Management of *Eucalyptus* short-rotation coppice and its outcome on fuel quality

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ABSTRACT

Earlier experiments with young *Eucalyptus* short-rotation coppice (SRC) in tropical environment have not evaluated the quality of whole-tree biomass fractions, and as such their total energy potential is still unknown. As this system is managed with a higher planting density and fertilization level compared to conventional plantations, the quality of forest biomass needs to be assessed. Hence, the goal of this study was to analyze how the short-rotation coppice affected the quality of stem, branches, and leaves used for power generation. Samples were collected from high-density plantation of *Eucalyptus* at two years old, and the thermochemical properties were evaluated. Carbon and ash content were lower for the stem fraction in higher density of planting, although the higher heating value was not significantly different from each treatment. Overall, the fuel quality of whole-forest biomass was not influenced by management practices. Statistically significant differences were found only between the whole-tree fractions. *Eucalyptus* SRC provided biomass qualitatively close to that from conventional forest systems and has potential to be quickly and feasible energy option.

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1. Introduction

Biomass feedstock is a pathway to achieve a low carbon footprint in the future [1,2]. Perennial bioenergy crops appear to be important players for developing sustainable land use [3].

Solid biomass be combusted directly in boilers to produce heat and electricity or used to provide derived fuels from thermochemical processes (viz., pyrolysis, gasification, and liquefaction) [4] or as bio-oil [5]. With respect to biomass use in power generation, knowledge about their composition and properties as well as environmentally safe handling are necessary [6,7].

Considerable variation is seen in the elemental, immediate, structural, and chemical composition of the biomass (agricultural and forest crops) types [8—10]. These variations have notable impact on each step of the whole supply chain, such as handling of raw materials, transportation, drying, storage, and the design of the power conversion systems [11]. Moreover, thermochemical properties are very important in ranking the best resources for power generation [12,13].

High-density energy wood plantation has been regarded as a renewable resource worldwide. Studies have been conducted on *Salix* and *Populus* species managed in SRC in Europe [14,15]. In South America, especially in Brazil, *Eucalyptus* species have been used for SRC management [16], as these plantations provide a high productivity in a small planting area, about 19 t dry matter ha^{-1} year^{-1} with harvesting cycles of two to three years [17]. Whole-tree biomass from SRC is harvested and chipped simultaneously by a modified forager and transported to thermal power plants [18].

Some doubts remain about the effect of this management system on the fuel quality (proximate and elemental chemical composition) of such young material. For *Populus* species, Monedero et al. [13] observed that planting density had a more significant effect on combustion properties than site characteristics (such as soil properties).

Recent experiments with young *Eucalyptus* SRC in a tropical environment [14,15] did not evaluate the quality of whole-tree biomass fractions (stem, branches, and leaves), and very little is known about its energy potential. Hence, the goals of this study were: (1) to determine the thermochemical properties of *Eucalyptus* SRC for bioenergy purposes, and (2) the effect of different

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planting densities and fertilization regimes on whole-tree biomass.

2. Materials and methods

2.1. Sampling and material preparation

This work was carried out at Botucatu (22° 53′ 09″ S and 48° 26′ 42″ W) in São Paulo state of Brazil. The local area has an average altitude of 872 m a.s.l., a mean annual precipitation of about 1428 mm year^{-1}, and an annual average temperature of 20 °C.

Plantations of interspecific hybrid clone, *Eucalyptus urophylla* × *Eucalyptus grandis* were established for two years, each with high, but different, planting densities and fertilization regimes. Plots (450 m^2 each) had two different spacing modules: 2.8 × 0.5 m (7142 trees hectare^{-1}) and 2.8 × 1.5 m (2380 trees hectare^{-1}). Table 1 shows the two different fertilization regimes in which dose 1 corresponds to one-quarter of dose 2 (the conventional dose).

Two years after planting, the diameter at breast height (DBH) and height of all trees on the plots, as well as of randomly selected four mean tree samples per treatment were measured. Each tree was divided into three fractions: stem, branches, and leaves, and a composite sample was used for each biomass fraction. The branches and leaves of the trees were removed. Then, five discs were collected at the following positions along the stem: 0%, 25%, 50%, 75%, and 100% of total stem height according to the method described by Ref. [19].

For the fuel quality analysis, an experimental design of completely randomized blocks with 2 spacing density × 2 fertilization regimes × 3 biomass fractions × 3 repetitions was finalized.

2.2. Laboratory procedures and properties

Forest biomass was sawed in Wiley type mill followed by sifting in 40−60 mesh screens. The thermochemical properties were determined according to standard methods (see Table 2).

Ultimate composition (CHNS) was obtained at elemental analyzer model 2400 Parkin Elmer by modified Pregl-Dumas method. Then, oxygen content was determined as the balance out of 100% [20].

2.3. Statistical analysis

Data normality was assessed by Shapiro-Wilk's test (p < .05). The effect of density planting (D), fertilization level (F), and biomass fraction (B) on thermochemical properties of *Eucalyptus* SRC was evaluated by ANOVA complemented by Tukey's test (p < .05). Biomass fraction was taken into account as the whole-tree biomass was used for bioenergy purposes [26,27].

Table 1
Description of the fertilization regimes.

Fertilizing levels	Days after planting	Dose 1	Dose 2
Fertilizer		g plant^{-1}	
NPK (6-30-10)	0	35.0	140
NPK (19-00-19) + B (0.7%) e Zn (3%)	180	27.5	110
NPK (19-00-19) + B (0.7%) e Zn (3%)	360	27.5	110

Table 2
Summary of standards and methods used to assess the forest biomass properties.

Properties	Initials	Standards and methods
Carbon, hydrogen, nitrogen, sulfur	CHNS	Pregl-Dumas method
Oxygen	O	[20]
Ash	A	[21]
Fixed carbon	FC	[20]
Volatile matter	VM	[22]
Holocellulose	HC	Delignification using NaClO$_2$
Acid-insoluble lignin	L	[23]
Total extractives	E	[24]
Higher Heating Value	HHV	[25]

3. Results and discussion

3.1. Fuel quality of whole-biomass of Eucalyptus SRC for bioenergy use

All treatments were statistically different among biomass fractions—stem, branches, and leaves (Table 3), and larger differences were observed between woody fractions and leaves.

Leaf biomass had higher hydrogen and carbon content than other fractions, which contributed to more energy released on combustion. Positive correlation has been observed between the amount of these elements and the calorific value of the biomass [28]. However, the leaves have a higher amount of nitrogen and sulfur which can damage the environment due to emissions of their ozone-depleting oxides [29]. Results above the limiting content of 0.6% and 0.2% for N and S, respectively, can induce emission problems [30].

Further, the C/N ratio was higher for woody fractions (104 and 120 for branches and stem, respectively) than leaves (28). Greater C/N ratio implies a lower decomposition rate when the biomass is left on the field after harvesting for reduction of moisture content and, consequently, energy content is slightly affected.

For proximate analysis, the stem fraction showed greater volatile matter, which contributes to the ignition of biomass, and the leaves fraction had a higher fixed carbon content, which increases its burning period in the boiler [12]. High results of ash content for leaves mean the trees could be defoliated before use.

Levels of acid-insoluble lignin and total extractives in the stem are similar to those reported by Ref. [8] and are statistically different for the leaves fraction. Among the biomass fractions, lignin content was similar for the stem and branches.

Energy of combustion varies considerably with the chemical composition. Compounds such as resin, tannins, lignin, terpenes, and waxes have high energy values whereas carbohydrates have

Table 3
Effect of biomass fraction on thermochemical properties of *Eucalyptus grandis* × *E. urophylla* at 2 years old grown on short rotation forest.

Properties	Unit	Stem	Branches	Leaves
Carbon	wt% (d.b.)	44.3 ± 0.5 b	44.7 ± 0.5 b	49.1 ± 0.6 a
Hydrogen	wt% (d.b.)	7.4 ± 0.5 b	7.5 ± 0.3 b	8.2 ± 0.3 a
Oxygen	wt% (d.b.)	46.7 ± 1.0 a	45.8 ± 0.8 b	37.5 ± 0.8 c
Nitrogen	wt% (d.b.)	0.37 ± 0.1 c	0.43 ± 0.1 b	2.0 ± 0.3 a
Sulfur	wt% (d.b.)	0.09 ± 0.0 b	0.10 ± 0.0 b	0.13 ± 0.0 a
Ash	wt% (d.b.)	1.1 ± 0.2 c	1.5 ± 0.3 b	3.1 ± 0.6 a
Fixed carbon	wt% (d.b.)	14.4 ± 1.2 c	17.3 ± 1.0 b	18.4 ± 0.6 a
Volatile matter	wt% (d.b.)	84.5 ± 1.3 a	81.2 ± 1.1 b	78.5 ± 0.7 c
Holocellulose	wt% (d.b.)	81.5 ± 1.5 a	68.4 ± 2.1 b	34.9 ± 1.9 c
Acid-insoluble lignin	wt% (d.b.)	21.6 ± 0.8 a	20.7 ± 0.9 ab	20.2 ± 2.7 b
Total extractives	wt% (d.b.)	2.0 ± 0.8 c	12.4 ± 1.2 b	37.9 ± 1.3 a
Higher Heating Value	MJ kg^{-1}	18.9 ± 0.3 c	19.2 ± 0.3 b	22.0 ± 0.2 a

The means that do not differ from each other at the 0.05 significance level by Tukey's test are marked with the same letters in the same line.

relatively low values [31]. Leaves showed high total extractives content so that their heating values (HHV) were higher than for woody fractions.

Results found were similar than those reported for conventional plantations in Brazil [12]. It showed the potential of these energy crops to provide a high-quality raw material within a short time, say two to three years after planting.

3.2. Effect of planting density and fertilization level on thermochemical properties

The thermochemical properties of forest biomass grown on SRC are shown in Table 4. These results were complemented by the analysis of variance, which showed the effect of density planting (D), biomass fraction (B), and fertilization level (F) in the treatments (Table 5).

Results indicated double and triple interactions among the variation factors (D, F, B). It is clear from Table 3 that biomass fraction had a significant effect on all thermochemical properties.

3.2.1. Ultimate analysis

Carbon content was higher for lower planting density and higher fertilization level as shown in Table 6. As discussed earlier, carbon content has a positive effect during combustion and contributes to enhance energy potential.

Increased density of planting on *Eucalyptus* SRC provided higher biomass yield per hectare [17] and probably more carbon sequestration from the atmosphere, but there is less allocation of C by unit of mass. Hence, the higher density planting and lower fertilization level suggest a reduction of carbon dioxide emissions on combustion of these energy crops.

Nitrogen and oxygen showed a triple interaction for variance factors (Fig. 1). Nitrogen content on leaves showed a positive trend with increased density of planting irrespective of fertilization level. For woody fractions, the increase in N content did not reach the limiting level to cause emission problems (0.6%) as reported by

Table 4
Thermochemical properties of forest biomass from short rotation coppice of *Eucalyptus grandis* × *E. urophylla* at 2 years old.

Properties	Spacing (m)	2.8 × 0.5	2.8 × 0.5	2.8 × 1.5	2.8 × 1.5
	Fertilization	Level 1	Level 2	Level 1	Level 2
Carbon (%)	Stem	43.9 ± 0.3	43.9 ± 0.4	44.7 ± 0.1	44.8 ± 0.2
	Branches	44.6 ± 0.2	44.6 ± 0.3	44.4 ± 0.9	45.0 ± 0.2
	Leaves	48.9 ± 0.4	49.1 ± 0.1	48.7 ± 0.8	49.7 ± 0.7
Hydrogen (%)	Stem	7.1 ± 0.6	7.4 ± 0.5	7.7 ± 0.4	7.5 ± 0.5
	Branches	7.5 ± 0.1	7.8 ± 0.1	7.2 ± 0.4	7.6 ± 0.1
	Leaves	8.2 ± 0.2	8.4 ± 0.0	8.2 ± 0.1	8.1 ± 0.5
Oxygen (%)	Stem	47.5 ± 1.0	47.2 ± 0.8	45.8 ± 0.3	46.2 ± 0.6
	Branches	45.4 ± 0.5	45.8 ± 0.3	46.7 ± 1.1	45.2 ± 0.2
	Leaves	37.5 ± 0.6	36.6 ± 0.4	37.8 ± 0.5	37.8 ± 1.2
Nitrogen (%)	Stem	0.5 ± 0.0	0.4 ± 0.1	0.3 ± 0.0	0.2 ± 0.0
	Branches	0.6 ± 0.0	0.5 ± 0.0	0.4 ± 0.1	0.3 ± 0.1
	Leaves	2.4 ± 0.0	2.1 ± 0.1	1.6 ± 0.1	1.8 ± 0.1
Sulfur (%)	Stem	0.09 ± 0.0	0.09 ± 0.0	0.10 ± 0.0	0.09 ± 0.0
	Branches	0.10 ± 0.0	0.10 ± 0.0	0.10 ± 0.0	0.09 ± 0.0
	Leaves	0.14 ± 0.0	0.14 ± 0.0	0.13 ± 0.0	0.14 ± 0.0
Ash (%)	Stem	0.86 ± 0.1	0.94 ± 0.1	1.39 ± 0.2	1.18 ± 0.2
	Branches	1.73 ± 0.2	1.22 ± 0.1	1.23 ± 0.1	1.79 ± 0.2
	Leaves	2.77 ± 0.1	3.62 ± 0.2	3.55 ± 0.3	2.44 ± 0.1
Fixed carbon (%)	Stem	14.3 ± 1.2	13.2 ± 1.2	15.0 ± 0.6	15.0 ± 1.3
	Branches	16.7 ± 0.6	16.6 ± 1.2	17.4 ± 0.6	18.4 ± 1.3
	Leaves	18.5 ± 0.5	17.8 ± 0.4	18.5 ± 0.6	18.7 ± 0.9
Volatile matter (%)	Stem	84.8 ± 1.1	85.9 ± 1.2	83.6 ± 0.5	83.8 ± 1.3
	Branches	81.6 ± 0.5	82.2 ± 0.8	81.4 ± 0.9	79.8 ± 0.4
	Leaves	78.8 ± 0.5	78.6 ± 0.6	77.9 ± 0.5	78.9 ± 0.9
Holocellulose (%)	Stem	83.1 ± 0.5	81.8 ± 1.2	80.6 ± 0.4	80.6 ± 1.8
	Branches	70.3 ± 0.3	69.4 ± 0.1	67.2 ± 2.8	66.9 ± 2.2
	Leaves	34.6 ± 0.3	33.0 ± 0.4	35.3 ± 1.6	36.7 ± 2.3
Acid-insoluble lignin (%)	Stem	21.7 ± 0.4	21.2 ± 0.4	22.4 ± 0.3	20.9 ± 1.3
	Branches	20.8 ± 0.6	21.0 ± 0.2	21.3 ± 0.3	19.8 ± 1.4
	Leaves	17.9 ± 1.4	18.4 ± 2.2	21.7 ± 1.9	22.8 ± 1.8
Total extractives (%)	Stem	2.1 ± 1.0	2.7 ± 0.2	1.5 ± 0.7	1.6 ± 0.4
	Branches	11.2 ± 1.0	12.4 ± 0.3	13.0 ± 1.0	12.9 ± 1.6
	Leaves	38.4 ± 1.2	37.5 ± 0.8	37.6 ± 1.3	38.2 ± 2.2
Higher Heating Value (MJ kg^{-1})	Stem	18.6 ± 0.3	18.9 ± 0.1	19.1 ± 0.2	19.0 ± 0.2
	Branches	19.3 ± 0.2	19.2 ± 0.3	19.1 ± 0.1	19.3 ± 0.4
	Leaves	22.2 ± 0.1	21.9 ± 0.1	21.8 ± 0.1	22.2 ± 0.1

Table 5
P-values of analysis of variance (ANOVA) for factors - density planting, biomass fraction and fertilization level on chemical properties of *Eucalyptus* SRC at 2 years old.

Properties	D	F	B	D × F	D × B	F × B	D × F × B
Carbon	0.019*	0.042*	0.000**	0.086	0.097	0.326	0.587
Hydrogen	0.916	0.261	0.000**	0.456	0.102	0.548	0.536
Oxygen	0.687	0.199	0.000**	0.883	0.003**	0.541	0.040*
Nitrogen	0.000**	0.000**	0.000**	0.004**	0.000**	0.472	0.000**
Sulfur	0.235	0.625	0.000**	0.914	0725	0.305	0.452
Ash	0.212	0.321	0.000**	0.002*	0.001**	0.540	0.000**
Fixed carbon	0.001**	0.700	0.000**	0.080	0.409	0.335	0.958
Volatile matter	0.001**	0.547	0.000**	0.258	0.123	0.243	0.060
Holocellulose	0.119	0.346	0.000**	0.101	0.001**	0.876	0.602
Acid-insoluble lignin	0.004**	0.515	0.034*	0.393	0.000**	0.183	0.554
Total extractives	0.847	0.481	0.000**	0.849	0.114	0.788	0.275
Higher Heating Value	0.351	0.183	0.000**	0.107	0.058	0.735	0.006**

Density planting − D; Fertilizing level − F; Biomass fraction − B. $p < .05$ (*) and $p < .01$ (**) significant by test F.

Table 6
Simple effect of planting spacing and fertilization level on carbon content of *Eucalyptus grandis × E. urophylla*, at 2 years old.

Factors	Carbon (%)
Spacing (m)	
2.8 × 0.5	45.9 B
2.8 × 1.5	46.2 A
Fertilization levels	
1	45.9 B
2	46.2 A

The means that do not differ from each other at the 0.05 significance level by Tukey's test are marked with the same letters in the same column.

Ref. [30].

Oxygen content showed a similar trend for both treatments studied. Thus, the triple interaction was not clearly defined, probably due to the strong effect of biomass fraction factor on the variance analysis. Significant differences occurred between the leaves and woody fractions.

There is a lack of information about mean values of chemical elements of ultimate composition from eucalypt plantations.

Usually, researchers have been considered for wood from conventional planted which carbon element represents 50% of dry matter biomass, but it is higher than determined for *Eucalyptus SRC*, about 44.3%, 44.7% and 49.1% for stem, branches and leaves fractions, respectively.

3.2.2. Proximate analysis

Fixed carbon content and volatile matter content behaved in opposing ways with respect to density of planting (Table 7). Further, as confirmed in the ultimate analysis, the fixed carbon followed the results of C content, wherein higher content was found to at a lower density of planting.

Ash content, another important property, had a limiting effect on bioenergy use. It caused encrustations in the boilers when the biomass was used for direct combustion and greater damage in metallic equipment used in the production of briquettes or pellets. Ash content was higher for leaves fractions following branches and stem. Ash content of stem showed a reducing trend for increasing density of planting, as shown in Fig. 2. The fertilization effect showed different results for each treatment, and it was not possible to identify a regular behavior.
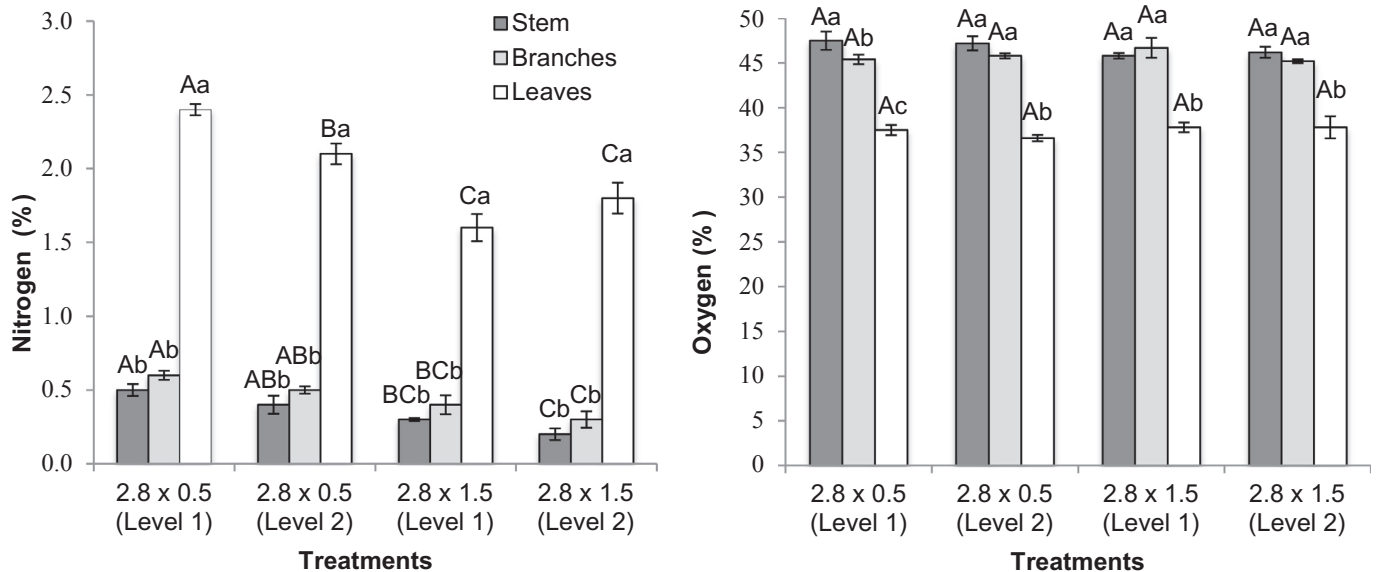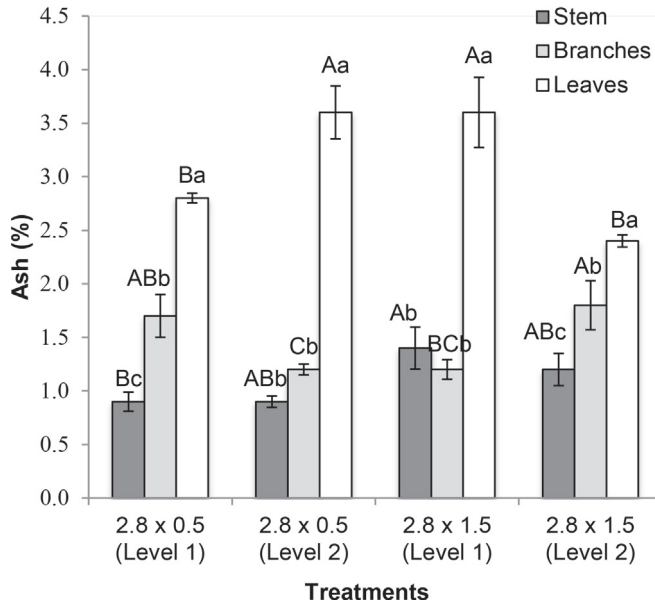

Fig. 1. Triple interaction (planting spacing, fertilization level and biomass fraction) on nitrogen and oxygen content of *Eucalyptus* SRC. The same small letters (at the same planting spacing and fertilization level) and the same capital letters (at the same biomass fraction) do not differ statistically by Tukey test ($\alpha = 0.05$).

Table 7
Simple interaction of density planting on properties of *Eucalyptus grandis* × *E. urophylla*, at 2 years old.

Spacing (m)	Properties	
	Fixed carbon	Volatile matter
2.8 × 0.5	16.2 B	82.0 A
2.8 × 1.5	17.2 A	80.9 B

The means that do not differ from each other at the 0.05 significance level by Tukey's test are marked with the same letters in the same column.

Fig. 2. Triple interaction (planting spacing, fertilization level and biomass fraction) on Ash content of *Eucalyptus* SRC. The same small letters (at the same planting spacing and fertilization level) and the same capital letters (at the same biomass fraction) do not differ statistically by Tukey test (α = 0.05).

3.2.3. Structural chemical analysis

Structural chemical composition of *Eucalyptus* biomass SRC was similar of softwood species as reported by Ref. [31].

Statistically significant difference for holocellulose and acid-lignin content was observed (Table 8).

Holocellulose of branches fraction was influenced by the increasing density of planting. The acid-lignin content of leaves decreased with higher density of planting. These differences did not change the energy content among the treatments for the same biomass fraction.

If we consider only the use of stem fraction for other purposes as

Table 8
Double interaction of density planting and biomass fraction on holocellulose and lignin of *Eucalyptus grandis* × *E. urophylla*, at 2 years old.

Spacing (m)	Biomass fraction		
	Stem	Branches	Leaves
Holocellulose (%)			
2.8 × 0.5	82.4 Aa	69.8 Ab	33.8 Ac
2.8 × 1.5	80.6 Aa	67.1 Bb	36.0 Ac
Lignin (%)			
2.8 × 0.5	21.5 ± Aa	20.9 ± Aa	18.1 Bb
2.8 × 1.5	21.7 ± Aa	20.5 ± Aa	22.2 Aa

The means that do not differ from each other at the 0.05 significance level by Tukey's test are marked with the same small letters (at the same line) and the same capital letters (at the same column) for each chemical property.

paper and fiber industry, the increasing of density planting and fertilization have not effect on its structural chemical composition.

3.2.4. Higher heating value

As seen with oxygen content, the triple interaction in HHV only showed effect for the biomass fractions and did not vary among the treatments (Fig. 3). Hence, the planting density and fertilization level did not influence this property as verified by other authors for planted forests of *Eucalyptus* and other species in Brazil [32,33]. The small change of ultimate biomass quality with fertilization and density planting factors were not adequate to change the HHV. It is known that increase of HHV could be more associated with age of trees [34,35].

HHV of branches fraction were observed to be statistically similar to the stem fraction, whereas the leaves showed an average HHV 13.4% higher than the woody fraction. The greater HHV of leaves can be explained by the results of ultimate analysis (higher hydrogen content) and chemical analysis (higher total extractives content).

Eucalyptus biomass showed a better thermochemical performance for energy purposes (higher values of HHV and lower ash content) than poplar genotypes from short rotation forest [13]. However, this performance was worse when compared with new clones of willow cultivated in one and three year rotation cycles [36].

This paper complements the work published by Ref. [17], who studied the biomass and energy yield of *Eucalyptus* SRC in the same conditions presented in this experiment. Forest management is a tool to increase the efficiency and sustainable use of dedicated energy crops.

4. Conclusions

Fuel quality of biomass from a *Eucalyptus* short rotation coppice did not change with planting densities and fertilization levels. Only punctual and specific changes in some biomass properties were observed, but they did not promote effects on heating value.

For all properties evaluated statistically significant differences were found between the woody fractions (stem and branches) and leaves.

The findings can also be used by chemical and other industries associated with biorefinery processing to consider whole-tree
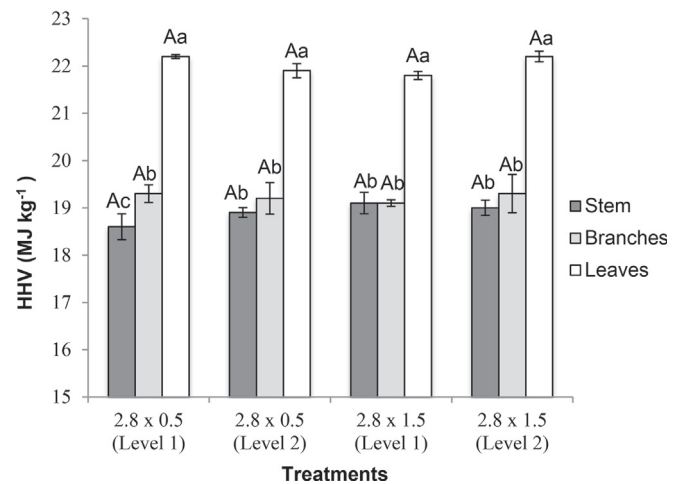
Fig. 3. Triple interaction (planting spacing, fertilization level and biomass fraction) on Higher Heating Value (HHV) of *Eucalyptus* SRC. The same small letters (at the same planting spacing and fertilization level) and the same capital letters (at the same biomass fraction) do not differ statistically by Tukey test (α = 0.05).

biomass for any application.

Acknowledgments

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