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Production and Regression Models for Biomass and Carbon Captured in *Gmelina arborea* Roxb. Trees in Short Rotation Coppice Plantations in Costa Rica

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Abstract: Mortality, diameter at 30 cm over ground level, height, biomass production, and carbon capture (CC) for different tree components (trunk, bark, branches, and leaves) in two locations in Costa Rica, during their first three years and with three plantation spacings (1.0 × 0.5 m, 1.0 × 1.0 m, and 1.0 × 2.0 m) were obtained for *Gmelina arborea* Roxb. trees growing in short rotation coppice systems (SRC). In addition, regression models were developed to predict biomass production and CC using location, age, spacing, and their interactions. Biomass production was measured by weight of trees without considering dendrometric variables. Results showed that mortality was lower than 15% for one location, with probable high fertility, and almost 85% for the other location. Diameter and height of trees increased with plantation age in both locations. The highest biomass production and CC were observed in the spacings of 1.0 × 0.5 m^2 and 1.0 × 1.0 m^2, with 20 Mg/ha/year and 8 Mg/ha/year, respectively. The models to predict biomass production in trunk with bark, branches, leaves, total biomass without leaves, and CC in trunk, branch, and total biomass were developed using this equation: Y = β_1 + β_2 (location × age) + β_3 (age) + β_4 (spacing). The R^2 values varied from 0.66 to 0.84, with error from 0.88 to 10.75 and indicators of goodness of fit from 60 to 83%.

Keywords: fast growth; tropical species; plantation density; carbon storage

1. Introduction

During the coming decades, fossil fuels will continue to be the main source of energy, while renewable energy will triple between 2008 and 2035 [1–3]. In this context, biomass is considered a renewable material and is considered an important source of energy [4,5]. Biomass can be produced by short rotation coppice (SRC) systems [6]. These plantations are of major interest, as they use short return periods compared to traditional plantations for wood production [6]. In SRC systems, fast-growing tree species are grown under intensive agricultural practices (weed control, fertilizing, and irrigation) in order to achieve high biomass yields [2,7]. Furthermore, the use of SRCs positively contributes to solving the problem of carbon dioxide (CO_2) emissions, as trees capture C and store it temporarily, mainly in the trunk [8–10].

Although the efforts to establish SRCs for energy purposes in Latin America have been slow [11,12], they are gaining importance in countries like Chile [13,14], Brazil [15,16], and in some countries in Central America, as is the case of Costa Rica [17–19]. Research conducted on this kind of plantation in tropical regions has been characterized by a limited number of species, of which some varieties of eucalyptus [15,16,20] and *Gmelina arborea* Roxb. stand out [18].

G. arborea plantations in the Mesoamerican region (Mexico to Colombia), have presented a good production of sawn timber [21,22]. More recently, *G. arborea* in SRC systems was introduced for biomass production [18,23]. Tenorio et al. [18,23] reported the first results from this species under SRC conditions, where, during the first two years of growth, the densities of 0.5 × 1.0 m (20,000 trees per hectare) and 1.0 × 1.0 m (10,000 trees per hectare) presented better productivity (Mg/ha) and biomass characteristics compared to densities of 2.0 × 1.0 m (5000 trees/hectare). The mentioned authors pointed out that site is the determining factor in biomass production, and that the characteristics of trees growing in SRC systems vary considerably from one year to the next.

On the other hand, the methods for biomass estimation are important for quantifying the energy potential or captured carbon (CC) of a particular forest stand [24–26]. Biomass allometric equations are one of the major tools. These are mathematical relationships that transform variables per tree or per stand (hectare) into biomass estimations [24,27]. The majority of the estimations of biomass are realized by means of allometric models based on the diameter and total height of the tree, and sometimes some measurements of the tree form are also used [28]. Allometric models have been developed to be used in species in SRC systems cultivated in Africa [29], Europe [30,31], and South America [32].

However, the models for biomass estimation for SRC based on variables such as site, age, and spacing are limited, despite their relevance for performing simulations for different sites or growing conditions [33,34]. For example, Fang et al. [35] developed regression models to estimate biomass for the different parts of the tree in poplar growing in China, using variables such as stand age and plantation density. Langholtz et al. [36] established a biomass estimation model of the form $Y\ (Mg\ ha^{-1}) = e^{[b + c + \ln(t) - d(t)]}$ for a 3–5 year old SRC of *Eucalyptus amplifolia* in Florida, USA, where t is the age in years, while Guo et al. [37] developed a complex model for the estimation of biomass in hybrid poplar for a 6 year old SRC to predict productivity in different sites in Europe.

Considering this situation, the present study developed a determination of biomass and captured carbon in *G. arborea* trees under SRC conditions in two locations and three different spacings in Costa Rica, considering weight per trees and not dendrometric variables, for example, diameter or height. Additionally, regression models for the estimation of biomass (Mg/ha) and amount of CC for an area unit were estimated, considering biomass in the trunk with bark, branches, leaves, and total biomass without leaves and carbon in the trunk without bark, branches and total, using as dependent variables the location (two locations), age (three years), and spacing (three spacings). The development of these models will allow estimation of the biomass production and the carbon capture capacity of this species in different management conditions across two locations, ages, and spacings, in order to carry out a financial evaluation in this type of plantation or the feasibility for CO_2 capture.

2. Methodology

2.1. Conditions and Sampling of the Plantation

SRCs of 3 year old *G. arborea* located in two different locations in Costa Rica with different conditions of fertility, precipitation, weed control, and fertilization were analyzed. The location, climatic, geographic, establishment, and management conditions of each location can be seen in Table 1. Three spacing treatments were set: 1.0 × 0.5 m, 1.0 × 1.0 m, and 1.0 × 2.0 m [18,23]. In each location, three different experimental units or plots of each spacing were established, covering an effective area of 49 × 49 individuals. Location 1 (Location-1) had an area of 100 m^2 per treatment and Location 2 (Location-2) had 400 m^2 per treatment. Therefore, 18 experimental units were sampled (2 locations × 3 plantation densities × 3 experimental units = 18 experimental units).

Table 1. Climatic, planting, and management conditions of short-rotation *Gmelina arborea* Roxb. plantations in two different location in Costa Rica.

Location	Elevation and Life Zone	Climatic Conditions and Soil Type	Planting and Management Features
Location-1	700 masl, premontane wet forest, premontane belt	Average annual precipitation from 1500 to 2000 mm Average annual temperature 22–24 °C Ultisol (Humults)	Pre planting: soil plowing and raking. Manual initial weed control. Planting: seedlings cultivated in Jiffy forestry pellet and fertilization. Management: manual weed control with herbicides every three months until crowns close.
Location-2	100 masl, tropical moist forest, basal belt	Average annual precipitation from 2000 to 3000 mm Average annual temperature 22–24°C Inceptisol (Udepts)	Pre planting: soil plowing and raking. Planting: seedlings cultivated in Jiffy forestry pellet, no fertilization. Management: no management.

Five trees were sampled in each experimental unit per year (3 years × 2 locations × 3 spacings × 3 blocks × 5 trees = 270 trees). The trees to be sampled had a diameter approximate equal to the average diameter of the plantation, which was obtained previously by measuring the diameters of the temporary plots of 25 m^2 in area. Diameter at 30 cm above ground level and height were measured in each sampled tree (Table 2). The trees were then cut at ground level, and branches and leaves were separated from the trunk. In addition, the mortality per year in each plantation treatment was determined by counting the quantity of trees present in each experimental unit, and it was reported in relation to initial total trees.

Table 2. Diameter at 30 cm over ground (mm) obtained in temporary plot of short-rotation *Gmelina arborea* plantations in two different location in Costa Rica.

Year	1.0 × 2.0 m		1.0 × 1.0 m		1.0 × 0.5 m	
	Location-1	Location-2	Location-1	Location-2	Location-1	Location-2
1	2.0	30.8	2.7	37.4	3.7	41.0
2	7.0	81.2	8.2	73.2	9.1	66.3
3	13.9	131.7	13.5	113.0	12.4	80.2

2.2. Determination of Biomass Productivity

Each part (leaves, branches, and trunks) of the sampled trees was weighed independently, employing a 0.01 kg scale. Following this, 10 cm long cross sections were extracted from three different heights: the base of the tree, at total height, and at 50% total height. These samples were used for determination of the moisture content of trunk and bark. All this material was packed in plastic bags to retain moisture. The remaining trunk material was ground to obtain chips no greater than 3 mm long.

Moisture content (MC) of biomass was calculated as a function of the MC in green condition utilized in biomass studies. The leaves and branches in green condition were weighed, and then placed into an oven at 50 °C for 76 h and reweighed after that period. The MC was calculated using Equation (1). Meanwhile, to calculate the MC of the bark and the 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. Weights before and after drying were determined and used to find the MC with the percent ratio, as described above.

When calculating the trunk's MC and the weight of the different parts of tree (trunk, leaves, bark, and branch) or total weight in green condition, biomass oven-dried condition (0% MC) of the those parts of individual trees were determined (Equation (2)). The oven-dried condition biomass values obtained were then projected to estimate biomass per hectare (Equation (3)) for each type of plantation spacing. Oven-dried biomass per individual tree was multiplied per plantation density at different ages (Equation (3)).

$$Moisture\ content(\%) = \frac{(\text{weight before drying } - \text{weight after drying})}{\text{weight before drying}} \times 100 \quad (1)$$

$$Biomass_{tree\ or\ part\ of\ trees} = \text{biomass in green condition} \times \left(1 - \frac{moisture\ content}{100}\right) \quad (2)$$

$$Biomass\left(\frac{Mg}{ha}\right) = Biomass_{tree\ or\ part\ of\ trees}\left(\frac{\text{Mg}}{\text{tree}}\right) \times \text{plantation density}\left(\frac{\text{tree}}{\text{ha}}\right) \quad (3)$$

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

2.3. Calculation of Captured Carbon

The chipped material of the trunk (wood and bark) of the five trees of each experimental unit was combined into one sample. This sample was air dried to 12% MC. Next, 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 five trees sampled. The percentage of carbon concentration in the laboratory was determined using an Elementar Analysensysteme, Vario Macro Cube model.

The weight of the CC per tree was calculated using carbon concentrations in the laboratory, multiplied by the dry weight of both the trunk and the branches. These values obtained were projected to estimate CC per hectare for each type of plantation spacing (1.0 × 0.5 m, 1.0 × 1.0 m, and 1.0 × 2.0 m), considering the mortality of each plantation treatment per year.

2.4. Regression Models for Biomass Production and CC

Regression models were used to determine biomass production prediction equations (in trunk with bark, branches, leaves, and total without leaves) and CC (in trunk, branches, and total) per hectare. For the development of these regression models, location, age, spacing, and interactions location × age, location × spacing, and age × spacing were used as independent variables. Linear regression models were tested (Equation (4)), and the models with interaction of location × age, age, and spacing presented the best results, so they were selected as the final models. For both models, each variable (location and age) was independent from the others, and any colinearity was presented between them. For this selection, the parameters considered were the determination coefficient (R^2), the adjusted determination coefficient (R^2-adjusted), error, the F-value, and the residuals.

Due to the high variability of data from location-2 in Year 3 as a consequence of high mortality (Table 1), these data were eliminated at the time of performing the regression models in order to achieve the best possible adjustment.

$$\text{Y (Mg/ha)} = -k_0 + k_1 \times \beta_1 + k_2 \times \beta_2 + k_3 \times \beta_3 + k_4 \times \beta_4 + k_5 \times \beta_5 + k_6 \times \beta_6 + \varepsilon \quad (4)$$

where Y represents biomass production (Mg/ha) and carbon content (Mg/ha) for different parts of the trees, k_i represents a coefficient determined by statistical model, β_1 is a fixed effect of age, β_2 is a fixed effect of spacing, β_3 is a fixed random location, β_4 is the interaction of age and spacing, β_5 is the interaction of age and location, β_6 is the interaction of spacing and location, and ε is the error of the model.

2.5. Statistical Analysis

Compliance of the variables with the theories of normal distribution and homogeneity of variance, as well as the presence of outliers, were verified for diameter, tree height, and biomass production in trunk, branch, leaves, and total biomass without leaves per tree and per hectare. An analysis of variance using the SAS software (SAS Institute Inc., Cary, NC, USA) was applied to verify the effects of the location, spacing, age, and their interactions (Equation (3)). Although all interactions were considered, the regression analysis presented the significant interactions.

$$Yijk = \mu + Li + Sj + A_k + Li \times Sj + Li \times A_k + Sj \times A_k + Li \times Sj \times A_k \quad (5)$$

where μ is the variable mean, *Li* is the location effect (fixed effect), *Sj* is the spacing effect (fixed effect), A_k is the age effect, $Li \times Sj$ is the interaction between location–spacing, $Li \times A_k$ is the interaction location–age, $Sj \times A_k$ is the interaction between spacing–age, and $Li \times Sj \times A_k$ is location–site–age.

3. Results

The mortality percentages obtained for Location-1 in Year 2 and in Year 3 were lower than those obtained in each plot of Location-2; for Year 3, the values for Location-1 ranged between 3% and 21%, while in Location-2, the percentages of mortality were from 62% to 83% (Table 3). In both, the percentages of mortality were higher in Year 3 than in Year 2 in Plot 2 of spacing 1.0 × 2.0 mm, Plots 1 and 3 of spacing 1.0 × 1.0 m, and all plots of spacing 1.0 × 0.5 m for Location-1, and the mortality was higher in Year 3 than Year 3 in Location-2 (Table 3).

Table 3. Remaining trees and mortality in short rotation *Gmelina arborea* plantations in two different locations in Costa Rica.

Location	Spacing	Plot	Stand Density at Different Ages			Mortality (%) [1]	
			1 Year Old	2 Year Old	3 Year Old	2 Year Old	3 Year Old
Location-1	1.0 × 2.0 m	1	5000	4850	4812	5.0	3.8
		2	5000	4850	3937	5.0	21.3
		3	5000	4850	4750	5.0	5.0
	1.0 × 1.0 m	1	10,000	9585	8937	6.2	10.6
		2	10,000	9585	7875	6.2	21.3
		3	10,000	9585	9500	6.2	5.0
	1.0 × 0.5 m	1	20,000	19,156	18,625	4.2	6.9
		2	20,000	19,156	18,375	4.2	8.1
		3	20,000	19,156	17,937	4.2	10.3
Location-2	1.0 × 2.0 m	1	5000	3350	1700	33.0	66.0
		2	5000	3350	1900	33.0	62.0
		3	5000	3350	1500	33.0	70.0
	1.0 × 1.0 m	1	10,000	5916	2100	40.8	79.0
		2	10,000	5916	1700	40.8	83.0
		3	10,000	5916	1700	40.8	83.0
	1.0 × 0.5 m	1	20,000	12,233	4400	38.8	78.0
		2	20,000	12,233	4400	38.8	78.0
		3	20,000	12,233	4600	38.8	77.0

[1] Mortality is the relationship between trees present in each year and initial total trees (initial density) expressed perceptually as stand density means in quantity of trees per hectare.

3.1. Morphological Development (Diameter and Height)

The ANOVA showed that the location, spacing, and tree age effects and their interactions were statistically significant (p-value < 0.01) for the height and diameter of the trees (Table 4). Regarding height, growth with increasing age was observed for the two locations and the three spacings, except for the trees of Location-1 and 1.0 × 2.0 m, which showed a decrease in the height increment from Year 2 to Year 3 (Figure 1a). Moreover, height averages were greater in the trees of Location-2 during Years 2 and 3, and height values were very similar in this location among trees of spacings 1.0 × 2.0 m and 1.0 × 1.0 m (Figure 1a).

Table 4. F-values from ANOVA for diameter, height and biomass in short rotation energy plantations of *Gmelina arborea* in two different locations of Costa Rica.

Parameters		Location	Spacing	Tree Age	Location × Spacing	Location × Age	Spacing × Age	Location × Spacing × Age
DF		1	2	2	2	2	4	4
Diameter		211.3**	20.9**	543.1**	9.4**	30.5**	15.1**	14.1**
Height		304.5**	17.1**	935.0**	3.6**	116.9**	9.4**	24.5**
Tree level	Trunk	192.5**	15.0**	337.4**	13.6**	122.9**	18.7**	15.5**
	Bark	116.4**	19.3**	253.5**	6.7**	74.3**	13.7**	8.7**
	Branch	76.7**	28.2**	74.6**	6.2**	29.1**	12.9**	8.2**
	Leaves	33.7**	38.4**	24.8**	6.0**	12.1**	6.6**	6.2**
	Biomass without leaves	205.5**	22.6**	339.1**	14.2**	120.3**	21.0**	16.3**
Stand level	Trunk	7.0*	44.8**	100.1**	3.4NS	8.6**	5.8*	7.7*
	Bark	1.9NS	42.6**	80.4**	3.7NS	5.9*	5.7*	7.5**
	Branch	0.8NS	8.7**	3.6NS	1.3NS	5.6*	2.6NS	3.4NS
	Leaves	0.2NS	0.0NS	3.0NS	0.3NS	0.1NS	0.0NS	0.5NS
	Biomass without leaves	0.8NS	33.4**	62.1**	2.9NS	4.5*	4.5*	5.9*

Note: * means differences at 0.05; ** means differences at 0.01, and NS means not significant differences.

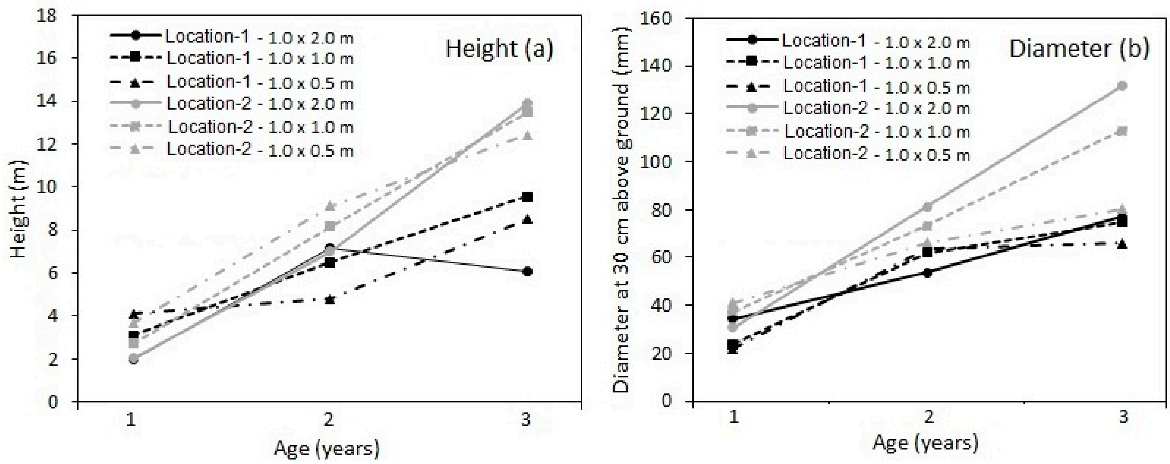

Figure 1. Height (**a**) and diameter (**b**) in short rotation energy plantations of *Gmelina arborea* in two different locations in Costa Rica.

With respect to diameter, as with height, an increase with age was observed (Figure 1b). The significant location effect on diameter (Table 4) shows that the trees in Location-2 presented the highest values of diameter in spacings 1.0 × 2.0 m and 1.0 × 1.0 m in Years 2 and 3 (Figure 1b), whereas the trees in spacing 1.0 × 0.5 m in Location-2 presented similar diameters as the trees in the three spacings in Location-1 for the three years of measurement.

3.2. Biomass Production

Biomass production was analyzed from two perspectives: biomass production per tree level and per stand level, or biomass per hectare. With regard to production per tree level, location, spacing, tree age, and their interactions were significant on biomass production in the different tree components (Table 4). Biomass production from the tree level (trunk, bark, branch, and leaves) increased through the years, especially in Location-2 from Year 2 to Year 3 for the spacings 1.0 × 2.0 m and 1.0 × 1.0 m (Figure 2). Other aspects to notice are: (i) the trees in spacing 1.0 × 0.5 m in Location-2 presented biomass production values similar to the trees in Location-1; (ii) the trees in spacing 1.0 × 2.0 m in

Location-2 presented higher biomass production values for each part of the tree, and (iii) in Location-1 the trees in spacing 1.0 × 1.0 m showed the highest values of biomass production in the trunk and total, while for biomass production of the bark, branches, and leaves, the trees in spacing 1.0 × 2.0 m had the highest values (Figure 2a,e).

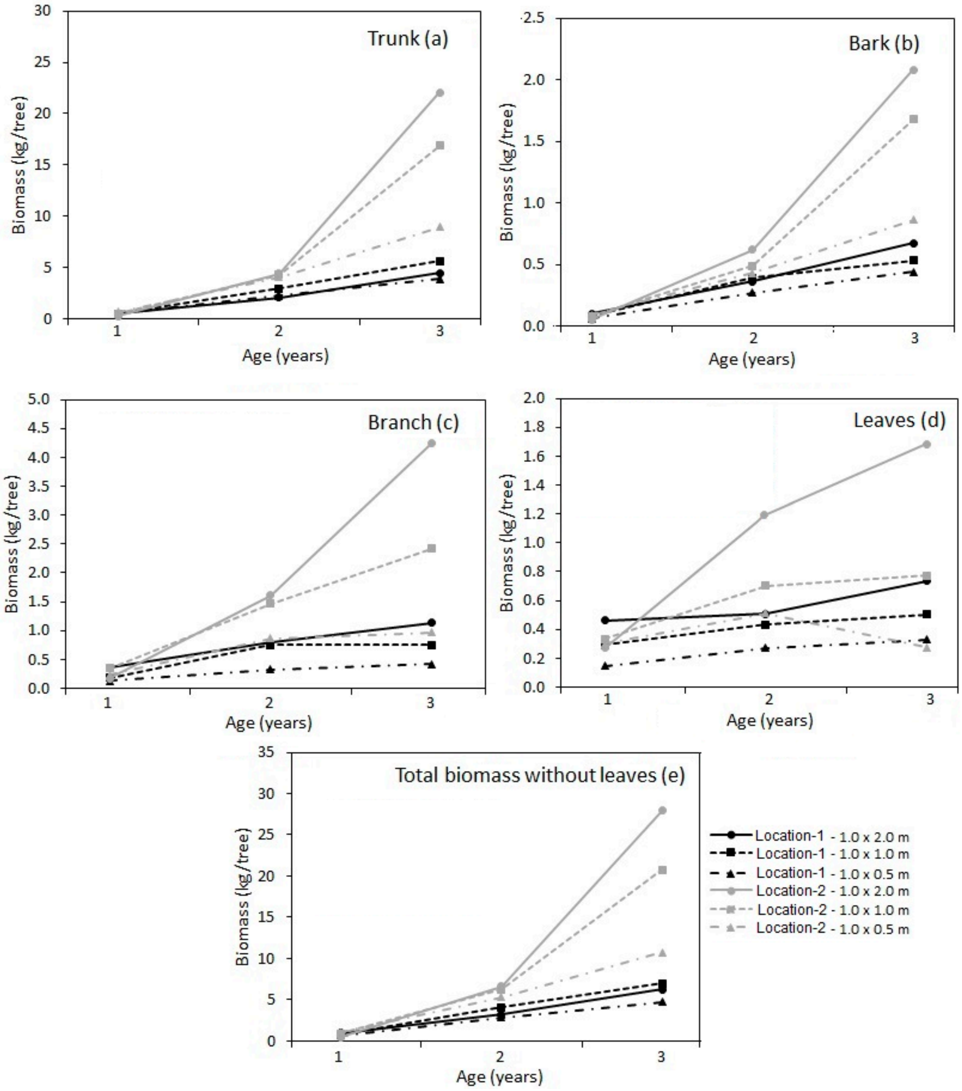

Figure 2. Biomass distribution in the trunk (**a**), in the bark (**b**), in the branch (**c**), leaves (**d**) and total biomass without leaves (**e**) per tree in short rotation of *Gmelina arborea* plantations in two different locations in Costa Rica.

As for biomass production per stand level, the effect of the location, spacing, and tree age and their interactions was not significant (Table 4). For example: (i) none of the variables mentioned was significant in biomass for leaves; (ii) the variable location was significant only in biomass for the trunk; (iii) the interaction location × spacing was not significant in biomass from any part of the tree; and (iv) the variable of tree age and the interactions spacing × age and location × spacing × age were not significant in biomass for the branches (Table 4).

Depending on the part of the tree, biomass varied significantly with spacing (Figure 3). For Location-1, during the three years of the evaluation, biomass in each part of the tree increased with increasing spacing. In Location-2, although this behaviour persisted for biomass of the trunk, bark, and total for spacings 1.0 × 2.0 m and 1.0 × 1.0 m, for spacing 1.0 × 0.5 m, biomass decreased from Year 2 to Year 3 for each one of the parts of the tree, particularly for branches and leaves (Figure 3).

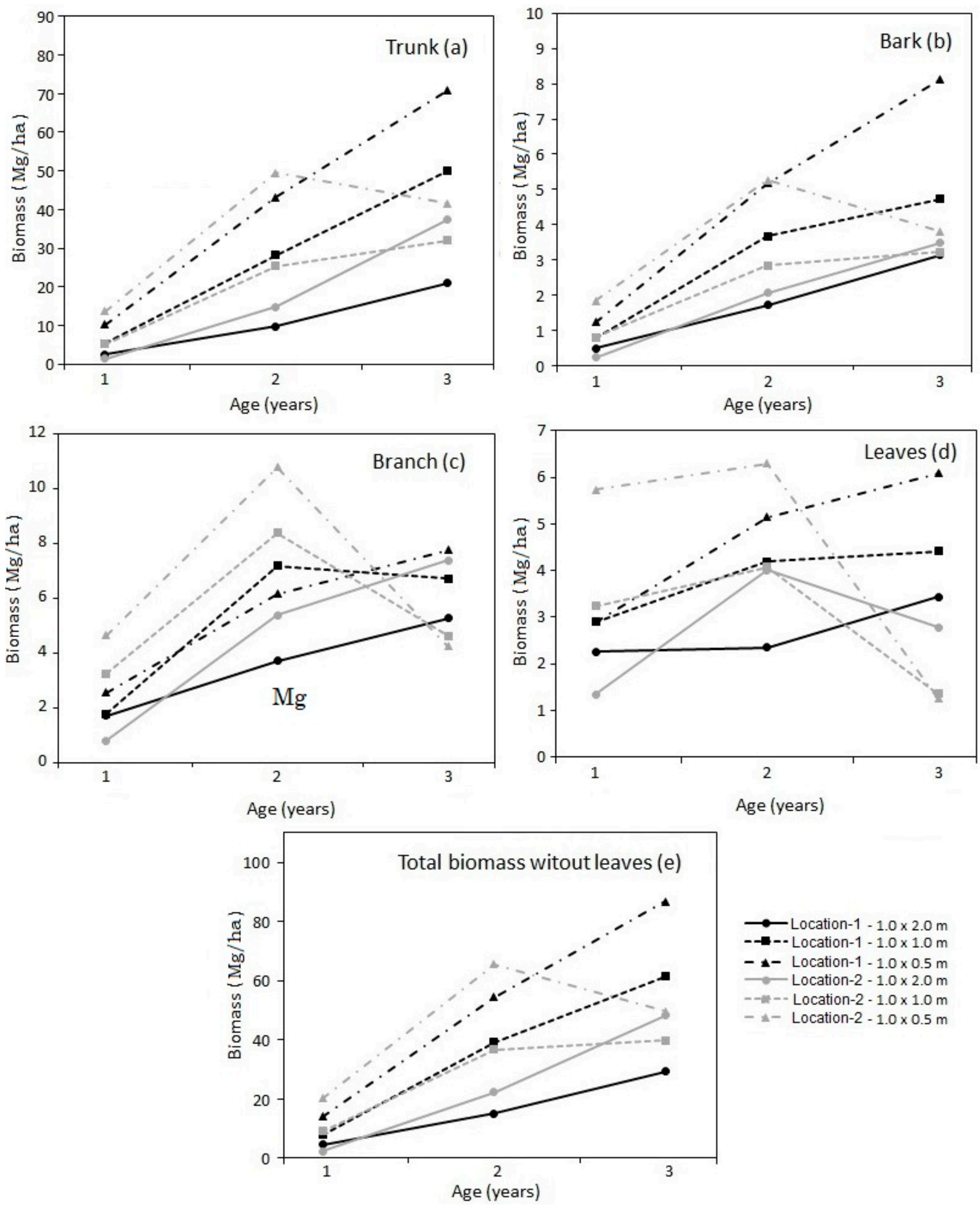

Figure 3. Biomass distribution in the trunk (**a**), in the bark (**b**), in the branch (**c**), in leaves (**d**) and total biomass without leaves (**e**) per hectare in short rotation *Gmelina arborea* plantations in two different location in Costa Rica.

3.3. Production of Captured Carbon

Mean concentrations of carbon of the trunk and of the branches varied between 45% and 48% (Table 5). Noticeably, both Location-1 and Location-2 presented differences among the mean carbon concentrations of the trunk and branches during the three years, with the exception of spacings 1.0 × 2.0 m in trunk and branches, 1.0 × 1.0 m in branches, and 1.0 × 0.5 m in the trunk in Location-1, and spacing 1.0 × 0.5 m in the trunk in Location-2 (Table 5). In the spacings presenting differences in the carbon percentage, the highest values were observed in Years 2 and 3 (Table 5).

Table 5. Carbon concentration determined in the laboratory per year in each part of the tree in short rotation *Gmelina arborea* plantations in two different locations in Costa Rica.

Location	Spacing	Component	Mean Carbon Concentration (% of Dry Weight) Per Year		
			1	2	3
Location-1	1.0 × 2.0 m	Trunk	45.6^{A} (0.30)	45.6^{A} (0.63)	46.2^{A} (0.19)
		Branch	46.6^{A} (0.22)	46.8^{A} (0.15)	47.0^{A} (0.68)
	1.0 × 1.0 m	Trunk	45.6^{A} (0.17)	45.6^{A} (0.21)	46.4^{B} (0.12)
		Branch	46.7^{A} (0.20)	46.9^{A} (0.25)	48.0^{A} (1.88)
	1.0 × 0.5m	Trunk	45.8^{A} (0.65)	45.9^{A} (0.71)	46.4^{A} (0.19)
		Branch	45.9^{A} (0.34)	47.2^{C} (0.14)	46.7^{B} (0.44)
Location-2	1.0 × 2.0 m	Trunk	45.3^{A} (0.31)	46.0^{AB} (0.60)	46.5^{B} (0.41)
		Branch	45.8^{A} (0.18)	46.3^{AB} (0.31)	46.5^{B} (0.38)
	1.0 × 1.0 m	Trunk	45.0^{A} (0.29)	45.5^{AB} (0.42)	46.4^{B} (0.34)
		Branch	45.6^{A} (0.52)	46.4^{B} (0.13)	46.8^{B} (0.24)
	1.0 × 0.5m	Trunk	45.4^{A} (0.47)	45.9^{A} (0.26)	46.0^{A} (0.39)
		Branch	46.2^{A} (0.38)	46.3^{AB} (0.22)	47.0^{B} (0.27)

Note: values in parentheses correspond to the standard deviation. Different letters indicate statistical differences at 95% between years.

According to the ANOVA, the CC in the trunk with bark per tree was significantly affected by the location, spacing, tree age, and the interactions location × age and spacing × age, while the evaluation per area unit (Mg/ha) showed that the CC was significantly affected only by the spacing, tree age, and interactions spacing × age and location × spacing × age. The analysis of CC in the branches per tree showed that it was affected by all the factors evaluated, while the results per area unit (Mg/ha) show that location and the interaction location × spacing did not affect CC significantly (Table 6). The evaluation of the total CC per tree and per Mg/ha showed no significant effect by the factors evaluated, except for tree age, the only variable that affected CC significantly.

Table 6. F-values from ANOVA of carbon in *Gmelina arborea* per tree, measured in kg tree^{-1}, and per area, measured in Mg ha^{-1}.

Source	Degraus of Freedom	Per Tree			Per Mg/ha		
		Trunk with Bark	Branch	Total/Tree	Trunk with Bark	Branch	Total/Tree
Location	1	34.0**	109.7**	2.0^{NS}	0.5^{NS}	0.3^{NS}	0.1^{NS}
Spacing	2	8.7**	8.0**	1.7^{NS}	8.4**	43.1**	0.0^{NS}
Tree age	2	26.0**	167.2**	701.0**	25.1**	86.4**	3.0*
Location × spacing	2	2.0^{NS}	6.2**	0.6^{NS}	2.3^{NS}	4.0^{NS}	0.3^{NS}
Location × age	2	10.1**	59.4**	0.6^{NS}	1.5^{NS}	6.3*	0.1^{NS}
Spacing × age	4	2.8*	8.9**	0.5^{NS}	6.6**	6.5**	0.0^{NS}
Location × spacing × age	4	1.5^{NS}	6.8**	1.5^{NS}	6.8**	9.5**	0.5^{NS}

Note: * means differences at 0.05; ** means differences at 0.01, and ^{NS} means not significant differences.

CC behaviour evaluation showed a pattern similar to that of biomass production, both per location and per spacing (Figures 2–4). This is because CC estimation is based on carbon concentrations and on biomass production in the trunk and the branches. Some specific changes to notice are: in Year 3, the highest value of total CC stored per tree was observed in spacing 1.0 × 2.0 m in Location-2, with 13.00 kg in the trunk and branches (Figure 4c), (ii) while per hectare, the highest value was found in spacing 1.0 × 0.5 m in Location-1, with 40.23 Mg (Figure 4f).

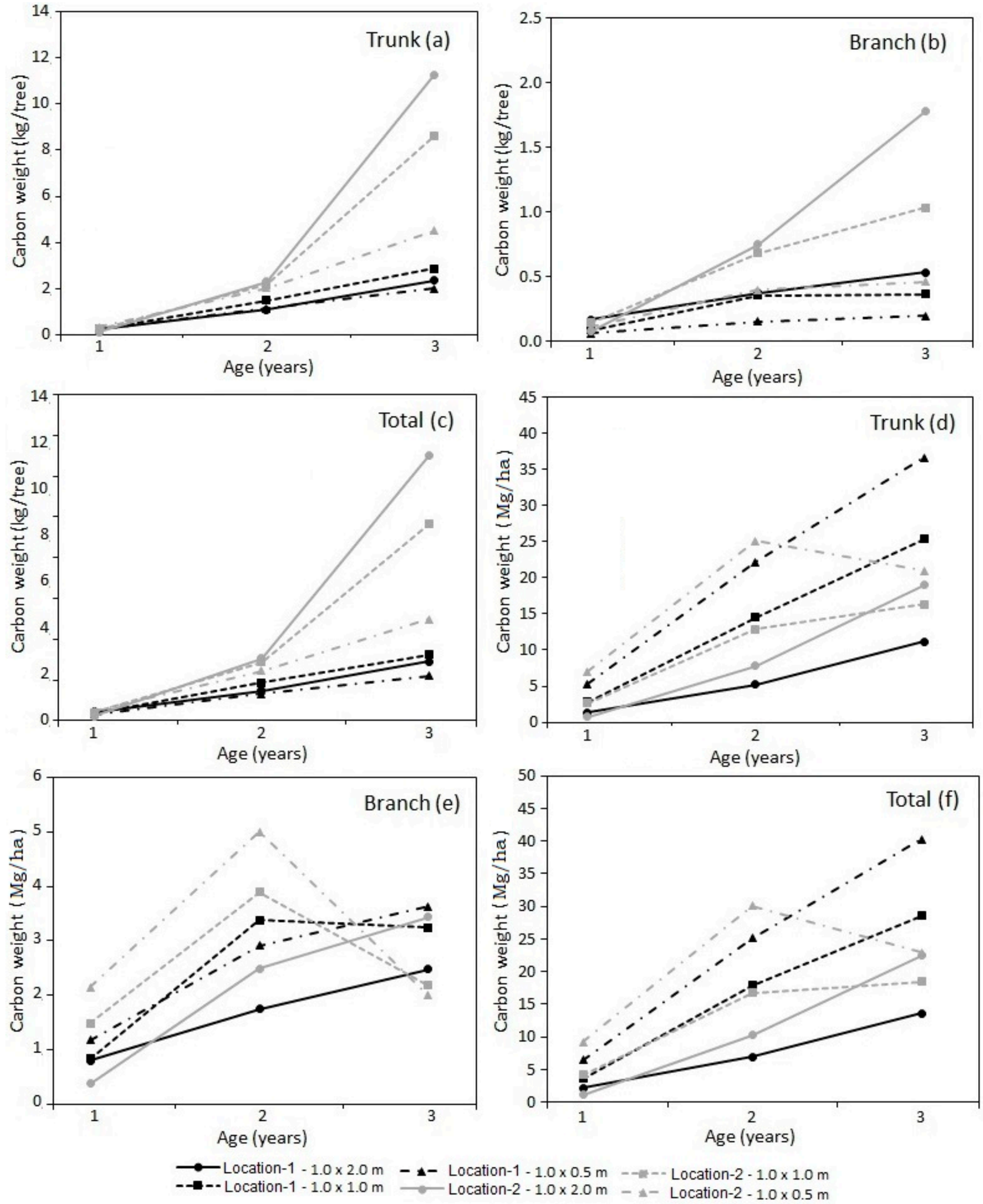

Figure 4. Carbon capture distribution per tree (**a**–**c**) and hectare (**d**–**f**) in short rotation *Gmelina arborea* plantations in two different locations in Costa Rica.

3.4. Biomass and Carbon Capture Production Prediction Model

Linear regression models were tested (Equation (4)), and showed that the model with interaction of location × age, age, and spacing presented biomass and CC per tree prediction (Table 7), but this behavior was not observed when these values were projected per area unit, due to mortality of trees in the plots. Although all interactions were considered in the model (Equation (4)), significant interactions were shown (Table 7). The fitting of the linear regression models to predict biomass production and CC per hectare of the trunk with bark, branch, and leaf biomass, total biomass without leaves, and CC in trunk, branches, and total CC are shown in Table 7. For all of them, the model was fitted using tree age, spacing, and the location × age interaction as independent variables. The final models developed by means of regression curves for the different tree components were significant ($p \leq 0.05$), with R^2 values between 0.63 and 0.84, the lowest being for leaf biomass and the highest for the trunk with bark, total biomass without leaves, trunk carbon, and total carbon (Table 7). The plots of predicted vs. observed biomass and CC indicated good fit and high predictive ability across the two locations and the three spacings used (Figure 5).

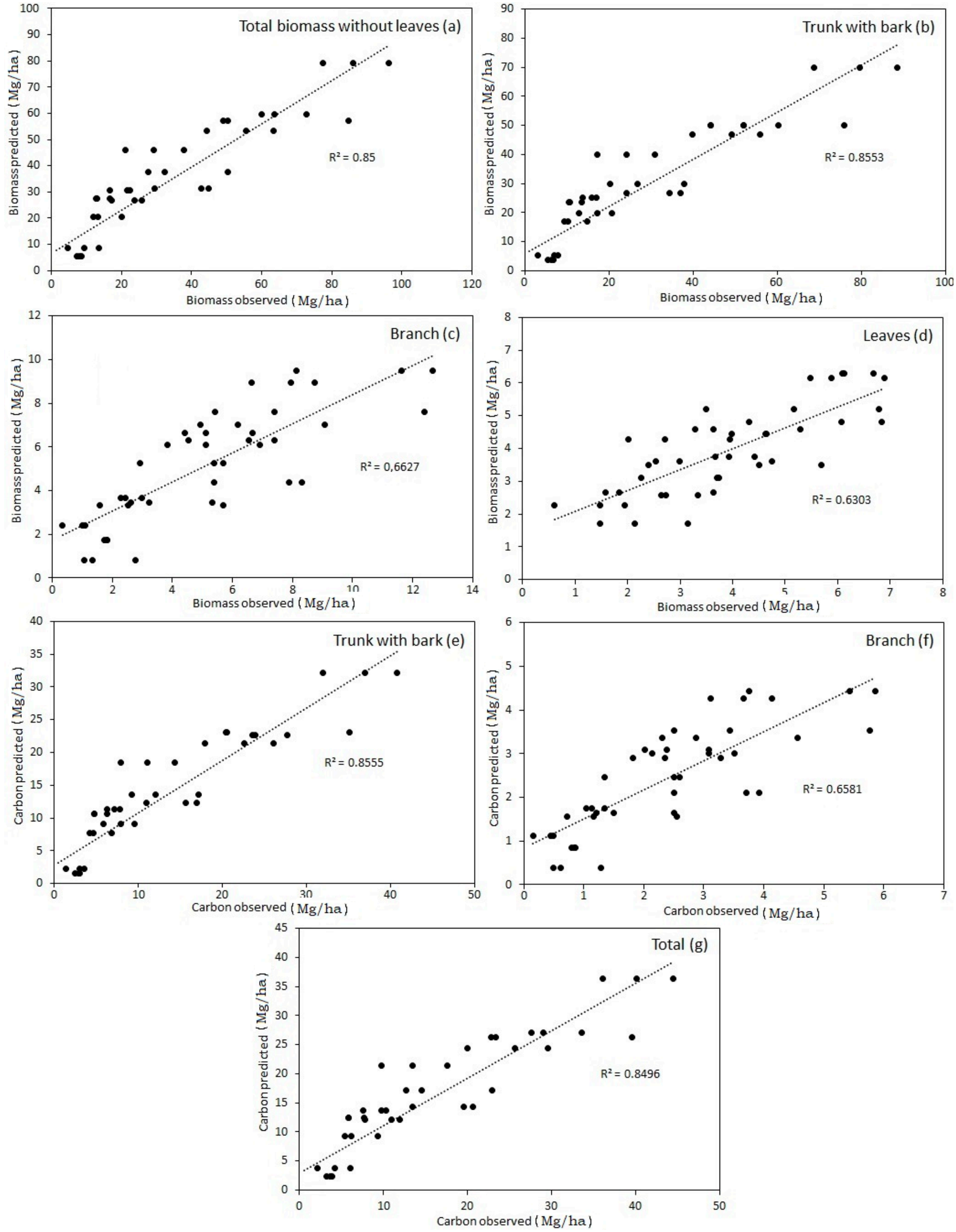

Figure 5. Observed vs. predicted for total biomass without leaves (**a**), for biomass trunk with bark (**b**), for biomass branch (**c**), for biomass in leaves (**d**), carbon in trunk with bark (**e**), carbon in branch (**f**), total carbon (**g**) in short rotation *Gmelina arborea* plantations in two different locations in Costa Rica.

Table 7. Results of regression for biomass and carbon predictive equations in Mg/ha in short rotation *Gmelina arborea* plantations in two different locations in Costa Rica.

Components	Models	R^2	R^2 Adjusted	Error	F-Value
Trunk with bark biomass	Y = −39.42** + 1.55**β_5 + 23.14**β_1 + 0.0020**β_2	0.84	0.82	9.79	70.0**
Branch biomass	Y = −2.79** + 1.60**β_5 + 2.64**β_1 + 0.00019**β_2	0.66	0.64	1.86	26.9**
Leaf biomass	Y = −0.07** + 0.54**β_5 + 0.94**β_1 + 0.00017**β_2	0.63	0.60	1.04	23.3**
Total biomass without leaves (trunk with bark and branches)	Y = −42.20** + 3.15**β_5 + 25.78**β_1 + 0.0022**β_2	0.84	0.83	10.76	70.8**
Trunk carbon	Y = −18.27** + 0.66**β_5 + 10.73**β_1 + 0.00091**β_2	0.84	0.82	4.54	69.7**
Branch carbon	Y = −1.32** + 0.72**β_5 + 1.26**β_1 + 0.00009**β_2	0.66	0.63	0.88	26.3**
Total carbon (trunk and branches)	Y = −19.60** + 1.39**β_5 + 11.98**β_1 + 0.0010**β_2	0.84	0.83	5.01	70.2**

Legend: β_1 is a fixed effect of age, β_2 is a fixed effect of spacing, and β_5 is interaction of age and location according to Equation (4). ** in coefficient of model and F-value mean that they are statistically significant at 99% of confidence level.

4. Discussion

4.1. Mortality and Morphological Development

Mortality is caused by many factors, above all, soil fertility, the degree of competition among the trees while growing [38], weed problems [39], diseases like rust infections, tree or seed selection during establishment [3], and underdeveloped tree roots, among a series of problems [40]. Location-1 presented lower mortality relative to Location-2 (Table 3), meaning that, most likely, Location-1 probably presented better fertility, fertilization was applied, and web control was carried out (Table 1); these conditions produce the best conditions for trees under high planting densities. Another important aspect to highlight regarding the values of mortality is that the increase occurred between Years 2 and 3 (Table 3). The explanation of this phenomenon is that in Year 3, an increased competition among the trees could lead to the death of unfit trees [40]. When comparing the values of mortality with those of other studies, the values for Location-1 were lower than those reported for populous (*Populus* sp.), willow (*Salix* sp.), and eucalyptus (*Eucalyptus* sp.), which are species also used in SRC systems in other regions of the world [39,41–43]. However, the mortality values in Location-2 were greater than the above species, reflecting again the low quality of Location-2 for the development of SRC systems with *G. arborea*.

With regard to tree morphology, an increase with age of the plantation (Figure 1) is a normal condition in the first years of trees growing in SRC systems; the tree tends to develop roots and foliage first, and then propitiate diameter and height development [39] until competition conditions appear [37]. At the age of 3 years, trees still tend to grow both in diameter (Figure 1a) and in height (Figure 1b), which seems to indicate that at this age, the trees have not reached still their maximum competition capability [44,45].

Despite the increase in diameter and height in trees of Location-2, Year 3, these seemed to continue their normal growth, since the high mortality observed in this location at the age of 2 and 3 years influenced the development of height and diameter of the trees at the age of 3 Years. According to Marsh and Burgers [46], stands with clearings, such as those of SRC systems due to mortality, present similar growth to stands established using lower planting density, which is a reason why growth was influenced by the low density of the plantation present in the trees of Location-2 during those years (Table 3).

A significant spacing effect is to be expected as regards tree height and diameter development (Figure 1, Table 4). This is because reduced spacings (such as 2.0 × 1.0 m) contribute to diameter and height growth, due to the development of a larger root system and foliage area [47,48] (Figure 1). Concerning the foliage area, Oswald and Aubrey [45] mention that the trees do not compete until the crowns intersect laterally, so that in plantations with wide spacings, there is no competition among the trees.

As regards the locations, tree development is governed by differences in fertility of various locations [49], as demonstrated in this study, where the location was significant in height and diameter development (Figure 1, Table 4). Location-1 likely presented more appropriate fertility and soil conditions for tree development in SRC systems.

Lastly, the effects of the interactions location × spacing, location × age, or spacing × age on height and diameter development (Table 4) indicate that *G. arborea* SRC systems are a combination of all these factors. This means that the morphological development of the tree in SRC with *G. arborea* depends on age, spacing, and location. However, as Dickmann [50] points out, one of the most influencing factors in the establishment of SRCs is location fertility, as shown in this work.

4.2. Production of Biomass and Captured Carbon

Based on the production of several species utilized in SRCs in tropical areas [20,51–54], an average biomass production can be established at 20 Mg/ha/year, that is, for a 3 year old plantation of *G. arborea* in an SRC system, like the one in this study, an average biomass production of 60 Mg/ha would be expected. Thus, considering the production of total biomass without leaves in the present study (Figure 3e), only two spacings (1.0 × 1.0 m and 1.0 × 0.5 m) in Location-1 at 3 years would exceed the optimum production of 60 Mg/ha for *G. arborea* in SRC systems. Therefore, Location-2 is inadequate for biomass production based on *G. arborea* in SRC systems with any of the spacings.

It was observed that there was a difference in effects of tree age, spacing, and location on biomass and CC when was applied at tree level and stand level (Table 4). This difference in biomass can be attributed to the high mortality presented in the different plots. The biomass and CC per individual tree was then affected by site, spacing, tree age, and their interactions, but in terms of the projection to area of biomass, these factors did not have the same effect, probably because of the high mortality presented.

Spacing and locations are the most influencing variables in biomass and CC production in the individual tree (Tables 4 and 6). Proe et al. [55] mentioned that close spacing, such as 1.0 × 0.5 m, reduced the size of individual trees, as occurred in the present study with *G. arborea* (Table 1), but there was an increased biomass productivity per area unit, and, consequently, in the amount of sequestered carbon, because there were many trees per area, as shown in the results obtained (Figures 3 and 4). Bergkvist and Ledin [56] also mentioned that maximum yields are generally achieved early in plantations with reduced spacing. However, such behavior may change with increasing age in *G arborea* SRC systems, for, as mentioned, under these growing conditions, wider spacing can exhibit the highest biomass yield in the long term [17,55,57,58]; as the rotation length increases, the early advantage of close spacing becomes lost [56].

The effect of location was shown clearly in SRC systems of *G. arborea* (Figure 3, Tables 3 and 4). Location conditions, such as effective depth, fertility, and edaphological features determined the degree of root and crown development, the morphological conditions of the tree, and, consequently, the biomass production [59,60].

SRC systems fix CO_2 from the atmosphere and store the fixed carbon above and below ground as biomass [61]. In this case, SRC 3 year old plantations would be storing over 15 Mg/ha of CC (Figure 4f), yielding 5 Mg/ha/year of CC on average. According to Tuskan and Walsh [62], location classification by CC productivity varies from 5.3 to 21 Mg/ha/year, with the lowest values obtained in locations with low productivity and the highest in locations with high CC productivity. Thus, after comparing Tuskan and Walsh's [62] results with the results found in the two locations in the present study (Figure 4f), the locations were catalogued as being of mean to high CC productivity.

4.3. Biomass and Carbon Capture Production Prediction Model

An important aspect to highlight of the models developed in the present study (Table 7) is that although they derive from trees/plantations growing under the climatic conditions of Costa Rica, the two locations evaluated showed important differences in growing conditions, with resulting variability in the morphological conditions of the trees (Figure 1a,b). Thus, it is possible to apply these models to other growing conditions for *G. arborea* plantations under SRC systems, for, in addition to representing the variability of the location, they can be applied to different spacings and tree ages to estimate biomass or CC.

On the other hand, one of the main advantages of the models provided in this paper is the possibility of assessing the economic profitability of SRC with *G. arborea*, because many variables are needed to calculate the cash flow throughout the rotation [63]. For example, Mitchell et al. [64] mentioned the following advantages of having biomass prediction models based on biomass estimation models of various species used in the United Kingdom, which can also be applied to models developed for *G. arborea*:

1. Most production costs, from establishment to delivery, can be calculated, as they are density-dependent, as is the case for plantation, localized fertilization, and weed control;
2. Plant material may account for up to 65% of establishment costs, and any advantage gained by high planting rates may be outweighed by increasing costs;
3. Stand harvesting costs constitute a major portion of total production costs (70%), and may have effects as important as those of stand establishment costs. The information provided in the model, particularly the average basal diameter, is also essential for deciding what type of harvesting to carry out.

5. Conclusions

The variation in the mortality values and biomass production and CC production observed in the SRC system of *G. arborea* clearly shows the suitability of some locations for utilization of these systems. For example, the fertility condition in Location-1 produced trees with reduced diameter and height but less mortality, yielding higher biomass production, and, consequently, higher carbon capture. In relation to spacing, 1.0 × 0.5 m and 1.0 × 1.0 m are recommended for SRC systems with *G. arborea*, as these presented higher biomass productivity and CC per area unit. Finally, the models developed to predict biomass in different part of tree and total carbon show a good correlation with location, spacing, tree age, and the interaction location × age. Thus, these models can help derive variables associated with other related activities, such as the costs involved in biomass and CC production.

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