Renewable Energy 153 (2020) 1238–1250

Contents lists available at ScienceDirect

Renewable Energy

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

Biomass and potential energy yield of perennial woody energy crops under reduced planting spacing

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A R T I C L E I N F O

Article history:
Received 7 August 2019
Received in revised form
30 December 2019
Accepted 19 February 2020
Available online 20 February 2020

Keywords:
Woody biomass
Planting spacing
Renewable energy sources
Solar radiation
Tree growth

A B S T R A C T

Woody biomass can be used for supplying energy as a strategy to mitigate climate change and increase energy security by reducing the dependency on fossil fuels. The aims of this study were: (i) to evaluate the biomass production for energy generation; and (ii) to determine the leaf area index, solar radiation interception and mean annual increment of three perennial woody crops *Eucalyptus grandis*, *Mimosa scabrella* and *Ateleia glazioviana*, grown under four planting spacings in Southern Brazil. A field experiment was conducted from September 2008 to September 2018 in Frederico Westphalen, Brazil. The above-belowground woody biomass was determined by the destructive method. Also, the solar radiation interception, leaf area index, potential energy yield, biomass yield and partitioning were evaluated. Findings have shown that the highest biomass yield and potential energy yield were obtained in the planting spacing (2.0 × 1.5 m) for the *Eucalyptus grandis*. Among the woody species studied, the *Eucalyptus grandis* was the one that presented the largest potential to produce biomass for energy, followed by *Mimosa scabrella* and *Ateleia glazioviana*. Therefore, reduced planting spacings should be recommended for woody energy crops plantations, changing the planting spacing pattern (3.0 × 1.5 m) used by the majority of the forest producers.

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, woody biomass appears to be the most important in terms of technical and economic feasibility in the coming decades [[1–5]]. The production of renewable energy from woody biomass is an alternative for the diversification of the Brazilian energy chain [6].

Woody biomass is one of the most promising strategies for the generation of renewable energy in Brazil [[7–10]]. In this context, new studies involving woody crops that present an energetic potential are needed, such as the species *Eucalyptus grandis*, *Mimosa scabrella* and *Ateleia glazioviana*, which are important for the Brazilian energy chain. Currently, much attention has been focused on identifying and characterizing suitable woody species and its essential characteristics, regarding ecological and silvicultural factors, and those related to the energy potential of woody biomass in order to provide high-energy outputs, to replace conventional fossil fuel energy sources.

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https://doi.org/10.1016/j.renene.2020.02.074
0960-1481/

In this context, an important question arises: When fossil fuels are depleted, will woody biomass converted to energy-fuel for several needs be enough to provide the energy needs of future generations? Certainly, woody biomass alone will not meet all the energy demand, however, together with different kinds of bioenergy [[11–15]] that have been deeply investigated, produced and used in the last years, it can provide a large amount of energy-fuel worldwide. Studies show that bioenergy will provide 30% of the world's energy demand by 2050 [16]. Considering the Brazilian energy chain, there is a great contribution of renewable resources that account for 43.5% of total energy demands in 2016 [17]. Brazil has been conducting research for large-scale production of energy derived from wood, investing in fast-growing woody crops plantations dedicated to the production of wood for energy (short-rotation woody crop).

The concept of short-rotation woody crops plantations (SRWC) was introduced in the 1980s to define woody crop 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 [18,19]. Moreover, woody biomass for energy generation is considered nearly carbon-neutral [20,21] because the amount of CO_2 released during combustion is nearly the same as taken up by the tree during growth.

In order to meet global energy demand, new research is needed to study woody crops energy plantations, considering different woody crops growing under different planting spacings in order to evaluate the potential for woody biomass production. According to Couto and Müller [18] and Welfle et al. [4], the woody crop management aimed at 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 perennial woody plantations.

The planting spacing is a key factor in the management of woody crops plantations that aimed biomass production. The most used spacings for biomass production for energy are those that provide a useful area varying from 3 m^2 to 9 m^2 [22]. The use of reduced planting spacing is being extensively studied and disseminated due to the benefits provided [23,24]. The tendency of reducing 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 woody crop management [25,26]. However, there is a lack of studies that evaluate in the field the response of different woody crops when grown under reduced planting spacing.

Woody crop management for biomass production is carried out mainly by companies and forest producers. The basic management regime adopted by them is planting with a spacing of 3.0 × 1.5 m and shallow-cut between the 6th and 8th year [[20,27,28]]. In this context, the authors proposed in this study to evaluate the feasibility of the use of reduced planting spacings, whereas trees grown in these spacings can maximize the solar radiation interception, and increase the biomass production for energy.

Climatic conditions have a great influence on tree growth and yield. Among meteorological variables, solar radiation is one of the most relevant, especially when woody crops plantations are conducted under reduced planting spacings. Wider planting spacings result in less competition for solar radiation while closer spacings can increase tree interaction, resulting in variations on tree growth and yield. Moreover, closer spacing promotes faster development of the leaf area index, which increases light interception and photosynthesis [28].

Woody energy crops have been deeply studied in the last years in the Brazilian forestry chain [[6,7,19]]. We intend with this study to evaluate the use of reduced planting spacings and study the feasibility of different woody crops in addition to *Eucalyptus* species. Also, it is important to quantify the potential use of residual woody biomass (including branches, leaves and roots) to generate energy.

We hypothesized that woody crop managers can accelerate growth and increase the production of woody biomass by manipulating available natural resources, especially solar radiation, using the most appropriate planting spacing. Therefore, the aims of this study were: (i) to evaluate the biomass production for energy generation; and (ii) to determine the leaf area index, solar radiation interception and mean annual increment of three perennial woody crops *Eucalyptus grandis*, *Mimosa scabrella* and *Ateleia glazioviana*, grown under four planting spacings in Southern Brazil.

2. Material and methods

2.1. Study area and experimental design

The 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 27°22′S, 53°25′W and an altitude of 480 m. The climate is characterized as Cfa, i.e., humid subtropical with mean annual temperatures of 19.1 °C, varying from 0 to 38 °C, according to Köppen's climates classification [29]. The soil was classified as Oxisol typical, clayey texture, deep and well-drained. Fertilization was performed before the experiment establishment and was based on the use of 150 g of formulated fertilizer for each seedling. Woody seedlings were manually transplanted in the field in September 2008.

The experimental design was characterized as a factorial arrangement of 3 × 4, with three perennial woody species (*Eucalyptus grandis*, *Mimosa scabrella* and *Ateleia glazioviana*) 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 12 experimental units, which was allocated the four levels of planting spacings. A sketch of an experimental unit can be seen in Schwerz et al. [30].

2.2. Woody species studied

This study proposes the evaluation of three woody species: (i) *Eucalyptus* (*Eucalyptus grandis* W. Hill ex Maiden), (ii) Bracatinga (*Mimosa scabrella* Benth) and (iii) Timbó (*Ateleia glazioviana* Baill). The main characteristics of each 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 1.2–1.8 m and has a relatively short cutting cycle and wide adaptation to different climate conditions [31]. *Eucalyptus* is the most cultivated forest species in Brazil, representing 72.0% of the total area of forest plantations in the country, which corresponds to 5.6 million hectares [32]. The average productivity of *Eucalyptus* plantations in Brazil is 36 m^3 ha^{-1} $year^{-1}$ [32]. Bracatinga belongs to the Fabaceae family and is originally from the Araucaria Forest (mixed ombrophylous forest) of Brazil. This species can reach up to 20 m in height and DBH up to 0.4 m [33]. Its average productivity is 15.5 m^3 ha^{-1} $year^{-1}$ [34]. Additionally, because it is a leguminous species, it has an important contribution to fix N and has been used to compose agroforestry systems. Timbó belongs to the Fabaceae family. It is characterized by being a deciduous tree. Its height can reach 5–15 m and DBH up to 0.20–0.30 m, and its average productivity is 9.8 m^3 ha^{-1} $year^{-1}$ [34].

2.3. Woody species characterization

Woody species growth characteristics such as total height (H), diameter at breast height (DBH), volume, basal area (BA), and final

Table 1
Woody species traits grown under four planting spacings in a short-rotation cycle 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

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 woody species *Eucalyptus grandis*, *Mimosa scabrella*, and *Ateleia glazioviana*. These reductions in woody crops stand were related to the mortality of the trees, caused mainly by diseases and pests.

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, and *Ateleia glazioviana* 8.8 m. On the other hand, for the diameter at breast height, volume and the basal area, variations according to the planting spacing were observed. This demonstrates that the planting spacing had effects on these traits.

2.4. Destructive assessments and sampling

The destructive assessment of the woody species was performed in September 2015 (7th year). During the assessment, nine trees of each planting spacing were selected and evaluated. Three trees were evaluated per block, resulting in a total of 36 trees per woody species.

Woody biomass data were obtained from strict cubing using destructive assessment. Each tree compartment was assessed using the “direct method”, which consists of cutting and weighing the different tree compartments [35]. Under field conditions, the total fresh biomass of sampled trees was assessed. In the 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 Fig. 1.

Destructive samples were collected through strict cubing. The samples were collected along the trunk, in the following sections: 0% (basis), 1.30 m DBH, 25%, 50%, 75% and 100% of the total height. For trunk were 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 they have reached a constant mass. Thereafter, the collected samples were macerated into a slicer and the fraction retained on the 270-mesh sieve was used.

In order to evaluate the contribution of roots to biomass and energy production, the authors performed an additional evaluation in October 2018. The belowground biomass determination was performed according to the methodology proposed by Sanquetta [35]. 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 [36]. Under field conditions, the root biomass of sampled trees was assessed (Fig. 2). 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 [37]. Twenty-four sample trees were evaluated, being eight trees per woody species, two of each planting spacing.

From the aboveground destructive assessments, the samples obtained were used to determine the gross calorific value. 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).

2.5. Gross calorific value and potential for energy production

The gross calorific value was assessed using a digital bomb calorimeter, C5000 Cooling System model, according to the technical standard NBR 8633 [38]. The gross calorific value was assessed for the three compartments (trunk, branches, and leaves) while for the roots we used an average gross calorific value obtained by Nurmi [39].

The potential energy yield was estimated for the three woody species studied in a short-rotation cycle, i.e., the woody species were seven years old during the assessments. The potential energy yield from woody biomass was estimated using biomass data of each species and the 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 was multiplied by the gross calorific value of each planting spacing, given by the following equation (1):

$$PEY = \frac{(BIO \times GCV)}{860} \quad (1)$$

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).

2.6. Leaf area assessment

The leaf area was determined for the *Eucalyptus grandis* and *Mimosa scabrella*. For the *Ateleia glazioviana* species was not possible to quantify the leaf area because this species presents deciduous characteristics, so, during the tree assessments, the leaves were not computed. For the other woody species, the leaf area was determined using a leaf area integrator (model LI−3000C).

Fig. 1. 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).

Fig. 2. Roots assessments to determine belowground biomass based on root excavation (A and B), cleaning (C), and root weighing (D) using dynamometer balance.

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 they have reached a constant mass. Lastly, the samples were weighed on a precision balance.

Thus, the leaf area of the tree was calculated as equation (2):

$$LA = \frac{LB \times Las}{DBs} \tag{2}$$

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 (3):

$$LAI = \frac{LA}{USA} \tag{3}$$

where: LAI = leaf area index; LA = total leaf area of the tree (m^2); USA = useful area utilized by the tree (m^2).

2.7. Climatic conditions and solar radiation interception

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. The air temperature during the years of the experiment ranged from −2.6 °C to 37.0 °C, with an average temperature of 18.8 °C. The flux of global solar radiation was 17.35 MJ m^{-2} day^{-1} on average, with a variation of 0.49–38.46 MJ m^{-2} day^{-1}. The rain values showed high variability during the experiment, with a monthly average of 171.8 mm. According to the climatic conditions, represented by air temperature and accumulated rainfall, we can highlight that the values observed during the study were adequate for the growth of the woody species studied.

The values for solar radiation interception (SRI) were measured annually, using a portable sensor pyranometer (LICOR PY32164) coupled with a Datalogger (LICOR 1400), which recorded measurements in the period from 10 to 12 h. 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 (4):

$$\% \, Intercepted = [100 - (Rn \times 100 \, / \, Rt)] \quad (4)$$

where: Rn = incident radiation under the canopy; Rt = incident radiation above the canopy.

The light extinction coefficient (k) was calculated according to Beer's Law approach and the methodology used can be seen in Schwerz et al. [30].

2.8. Statistical analysis

The analyses were performed using the software "Statistical Analysis System" [40]. The results were obtained through the analysis of variance, F test and Tukey test ($p < 0.05$). Also, The Shapiro–Wilk test was used to verify the normality distribution of all data while the homogeneity of variances was checked using the Bartlett test.

To identify major patterns of variation and ordination of the Growth × Yield × Climate interactions we used principal component analysis (PCA) and discriminant analysis. The growth traits were: H, DBH, LAI and MAI; yield traits: BIO and PEY; and climate traits: SRI and k. The woody species were coded as follows: *Eucalyptus grandis* (E), *Mimosa scabrella* (M) and *Ateleia glazioviana* (A).

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).

3. Results

3.1. Biomass yield and partitioning

The biomass yield for the three short-rotation woody species studied grown under four planting spacings is shown in Fig. 3. We observed a significant difference in the biomass yield. The woody crop *Eucalyptus grandis* presented the higher biomass yield when cultivated under the 2.0 × 1.5 m spacing, which was 21.6, 19.2 and 36.6% higher than 2.0 × 1.0, 3.0 × 1.0, and 3.0 × 1.5 m spacing, respectively. Moreover, the widest planting spacing was responsible for the lower production of biomass for all short rotations woody species.

Regarding the *Mimosa scabrella* species, we observed higher biomass yield for the 2.0 × 1.0 m spacing, with a subsequent decrease in biomass production as planting spacing increased. On the other hand, for *Ateleia glazioviana*, the spacings 2.0 × 1.0 and 3.0 × 1.0 m did not differ significantly, i.e., no response patterns according to the planting spacing were observed.

The biomass accumulation pattern in the tree compartments is shown in Fig. 4. The general pattern of biomass partitioning of the woody species was not affected by the planting spacing. The largest proportion of accumulated biomass was allocated to the stemwood production (secondary growth). The woody crop *Eucalyptus grandis* presented an average partitioning of 81, 4.1, 3.1, and 11.9% of the biomass accumulated in the trunk, branches, leaves, and roots components, respectively (Fig. 4a). 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.

The biomass partitioning for *Mimosa scabrella* species was 62.8, 18.7, 2.6, and 15.9% for trunk, branches, leaves, and roots, respectively. For *Ateleia glazioviana* species, it was not possible to account for the dry biomass of leaves, as this is a deciduous species. Therefore, the biomass partitioning was 64.3, 14.2, and 21.5% for the trunk, branches, and roots, respectively. We can highlight a notable difference between the biomass allocated to the trunk for the three woody species. For instance, *Eucalyptus grandis* species allocated 21.5% more to the trunk than the other two species studied.

3.2. Potential energy yield of the woody crops studied

The higher potential energy yield was observed for *Eucalyptus grandis* grown under 2.0 × 1.5 m spacing, while for the *Mimosa scabrella* and *Ateleia glazioviana*, the spacings 2.0 × 1.0 m and 3.0 × 1.0 m, respectively, were those that provided higher potential energy yield (Fig. 5). Moreover, the widest planting spacing 3.0 × 1.5 m, which is commonly used by forest companies and foresters in Brazil, presented the lowest potential energy yield compared to the other spacings studied.

Recently there is a strong interest in the whole use of woody biomass for energy production including branches, leaves and roots (considered as woody residues). Therefore, we consider the energy potential of these components. It was found that branches + leaves can contribute with 12.4% and roots 10.4% to the potential of energy production. This result demonstrates an average potential to increase the energy generation with the use of woody residues in 22.8%, without considering variations on spacing, species and factors related to economic feasibility.

Considering the individual trees, the highest energy potential by using root biomass was observed in the 3.0 × 1.5 m spacing. However, when considering the tree density of the stand, we verified variations in the potential for energy production according to the woody species and planting spacing (Fig. 6). Moreover, by using the reduced planting spacing, for instance, 2.0 × 1.0 m spacing for *Eucalyptus grandis*, even with a larger tree density (4450 trees ha^{-1}), the root biomass was significantly lower than the 3.0 × 1.0 m spacing (2967 trees ha^{-1}).

3.3. Leaf area index and mean annual increment

The leaf area index varied according to the planting spacings. For the *Eucalyptus grandis*, the higher values of leaf area index were observed in the 2.0 × 1.0, 2.0 × 1.5, and 3.0 × 1.5 m spacings (Fig. 7). Regarding the *Mimosa scabrella* species, we observed a higher leaf area index in the 2.0 × 1.0 m spacing compared with the other planting spacings. For *Ateleia glazioviana* species, it was not possible to quantify the leaf area index because this species presents deciduous characteristics, thus, during the tree assessments, the leaves were not computed. Moreover, we can highlight a notable difference in the leaf area index between woody species. The *Eucalyptus grandis* trees showed higher values than *Mimosa scabrella*.

The trend of mean annual increment was similar to that

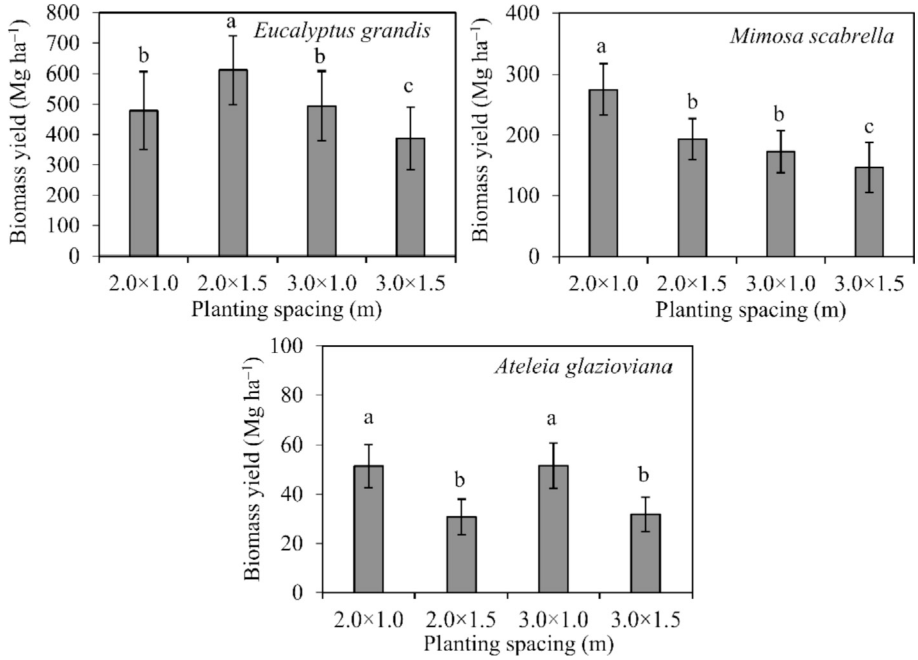

Fig. 3. Biomass yield of *Eucalyptus grandis*, *Mimosa scabrella*, and *Ateleia glazioviana* grown under four planting spacings in a short-rotation plantation. Different small letters indicate significant differences ($p < 0.05$) by Tukey test among planting spacings.

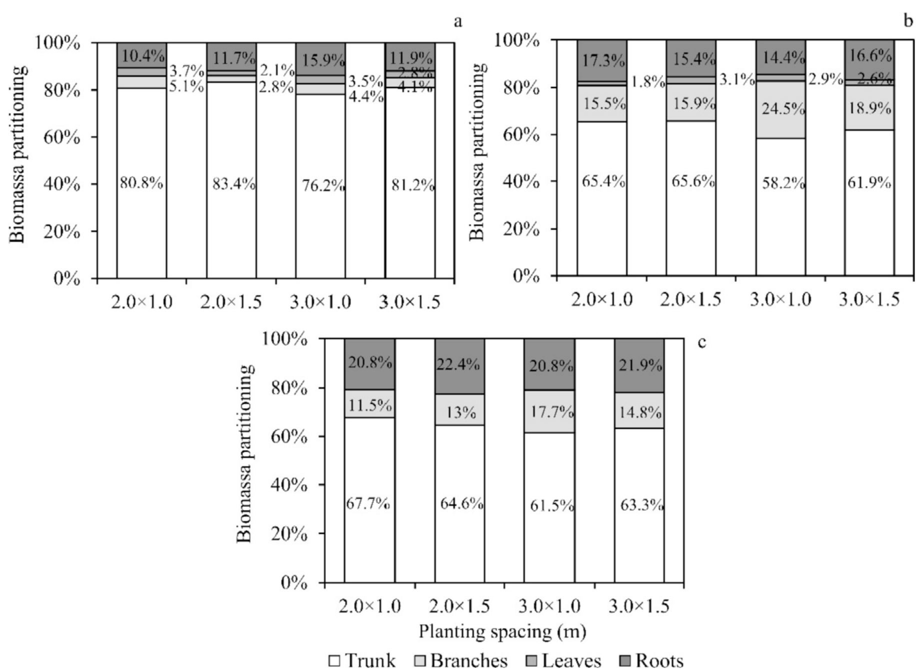

Fig. 4. Biomass partitioning in a short-rotation cycle of *Eucalyptus grandis* (a), *Mimosa scabrella* (b), and *Ateleia glazioviana* (c) grown under four planting spacings.

observed for biomass yield. The higher mean annual increment of *Eucalyptus grandis* was observed for the 2.0 × 1.5 spacing, while for *Mimosa scabrella*, it was the 2.0 × 1.0 m spacing and for *Ateleia glazioviana*, the 3.0 × 1.0 m spacing (Fig. 8). Furthermore, the widest planting spacing (3.0 × 1.5 m) presented the lowest mean annual increment compared to the other spacings studied.

We observed a mean annual increment considering all planting spacings for each woody species of 70.4, 18.6, and 5.1 Mg ha^{-1} yr^{-1} for *Eucalyptus grandis*, *Mimosa scabrella* and *Ateleia glazioviana* respectively.

3.4. Solar radiation interception by perennial woody crops

Solar radiation interception showed significant differences among the assessed years (Fig. 9), with a similar trend according to the different planting spacings. We observed a significant difference for the planting spacing 3.0 × 1.0 m for *Eucalyptus grandis*, which intercepted a smaller amount of solar radiation. This response is related to the lower values of leaf area index (Fig. 7). Considering the average of the woody species, we can highlight that trees intercepted between 75 and 85% of the solar radiation

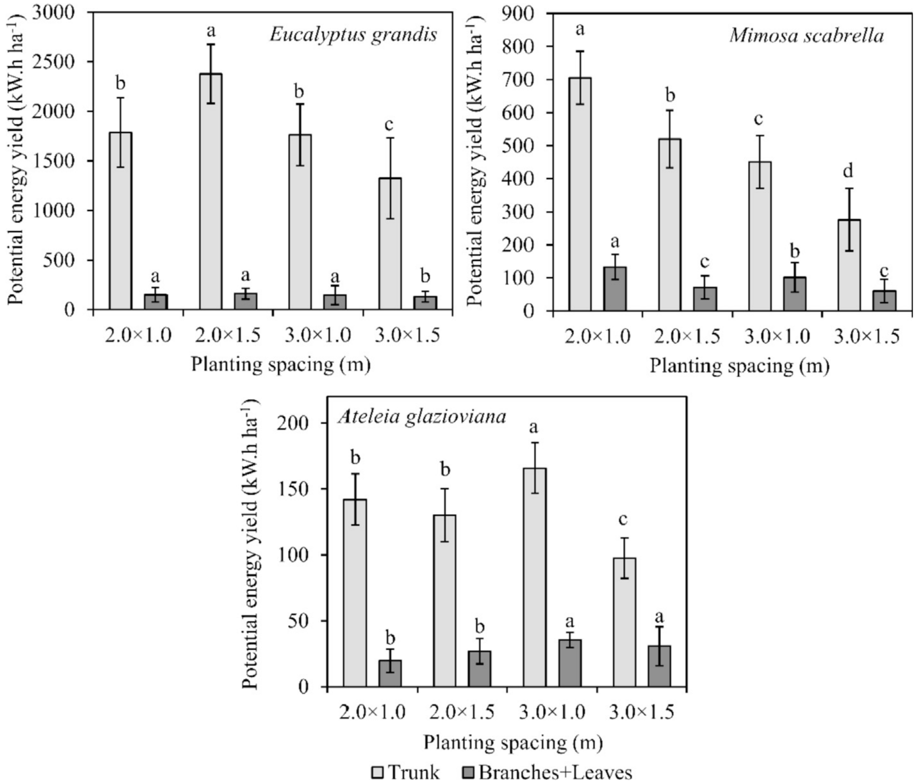

Fig. 5. Potential energy yield of the trunk and branches + leaves of *Eucalyptus grandis*, *Mimosa scabrella*, and *Ateleia glazioviana* grown under four planting spacings at seven years old in a short-rotation cycle. Different small letters indicate significant differences ($p < 0.05$) by Tukey test among planting spacings.

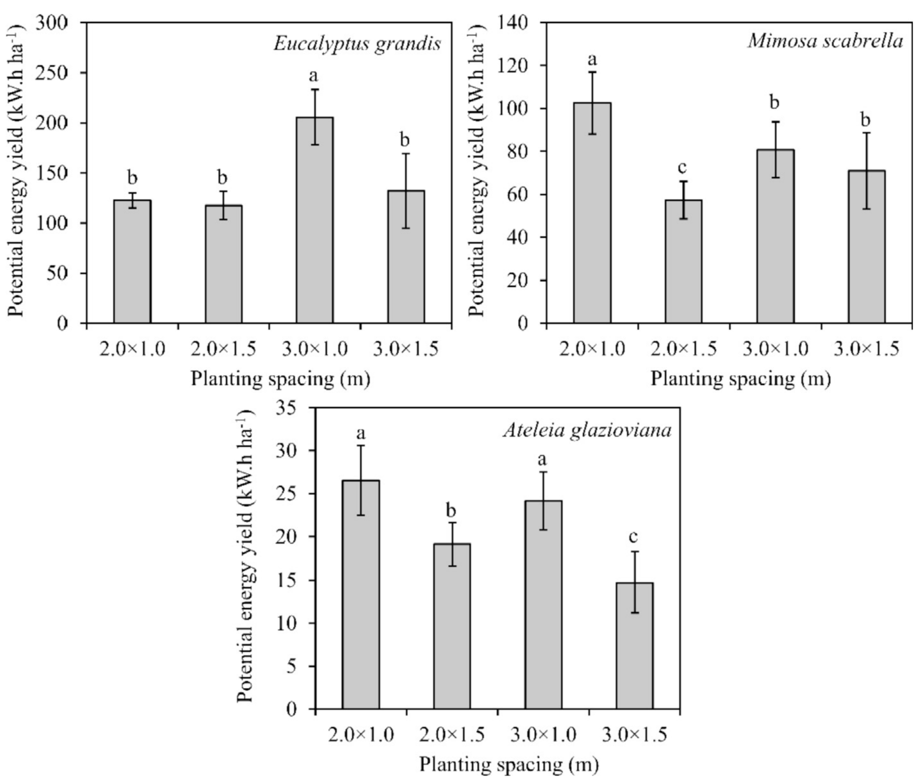

Fig. 6. Potential energy yield of the roots of *Eucalyptus grandis*, *Mimosa scabrella*, and *Ateleia glazioviana* grown under four planting spacings at nine years old in a short-rotation plantation. Different small letters indicate significant differences ($p < 0.05$) by Tukey test among planting spacings.

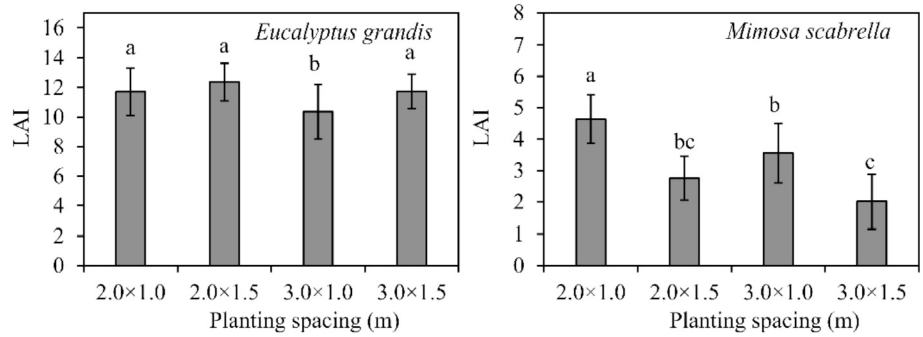

Fig. 7. Leaf area index (LAI) of *Eucalyptus grandis* and *Mimosa scabrella* grown under four planting spacings at seven years old. Different small letters indicate significant differences ($p < 0.05$) by Tukey test among planting spacings.

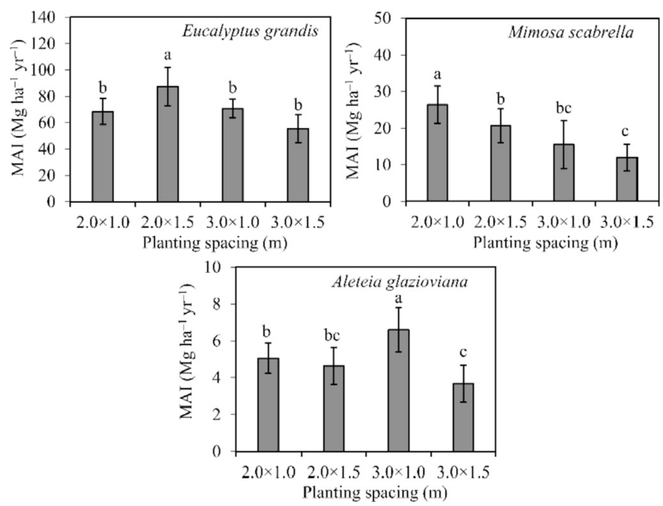

Fig. 8. Mean annual increment (MAI) of *Eucalyptus grandis*, *Mimosa scabrella*, and *Ateleia glazioviana* grown under four planting spacings at seven years old. Different small letters indicate significant differences ($p < 0.05$) by Tukey test among planting spacings.

incident during the short-rotation cycle. The highest variations were observed for the species *Ateleia glazioviana*, which intercepted a smaller amount of solar radiation during the rotation cycle.

3.5. Multivariate analysis for Growth × Yield × Climate traits of woody crop plantations

The PCA results of the woody crops grown under four planting spacings are presented in Fig. 10. The PCA analysis indicated that primary and secondary components were responsible for, respectively, 80.4% and 11.9% of the cumulated variance for all investigated woody species and planting spacings. For the Growth × Yield × Climate, PC1 was associated with PEY and BIO in contrast with k, while PC2 was associated especially with k in contrast with LAI and SRI.

Regarding the discriminant analysis, we observed the formation of three distinct groups. The first group was related to the *Eucalyptus grandis* species, with the four spacings. This group was characterized by high biomass and energy yield, as well as the growth traits such as mean annual increment, height, diameter at breast height, leaf area index and solar radiation interception. For the second group, intermediate PC loadings were observed, i.e., they were characterized by presenting intermediate values of the analyzed variables. This group was represented by the three spacings of *Mimosa scabrella* (2.0 × 1.0, 2.0 × 1.5 and 3.0 × 1.0 m). The last group was represented by the four *Ateleia glazioviana* spacings and 3.0 × 1.5 m spacing of the *Mimosa scabrella*. 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 Fig. 10.

4. Discussion

This study demonstrated that planting spacing has a significant influence on woody energy crop plantations. Our results showed that reduced planting spacing promotes higher values of biomass yield, potential energy yield and growth traits according to the woody species studied. Also, we observed a significant difference in the potential to produce woody biomass among species. This may be related to the ability of each species to acquire available resources, especially solar radiation, the efficiency of resource conversion to biomass and stand homogeneity.

4.1. Planting spacings affect the biomass yield of woody energy plantations

The most important component of woody energy plantations is the amount of biomass per hectare. According to our study, the individual relative biomass yield of trees is greater at the widest spacing levels (3.0 × 1.5 m), perhaps due to the higher availability of soil, moisture and light resources. However, when the tree density 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, the overall biomass yield per unit area can be quite different than the average tree size considered alone. In this context, the number of trees 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 most appropriate spacing was 2.0 × 1.5 m, while for the other woody species, it was 2.0 × 1.0 m.

The higher biomass production for *Eucalyptus* grown under the 2.0 × 1.5 m spacing can be related to the greater ability to acquire available resources and the efficiency of resource conversion into biomass. Also, we observed greater stand uniformity for this planting spacing with a reduced number of dominant and dominated plants within the area. Moreover, this study demonstrated that when *Eucalyptus* trees grew under closer spacing, i.e., smaller than 2.0 × 1.5 m, a reduction of the total biomass to produce energy was observed. This can be related to the increase in intra-interspecific competition for resources, i.e., the number of trees suppressed was higher.

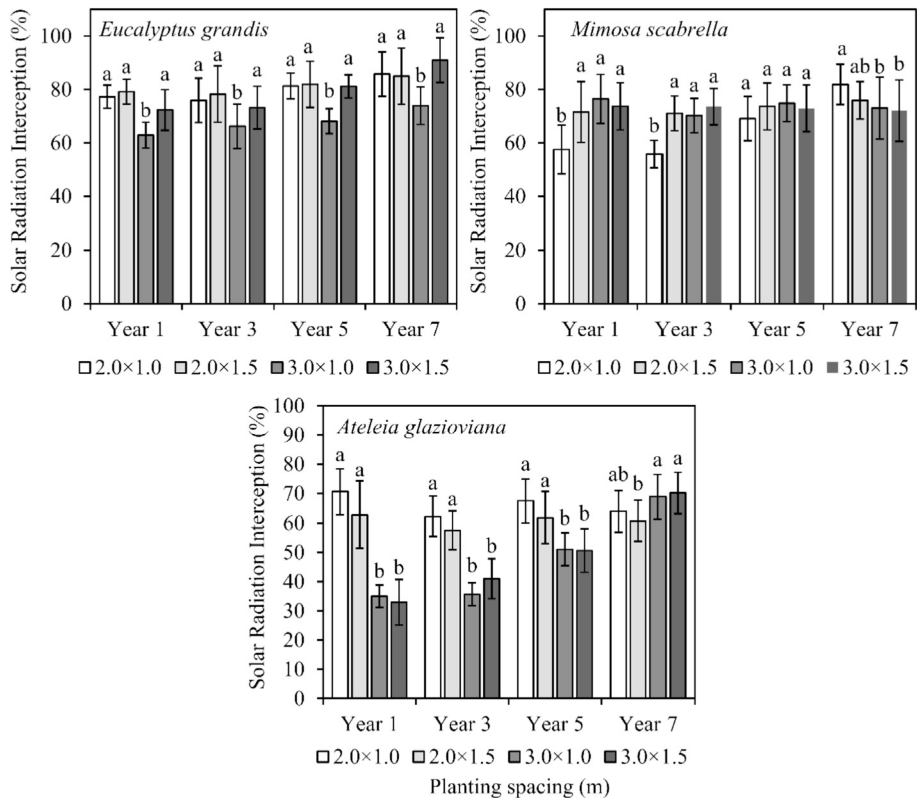

Fig. 9. Solar radiation interception during the assessed years of the woody species grown under four planting spacings. Different small letters indicate significant differences ($p < 0.05$) by Tukey test among planting spacings.

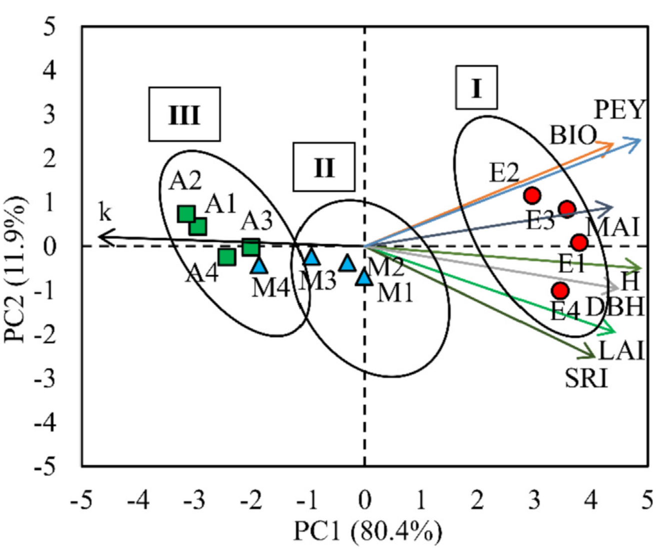

Fig. 10. PCA and discriminant analysis with biplot showing the Growth × Yield × Climate traits for the woody species E: *Eucalyptus grandis*, M: *Mimosa scabrella*, and A: *Ateleia glazioviana*. The growth traits: H, DBH, LAI and MAI; yield: BIO and ENER; and climate: SRI and k, are indicated by arrows, while the four planting spacing are indicated by 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 other woody 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, etc), as well as the biomass production capacity per unit area. Moreover, the intraspecific competition among plants of these species was not sufficient to reduce the biomass yield. Therefore, we can highlight that for production of biomass for energy generation, the use of reduced spacing should be prioritized.

The use of reduced woody plantation spacing is considered a favorable advantage not only because of its higher biomass yield for energy generation but also because the canopy closes sooner, resulting in lower maintenance costs with weed control [41]. On the other hand, with reduced spacings, the costs of establishing plantation are higher, and the harvest cost, which is the main cost of the forest management, tends 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 [42].

Another relevant point that we can highlight is the difference among the woody species to produce woody biomass. Although comparing the woody species was not the focus of this study, but to characterize and evaluate the potential of each one, it was possible to verify that the *Eucalyptus grandis* was the species with the greatest potential for biomass production for energy, followed by *Mimosa scabrella* and *Ateleia glazioviana*.

The significant difference in biomass yield among woody species can be related to the genetic characteristics. The *Ateleia glazioviana* and *Mimosa scabrella* species have aroused less interest among breeders and forest managers 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 [43]; the ready availability of genetically-improved seed and material for vegetative propagation; and the availability of knowledge about silvicultural treatments and techniques [[25,43,44]].

One of the main factors related to the productivity of woody energy crops plantations under reduced planting spacings is related to the uniformity of the trees across the plantation area. Due to the large number of trees competing for space and resources, it is possible to observe dominant and dominated plants within the tree stand [43]. These results were observed in the present study, mainly for the species *Mimosa scabrella* and *Ateleia glazioviana*. This notable heterogeneity can explain why no pattern (increase/decrease) was observed in biomass yield for *Ateleia glazioviana* with an increase of planting spacing.

For *Eucalyptus grandis*, the higher stand heterogeneity was observed in the 2.0 × 1.0 m spacing. The results found in this study agree with those reported by Resende et al. [45], who highlighted that the major determinants factors of productivity in woody plantations include the site productive capacity, local environmental uniformity [46,47], and the tree genetics, which impact their growth potential and competitiveness. Also, Stape et al. [43] 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.

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 to the exportation of nutrients. This point of view needs to be highlighted and considered during forest management. Short rotations with high biomass production results in large amounts of nutrients being removed [[49–51]]. Special attention should be given to the nutrient status of soil when practicing short-rotation forestry [49]. This is related to the frequent repetition of nutrient drains, which could result in the nutrient impoverishment of the site. An important focus of research in programs developing woody biomass plantations is to establish fertilization regimes optimizing growth with minimal adverse environmental consequences [49]. In this context, a correct fertilization regime, with respect to timing and rates, is one of the most important ways to improve woody energy crops production and maintain the quality of the site. Therefore, future studies should focus on understanding the impact of fertilization rates on growth traits and biomass yield of woody energy plantations.

4.2. Biomass partitioning of woody energy crops

The difference among the studied woody species to allocate biomass in the different compartments can be related to the genetic characteristics and capacity of each species to produce biomass. For instance, for the trunk compartment, which is the main feedstock used by the industries, the *Eucalyptus grandis* allocate 81% of the total biomass produced while for the other species, it was observed an average of 64.3%. This difference can be related to the capacity of *Eucalyptus* to produce and storage carbon in the trunk when compared with the other woody species, which allocate more quantity of biomass in branches, leaves and roots. These components are important for tree growth, but considering the energy generation, the biomass partitioned for the trunk is more desirable.

The use of branches, leaves and roots (residual woody biomass) shows a disadvantage when compared to wood biomass in the combustion process [52]. 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, leaves and roots) can improve the potential energy yield in 22.8%, as presented in Figs. 5 and 6.

Similar woody biomass partitioning patterns were observed by other authors. Ribeiro et al. [53] 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. Also, Campoe et al. [54] reported an average partitioning of the total biomass stored in *Eucalyptus grandis* of 82.8, 10.7, 3.6, and 3.0%, for the trunk, roots, branches and leaves, respectively. A similar pattern of productivity-dependent biomass allocation was observed in other studies dealing with water and nutrient manipulations in woody plantations [[48,55,56]].

We reported in this study higher root biomass in the 3.0 × 1.0 m spacing for *Eucalyptus* species in relation to the other planting spacings. This difference can be related to the lower values of leaf area index obtained in this spacing (Fig. 7). In this way, trees grown under the 3.0 × 1.0 m spacing directed the assimilates for roots instead of leaves. This response is mostly related to tree physiology and biomass partitioning [57,58].

4.3. Potential energy yield was influenced by planting spacing

The results obtained in this study are relevant and aid the forest industries and producers to use the optimal planting spacing to produce woody biomass for energy generation. Among the woody species studied, the *Eucalyptus grandis* was the one that presented the largest potential to produce biomass for energy, followed by *Mimosa scabrella* and *Ateleia glazioviana*. Therefore, the use of *Eucalyptus* trees and reduced planting spacings should be prioritized and recommended for future exploitation of woody energy crops plantations. We highlight that when we use the sentence “reduced planting spacing”, we are being generalists. In a simple way, all results obtained in this study indicate optimal planting spacings that are smaller than the current ongoing pattern, which is 3.0 × 1.5 m.

The higher potential energy yield of the woody species obtained in the reduced planting spacing can be explained by the greater biomass yield. The potential to generate energy is directly related to the biomass yield, i.e., higher values of biomass results in higher energy potential. The potential energy yield depends on the total biomass per hectare and the gross calorific value of the biomass. As a consequence, significant differences in energy yield were caused mainly by differences in biomass yield.

Biomass has 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 [59]. Biomass is a renewable energy source because its supplies are not limited. We can always cultivate trees even if wastes 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 protect the native forest resource [60]. However, in order to compete with fossil energy sources, efficient conversion technologies need to be utilized. According to Welfle et al. [4], Brazil can be categorized as a global giant in terms of its productivity of biofuel feedstocks, especially biomass for energy and pellet production.

Here we are supposing a hypothetical example of the use of woody biomass for energy generation. For this purpose, we used data from *Eucalyptus grandis* species cultivated in 2.0 × 1.5 m spacing obtained in this study (2762 Gcal ha^{-1}) and population information for the city of Frederico Westphalen-RS. The following question will be answered: What is the wood energy plantation area to meet the energetic power demand in 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 [17] = 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: 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 = 2762 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}; and vi) Total area = 58,630,080 kW h 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 ha. This example is hypothetical. However, it shows us the energy potential of woody energy crop plantations and highlights the need for further studies that seek more efficient alternatives of converting biomass to energy.

Another study evaluated the potential use of biomass to produce energy. Brand et al. [61], evaluating the biomass produced in commercial plantations of *Pinus taeda*, at different ages and management systems, aiming at 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 $month^{-1}$ and, 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 woody biomass.

One of the main challenges to be overcome for widespread adoption of this woody energy plantation system is related to the efficiency in the conversion of woody biomass to energy. The conversion of biomass into energy can be achieved in a number of ways [59]. 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 [62]. Production of gaseous fuel from biomass can be achieved by the application of a number of technologies with specific requirements, advantages and disadvantages. However, the Brazilian forestry chain assumes a privileged position as one of the few countries in the world with the appropriate climate and technological conditions for woody energy production [26,44].

The Brazilian forest industry faces important challenges in technology, silviculture, tree improvement, and pests and disease management, which requires further studies and collaboration among the few players involved. The results generated in this study are relevant and provide information for companies interested in electricity generation from woody biomass. Also, they help the forest producers thereby assisting in the planning of optimal spacing to be used and confirm the feasibility of the woody crops energy plantations, especially with *Eucalyptus grandis*.

Moreover, the use of woody residues in order to produce energy need more studies and evaluations. When we consider only the use of woody biomass to produce energy, woody residues (considered in this study as branches, leaves and roots) can contribute significantly to energy generation, accounting for an average increase of 22.8% in the potential to produce energy. However, it is important to evaluate the operational and economic feasibility of this analysis, as factors such as minimum area, transport distance, field operating capacity and available technologies to forest producers may be limiting and hinder such operations [[6,8,62]].

On the other hand, the total removal of woody biomass (trunk, branches, leaves and roots) can significantly impact the nutrient cycling and consequently soil quality. In this context, forest producers will have to improve management practices, especially those related to fertility and soil structure, by increasing the use of fertilizers for example, in order to support the production of short-rotation woody crops.

4.4. Growth traits and solar radiation interception were influenced by planting spacings

The planting spacing influenced leaf area index, mean annual increment and interception of solar radiation of the woody species studied. However, it was not possible to observe response patterns for the different spacings studied.

Regarding the mean annual increment, we observed that the *Eucalyptus grandis* showed higher values, followed by *Mimosa scabrella* and *Ateleia glazioviana*. This response may be explained by the growth rates during the short-rotation cycle. These values of mean annual increment are higher than those reported in the literature. This response was related to 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, woody crops plantations grown under reduced planting spacings result in higher growth rates, and consequently, higher biomass accumulated for energy generation.

According to Binkley et al. [63], Brazilian *Eucalyptus* plantations are some of the most productive woody plantations in the world, sustaining mean growth rates of 25 Mg ha^{-1} yr^{-1} (50 m^3 ha^{-1} yr^{-1}). In the study conducted by Binkley et al. [63] 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}, which is 45.6% above the average increment observed in the study (25 Mg ha^{-1} yr^{-1}). This response demonstrates the great growth of different woody species when submitted to different conditions of climate, soil and management.

Our results demonstrated that the earlier canopy closure resulted in a higher percentage of solar radiation interception since the initial tree growth. Trees that intercepted more solar radiation used it more efficiently, consistent with general trends reported at the stand level by Binkley et al. [64].

4.5. Summarizing Growth × Yield × Climate interactions

The use of a multivariate approach was useful to summarize and understand the interactions existent among the different components of the woody 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 woody species as well as to identify the formation of groups, through the discriminant analysis, obtaining relevant information to understand the Growth × Yield × Climate interactions.

In a simple way, *Eucalyptus grandis* was characterized by presenting the highest biomass and energy production, as well as the growth variables such as leaf area index, height, and diameter at breast height. On the other hand, it presented a lower light extinction coefficient. For the other woody species, intermediate values were observed for *Mimosa scabrella* and lower values for *Ateleia glazioviana*, confirmed by the distinction between the groups formed by the discriminant analysis. Therefore, the use of multivariate analysis is recommended for future analyzes involving a large group of variables, in order to summarize the information obtained.

According to the results obtained in this study, it is possible to make the following final remarks: i) All results indicate optimal planting spacings that are smaller than the current ongoing pattern, which is 3.0 × 1.5 m. And most importantly, according to the woody species used, forest managers can manipulate the planting spacing to provide greater amount of woody biomass per unit of area, which is the feedstock to produce energy; ii) The results obtained in this study can be used by forest companies and foresters interested in producing woody biomass for energy generation. Although comparing woody species was not the main focus of this research, we recommend the use of *Eucalyptus* for energy generation due to its greater potential of woody biomass production; and iii) The woody biomass use of the native species *Mimosa scabrella* and *Ateleia glazioviana* can play an important role in the regional energy supply, although it is necessary to involve breeders and geneticists to improve the productive potential of these species.

5. Conclusion

The biomass yield and potential energy yield of the woody species studied were affected by the planting spacings. The highest biomass production and potential energy yield were observed for the *Eucalyptus grandis* grown under the 2.0 × 1.5 m spacing. Among the woody species studied, the *Eucalyptus grandis* presented the largest potential to produce biomass for energy, followed by *Mimosa scabrella* and *Ateleia glazioviana*.

The hypothesis of this study was confirmed since forest managers can accelerate growth and increase the production of woody biomass by using the most appropriate planting spacing. In this context, reduced planting spacings should be recommended for woody energy crop plantations, changing the planting spacing pattern (3.0 × 1.5 m) commonly used by the majority of the forest producers.

Eucalyptus grown under the 2.0 × 1.5 m planting spacing presented the highest potential to produce energy with 2762 Gcal ha^{-1} in a short-rotation cycle. Moreover, the use of woody residues can contribute with an average value of 22.8% in the potential energy yield, represented by 12.4% for branches + leaves and 12.4% for roots. This value is significant, however, it is important to highlight that economic and technical evaluations are required.

The growth traits and solar radiation interception were influenced by the planting spacing. Overall, we observed that woody species grown under reduced planting spacing showed higher growth traits compared with those cultivated under wider spacings. Changes in growth traits were related to the ability of the trees to acquire available natural resources, especially solar radiation, and woody crop stand uniformity. Therefore, future studies should focus on understanding the impact of tree dominance and stand uniformity on growth traits, solar radiation dynamics and consequently on woody biomass yield for energy generation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Felipe Schwerz: Conceptualization, Formal analysis, Investigation, Writing - original draft, Funding acquisition, Project administration. **Durval Dourado Neto:** Formal analysis, Writing - review & editing, Supervision. **Braulio Otomar Caron:** Conceptualization, Resources, Writing - review & editing, Funding acquisition. **Claiton Nardini:** Methodology, Writing - review & editing. **Jaqueline Sgarbossa:** Methodology, Writing - review & editing. **Elder Eloy:** Conceptualization, Methodology, Writing - review & editing. **Alexandre Behling:** Conceptualization, Writing - review & editing. **Elvis Felipe Elli:** Investigation, Visualization, Writing - review & editing. **Klaus Reichardt:** Writing - review & editing.

Acknowledgments

The authors are grateful to the National Council for Scientific and Technological Development (Grant No. 142261/2017-3) and São Paulo Research Foundation (FAPESP) (Grant No. 2018/06023-6) for the financial support of the author Felipe Schwerz. Also, I would like to thank the members of the Agrometeorology laboratory for the help in this project.

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