Energy Production and its Characteristics from Four Tropical Trees Species Planted in Short Rotation Woody Systems in Costa Rica

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GRAPHICAL ABSTRACT

Species	Spacing	Gross Calorific Value (MJ/kg)		Ash Content (%)		Biomass (ton/ha)	
		Trunk	Branch	Trunk	Branch	Trunk + bark	Branch
C. alliodora	S1	19.31A	18.07A	2.3A	2.9A	44.4A	44.6A
	S2	18.86A	18.80A	2.4A	2.7A	44.7A	44.3A
	S3	19.33A	18.95A	2.4A	2.5A	44.7A	44.2A
	S4	18.47A	18.92A	2.2A	2.4A	44.5A	45.0A
D. panamensis	S1	18.52A	17.73C	1.6A	3.3A	42.7A	42.7A
	S2	19.22A	18.41BC	1.2A	2.1B	42.9A	42.9A
	S3	18.61A	19.18B	1.7A	2.3B	43.2A	43.2A
	S4	19.56A	20.79A	1.6A	2.3B	43.7A	43.8A
G. arborea	S1	18.15A	18.38A	1.2A	1.8A	44.2A	45.5A
	S2	18.55A	18.61A	1.5A	1.7A	45.2A	45.8A
	S3	18.69A	18.32A	1.6A	1.8A	45.0A	45.3A
	S4	18.80A	18.22A	1.2A	1.4A	45.7A	45.6A
T. grandis	S1	18.51A	17.31B	2.3A	3.0A	42.3A	42.6A
	S2	18.49A	17.78AB	2.3A	3.2A	42.2A	42.8A
	S3	18.19A	18.61AB	2.7A	3.4A	41.8A	42.5A
	S4	17.91A	19.06A	2.7A	3.0A	42.3A	43.1A

Legend in figure:
D: *D. panamensis* S1: 0.5x1.0 m
C: *C. alliodora* S2: 1.0x1.0 m
G: *G. arborea* S3: 1.0x2.0 m
T: *T. grandis* S4: 2.0x2.0 m

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Short-rotation crop (SRC) systems with woody species have been planted in Costa Rica. However, information about different tree species and spacing is limited. The objective of the present study was to examine biomass production and the physical, energy, and chemical properties of feedstock of four tropical tree species (*Cordia alliodora*, *Dipteryx panamensis*, *Gmelina arborea*, and *Tectona grandis*) in 34-month-old plants planted at four spacings (0.5x1.0 m, 1.0x1.0 m, 1.0x2.0 m, and 2.0x2.0 m). The highest mortality rate (50%) was found in *G. arborea*; however, diameter, height, basal area, and biomass production in *G. arborea* plantations were higher than *T. grandis*, *C. alliodora*, and *D. panamensis*. Spacing effects on diameter, height, basal area, and biomass production were observed in 10-month-olds. Wide spacing presented the highest values in diameter and height, but the highest biomass production was found in the narrow spacing. Also, biomass distribution was different in *D. panamensis* in relation to other species. Specify gravity, density, and moisture content of biomass showed high variation between species and spacing, but the energy and chemical properties of biomass showed few differences. These results suggest that these four species were uniform in terms of their energy and chemical properties, regardless of the spacing used. Finally, three species (*G. arborea*, *C. alliodora*, and *T. grandis*) presented important potential for use in SRC systems. *G. arborea* was the species with the highest production but a high mortality rate.

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INTRODUCTION

Biomass is one of the main renewable energy resources due to its great potential, economic viability, renewability, and various social and environmental benefits (Amjith and Bavanish 2022). The energy obtained from biomass is called primary energy, which means that the energy comes from perennial plants (arboreal or not) and is used to produce biomass for energy (Giudicianni *et al*. 2021). Trees produced in short rotation crops (SRC) are an important potential source of biomass, which can be used as solid fuel with different shapes (firewood, wood chips, pellet) or processes, including thermic or thermo-chemical

(torrefaction, charcoal, gasification, liquation) (Rodrigues *et al*. 2021). SRC are a silvicultural system based on short rotation, less than 1 to 15 years (Eisenbies *et al*. 2021). Genetically superior trees and intensive management such as fertilisation, irrigation, and weed control are implemented in these systems (Johnston *et al*. 2022).

Woody species planted under SRC systems have been established in many countries around the world, especially in the European Union and North America (Djomo *et al*. 2015; Ile *et al*. 2022). However, limited experience in establishing SRC is found in the Latin America area (Moya *et al*. 2019; Silva *et al*. 2022); little by little, they have gained importance in countries including Chile (Yáñez *et al*. 2019), Brazil (Santos and Reichert 2022), and some Central American countries such as Costa Rica (Tenorio *et al*. 2019a,b). There are different species that can be used in SRC systems (Dickmann 2006). In temperate climates, there are *Populus*, *Salix*, *Pinus*, *Robinia*, and *Eucalyptus* in the EU region (Amichev *et al*. 2014; Djomo *et al*. 2015; Pleguezuelo *et al*. 2015), and in Latin America, a great diversity of species in the SRC, between 35 and 40 species (Moya *et al*. 2019), probably due to the great adaptability of the species to different soil conditions (Rockwood *et al*. 2019).

Costa Rica, a small country in Central America, developed its energy matrix around renewable sources (Hernández-Chaverri and Buenrostro-Figueroa 2021). Biomass represents 14% of the different energy sources (Popp *et al*. 2021), and a high percentage of this biomass comes from agricultural waste (Alonso *et al*. 2017). However, a characteristic of biomass from agricultural waste is that it presents a high moisture content, and in addition, its collection system is expensive (Abuelnuor *et al*. 2014). While forest biomass has a significant volume (Valverde *et al*. 2021) and potential as a renewable energy source, its use is limited (Moya *et al*. 2019), even though woody feedstock is more efficient at conversion to energy than many agricultural residues (Alonso *et al*. 2017).

Woody biomass currently comes from many sources in Costa Rica, among them residues in the plantation during logging, residues in primary sawmills, and short rotation (SRC) plantation systems (Valverde *et al*. 2021). The research and knowledge of species used in SRC are recent, and few species have been tested and planted (Moya *et al*. 2019). Notable species include *Gmelina arborea* (Salazar-Zeledón 2016; Tenorio *et al*. 2016, 2018; 2019a; Tenorio *et al*. 2019b), *Eucalyptus saligna* and *Eucalyptus camaldulensis* (Navarro-Camacho *et al*. 2014), and *Eucalyptus tereticornis* (Valverde *et al*. 2022).

For *G. arborea* in SCR, Tenorio *et al*. (2016 and 2018) reported that, during the first two years, 0.5x1.0 m and 1.0x1.0 m spacing presented higher growth in diameter and height and biomass production than 2.0x1.0 m spacing. In addition, these authors point out that the site is the main factor in the production of biomass and that the energy characteristics of the trees growing in SRC vary widely from one year to another. In another study carried out on *G. arborea* in SRC at 24 months of age with three spacings (1.0x1.0 m, 0.75x0.75 m, and 1.0x0.5 m) but using two clones used for wood production, the effect of the clone was found in the mortality, the morphological characteristics of the trees, the leaf area, the biomass production, and a few variations in energy biomass characteristics (Tenorio *et al*. 2019b).

In other species tested in SRC, such as *Dipteryx panamensis*, the chemical, physical, and energy properties of the biomass were evaluated at three different spacings (1.0x2.0 m, 1.0x0.5 m, and 1.0x1.0 m) at the age of 3 years (Gaitan-Alvarez *et al*. 2020). Increasing the spacing increased the plant's green density and moisture content, and 1.0x1.0 m and 1.0x0.5 m spacings were found to produce the highest biomass (Gaitan-Alvarez *et al*. 2020). The other two species, *Tectona grandis* and *Cordia alliodora* have

been used in fast-growing plantations for commercial reforestation in Costa Rica for sawlog production (Moya *et al*. 2019); therefore, information on the processes and properties of these species is abundant and known (Moya *et al*. 2019). However, the use of these species in the SRC system lacks information about biomass production and its energy properties (Shukla and Viswanath 2021).

The objective of this study was to determine the growth (mortality, diameter, height, and basal area), biomass production, and physical, energy, and chemical properties of four forest trees species (C. *alliodora*, *D. panamensis*, *G. arborea*, and *T. grandis*) planted under SRC at the age of 36 months, using four planting spacings (0.5x1.0 m, 1.0x1.0 m, 1.0x2.0 m, and 2.0x2.0 m). Knowledge of the information just mentioned will allow determination of the energy potential and biomass production of four different species according to spacing and establish the species with best volume productions and best energy characteristics.

EXPERIMENTAL

Geographic Location and Plantation Description

Four different plots of SCR system with *Cordia alliodora*, *Dipteryx panamensis*, *Gmelina arborea*, and *Tectona grandis* were planted in Florencia (Fig. 1a), San Carlos, Alajuela, Costa Rica (N 10 21´ 29.7," W 84 28´ 3.4"). The site where plots were planted was divided into three blocks. The site presented a slight slope in a west-to-east direction, so the site was separated into three blocks. For each of the species, four different spacings with three plots were established: 0.5x1.0 m equivalent to 20000 N/ha (S1), 1.0x1.0 m, equivalent to 10000 N/ha (S2), 1.0x2.0 m, equivalent to 5000 N/ha (S3), and 2.0x2.0 m, equivalent to 2500 N/ha (S4). A plot was established in each block and 64 trees were planted (8 trees in width and 8 trees in length). A total of 12 plots were randomly established (Fig. 1b) per species (4 spacings x 3 plots = 12 experimental units).
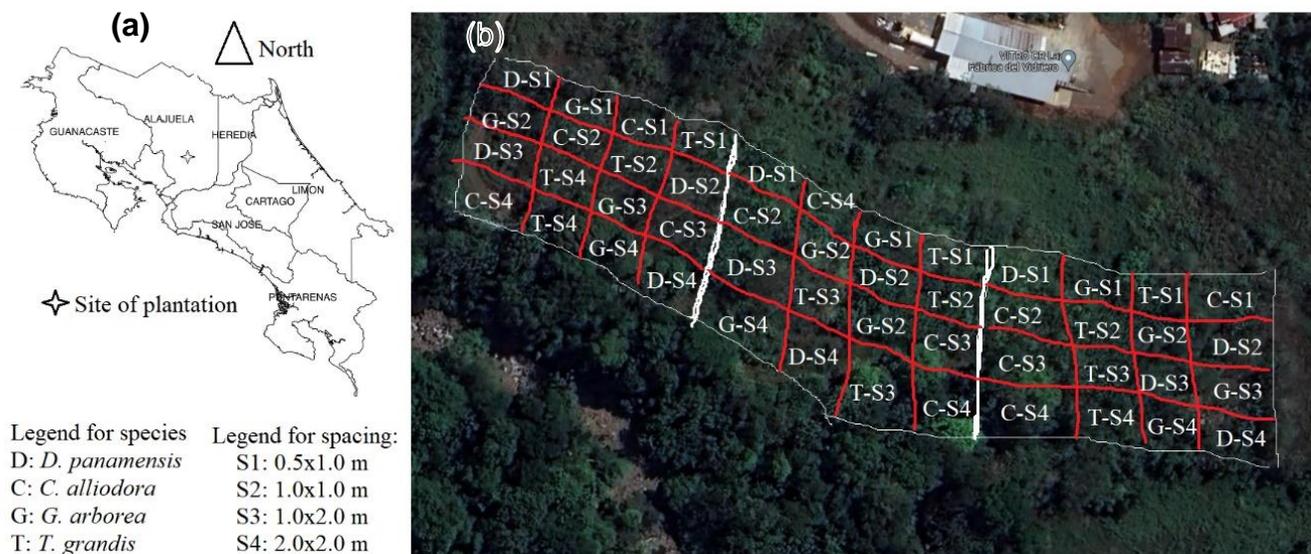
Fig. 1. Geographic location of SCR system in Costa Rica (a) and distribution of plot for each species in different spacing (b)

Determination of Mortality, Diameter, Height, and Basal Area

A plot was established in the center of every experimental unit, considering 36 trees (6x6 trees), and the trees with 2 external rows and 2 external columns of repetitions were not considered. The diameter and height were measured on 36 trees. A 30 cm diameter was measured from the basal part of the tree. These two parameters and mortality were determined at the ages of 6, 12, 19, 22, 29, and 34 months. The irregularity in the measurement age is attributed to the pandemic period between 2020 and 2021. The percentage of mortality and the basal area of each plot per species were determined. The mortality rate was determined based on the percentage relationship between the number of individuals within each plot and the total number of trees (36 trees) within the plot. The basal area of each plot was calculated using Eq. 1. The average value of the spacing was calculated and extrapolated to the hectare level. Then parameters determined (mortality, diameter, height, and basal area) will make it possible to know the behavior of the species in the trials, and in addition, to know the growing of the best species in the different spacing conditions.

$$Basal\ area\ (m^2) = \frac{\pi}{4} * diameter\ (m)^2 \qquad (1)$$

Tree Sampling and Sampling in the Tree

Biomass sampling was conducted at 34 months of age. Three trees were sampled in each plot, and then 144 trees per species were sampled (4 species x 4 spacings x 3 plots x 3 trees = 144 trees). Before cutting the sample tree, the diameter of 30 cm from the basal part of the tree was measured. After being cut at ground level, branches and leaves were separated from the trunk. Each part (leaves, branches, and trunks) was weighed separately. Then, six 10-cm-long cross sections were extracted from three different heights: two samples from the base of the tree, two samples at total height, and two samples at 50% total height. One sample from each height was used for specific gravity and green density determination, and the other sample was used for the determination of the moisture content of the trunk and bark. All this material was packed in plastic bags to keep it dry. The remaining trunk material was ground to obtain chips not greater than 3 mm long.

Biomass Determination and Energy Production

The biomass of the total trunk was estimated using the moisture content of the trunk (MC_{trunk}) and its weight in green condition (Eq. 2). The weight of all the leaves and branches after drying was used to determine the biomass for these parts of the tree. The calculated biomass of the trunk ($biomass_{trunk}$), leaves ($biomass_{leaves}$), and branches ($biomass_{branch}$) were used to calculate the percentage distribution of biomass for each of these parts of the tree. In addition, the biomass values obtained were projected to estimate biomass per hectare for each type of plantation spacing,

$$Biomass = \ weight * \left(1 - \frac{moisture\ content}{100}\right) \qquad (2)$$

where the biomass can be the biomass of trunk, biomass of bark, biomass of branch, or biomass of leaves.

Determination of the Moisture Content, Specific Gravity, and Green Density

To calculate the moisture content (MC), leaves (MC_{leave}) and branches (MC_{branch}) in green condition were weighed and then placed in an oven at 103 °C for 24 h and

reweighed after that period. The MC was calculated using the weight percent ratio of weight after drying and weight before drying (MC= (weight before drying-weight after drying)/weight after drying x 100). Meanwhile, to calculate the MC of the bark (MC_{bark}) and the trunk (MC_{trunk}), the 10 cm samples obtained at three different heights were used after removing the bark from the trunk. Both parts were oven-dried at 103 °C for 24 h. The weight before and after drying was measured and used to find the MC with the percent ratio as described above. The specific gravity (SG) was only determined for the trunk, using the trunk cross-section comprising the xylem and the bark. ASTM D-143 (2022) was used to determine the volume of this cross-section based on its weight and water displacement. Then, the cross-section was placed in the oven for 24 h at 103 °C according ASTM D-143 standard (2022). The SG was determined according to the ASTM D-4442 (2020). In the same manner, the trunk density was determined based on the green weight/green volume ratio.

Determination of the Chemical and Energy Characteristics

The chipped material from the trunks (wood and bark) of the three trees in each experimental unit was combined into one sample. This sample was air-dried to 12% MC. Following this, the material was sieved through 0.25 mm and 0.42 mm meshes (40 and 60 meshes, respectively). The same procedure was used with the branches of the three trees sampled. As for the chemical characteristics, the percentage of carbon (C), nitrogen (N), hydrogen (H), carbon-nitrogen ratio (C/N), and carbon-hydrogen ratio (C/H) was determined with the Elemental Analyzer, Vario Macro Cube model. Then C, N, H, C/N, and C/H content was measured for trunk and branch and named C_{trunk}, C_{branch}, H_{trunk}, H_{branch}, C/H_{trunk}, and C/H_{branch}.

Regarding the energy characteristics, the gross calorific value (GCV) and ash content of the trunk and branch were determined: GCV in the trunk and branch (GCV_{trunk} and GCV_{branch}), and ash content in the trunk and branch (Ash_{trunk} and Ash_{branch}). In order to determine GCV, a portion (approximately 10 grams) of the sieved material from the trunk (wood and bark) and the branches was dried at 103 °C for 24 h. To find GCV, Parr's calorific test was used according to the ASTM D-5865 (2019), using five samples weighing 2 g each. As for the ash content, 10 g of the sieved material of each experimental unit (trunk and branches) was used, and the procedure followed ASTM D-1102 (2021).

Again, all characteristics of biomass (production, moisture content, specific gravity and green density, and chemical and energy properties) make it possible to determine which species and different spacing conditions with better energy properties.

Data and Statistical Analysis

Compliance of the variables measured with the assumptions of a normal distribution and homogeneity of the variances, as well as the presence of outliers, were verified. A variance analysis was applied to verify the effect of spacing on each species. Spacing was the independent variable of the model and the variables measured (SG, density, carbon and hydrogen percentage and its ratio, GCV, ash content, and biomass) were the response variables. The Tukey test was used to determine statistical differences between the averages of the variables measured. The variance analysis and the Tukey tests were conducted using SAS software (SAS Institute Inc., Cary, NC).

RESULTS AND DISCUSSION

Mortality and Growth in Diameter and Height

According to Fig. 2, mortality rates are presented based on species and spacing. The S2 spacing presented the highest mortality percentage of all species. *C. alliodora* had a mortality of around 40% for S2 spacing at 34 months, which is attributed to the loss of a plot after the establishment of the plantation (Fig. 2a). Mortality rates of 22% and 15%, respectively, were observed at S1 and S4 spacings (Fig. 2a). The S3 spacing presented a low mortality rate, less than 8% (Fig. 2a). In *D. panamensis*, the S2 spacing presented a mortality of 28% at 34 months, followed by the S1, S3, and S4 spacings (Fig. 2b). *G. arborea* presented the highest mortality in all spacings tested (Fig. 2c). The S2, S3, and S4 spacings showed the lowest values before 12 months; however, an increase in mortality was observed up to 34 months (Fig. 2c). The S1 spacing presented values higher than 15% from the sixth month, up to 44% at 34 months (Fig. 2c). Finally, *T. grandis* presented the highest mortality (34%) at 34 months at S1 and S2 spacings, followed by S4 and S3 spacings (Fig. 2d).
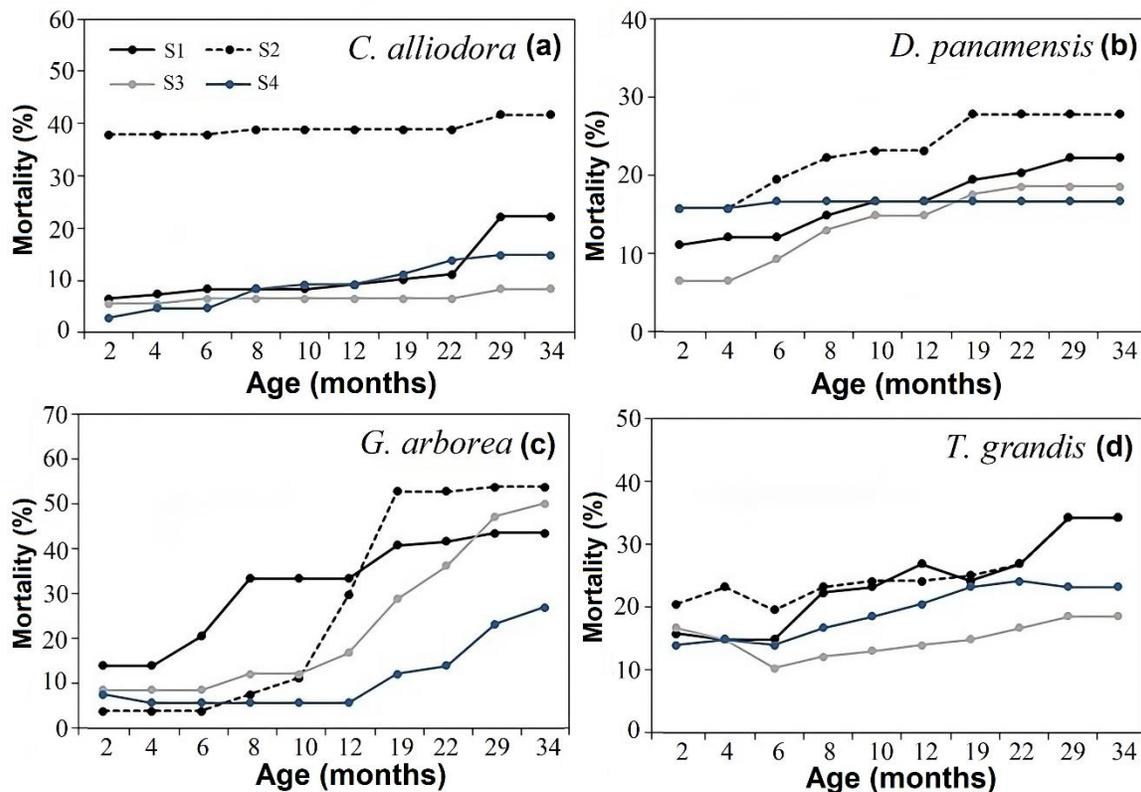
Fig. 2. Mortality by age and spacing of four tropical species grown in a short rotation system: (a) *C. alliodora*, (b) *D. panamensis*, (c) *G. arborea*, and (d) *T. grandis*.

The trees' height and diameter increased with age (Figs. 3 and 4). The spacing effect on the height and diameter was observed after 10 months; the wider spacing showed the highest values of height and diameter (Figs. 3 and 4). Another aspect to highlight is that the S3 and S4 spacings had the most effective development in height and diameter at the end of 34 months in all the species, and between these two spacings, there was little difference in height but a greater difference in diameter (Figs. 3 and 4).
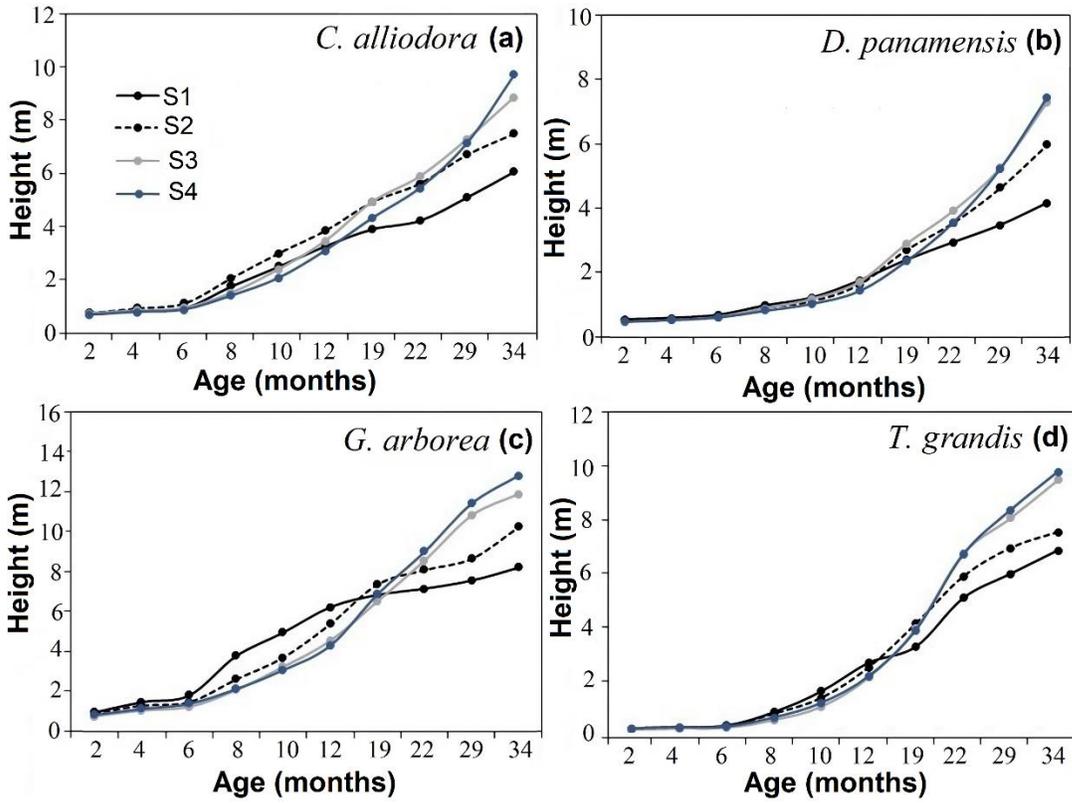
Fig. 3. Average height by age and spacing of four tropical species grown in a short rotation system: (a) *C. alliodora*, (b) *D. panamensis*, (c) *G, arborea* and (d) *T. grandis*
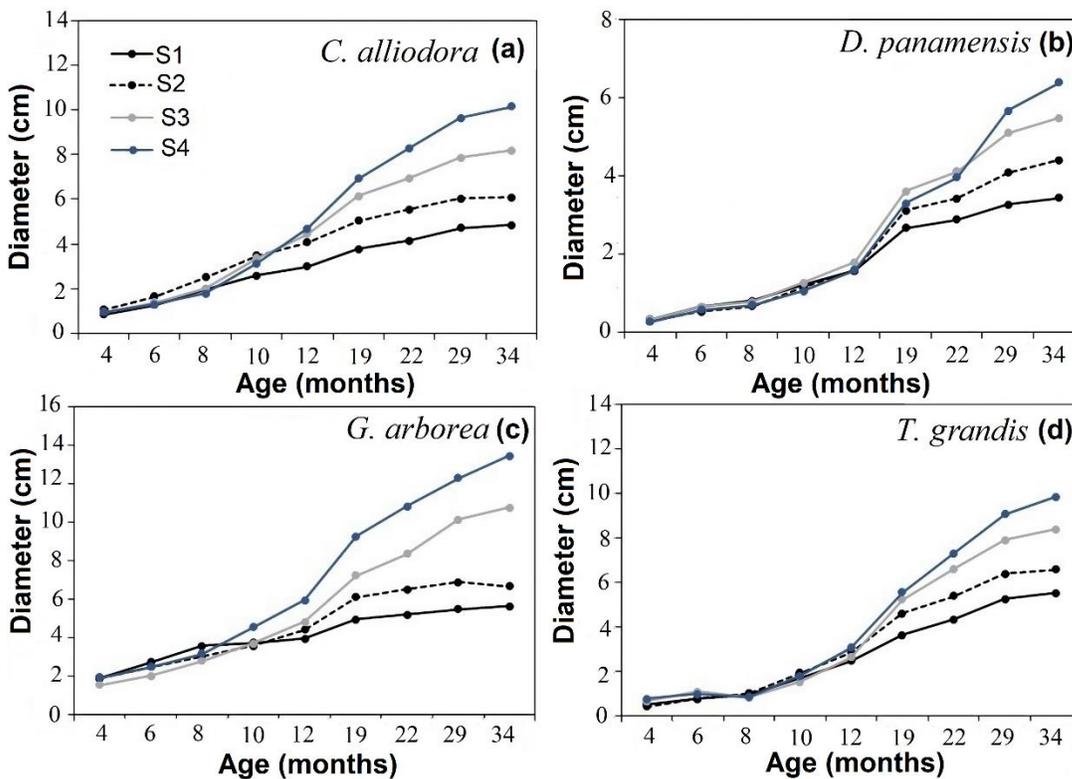
Fig. 4. Average diameter by age and spacing of four tropical species grown in a short rotation system: (a) *C. alliodora*, (b) *D. panamensis*, (c) *G. arborea* and (d) *T. grandis*

In general, *G. arborea* trees presented the highest values of height and diameter, followed by those of *T. grandis*, *C. alliodora*, and *D. panamensis* (Figs. 3 and 4). *G. arborea* presented variation across age: between 6 and 12 months, the S1 spacing presented the highest average height, but this spacing presented the lowest average after 12 months in relation to the other spacings (Fig. 3c).

Regarding the basal area, *G. arborea* presented the highest average in each spacing, followed by *C. alliodora*, *T. grandis*, and *D. panamensis*, except for the S1 spacing of *T. grandis*, which presented an average basal area greater than *C. alliodora* (Fig. 5). The basal area decreased with spacing in all species. S4 spacing (narrow spacing) presented the lowest average basal area, while S1 spacing presented the highest average (Fig. 5). For *G. arborea*, the spacings S4 and S3 presented similar basal areas in different tree ages (Fig. 5c). In *T. grandis*, during the first 8 months, no differences were observed in the basal area at four spacings (Fig. 5d). In addition, after 34 months of measurement for both *G. arborea* and *T. grandis*, in the S2 spacing, the basal area decreased (Figs. 5c and d).
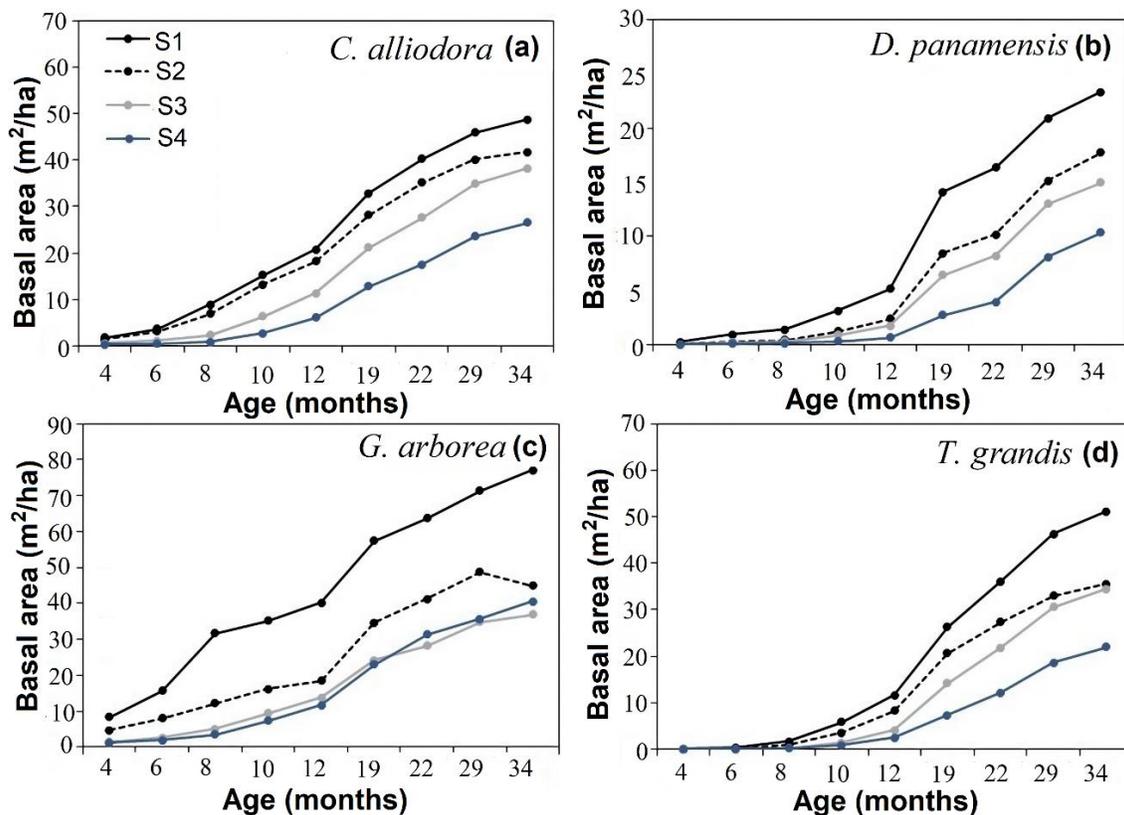
Fig. 5. Average basal area by age and spacing of four tropical species growing in a short rotation system: (a) *C. alliodora*, (b) *D. panamensis*, (c) *G. arborea*, and (d) *T. grandis*

Biomass Distribution

Table 1 presents the biomass averages for the different parts of the tree. The highest averages of $Biomass_{trunk}$ and $Biomass_{branch}$ occurred in *G. arborea*, followed by C. *alliodora*, *T. grandis*, and *D. panamensis*. Regarding $Biomass_{bark}$, *T. grandis* presented the highest average, followed by *G. arborea*, *C. alliodora*, and *D. panamensis*. In $Biomass_{leaves}$, *D. panamensis* presented the highest average, followed by *T. grandis*, *C. alliodora*, and *G. arborea* (Table 1). Statistical differences were observed only between spacings in the $biomass_{bark}$ of *C. alliodora* and *D. panamensis*. S1 presented the statistically highest value

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and S4 the lowest for *C. alliodora* and *D. panamensis*. S1 presented the statistically highest value, and no differences were observed between S2, S3, or S4 (Table 1). In the case of *G. arborea*, no differences were observed between spacings for any of the different types of biomasses (Table 1). In the case of *T. grandis*, no differences were observed in $biomass_{trunk}$, $biomass_{branch}$, and $biomass_{leaves}$, the $biomass_{bark}$, $biosmass_{trunk+bark}$, and $biomass_{trunk+bark+branch}$ had the highest statistical value of S1 spacing, while S4 presented the lowest values of these biomasses (Table 1).

Table 1. Average Biomass at 34 Months per Tree Part and Spacing for Four Tropical Species Growing in a Short Rotation System

Species	Spacing	Biomass (ton/ha)					
		Trunk	Bark	Trunk + bark	Branch	Trunk+bark+branch	Leaves
C. alliodora	S1	31.0A	6.0A	37.0A	4.8A	41.7A	2.3A
	S2	27.2A	4.4AB	31.5A	4.6A	36.1A	1.6A
	S3	27.9A	4.0AB	31.9A	5.0A	36.9A	2.1A
	S4	25.3A	3.6B	28.8A	8.4A	37.2A	3.4A
D. panamensis	S1	24.3A	3.5A	27.8A	1.3A	29.2A	5.4A
	S2	27.1A	3.0B	30.1A	2.6A	32.7A	5.7A
	S3	22.8A	2.2B	25.0A	2.6A	27.5A	4.6A
	S4	14.4A	1.3B	15.7A	3.4A	19.0A	4.4A
G. arborea	S1	52.7A	6.8A	59.5A	6.2A	65.6A	2.1A
	S2	35.2A	4.4A	39.6A	5.3A	44.9A	1.8A
	S3	51.1A	5.7A	56.8A	8.5A	65.3A	5.1A
	S4	44.4A	3.9A	48.3A	7.8A	56.1A	2.7A
T. grandis	S1	34.4A	8.6A	43.0A	3.0A	46.0A	4.2A
	S2	28.6A	6.5AB	35.0AB	2.5A	37.5AB	2.0A
	S3	23.0A	5.1BC	28.2AB	2.1A	30.2AB	4.0A
	S4	17.0A	3.5C	20.5B	2.4A	22.8B	3.2A

Different letters in values of biomass mean statistical differences at 95% in different spacings.

Figure 6 presents the percentage distribution of biomass for the different parts of the tree at 34 months. A different biomass distribution was observed for different types of biomasses for four species, and as expected, the $biomass_{trunk}$ showed the highest percentage. For *C. alliodora*, the spacings S1 and S2 presented a similar biomass distribution; the highest percentage corresponded to the $biomass_{trunk}$, followed by the $biomass_{bark}$, $biomass_{branch}$ and the lowest percentage was for $biomass_{leaves}$. Among these species, the biomass distribution was different in S3 and S4 spacing; $biomass_{trunk}$, accounted for the highest percentage, followed by $biomass_{branch}$, $biomass_{bark}$, and $biomass_{leaves}$ (Fig. 6a). The biomass distribution of *D. panamensis* was similar in S1, S2, and S3 spacing; the highest percentage was for $biomass_{trunk}$, followed by $biomass_{leaves}$, $biomass_{bark}$, and the lowest percentage was for $biomass_{branch}$. For S4 spacing, the biomass distribution was different; the highest percentage was found in $biomass_{trunk}$, followed by $biomass_{leaves}$, $biomass_{branch}$, and $biomass_{bark}$ presented the lowest percentage (Fig. 6b). For *G. arborea*, the highest percentage was in $biomass_{trunk}$ at four spacings, followed by $biomass_{branch}$, $biomass_{bark}$, and $biomass_{leaves}$ (Fig. 6c). *T. grandis* exhibited the highest $biomass_{trunk}$, followed by $biomass_{bark}$, $biomass_{leaves}$, and $biomass_{branch}$ at all spacings (Fig. 6d).
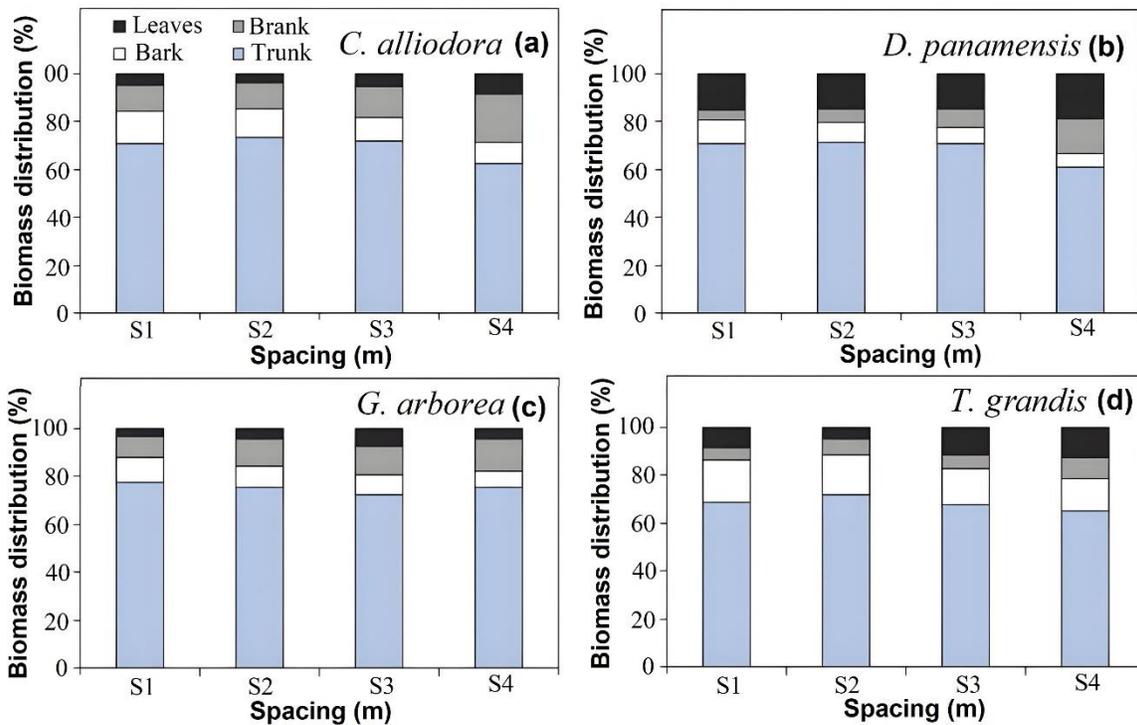
Fig. 6. Biomass distribution at 34 months per tree part and spacing for four tropical species grown in a short rotation system: (a) *C. alliodora*, (b) *D. panamensis*, (c) *G. arborea* and (d) *T. grandis*

Tree Sampling and Sampling in the Tree

Table 2 presents biomass physical properties. The MC of branches presented the highest values, followed by the bark and trunk + bark.

Table 2. Physical Properties of Biomass at 34 Months for Four Tropical Species Growing in a Short Rotation System

Species	Spacing	Biomass (ton/ha)				Specific Gravity	Density (g/cm³)
		Trunk	Bark	Trunk + bark	Branch		
C. alliodora	S1	44.0B	69.9A	50.8A	60.0A	0.38A	0.67A
	S2	48.1AB	71.8A	54.4A	62.3A	0.33B	0.64A
	S3	48.3A	71.6A	53.0A	56.5A	0.34AB	0.66A
	S4	47.4AB	71.6A	52.4A	49.1A	0.36AB	0.69A
D. panamensis	S1	38.6A	64.2A	43.8A	71.5A	0.71B	1.15B
	S2	38.4A	65.1A	42.9A	71.3A	0.73AB	1.17AB
	S3	36.7AB	64.1A	40.7B	66.7A	0.75A	1.18A
	S4	36.3B	64.2A	40.1B	66.1A	0.75A	1.18AB
G. arborea	S1	59.3A	80.8A	63.9A	63.3A	0.38AB	0.93BC
	S2	62.7A	80.9A	66.0A	63.2A	0.34B	0.90C
	S3	62.7A	81.2A	66.1A	61.8A	0.36AB	0.97AB
	S4	60.2A	80.6A	63.4A	59.6A	0.38A	1.00A
T. grandis	S1	56.1A	82.5A	66.5A	73.1A	0.48A	1.10A
	S2	54.7A	81.4A	64.2A	72.9A	0.45A	1.10A
	S3	59.1A	83.7A	67.9A	73.6A	0.47A	1.10A
	S4	56.0A	82.5A	65.2A	72.1A	0.49A	1.11A

Different letters in values of biomass mean statistical differences at 95% in different spacings.

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The lowest value was in the trunk for *C. alliodora*, *D. panamensis*, and *T. grandis*, but in *G. arborea*, the MC of bark was the highest value, followed by similar values for branch, trunk, and trunk + bark. Specific gravity and density varied between species; *D. panamensis* displayed the highest value, followed by *T. grandis*, *G. arborea*, and *C. alliodora* with the lowest values (Table 2).

Regarding spacing, a greater effect was observed in *C. alliodora*, *D. panamensis*, and *G. arborea*, but a lesser effect was observed in *T. grandis* (Table 2). In *C. alliodora*, no statistical differences were observed between the spacings for MC_{bark}, $MC_{trunk+bark}$, MC_{branch}, and density (Table 2). The highest values of MC_{trunk} are presented in S3 spacing, and the lowest value is in S1 spacing. For SG, S1 spacing presented the highest value, while the S2 spacing had the lowest value (Table 2). In *D. panamensis*, no differences were observed among spacings for MC_{bark} and MC_{branch}, while for MC_{trunk} and $MC_{trunk+bark}$, S1 and S2 spacings showed the highest values and S4 spacing was the lowest in MC_{trunk}, but S3 and S4 spacing presented the lowest in $MC_{trunk+bark}$. For SG and density, the largest spacings (S3 and S4) presented the highest values, while S1 presented the lowest values (Table 2). In *G. arborea*, no differences were observed between the MC_{trunk}, MC_{bark}, $MC_{trunk+bark}$, and MC_{branch} variables in SG. The S4 spacing presented the highest value of density, and the S2 spacing presented the lowest. No differences were observed between spacings for any of the variables evaluated for *T. grandis* (Table 2).

Table 3 presents the energy and chemical properties evaluated at 34 months. There were no differences in GCV, C, H, or the ratio C/H between species or between trunk and branch. Some differences were observed in ash content, and this variable ash content in the branches was higher than in the trunks of all species (Table 3).

Table 3. Physical Properties of Biomass at 34 Months for Four Tropical Species Growing in a Short Rotation System

Species	Spacing	Gross Calorific Value (MJ/kg)		Ash Content (%)		Carbon Content (%)		Hydrogen Content (%)		C/H Ratio	
		Trunk	Branch	Trunk	Branch	Trunk	Branch	Trunk	Branch	Trunk	Branch
C. alliodora	S1	19.31A	18.07A	2.3A	2.9A	44.4A	44.6A	6.5A	6.4A	6.8BC	7.0A
	S2	18.86A	18.80A	2.4A	2.7A	44.7A	44.3A	6.6A	6.3A	6.8C	7.0A
	S3	19.33A	18.95A	2.4A	2.5A	44.7A	44.2A	6.5A	6.3A	6.9A	7.0A
	S4	18.47A	18.92A	2.2A	2.4A	44.5A	45.0A	6.5A	6.5A	6.9AB	7.0A
D. panamensis	S1	18.52A	17.73C	1.6A	3.3A	42.7A	42.7A	6.3C	6.2B	6.8A	6.8B
	S2	19.22A	18.41BC	1.2A	2.1B	42.9A	42.9A	6.4BC	6.3A	6.7B	6.8AB
	S3	18.61A	19.18B	1.7A	2.3B	43.2A	43.2A	6.5AB	6.3A	6.6BC	6.8A
	S4	19.56A	20.79A	1.6A	2.3B	43.7A	43.8A	6.6A	6.4A	6.6C	6.8A
G. arborea	S1	18.15A	18.38A	1.2A	1.8A	44.2A	45.5A	6.4B	6.6A	6.9AB	6.9A
	S2	18.55A	18.61A	1.5A	1.7A	45.2A	45.8A	6.5AB	6.5A	6.9AB	7.0A
	S3	18.69A	18.32A	1.6A	1.8A	45.0A	45.3A	6.5AB	6.5A	6.9A	7.0A
	S4	18.80A	18.22A	1.2A	1.4A	45.7A	45.6A	6.7A	6.5A	6.8B	7.0A
T. grandis	S1	18.51A	17.31B	2.3A	3.0A	42.3A	42.6A	6.4A	6.2A	6.6A	6.8A
	S2	18.49A	17.78AB	2.3A	3.2A	42.2A	42.8A	6.3A	6.2A	6.7A	6.9A
	S3	18.19A	18.61AB	2.7A	3.4A	41.8A	42.5A	6.5A	6.2A	6.5B	6.9A
	S4	17.91A	19.06A	2.7A	3.0A	42.3A	43.1A	6.5A	6.3A	6.5B	6.9A

Note: different letters in values of biomass mean statistical differences at 95% in different spacings.

Regarding the different species, *C. alliodora* presented the highest GCV values, followed by *D. panamensis*, *G. arborea*, and *T. grandis*. For the ash content, *T. grandis* presented the highest averages, followed by *C. alliodora*, *D. panamensis*, and *G. arborea* (Table 3). For *C. alliodora* and *G. arborea*, no differences were observed between spacings for GCV_{trunk}, GCV_{branch}, Ash_{trunk}, and Ash_{branch}. In *D. panamensis*, no statistical differences were observed in GCV_{trunk} and Ash_{trunk}, while S4 spacing presented the highest value for the GCV_{branch} and the lowest value was measured in S1 spacing. In relation to Ash_{branch}, S1 spacing presented the highest value, and no differences were observed between S2, S3, and S4 spacings (Table 3). For *T. grandis*, statistical differences were only observed for the GCV_{branch}, where S4 spacing presented the highest value and S1 the lowest. In other variables (GCV_{trunk}, Ash_{trunk}, and Ash_{branch}), no differences were observed (Table 3).

Regarding the chemical properties, *G. arborea* presented the highest average of C, H, and C/H ratio (trunk and branch), followed by *C. alliodora*, *D. panamensis*, and *T. grandis* (Table 3). For *C. alliodora*, no statistical differences were observed between the spacings for C_{trunk}, C_{branch}, H_{trunk}, H_{branch}, and C/H_{branch}. According to Table 3, S3 spacing was the highest and S2 spacing was the lowest in this species for C/H_{trunk}. *D. panamensis* showed the greatest number of statistical differences between spacings. The spacings S2, S3, and S4 presented the highest values of C_{branch}, while the S1 spacing presented the lowest. For H_{trunk}, S4 spacing presented the highest value and S1 had the lowest value. In H_{branch}, S2, S3, and S4 spacing presented the highest values, while S1 spacing presented the lowest value. For C/H_{trunk}, S1 spacing presented the highest value and S4 the lowest value. For C/H_{branch}, S3 and S4 spacing presented the highest values, and S1 spacing presented the lowest values. Finally, C_{trunk} did not present differences between the spacings (Table 3). In *G. arborea*, statistical differences were observed between spacings in H_{trunk}, where S4 spacing presented the highest value and S1 the lowest values, and in C/H_{trunk}, S3 spacing presented the highest value and S4 the lowest values; for C_{trunk}, C_{branch}, H_{branch}, and C/H_{branch}, no differences were observed between the spacings (Table 3). For T. grandis, differences were observed between spacings in C/H_{trunk}, where S1 and S2 spacing presented the highest values and S3 and S4 spacing presented the lowest values (Table 3). For the variables C_{trunk}, C_{branch}, H_{trunk}, H_{branch}, and C/H_{branch}, no differences were observed between the spacings (Table 3).

Mortality and Growth

The high percentage of mortality found in *C. alliodora* in S2 spacing (Fig. 2a) was due to the loss of one plot, which could be the consequence of poor handling of the plant seedlings during the establishment of the plot. This problem was found only in this plot. An increase in mortality was observed after 10 months in the S2 and S3 spacings of *G. arborea* (Fig. 2c) due to a tree in the natural forest near the boundary of the plantation falling on the plantation, which directly affected the plots of these two spacings, causing from this moment on an increase in tree mortality. However, apart from these events, for the four species, the wide spacings (S4 and S3) had lower mortality than the narrow spacings (S2 and S1). This result suggests that the level of tree competition at narrow spacing causes an increase in their mortality. Several factors contribute to mortality in SRC (Paris *et al*. 2011): (i) initial implantation of a plantation leads to the tree's growth until it reaches the maximum resource availability that the site can support (Paris *et al*. 2011). However, growth is limited once competition among the trees begins and resource release through mortality occurs (DeBell *et al*. 1996). (ii) The second aspect is the amount of

resources in the soil, which conditions tree survival (Laureysens *et al.* 2004). Competition is greater on sites that lack the necessary resources for tree growth, which leads to the mortality of some individuals (Dillen *et al.* 2013).

So, the conditions of the soil and the demand for resources at the site where the SRC system was established were probably inadequate for *D. panamensis*, *G. arborea*, and *T. grandis* (Fig. 2b-d), more so given the tree's need for resources at the spacings applied (Paris *et al.* 2011). As a result, tree mortality at the various spacings was high, so tree survival was low (Fig. 2c).

In the comparison of mortality of the different species with other studies, it was found that Tenorio *et al.* (2016; 2018) reported mortality between 23 and 60% at 24 months old for *G. arborea* in different spacings and 44 to 56% in two clones of this species at 24 months old (Tenorio *et al.* 2019), which agreed with values found for this species in this study (Fig. 2c). According to the above authors and the results obtained in this study, site fertility is important for the establishment of the SRC of *G. arborea* since some of the sites analyzed in Costa Rica showed survival rates of 95% due to favorable site conditions. In relation to *D. panamensis*, it was reported that mortality was 50% at 36 months (Gaitan-Alvarez *et al.* 2020), values higher than those obtained for these species in the presented study (Fig. 2b). The fact that *D. panamensis* is a species with less mortality seems to indicate that it is the species that is best adapted to the conditions of the site.

Tree height and diameter increased with age for all four species (Figs. 3 and 4). The increase in diameter and height with age corresponds to the normal development of trees in the early years, where the tree tries to position itself in height and then begins its development in diameter (Ryan and Yober 1997). For these two dasometric parameters, the effect of spacing was observed; the wider spacings (S4 and S3) presented greater diameter and height than the narrow spacings (S2 and S1) but with a more evident effect on the diameter parameter (Figs. 3 and 4). SCR with high density (narrow spacing, such as S2 and S1) have small diameters due to the high competition between trees (Gspaltl *et al.* 2013), which was observed in all species studied (Figs. 3 and 4).

This difference in spacing was presented after 22 months for height (Fig. 3) and 12 months for diameter (Fig. 4). The lack of this difference in the first months is attributed to the fact that during these months, the level of competition between the trees is still too low to produce differences (Widyati *et al.* 2022). Although this study did not determine crown intertwining among trees (the visible evidence that competition begins), it barely started, so competition was low (Li *et al.* 2017). From a physiological point of view, trees during their early years will focus their development mainly on stability and subsistence in order to survive (Li *et al.* 2017), so at early ages, the tree's growth will be in height at narrow spacings such as S3 and S4 (Fig. 3), which produce greater competition. This spacing presents less development than the wider spacings such as S1 and S2 (Fig. 3), since diameter growth is not important for survival.

The average basal area is an important parameter widely used in plantations for sawlog production (Niemczyk 2021). The narrower spacings (S1 and S2) presented higher basal area averages than the wider spacings (S3 and S4) in the four species (Fig. 5). This behavior was to be expected, since the basal area is defined as the sum per unit area of all the trees, which means that it is a combination of the diameter and the quantity of trees. Therefore, wider spacings, such as S3 and S4, will present a greater basal area than those with the lowest density, such as S1 and S4. This result agrees with the eucalyptus species growing in *SRC* (Rockwood *et al.* 2019). On the other hand, it is observed that in *C. alliodora* (Fig. 5a), *G. arborea* (Fig. 5c), and *T. grandis* (Fig. 5c), a decrease in basal area

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in S2 spacing was observed at the age of 34 months. The performance of these trees suggests they are already entering the competition, so it would be prudent to harvest these species if that spacing is used (Rockwood *et al*. 2019).

In general, the *G. arborea* trees presented the highest height, diameter, and basal area, followed by *T. grandis*, *C. alliodora,* and *D. panamensis* (Figs. 3-5). *G. arborea* and *T. grandis* are exotic species widely used in commercial reforestation for sawlog production with high production (Murillo 2018), but *C. alliodora* and *D. panamensis* (native species of Costa Rica) grow slowly. Mainly *D. panamensis* (Murillo 2018). *G. arborea* and *T. grandis* in SRC systems also showed higher production. Then the use of species in plantations for biomass production could benefit from the development of sawlog production techniques such as clonal reproduction, management, control of pests and diseases, and logging. However, for the other native species (*C. alliodora* and *D. panamensis*), it is still necessary to improve the previous aspects to have greater growth.

Biomass

The lack of differences in the biomass volumes for different parts of the tree as a function of the spacings (Table 1) may be due to the high variability observed (variation coefficients higher than 20%) within each species. The higher variability is attributed to differences in soil fertility, topography, microclimate, and previous uses of the soil (Stolarski *et al*. 2011). Although the area where the trial was established was small, differences in topography were observed across the different blocks where plots were planted. One part of the first block presented a greater slope in relation to the second and third plots, which were flatter. In addition, the third block presented moisture content problems. All these factors contributed to variation in the growth of the trees, mainly due to mortality (Fig. 2). Tree mortality caused spaces to be generated within the same unit, which led to trees close to these spaces to present greater growth in relation to other trees in the same plot (Domec *et al*. 2017), which explains the high variability observed at the level of the biomass and therefore the lack of differences between the four spacings evaluated (Fig. 2 and Table 1).

Regarding biomass distribution, Biomass$_{trunk}$ presented the highest values in all species/spacings, while biomass distribution in other parts of trees varied among species (Fig. 6). According to these results, the biomass distribution was independent of the spacing and was related to the tree morphology of each species. In general, a high percentage of biomass is concentrated in stems and branches in trees growing in SRC systems (Djomo *et al*. 2015), as occurred in all species except for *D. panamensis*. *C. alliodora* and *G. arborea* tended to produce a higher percentage of biomass$_{trunk}$ and biomass$_{branch}$. Figure 6 shows that *D. panamensis* produced high percentages of biomass$_{trunk}$ and biomass$_{leaves}$, and *T. grandis* produced high percentages of biomass$_{trunk}$ and biomass$_{bark}$ (Fig. 6).

The architecture of the trees growing in SRC has been recently studied, and it is mentioned that the leaf area is the most important part of biomass production (Schwerz *et al*. 2020; Tenorio *et al*. 2018). But *C. alliodora* and *G. arborea* disagreed with these results; the highest biomass$_{trunk}$ and biomass$_{branch}$ were found, and the lowest values were found in biomass$_{leaves}$ (Figs. 6a and 6c). Meanwhile *D. panamensis* and *T. grandis* exhibited a higher percentage of biomass$_{leaves}$ (Figs. 6b and 6d). In the juvenile stage, the tree develops roots and leaves to capture the nutrients from the environment (soil and air) necessary to grow and survive (Guo *et al*. 2015; Mensah *et al*. 2016). So, it is to be expected that the biomass distribution in *D. panamensis* and *T. grandis* was different than in the other two species,

where high biomass was found in leaves at 34 months old. In fact, these two species presented the highest percentages and lower mortality rates (Fig. 2), which is an indicator that the tree needs significant leaf area to be able to keep growing in SRC systems.

Comparing biomass production with other studies, only *G. arborea* and *D. panamensis* reported biomass production in SRC systems. At 34 months old, *G. arborea* produced 44 to 66 tons/ha in the present study (Table 1), and these values are consistent with the values reported from 24-month-old plantations (Tenorio *et al*. 2019a,b). Three different locations in Costa Rica reported 31.5 tons/ha to 63.0 tons/ha and two clones at the same spacing reported 50 to 70 tons/ha. While SRC of *D. panamensis* reported a production of 6.8 and 24.0 tons/ha in 24-month-old plantations (Gaitan-Alvarez *et al*. 2020), these values were consistent with values obtained in the present study (Table 1).

Biomass production was highly variable among the different species in the tropical region of Latin America growing in SRC and at different spacings; it could range from 10.00 to 50 tons/ha (Moya *et al*. 2019). Then the biomass production obtained in four tropical species in Costa Rica argued with those values. An important aspect to highlight about biomass production in four tropical species is that these values can be reached in the USA or EU on older plantations (Dickmann 2006). Besides, the establishing od SCR systems of each of the species in monoculture, could facilitate harvest and transport activities and could be uniformizer combustion operation for energy production.

Another important aspect to mention is that the tree's biomass above the soil level (trunk, bark, branches, and leaves) was measured in the present study, from of these biomasses, trunk, bark, and branches must be collected during the harvesting using an efficient utilization system. In addition to this, it is advisable that leaves must be left since this part of the tree plays an important role in the sustainability of the soil (Schwerz *et al*. 2020).

Physical, Energetic, and Chemical Properties

The statistical differences found in SG, density, and MC for the different parts of the tree (Table 2) are basically attributed to SG variations in each species. This physical parameter is an intrinsic property of each species, and several studies (Ogle *et al*. 2014; Pati *et al*. 2022) mentioned that this property determines the survival, mechanical stability of the tree, and tolerance to drought, among many other biological, physiological, ecological, and evolutionary functions of the species. However, the growth rate is negatively associated with SG (Muller-Landau 2004). As a result, species tested with a lower diameter (*D. panamensis* and *T. grandis*) presented higher SG values. On the contrary, the species with the highest growth rate, *C. alliodora* and *G. arborea,* presented lower SG (Table 2). In general, considering the SG parameter in wood produced in plantations for sawlog production and its application to biomass produced in SCR systems, *D. panamensis* and *T. grandis* are classified as very heavy and heavy wood species, respectively (Moya *et al*. 2019), while *C. alliodora* and *G. arborea* are classified as moderately light woods (Moya *et al*. 2019).

It was mentioned that SG is related to other biomass parameters, such as MC and density; MC is negatively correlated with SG, while for density, the trend is not clear (Muller-Landau 2004). However, these two parameters have an important influence on biomass utilization. Species with high MC values need more energy during drying, which decreases the amount of energy they supply (Rodrigues *et al*. 2021). Thus, *G. arborea* and *T. grandis*, due to high MC, present unfavorable MC conditions (Table 2), and on the contrary, *C. alliodora* and *D. panamensis* present more favorable moisture conditions with

low MC values (Table 2). While the density parameter has implications during the transport of biomass, species with high density present greater weight in less volume, so species such as *D. panamensis*, *G. arborea,* and *T. grandis* are of high weight in transport, while *C. alliodora* does not present this condition. In addition, this last species has a low MC, which makes it more favorable in relation to the other species.

In relation to the spacing, the physical, energy, and chemical properties presented low differences between the spacings at 34 months (Tables 2 and 3). Some differences were observed in SG, density, and MC_{trunk} of *C. alliodora*, *D. panamensis*, and G. *arborea* (Table 2). Firstly, there was a tendency to decrease the SG with increasing spacing, from S1 to S4. This result agreed with other studies of these species (Tenorio *et al*. 2016, 2018; Gaitan-Alvarez *et al*. 2020), where SG decreased with spacing.

Regarding the energy properties, some differences were observed between species. For example, low values of ash content and differences between C and H content were observed in G. *arborea*, but in other species, they were not observed. According to this result, the energy properties were found to be uniform among species and between spacings. For example, there were no differences at the level of branches in *D. panamensis* and *T. grandis*, in the H content of *D. panamensis* and *G. arborea,* in the C/H ratio of the trunk of all species, or in the branches of *D. panamensis* (Table 3). Then, according to these results, it is evident that there were few variables that presented differences between species and spacing, which indicates that the biomass of the four species is relatively uniform, a situation that is common when biomass comes from woody species (Boggia *et al*. 2022).

CONCLUSIONS

1. The growth parameters of trees (mortality, diameter, height, and basal area) and characteristics and production of biomass for the four species tested showed differences between species. There were three species (*G. arborea*, *C. alliodora*, and *T. grandis*) that presented important potential for use in SRC systems. *G. arborea* was the species with the highest production but a high mortality rate; however, this is a problem due to inappropriate management and initial establishment. On the other hand, narrow spacings, such as 0.5x1.0 m or 1.0x1.0 m, produced the highest biomass production. However, the trees produced were smaller in diameter and height at 34 months old.

2. The evaluation of the physical properties of biomass (specify gravity, density, and moisture content) and parameters related to logging, transport, drying, processing, and energy densification are related to the intrinsic properties of each species, so the spacing effect presented little effect on physical properties. In addition, the few variations in energy properties per species and spacing presented an important advantage from the point of view of its energy use and performance in industrial processes. These results suggested that four species at different spacings were uniform in energy and chemical properties.

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