, with 5, 14, 20 and 32 years and *Acacia mearnsii*, with 2 to 8 years studied by CALDEIRA et al. (2002).

Our study showed that planting spacing and the forest species studied did not influence the carbon stock in the soil. This answer can be related to two main reasons. The first one is related to the age of the forest stand and the change of soil use. In the area where the experiment was performed, it was previously cultivated with *Ilex paraguariensis*, in this sense, it was necessary to prepare the soil (harrowing and plowing). This change in the soil use can modified the soil carbon contents. Therefore, the duration of the forest species growth (nine years) was not sufficient to modify the carbon stock of the soil, because these main reasons, both planting spacing and forest species showed no difference in the carbon stock.

This result agree with that observed by PAUL et al. (2003), who reported that forest plantation with *Eucalyptus grandis* and *Eucalyptus globulus* generate a decrease of carbon up to 30 cm in the first 10 years, increasing only from 10 to 14 years of age. The reduction was associated with the impact of the soil management practices to perform the forest implantation and that can be reestablished when the forest begins to stabilize and allows the significant return of carbon from the forest biomass cycling.

The second reason is related to the depth of the soil layer evaluated. In this study, we evaluate two layers (0−20 cm) and (20−40 cm), which were defined in order to contemplate the soil layer in which it contains most of the carbon stored in the soils. However, due to the greater interaction between forest litter and carbon stock in the superficial layers (0−5 cm) and (5−10 cm), we believe that the 0−20 cm used in our study was not adequate to capture the effect of these superficial layers. Therefore, this study did not showed result in soil stock carbon variation in the different spacings and species studied.

The differences in the soil carbon stock in the superficial depths can be related with the accumulation of vegetal residue, the quantity of organic matter, the radicular activity and the microorganisms. Also, the alteration of the native vegetation decreases the soil carbon

(POST; KWON, 2000), being this due to the species, the amount of litter, the production of roots, and the age of the plantations, being the balance restored only after 40 years with the forest cultivation (GUO; GIFFORD, 2002). On the other hand, LIMA (2004) found the highest carbon content in the 0–5 cm layer in *Eucalyptus* forest compared to pasture, due to the forest litter. Moreover, short-rotation forest plantations without any nutritional enrichment can cause total carbon loss (TURNER and LAMBERT, 2000). Therefore, reforestation, for BASHKIN and BINKLEY (1998), does not promote a carbon increase up to 55 cm after the 10 to 13 years. Therefore, to increase carbon stocks in the soil some forest management need to be adopted including site preparation, species management/selection, use of fertilizers and soil amendments. Since the forest harvesting may decrease C stock, at least temporarily (LAL, 2005).

The carbon partitioning in the forest system (soil + tree biomass) was only performed to observe the contribution of each component in the total carbon accumulation in a forest plantation (Figure 15). In order to analyze the carbon partition, we observe an average of 54.8%, 18.7% and 21.42%, for the *Eucalyptus grandis* trunk, roots and soil, respectively. The other tree compartiments account for the remainder. For the forest species *Mimosa scabrella* and *Ateleia glazioviana*, a greater contribution of the soil was observed in the total carbon stock in the forest plantation system. This response was related to the lower potential of these species to produce biomass and consequently to store carbon both aboveground and belowground. We observed an average of 31.2%, 20.2% and 42%, for the *Mimosa scabrella* and 15%, 9.4% and 71.3%, for *Ateleia glazioviana*, for the component trunk, root and soil, respectively.

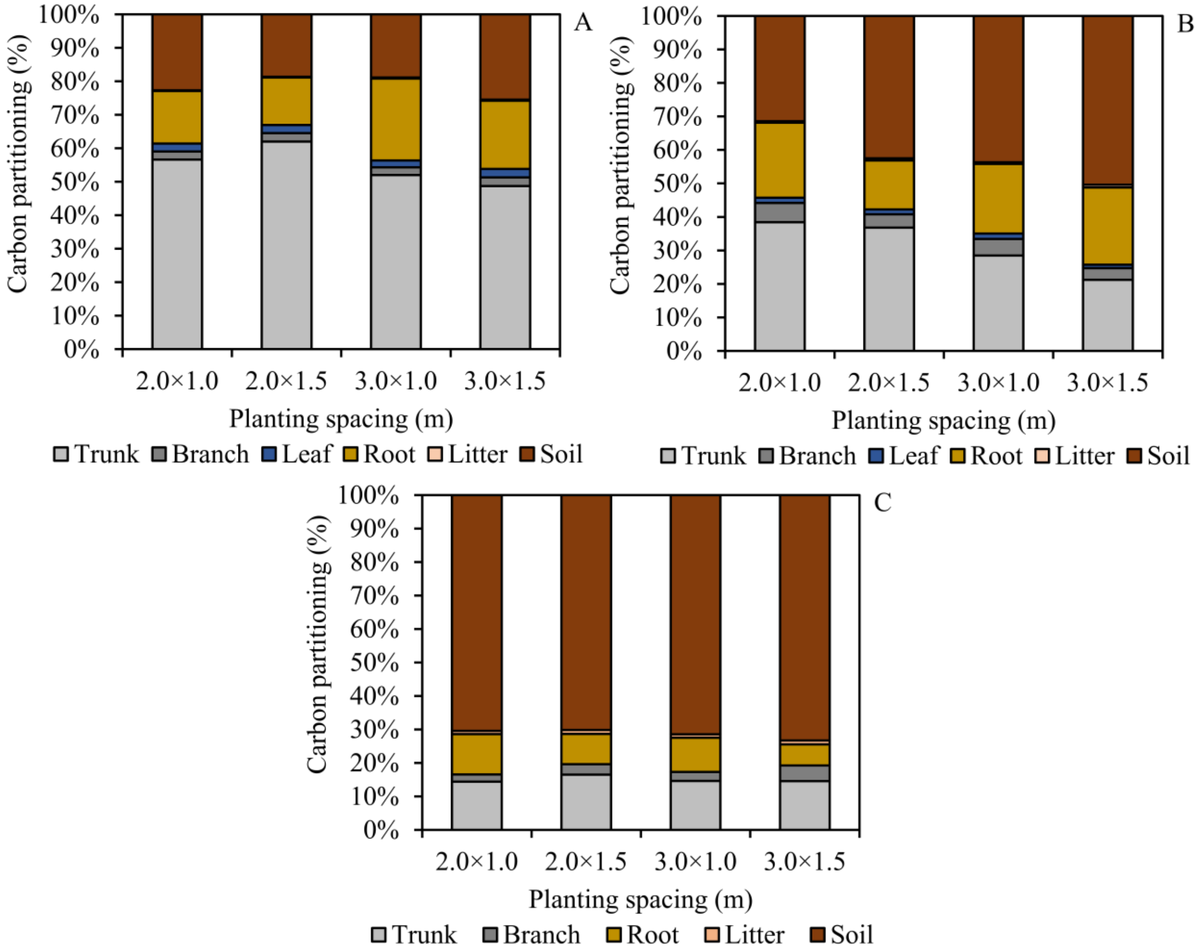

Figure 15. Carbon partitioning in the system (tree biomass + soil) in a short-rotation cycle of *Eucalyptus grandis* (A), *Mimosa scabrella* (B), and *Ateleia glazioviana* (C) grown on four planting spacings.

As there was no difference in soil carbon storage for the different species and plant spacings (Table 2), the total carbon partition in the forest system was basically related to the amount of carbon stored in the above-belowground biomass. From this, it was possible to highlight that in plantations with *Eucalyptus* species, the accumulation of biomass in the aboveground was greater than that stored in the soil. Different from which happens for the other forest species, due to the low potential to store carbon in both above-belowground biomass.

4.4 Forest species composition and properties

Main PCA results of forest species properties grown on four planting spacing are presented in the Figure 16. The *Eucalyptus grandis* PCA analysis indicated that primary and secondary components were responsible for, respectively, 69.9% and 24.9% of the cumulated variance for all investigated tree compartments and planting spacing. For the other species was observed that primary and secondary components were responsible for, respectively, 72.9% and 22.8% for *Mimosa scabrella*, 53.4 and 36.6 for *Ateleia glazioviana* and 68.9 and 29.5 for *Acacia mearnsii*. Overall, it was observed that for the four species studied the principal component analysis allowed the explanation of more than 90% of the cumulated variance for all investigated tree compartments and planting spacing.

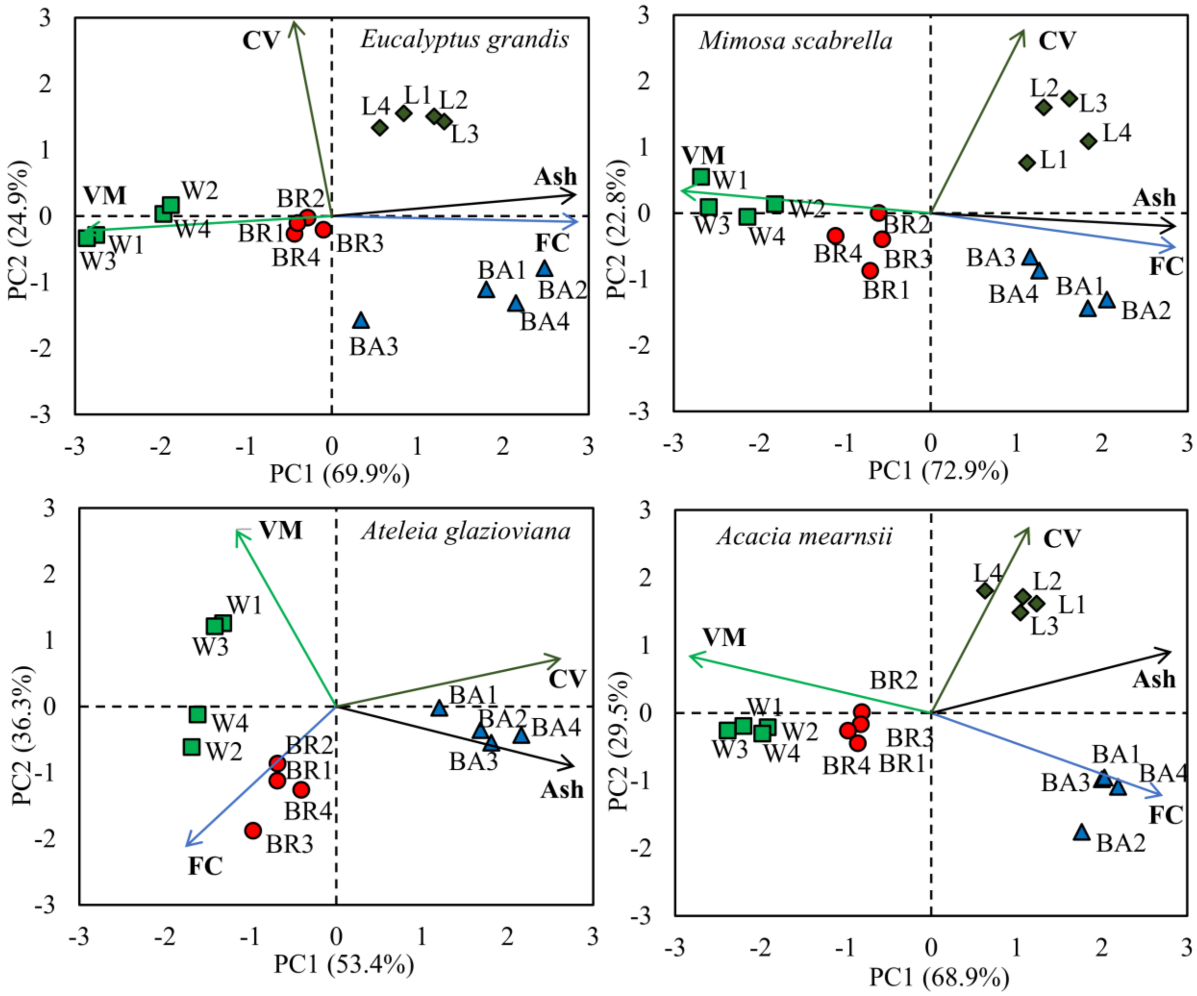

Figure 16. PCA with biplot showing forest species properties grown on four planting spacing (previously identified). The variables fixed carbon (FC), volatile material (VM), ash content (Ash) and calorific value (CV) are indicated by arrows, while the four tree compartments W (wood), BA (bark), BR (branch) and L (leaf) and four planting spacing are indicated as points 1 (2.0×1.0 m), 2 (2.0×1.5 m), 3 (3.0×1.0 m), and 4 (3.0×1.5 m).

For the *Eucalyptus grandis* properties, PC1 was associated with fixed carbon and Ash in contrast with volatile material, while PC2 was associated especially with calorific value. This same response was observed for the forest species *Mimosa scabrella* and *Acacia mearnsii*. For the tree compartments we can observe that the leaves were strongly associated with calorific value and ash content. In other hand, the wood and branches were associated with volatile material in contrast with fixed carbon. Also, the bark was characterized to be strongly associated with fixed carbon.

Regarding the *Ateleia glazioviana* forest species, PC1 was associated with calorific value and ash content in contrast with fixed carbon, while PC2 was associated especially with volatile material. For the tree compartments we can observe that the wood was strongly associated with fixed carbon and volatile material in contrast with ash content. Also, the bark was characterized to be strongly associated with ash and calorific value. Another important point that we need emphasize is that the planting spacing had not influence on forest species properties, since they presented a similar pattern of response (Figure 16).

For the elemental composition of the forest species studied, the *Eucalyptus grandis* PCA analysis indicated that primary and secondary components were responsible for, respectively, 74.1% and 17.5% of the cumulated variance for all studied tree compartments and assessment years (Figure 17). For the other species was observed that primary and secondary components were responsible for, respectively, 77.7% and 14.1% for *Mimosa scabrella*, 38.1 and 34.1 for *Ateleia glazioviana* and 76.5 and 16.2 for *Acacia mearnsii*.

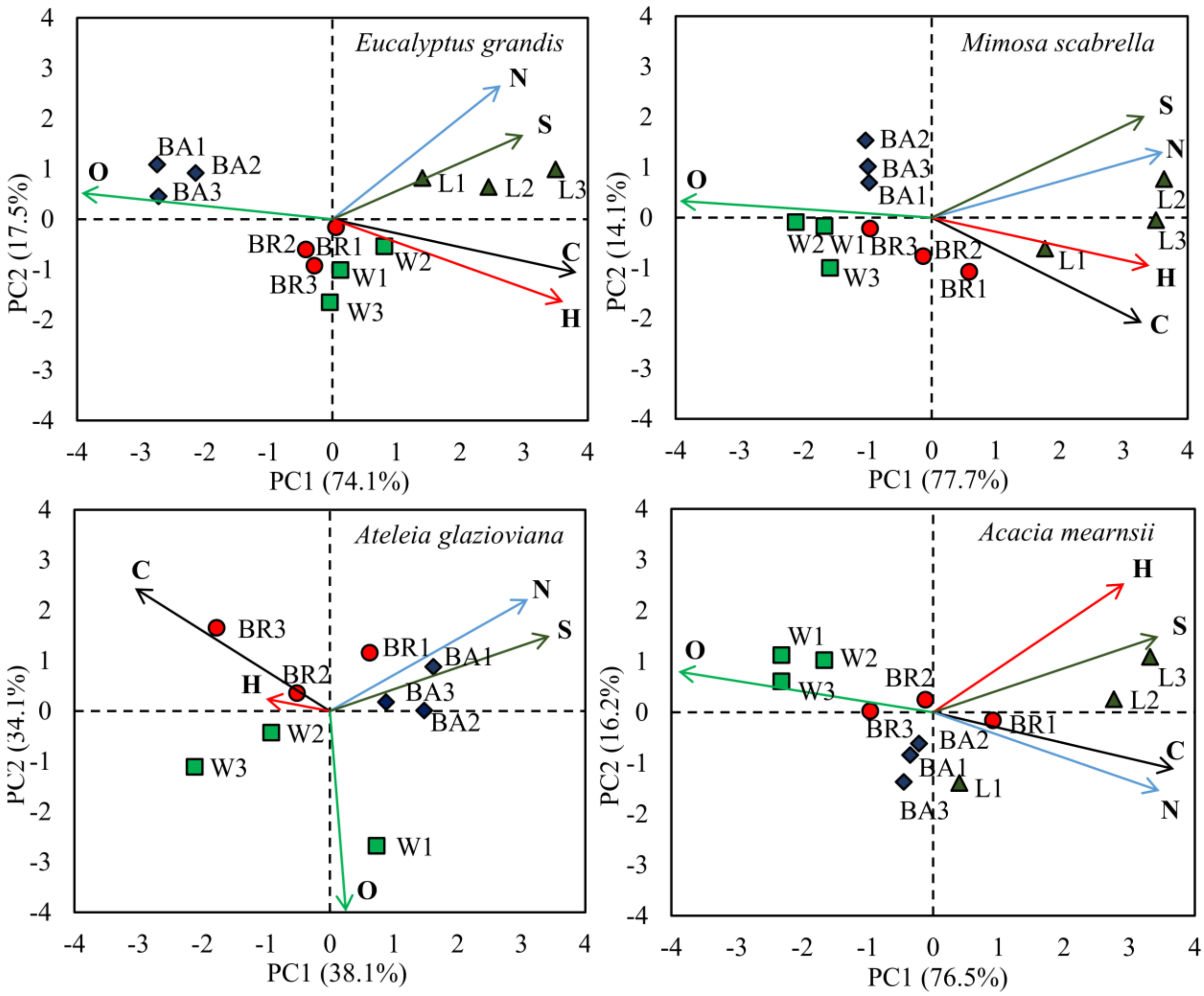

Figure 17. PCA with biplot showing the elemental composition of the different forest species. The elementary components Carbon (C), hydrogen (H), oxygen (O), nitrogen (N) and sulfur (S) are indicated by arrows, while the four tree compartments W (wood), BA (bark), BR (branch) and L (leaf) and three assessment years are indicated as points 1 (2009), 2 (2011), and 3 (2013).

For the *Eucalyptus grandis* elemental composition, PC1 was associated with C and H in contrast with O, while PC2 was associated especially with O. For the other forest species, we observed that PC1 was associated with N and S in contrast with O, while PC2 was associated especially with O in contrast with C. Similar with the pattern observed for the forest properties, the assessment years had not great influence on forest species composition. For the tree compartments we can observe that the wood was strongly associated with C and H in contrast with O. In other hand, the leaves were associated with N and S. Moreover, the bark and branch were characterized with average PC loadings both for the energy properties and for the elemental composition.

The study and characterization of the properties and composition of a given forest-based biomass fuel is the initial and most important step during the investigation and application of such fuel. Our study demonstrates that as important as the amount of biomass produced, the forest biomass quality is of essential importance, since the forest species composition and properties can influence the potential for energy generation.

Elemental composition is one of the most important characteristics for biomass utilization. The results presented in this study indicate that forest species properties and composition did not vary much with planting spacing and assessment years (Figure 16 and 17). However, for the different tree compartments we observed clearly variability among the elemental composition and properties. As the aim is the wood production, we highlighted the results regarding wood composition and properties. In increasing order of abundance, the forest species studied elements in wood biomass are C, O, H, N, and S. The elemental contents through principal component analysis show that the forest species wood contain higher proportion of carbon content compared with hydrogen and oxygen which increased the energy value. This result was more evident for the *Eucalyptus grandis* species.

Another important point is related with the emission of pollutants elements during the biomass combustion process. The lower percentage of nitrogen and sulfur in woody biomass is important in the view of environmental point (KUMAR et al., 2010; VASSILEV et al., 2010). The concentrations of these elements are of major importance because they are pollutants and cause gaseous emissions sulfur (SOx) and nitrogen (NOx), which lead to acid rain and ozone depletion (DEMIRBAS, 2004). Recent studies have shown that one of the main environmental impacts of solid biofuels combustion is caused by NOx emissions (NUSSBAUMER, 2002). Therefore, the low nitrogen and sulfur values found for the forest species wood did not compromise its bioenergetic use.

Therefore, when it is intended to produce biomass for energy, it is desirable that the wood presents high levels of carbon and hydrogen and low levels of oxygen and ash content, which was observed in this study. The forest species wood was characterized to present high volatile matter and reduced values of ash content (Figure 16). The potential as a fuel reduces with the amount of ash present in the biomass. The higher amount of ash in biomass makes it less desirable as fuel (DEMIRBAS; DEMIRBAS, 2009).

The forest biomass that provides better results for energy generation has low moisture and ash content, and high wood density, C content and heating value (LABRECQUE et al., 1997; KLASNJA et al., 2002; ELOY et al., 2014). According CARDOSO et al. (2015), several traits have an effect on biomass quality for energy generation, among them are moisture content, wood density, heating values, ash and C content. Moreover, several factors can modify the anatomical structure and properties of the wood, among them are genetics, silvicultural practices (irrigation, fertilization) and the environment (soil, temperature, rainfall) (RAYMOND, 2002; THARAKAN et al., 2005). In forest energy plantations, species, plantation density, rotation length and management practices can influence both wood yield and quality, affecting its ability to generate energy (LABRECQUE et al., 1997; THARAKAN et al., 2003, 2005; ELOY et al., 2014).

With the results obtained in this study, we can highlight that all forest species studied presents adequate characteristics to produce energy, such as energy properties and elemental composition, especially the forest species *Eucalyptus grandis* and *Acacia mearnsii*, and can be recommended for energy plantations under reduced planting spacing.

4.5. Multivariate analysis among Growth×Yield×Climate of forest plantations

To the best of our knowledge, this is the first study to examine the multivariate relationships between climate and tree variables (tree growth, yield, and climate) in forest plantations. Our study demonstrated that the use of multivariate approach was a valuable tool to understanding the correlations between Growth×Yield×Climate.

Main PCA results of forest species Growth×Yield×Climate grown on four planting spacing are presented in the Figure 18. The PCA analysis indicated that primary and secondary components were responsible for, respectively, 82.7% and 14.1% of the cumulated variance for all investigated forest species and planting spacing. For the Growth×Yield×Climate, PC1 was associated with energy yield (ENER), biomass yield (BIO), and volume (VOL) in contrast with light extinction coefficient (k), while PC2 was associated especially with k in contrast with leaf area index (LAI) and solar radiation interception (SRI).

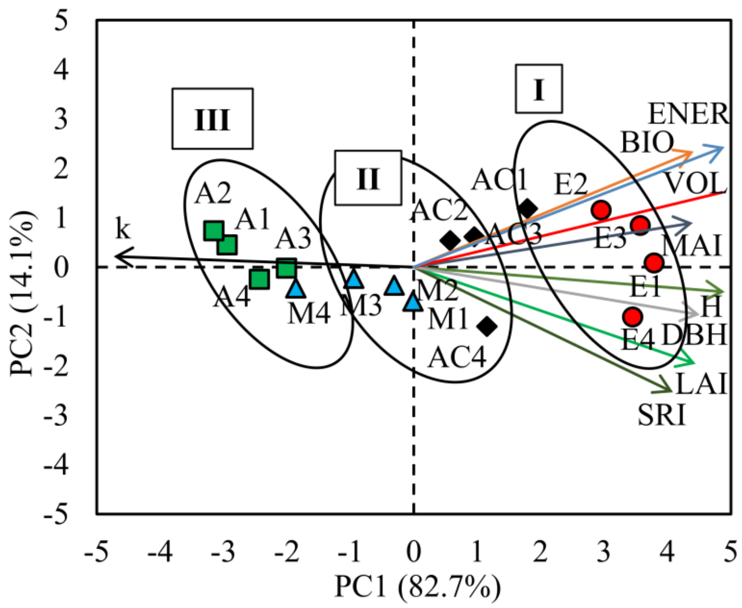

Figure 18. PCA and discriminant analysis with biplot showing the growth×yield×climate of the different forest species (previously identified). The growth traits: H, DBH, LAI and MAI; yield: VOL, BIO and ENER; and climate: SRI and k, are indicated by arrows, while the three forest species *Eucalyptus grandis* (E), *Mimosa scabrella* (M), *Ateleia glazioviana* (A), and *Acacia mearnsii* (AC) and four planting spacing are indicated as points 1 (2.0×1.0m), 2 (2.0×1.5m), 3 (3.0×1.0m), and 4 (3.0×1.5m).

Regarding the discriminant analysis, we observed the formation of three distinct groups. The first group was related to the species *Eucalyptus grandis*, with the four spacings and the 2.0×1.0 m spacing of the *Acacia mearnsii* species. This group was characterized by high biomass and energy yield, as well as the growth traits volume and mean annual increment, related to the leaf area index and solar radiation interception. For the second group was observed PC loadings intermediate, i. e., they were characterized by presenting intermediate values of the analyzed variables. For this group were the three spacings of the *Mimosa scabrella* (2.0×1.0, 2.0×1.5 and 3.0×1.0 m) and the other three planting spacing of the *Acacia mearnsii*. The last group was represented by the four *Ateleia glazioviana* pacings and 3.0×1.5 m spacing of the *Mimosa scabrela*. This group was characterized by low biomass and energy yield, as well as lower leaf area index and intercepted solar radiation. This multivariate analysis enabled a simple summarization of the relationship between Growth×Yield×Climate, represented in this study by the variables mentioned in Figure 18.

Forest plantations in Brazil are very productive mainly due to favorable climatic conditions (STAPE et al., 2010; GONÇALVES et al., 2013; FEREZ et al., 2015; VENEGAS-

GONZÁLEZ et al., 2016). In this study, was possible to identify differences in the potential of the forest species into produce forest biomass and energy. The *Eucalyptus grandis* showed the greatest potential for biomass and energy production, and there was a huge difference when compared to the other forest species. Regarding the other species, it was possible to observe that *Acacia mearnsii* showed average potential for biomass and energy production, although it is lower than *Eucalyptus*. The other species *Mimosa scabrella* and *Ateleia glazioviana* presented low potential of biomass and energy production when compared to *Eucalyptus*. However, these species being native, they have a great environmental and social importance. They are commonly used for environmental reforestation and their wood used for energy production by farmers.

The results obtained for the *Eucalyptus* trees can be related with the higher leaf area index and by the amount of solar radiation intercepted and used. The leaf area index, determines the quantity of solar radiation interception which influences the rate of photosynthesis. Most physiological processes are affected by environmental conditions: changes in their rates may be caused by changes in solar radiation avaibility, temperature or in the state of the plant, in terms of nutrient concentrations or the water status.

Considering the relationship between Growth×Yield×Climate under the conditions of this study, it was observed that the availability of water and nutrients were adequate for the tree growth, and the growth rates, and consequently, the biomass productivity was directly related with the solar radiation intercepted by the canopy of the trees and by the efficiency with the solar radiation was converted into photoassimilates.

The results obtained in this study agree with that reported by LANDSBERG and SANDS (2011), who related that the forest productivity depends on the interception of radiant energy by leaves and the conversion of this energy into carbohydrate by the process of photosynthesis, relative to the rate of loss by respiration, the death and shedding of organs and the death of individual trees. The effectiveness with which radiant energy is converted to chemical energy depends on the photosynthetic properties of leaves and stand structure and canopy architecture. Moreover, the forest density is an important determinant of canopy structure, and since this determines radiation interception, also of the potential growth rate of the plants.

This study demonstrates that the use of multivariate approach was a valuable tool to analyse and understand the interactions existent among the different components of the forest plantation systems. There is a clear need to use as much information as is available to achieve a consistent result. However, according to the results obtained in this study, it was possible to characterize the different forest species as well as to identify the formation of groups, through the discriminant analysis, obtaining information relevant to understanding the Growth×Yield×Climate interactions. Therefore, it is recommended for future analyzes involving a large group of variables, the use of multivariate analysis in order to summarize the information obtained.

4.6 Radiation use efficiency of *Eucalyptus* trees

Radiation use efficiency was influenced by the planting spacing (Figure 3). The highest radiation use efficiency (0.0062 kg MJ^{-1}) was found for the planting spacing of 2.0×1.5 m. Of the total, the trunk (wood + bark) was responsible for 0.0048 kg MJ^{-1} and the canopy (branches + leaves) for 0.0009 kg MJ^{-1}. The values of radiation use efficiency found in this study are higher than that found by other authors for other forest species. LANDSBERG and HINGSTON, (1996), analyzing the εb of *Eucalyptus globulus* in Western Australia, found average values of 0.00093–0.00223 kg MJ^{-1}; CAMPOE et al. (2013a) found values of εb from 0.00075 to 0.00103 kg MJ^{-1} for dominant and non-dominant trees of *Eucalyptus grandis* in Brazil; LE MAIRE et al. (2013), studying *Eucalyptus grandis* and *Acacia mangium* plantations in southern Brazil, found average values of 0.00105 and 0.00087 kg MJ^{-1}, respectively; FORRESTER et al. (2013), found values of εb which vary from 0.00084 to 0.00114 kg MJ^{-1}. We believe that the divergence in radiation use efficiency values between the literature studies and that found in this study can be associated with different site characteristics, species, age and stand management practices.

Considering an average of the radiation use efficiency of the tree compartments, we observe that the trunk was responsible for 86% and the canopy 14%. In forest energy plantations, the most important product is wood biomass. However, in the initial periods of tree growth, the canopy is of essential importance due the need to intercept a large amount of radiation in order to meet its energy demand. In this context, the evaluation of radiation use efficiency that takes into account the total biomass of trunk and canopy would seem appropriate, as it simplifies the responses of higher importance, which was confirmed in this study.

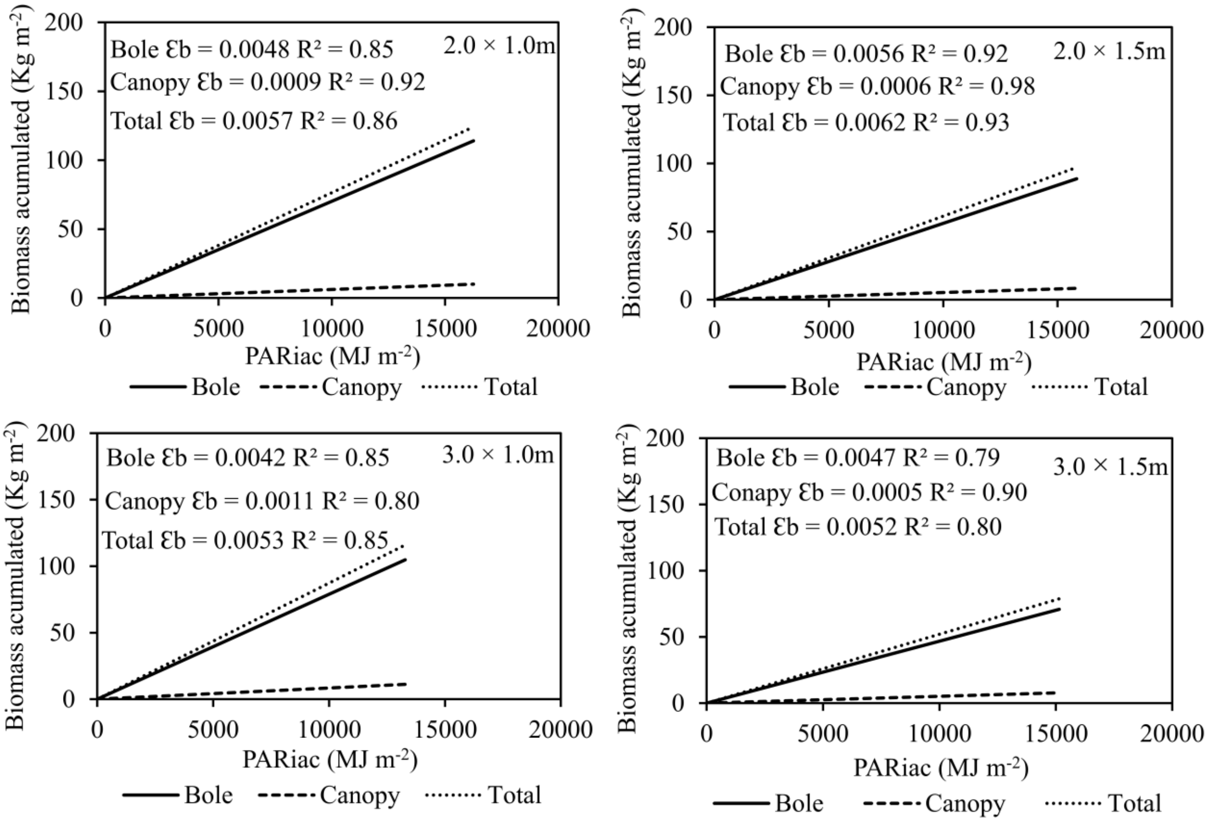

Figure 19. Radiation use efficiency for the compartments bole, canopy, and total biomass obtained for each planting spacing of *Eucalyptus grandis* during the cycle. Where: *εb*=Conversion efficiency of intercepted photosynthetically active radiation into biomass, PARiac=accumulated photosynthetically active radiation intercepted.

Studies that evaluate the influence of planting spacing in the radiation use efficiency of different species reported the same response observed in this study. CARON et al. (2012) , SANQUETTA et al. (2014b), SCHWERZ et al. (2017), and SCHWERZ et al. (2019), reported that plants grown at high densities are more efficient in converting solar radiation into biomass. This difference may be related with the ability in use efficiently the available resources and the values of leaf area index and intercepted solar radiation, parameters that are necessary to determine the efficiency of this conversion.

The radiation use efficiency observed for the planting spacing of 2.0×1.5 m was 8%, 14.5% and 16.1% higher than the planting spacings 2.0×1.0, 3.0×1.0, and 3.0×1.5, respectively. Our study demonstrated that the higher radiation use efficiency value for total biomass was obtained on the spacing 2.0×1.5 m. This result can be related to the greater amount of radiation intercepted by the tree canopy, which resulted in a higher photosynthetic rate, and consequently greater radiation use efficiency in forest biomass. Moreover, the higher radiation use efficiency can be explained by the ability of a tree to acquire resources. One of the main factors related to the radiation use efficiency and productivity of forest energy plantations under high plant densities is related to the uniformity of the plants within the area. Due to the large number of trees competing for space and resources, it is possible to have dominant and non-dominant plants within the forest stand (STAPE et al., 2010). In a simple way, the *Eucalyptus* tree grown in the 2.0×1.5 m spacing showed more stand uniformity than the others planting spacing.

Moreover, this study demonstrated that when Eucalyptus trees were grown in planting spacing more densified, that is, smaller than 2.0×1.5 m resulted in a trend to reduce the radiation use efficiency and consequently lower production of biomass for energy (Figure 8 and 10). This can be explained due to the increase in intra-interspecific competition for resources and the greater heterogeneity within the forest stand, where some plants were suppressed by the others, reducing the efficiency of the use of radiation when considering the area as a whole.

As long as enough resources are available (i.e. canopy closure is not reached) all trees of a stand are equally efficient. However, when inter-tree competition starts, larger trees are able to acquire enough resources, whereas smaller trees might already reach their resource compensation point, i. e., the minimum resource quantity needed to produce a positive growth (BINKLEY, 2004; FERNÁNDEZ; GYENGE, 2009). According CAMPOE et al. (2013a) and GSPALTL and BAUERLE, (2013), larger trees within a stand grow faster than smaller trees, not only because they intercept more light but also because they use that light more efficiently.

The general trend of increasing radiation use efficiency with increasing tree size and stand uniformity was consistent with results obtained by (CAMPOE et al., 2013a). They reported that across a productivity gradient, on average dominant trees (20% largest) showed 37% greater radiation use efficiency than suppressed trees (20% smallest). Moreover, the differences in radiation use efficency between dominant and non-dominant trees are consistent and become larger on more productive plots. This pattern was also observed by CAMPOE et al. (2013b) on a *Pinus taeda* plantation in the USA. These results suggest that dominant trees will become even more dominant over suppressed trees on sites with higher resource availabilities.

In an intensive exploitation of forest energy plantations, at the stand level, higher radiation use efficiency in more productive stands might result from a greater rate of photosynthesis per unit absorbed photosynthetically active radiation, or from increased partitioning of carbohydrates to tree growth (GIARDINA et al., 2003; O'GRADY et al., 2010; RYAN et al., 2010; CAMPOE et al., 2012). The pattern of a strong dominance influence on radiation use efficiency is consistent with the idea that high variation in tree sizes within plantations lowers stand growth, as a result of a greater proportion of absorbed solar radiation being used less efficiently by non-dominant trees (BINKLEY et al., 2010). Therefore, future studies should focus on understanding the impact of tree dominance and stand uniformity on radiation use efficiency and consequently in forest biomass yield.

4.7 Final remarks

According to the results obtained in this study, it is possible to make the following final remarks:

(i) Our results confirm the hypotheses of this study, since the forest planting spacing influenced the biomass production for energy generation and carbon storage, while the climatic conditions, especially the solar radiation interception was decisive on growth, yield and radiation use efficiency of *Eucalyptus* trees.

(ii) The forest growth traits and solar radiation interception was influenced by the planting spacing. Overall, we observed that forest species grown in reduced planting spacing showed higher growth traits compared with that cultivated in widely spacings. This variations in growth traits were related with the stand uniformity and the hability of the trees into acquire available resources. Moreover, multivariate analysis considering the relationship between Growth×Yield×Climate explain in a simple way the greater biomass and energy yield, as well as the relationship between leaf area index and the interception of solar radiation, which were essential for the higher biomass yield for *Eucalyptus* trees grown in the 2.0×1.5 m spacing.

(iii) We recommend the use of multivariate approach to analyse and understand the interactions existent among the different components (Growth×Yield×Climate) of the forest plantation systems. Also, future studies should focus on understanding the impact of tree dominance and stand uniformity on radiation use efficiency and consequently in forest biomass yield.

(iv) This study reveled that the different forest species and planting spacing did not affect the carbon stocks in the soil. We observed that the carbon stocks in the soil ranged only between soil layers. The soil carbon stock for the layer 10−20 cm was 43.4 Mg C ha^{-1} and for the layer 20−40 cm 34 Mg C ha^{-1}, i. e., a reduction in 21.7% of the C stored between the layers, considering all forest species and planting spacing.

v) Another important point to be highlighted in the final remarks is the composition and properties of the forest species which are directly related to the quality of the wood to produce energy. We observe variations among forest species and could consider that *Eucalyptus grandis* and *Acacia mearnsii* showed overall desirable characteristicas, while the forest species *Mimosa scabrella* and *Ateleia gazioviana* showed high levels of oxygen which reduces the quality as a source of energy generation. However, this is not a limiting factor in the use of forest biomass of these species for energy production. It should be emphasized that, as important as the amount of biomass produced, the forest biomass quality is essential, since the forest species composition and properties can influence the potential for energy generation.

(vi) Information generated in this study is relevant and provides information for companies interested in electricity generation from forest biomass and forest producers thereby assisting in the planning of optimal spacing to be used.

5. CONCLUSIONS

According to the results obtained in this study, and answering the objectives proposed, it is possible to make the following conclusions:

a) The biomass yield and potential energy yield of the forest species studied were affected by the planting spacing. The highest biomass production and potential energy yield was observed for the *Eucalyptus grandis* grown on the 2.0×1.5 m spacing. Among the forest species studied, the *Eucalyptus grandis* was the one that presented the largest potential to produce biomass for energy, followed by *Acacia mearnsii*, *Mimosa scabrella* and *Ateleia glazioviana*. Therefore, the use of reduced planting spacing should be prioritized and recommended for future exploitation of forest energy plantations.
b) The carbon stock of the forest plantations was influenced by the planting spacing. The average amount of above-belowground carbon stored considering the four planting spacing for *Eucalyptus grandis* was 293.2 Mg C ha^{-1}, followed by *Acacia mearnsii* (124.1 Mg C ha^{-1}), *Mimosa scabrella* (109.1 Mg C ha^{-1}), and *Ateleia glazioviana* (31.1 Mg C ha^{-1}). The pattern of carbon stored in the tree compartments were trunk > roots > branches > leaves > litter, being that for *Eucalyptus grandis* it was observed a partition pattern of 69.7% trunk, 3.1% branch, 2.98% leaf, 0.42% litter and 23.8% roots. For the carbon stocks in the soil we observed variations only between soil layers, since for the forest species and planting spacings was not observed differences. The average accumulated soil carbon stock for the forest species was 77.4 Mg C ha^{-1} (0−40 cm).
c) The efficiency of conversion of the intercepted photosynthetically active radiation into biomass of the *Eucalyptus grandis* varied with the planting spacings. The highest radiation use efficiency of (0.0062 kg MJ^{-1}) for *Eucalyptus grandis* trees was obtained in the 2.0×1.5 m planting spacing. We suggest, in future studies, to determine the radiation use efficiency of the other forest species and analyze the climate change effects on these forest species growth and yield.
d) This study reveled that forest species properties and composition were not affected by planting spacing and assessment year, only for the different tree compartments. For instance, the *Eucalyptus grandis* and *Acacia mearnsii* species were characterized to present high levels of carbon and hidrogren and lower percentages of oxygen. Also, these species showed lowers percentages of nitrogen and sulfur in woody biomass which are desirable characteristics to be used as biomass source for energy generation.

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