Agroforest Syst (2023) 97:1435–1446
https://doi.org/10.1007/s10457-023-00868-6

Growth and carbon sequestration in biomass of *Cordia alliodora* in Andean agroforestry systems with coffee

Hernán J. Andrade · Milena A. Segura · Juan Carlos Suárez

Received: 31 October 2022 / Accepted: 16 June 2023 / Published online: 19 July 2023
© The Author(s) 2023

Abstract Timber production and carbon sequestration in trees in agroforestry systems (AFS) are key to productivity and climate change mitigation. There are no studies about dynamics of growth and carbon sequestration of *Cordia alliodora* during all plantation cycle. The objective of this study was to develop models for diametric growth and carbon sequestration in aboveground biomass of *C. alliodora* in AFS with coffee in Líbano, Tolima, Colombia. Nonlinear models of growth and carbon sequestration in aboveground biomass of *C. alliodora* in AFS with coffee were developed. A total of 90 trees, ranging in age from 1 to 19 years, were randomly selected in farms and measured (diameter at breast height -dbh- and total height -h) in AFS with a basal area of *C. alliodora* between 0.22 and 17.8 m^2/ha. Timber volume and aboveground biomass were estimated with allometric models, while carbon was estimated by multiplying aboveground biomass by 0.47. The best-fit models were selected according to the coefficient of determination (R^2), Akaike's information criterion (AIC), predicted residual error sum of squares (PRESS), biological logic and a residual analysis. The highest growth rate of this species was reached at 4–6 years for dbh and h (3.6 cm/year and 2.9 m/year, respectively) and at 20 years for timber and carbon (0.60 m^3/tree/year and 88.9 kg C/tree/year, respectively). In 20 years, a *C. alliodora* tree would store 1.1 Mg C and a AFS with 60 trees/ha would sequester between 260 Mg CO_2/ha in aboveground biomass. The results show that *C. alliodora* trees could be maintained in the field for more than 20 years, thus increasing the volume per individual and carbon sequestration for a longer time. This demonstrates the importance of this species mainly when timber production and carbon sequestration are priorities for its profitability.

H. J. Andrade (✉) · M. A. Segura
Grupo de Investigación Producción Ecoamigable de Cultivos Tropicales (PROECUT), Tolima, Colombia
e-mail: hjandrade@ut.edu.co

M. A. Segura
e-mail: masegura@ut.edu.co

H. J. Andrade
Facultad de Ingeniería Agronómica, Universidad del Tolima, Ibagué, Tolima, Colombia

M. A. Segura
Facultad de Ingeniería Forestal, Departamento de Ciencias Forestales, Universidad del Tolima, Ibagué, Tolima, Colombia

J. Suárez
Facultad de Ingeniería, Programa Ingeniería Agroecológica, Universidad de La Amazonía, Florencia, Caquetá, Colombia
e-mail: ju.suarez@udla.edu.co

J. Suárez
Centro de Investigaciones Amazónicas CIMAZ Macagual César Augusto Estrada González, Grupo de Investigaciones Agroecosistemas Y Conservación en Bosques Amazónicos-GAIA, Florencia, Caquetá, Colombia

Keywords Aboveground biomass · Current annual increment · Nonlinear models · Mean annual increment · Timber volume

Introduction

Agroforestry systems (AFS), commonly understood as the interactive association of woody species with agricultural production systems (Somarriba 1992; Nair 1993), are one of the key mechanisms for climate change mitigation given their potential for carbon (C) sequestration in biomass and soil (Albrecht and Kandji 2003; Beer et al. 2003; Montagnini and Nair 2004; Oelbermann et al. 2004; Swamy and Puri 2005; Andrade et al. 2008; Soto-Pinto et al. 2010). In addition, AFS represent a sustainable alternative that favors agricultural production, timber production and the provision of environmental services (Beer et al. 2003; Montagnini et al. 2004; Farfán 2014; Detlefsen and Somarriba 2015), which contributes to reducing pressure on natural forests, who are the largest terrestrial C sinks (Montagnini and Nair 2004). It is estimated that AFS can store between 12 and 228 Mg C/ha in biomass (Winjum et al. 1992; Schroeder 1994; Dixon 1995; Beer et al. 2003). Authors such as Montagnini and Nair (2004), consider that 400 million hectares of AFS have the potential to sequester one million tons of carbon by 2040.

In Central America, AFS cover between 27 and 50% of the agricultural area (Detlefsen and Somarriba 2012). One of the best traditional models is *Cordia alliodora* in association with coffee crops (Somarriba and Beer 1987), which is widely used in the 920 thousand hectares of coffee production systems in Colombia (Farfán 2012). One of the reasons for implementing this type of system is the production of commercial timber, which provides an alternative source of income to the producer in the medium and long term, allowing to mitigate income loss due to fluctuating coffee prices (Beer et al. 1998; Detlefsen and Somarriba 2015; Montagnini et al. 2015). Dzib (2003) states that revenues amount to U$6410 from timber sales (123 m^3/ha) of *C. alliodora* in AFS in Costa Rica.

C. alliodora, also known as coffee walnut or laurel, is a fast-growing forest species widely distributed in tropical America (Graves and McCarter 1990). In Colombia, it is distributed along the three mountain ranges and the Sierra Nevada de Santa Marta, from 0 to 1900 m altitude (Ospina et al. 2010). According to Holdridge (1967), this species is found in dry to humid tropical and humid and very humid premontane forests (Van der Poel 1988). Given its silvicultural characteristics, *C. alliodora* is an ideal component to be implemented in AFS (Valdivieso et al. 1998), since it produces high quality timber, is self-pruning, has a straight trunk free of branches for 50–60% of its height, a compact crown and is easy to regenerate naturally on cleared sites (Graves and McCarter 1990; Valdivieso et al. 1998).

The density of this species is continuously controlled to adjust to the shade needs of the agricultural species (Somarriba 1990). In coffee AFS, it is recommended to maintain densities between 100 and 180 trees/ha of *C. alliodora*, so as not to significantly affect crop productivity (Hernández et al. 1997; Ospina et al. 2010). Shading is considered to strengthen the resilience of coffee to climatic or economic disturbances that providing a microclimate suitable for coffee production and improve the productivity of the system (Ospina et al. 2010; Salgado 2012; Andrade et al. 2014a; Chait 2015; Rapidel et al. 2015). Some authors have found that crop production can be reduced by 22–50% under *C. alliodora* shade (Glover 1981; Detlefsen 1988; Farfán and Urrego 2004); however, other researchers have found an incremented productivity and C sequestration at 30–65% of shade, including legume trees (Beer et al. 1998; Staver et al. 2001; Righi et al. 2007; Andrade et al. 2014a).

Multiple studies on the growth in diameter, height and volume of *Cordia alliodora* have been conducted in Central America, mainly in Costa Rica (Rosero and Gewald 1979; Somarriba 1990; Hernández et al. 1997; Somarriba et al. 2001; Aristizábal et al. 2002; Farfán and Urrego 2004; Parresol and Devall 2013). Somarriba et al. (2001) suggest that the growth of the species is greater in AFS than in pure plantations. The objective of this study is to quantify the growth and carbon sequestration of individual trees of *C. alliodora* in AFS with coffee in the municipality of Líbano, Tolima, Colombia, by developing growth models. Additionally, the results will allow estimating the rate of growth and carbon sequestration at any age of this tree species, which can contribute to determine the tree density necessary to reach a certain level of carbon sequestration. This would allow

achieving climate change mitigation objectives and reaching carbon neutrality in coffee production. The novelty of this research is the tool to estimate the rates of growth and carbon sequestration of *C. alliodora* in AFS with coffee during all plantation cycle, so that management can be optimized to maximize wood production or carbon sequestration. Although the results are focused on the department of Tolima in Colombia, the findings could be used in a wider region: the Colombian coffee-growing zone, located in the Andean region of the country and others Andeans zones of the tropics.

Materials and methods

Study area

The study was carried out in the municipality of Líbano, located in the north of the department of Tolima (Colombia), in a very humid premontane forest (Holdridge 1967). The area is located at an altitude of 1565 m, 2235 mm of annual precipitation and an average temperature of 19.1 °C (Instituto de Hidrología, Meteorología y Estudios Ambientales [IDEAM] 2010). The soils in the study area are classified as Andisols, with good physical characteristics, high fertility, and slopes between 25 and 60%. Líbano contains a high variety of coffee production systems ranging from monoculture plantations and AFS with musaceae, rubber (*Hevea brasiliensis*) and *C. alliodora* (Andrade et al. 2014b).

Measurement of trees and estimation of volume, biomass and carbon

Eleven coffee farms with AFS with *C. alliodora* larger than 1 ha and with shades between 20 and 60%, a basal area between 0.22 and 17.8 m^2/ha and trees between 1 and 19 years old were selected. These systems are managed conventionally, except for shade regulation through thinning of *C. alliodora*, which is a self-pruning species. All AFS were established planting *C. alliodora* trees at the same time, having just one cohort. These producers were selected with the support of extension agents from the *Comité de Cafeteros del Líbano* (Tolima). Among these, 90 individuals of this species were randomly selected, which were typical and representative of those found in the system. The age of each individual tree was consulted with the coffee growers, whose answers were verified with those extension agents who have been familiar with these production systems since their establishment. The diameter of the trunk at breast height (dbh) was measured with a diametric tape (varying between 4.0 and 76.4 cm) and the total height (h) was estimated with a metric tape and clinometer (ranging from 2.4 to 36.3 m).

The total volume of timber with bark (overbark) was estimated using the model of Somarriba and Beer (1987) (Eq. 1) developed for *C. alliodora* trees less than 41 years old in cocoa, coffee, sugarcane and pasture plantations in Costa Rica.

$$V = e^{(-9.62+2.697*Ln(dbh))} \quad (1)$$

where V: total volume of timber with bark (m^3/tree), dbh: trunk diameter at breast height (cm), Ln: natural logarithm

Total aboveground biomass was estimated using the allometric model developed by Andrade et al. (2022) for individual *C. alliodora* trees with dbh between 3.9 and 102 cm in AFS with cocoa in Talamanca, Costa Rica (Eq. 2). Total aboveground carbon per tree was obtained using a carbon fraction of 0.47, which is recommended by Intergovernmental Panel on Climate Change [IPCC] (2006).

$$B = e^{(-2.70+2.49*Ln(dbh))} \quad (2)$$

where B: total aboveground biomass (kg/tree), dbh: trunk diameter at breast height (cm), Ln: natural logarithm.

Model development

Nine nonlinear regression models were tested to describe the growth in height, diameter, volume, aboveground biomass and carbon of *C. alliodora* trees as a function of age (Table 1). These models are some of the most commonly used for the development of growth curves (Sit and Poulin-Costello 1994; Adesuyi et al. 2020; Yang et al. 2021). In selecting the best fitting model, the three models with the highest coefficient of determination (R^2) value and the lowest Akaike Information Criterion (AIC) and predicted residual error sum of squares (PRESS) values were considered. The three best models per dependent variable were plotted in order to select the one with

Table 1 Generic non-linear models tested for the development of growth curves and biomass and carbon accumulation in *Cordia alliodora* growing in agroforestry systems with coffee in Líbano, Tolima, Colombia

Name	Generic equation
Quadratic	$y = ax^2 + bx + c$
Potential	$y = ax^b + c$
Exponential	$y = ae^{bx} + c$
von Bertalanffy	$y = a(1 - be^{-cx})$
Michaelis–Menten	$y = \frac{ax}{b+x}$
Logistic	$y = \frac{a}{1+be^{-cx}}$
Gompertz	$y = ae^{be^{cx}}$
Gaussian	$y = ae^{-\frac{(x-b)^2}{2c^2}}$
Hill	$y = d + \frac{(a-d)}{1+\left(\frac{x}{b}\right)^c}$

y Dependent variable (diameter at breast height -dbh-, total height -h-, total volume of timber with bark -V-, aboveground biomass -B or carbon in aboveground biomass -C); a, b, c and d: model parameters; x: age.

the best fit in terms of biological logic and finally, a residual analysis was carried out to corroborate this selection. All statistical analyses were performed in Past4 version 4.11 (Hammer et al. 2001).

Estimation of growth and carbon sequestration rates

Growth and carbon sequestration rates were estimated as the current annual increment (CAI) and mean annual increment (MAI), using Eqs. 3 and 4. A simulation was carried out to estimate the carbon sequestration rate in aboveground biomass at the agroforestry system level, using densities of 60 trees/ha of *C. alliodora*.

$$CAI = V_{t+1} - V_t \quad (3)$$

where CAI: current annual increment (cm/tree/year, m/tree/year, m^3/tree/year or kg tree/year), V_{t+1} and V_t: value of the variable in the year t + 1 and t (cm/tree, m/tree, $m.^3$/tree or kg tree/tree)

$$MAI = \frac{V_t}{A} \quad (4)$$

MAI: mean annual increment (cm/tree/year, m/tree/year, m^3/tree/year or kg/tree/year)

V_t: value of the variable in year t (cm/tree, m/tree, m^3/tree, or kg/tree).

A: age of the tree (years)

Results

Fitting of growth models

Three nonlinear growth models were developed for each of the variables under study: dbh, h, V, B and C (Table 2). These models presented the best statisticians (R^2, AIC and PRESS), and the first of them also presented the best biological logic, being the most recommended to study the growth of this species under the mentioned conditions (Hill model for dbh, B and C, logistic for h and exponential for V). These models were selected to develop the growth and carbon sequestration curves. Likewise, the selected models presented a random distribution of the residuals (Figs. 1 and 2), whose variance increases slightly in large trees (age > 13 years). The Hill model proved to be the best fit for three of the five growth variables analyzed (dbh, B and C); while the logistic and potential models were the best fit for total height and total timber volume, respectively (Table 2). In all cases, the R^2 was higher than 0.61, being the highest in dbh and h (0.77 and 0.75, respectively).

Growth of diameter and total height

During the ages analyzed (1 to 19 years), *C. alliodora* trees grew an average of 3.0 cm/year in dbh and 1.3 m/year in h (Fig. 1). The highest growth rate of the species was reached between 4 and 6 years of age (3.6 cm/year in dbh and 2.9 m/year in h). After 6 years, growth in these two variables had different trends, since while dbh continues to grow at a slower rate (up to 2.1 cm at 20 years), growth in height stagnated and stopped at 20 years (Fig. 2b). The dispersion of the data could indicate differences in growth between sampling sites, which were more noticeable at h than at dbh. The 20-year-old *C. alliodora* trees would reach, on average, 63.6 cm in dbh and 26.2 m in h.

Volumetric growth

C. alliodora trees grew, on average, at a rate of 0.30 m^3/tree/year during the measurement period, showing an increasing trend with age, i.e., the highest rate of

Table 2 Best fit growth models for growth and carbon sequestration of *Cordia alliodora* in agroforestry systems with coffee in Líbano, Tolima, Colombia

Model		R^2	AIC	PRESS
Diameter at breast height (dbh)				
Hill	$dbh = 4.567 + \frac{128.41}{1+\left(\frac{A}{22.69}\right)^{-1.274}}$	0.77	6169	6157
Quadratic	$dbh = 2.385 + 3.99A - 0.045A^2$	0.77	6176	6166
Gompertz	$dbh = 75.098e^{-2.471e^{-0.129A}}$	0.77	6202	6193
Total height (h)				
Logistic	$h = \frac{26.21}{1+15.27e^{-0.495A}}$	0.75	1443	1437
Hill	$h = 3.17 + \frac{23.797}{1+\left(\frac{A}{6.047}\right)^{-3.475}}$	0.75	1429	1420
Gompertz	$h = 26.94e^{-4.43e^{-0.336A}}$	0.75	1468	1462
Total volume of timber (V)				
Exponential	$V = -1.863 + 1.468e^{0.08A}$	0.61	129	123
Potential	$V = -0.159 + 0.025A^{1.793}$	0.61	129	122
Quadratic	$V = -0.20 + 0.043A + 0.012A^2$	0.61	129	123
Aboveground biomass (B)				
Hill	$B = -53.383 + \frac{17208.33}{1+\left(\frac{A}{56.2}\right)^{-1.83}}$	0.63	2.0×10^7	2.0×10^7
Potential	$B = -69.69 + 14.91A^{1.68}$	0.63	2.0×10^7	2.0×10^7
Quadratic	$B = -101.75 + 30.97A + 4.39A^2$	0.63	2.0×10^7	2.0×10^7
Carbon in aboveground biomass (C)				
Hill	$C = -26.692 + \frac{8604.39}{1+\left(\frac{A}{56.2}\right)^{-1.83}}$	0.63	5.1×10^6	4.6×10^6
Potential	$C = -34.845 + 7.457A^{1.68}$	0.63	5.1×10^6	4.6×10^6
Quadratic	$C = -50.873 + 15.49A + 2.17A^2$	0.63	5.1×10^6	4.6×10^6

R^2 Coefficient of determination; *AIC* Akaike information criterion; *PRESS* Predicted residual error sum of squares; *dbh* Diameter at breast height (cm); *A* Age (years); *h* Total height (m); *V* Total timber volume (m^3/tree); *B* Aboveground biomass (kg/tree); *C* Carbon in aboveground biomass (kg/tree).

accumulation of total timber volume was reached at 20 years of age (0.60 m^3/tree/year) (Fig. 2a). As with dbh, and as expected, a high variability in volume was found, mainly at high ages (Fig. 2a). Total aboveground biomass showed a similar trend to volume, with an average of 118.2 kg/tree/year and a maximum at 20 years of 177.8 kg/tree/year (Fig. 2b). Each 20-year-old *C. alliodora* tree would reach, on average, 5.4 m^3 of total timber volume and 2203.8 kg of total aboveground biomass (Fig. 2b).

Rate of carbon sequestration in biomass

C. alliodora trees sequestered, on average, 59.1 kg C/tree/year (217.0 kg CO_2/tree/year) in aboveground biomass up to 20 years of age. The maximum carbon sequestration was reached at 20 years of age, being 88.9 kg C/tree/year (Fig. 2c). During the entire study period, a tree of this species would have sequestered 1.1 Mg C, equivalent to 4.0 Mg CO_2 (Fig. 2c). This implies that *C. alliodora* in AFS with coffee in Líbano (Tolima, Colombia), at a tree density of 30, 60 and 90 trees/ha, would sequester on average 1.8, 3.5 and 5.3 Mg C/ha/year, respectively (Fig. 3). The maximum carbon sequestration rate would be 2.7, 5.3 and 8.0 Mg C/ha/year for 30, 60 and 90 trees/ha, respectively in year 20 (Fig. 3).

Discussion

The models developed present a good fit and allow predictions of *C. alliodora* growth in coffee AFS in the study area. Other authors have developed growth models for forest species using nonlinear regressions with similar fit statistics (Adesuyi et al. 2020; Doyog et al. 2021; Yang et al. 2021). Parresol and Devall (2013) found that the growth of *C. alliodora* trees in forests mostly follow a sigmoid (sigmoidal) pattern, which is similar to that found in this study. These

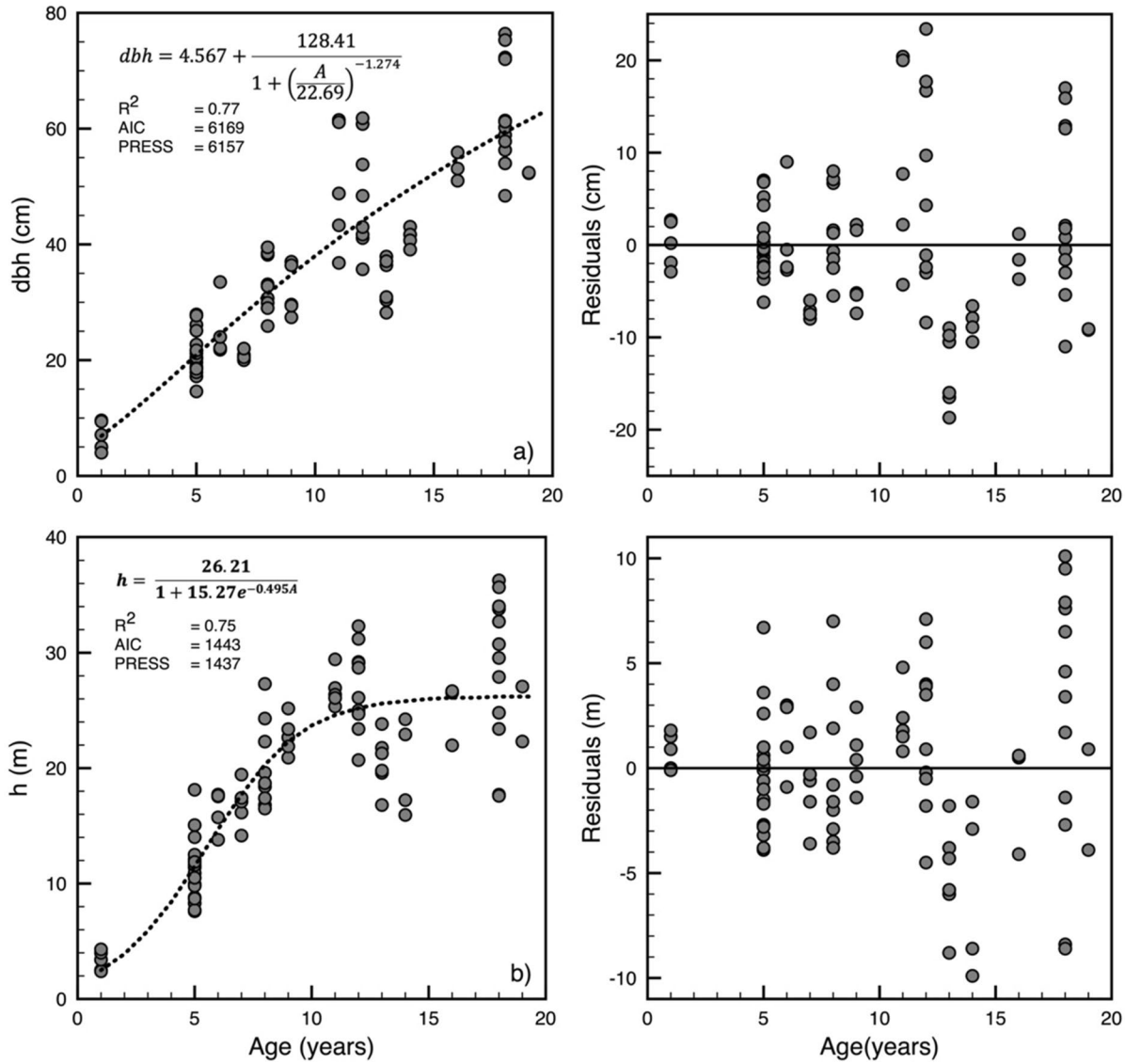


Fig. 1 Best-fit diameter and height growth models and their corresponding residual plots for *Cordia alliodora* in agroforestry systems with coffee in Líbano, Tolima, Colombia. dbh: diameter of trunk at breast height; h: total height; A: age (years); R^2: coefficient of determination; AIC: Akaike's Information Criterion; PRESS: predicted residual error sum of squares

models allow to manage adequately *C. alliodora* trees to reach the objective of timber production of climate change mitigation.

Diametric and height growth showed different trends, but which corresponds to what was expected and to other similar studies (Houllier et al. 1995; Somarriba et al. 2001; Jaimez et al. 2013). The peak growth of these two variables was reached at year 4–6, which coincides with Hernández et al. (1997), who found that the increase in diameter and height of *C. alliodora* in AFS with coffee decreases progressively over the seventh year, possibly due to increased competition between canopies. Parresol and Devall (2013) also found a reduction in the growth of *C. alliodora* in Panamá forests at seven years of age. The dimensions reached by trees in this area at 20 years of age (63.6 cm in dbh and 26.2 m in h) are much higher than data reported by Liegel and Stead (1990)

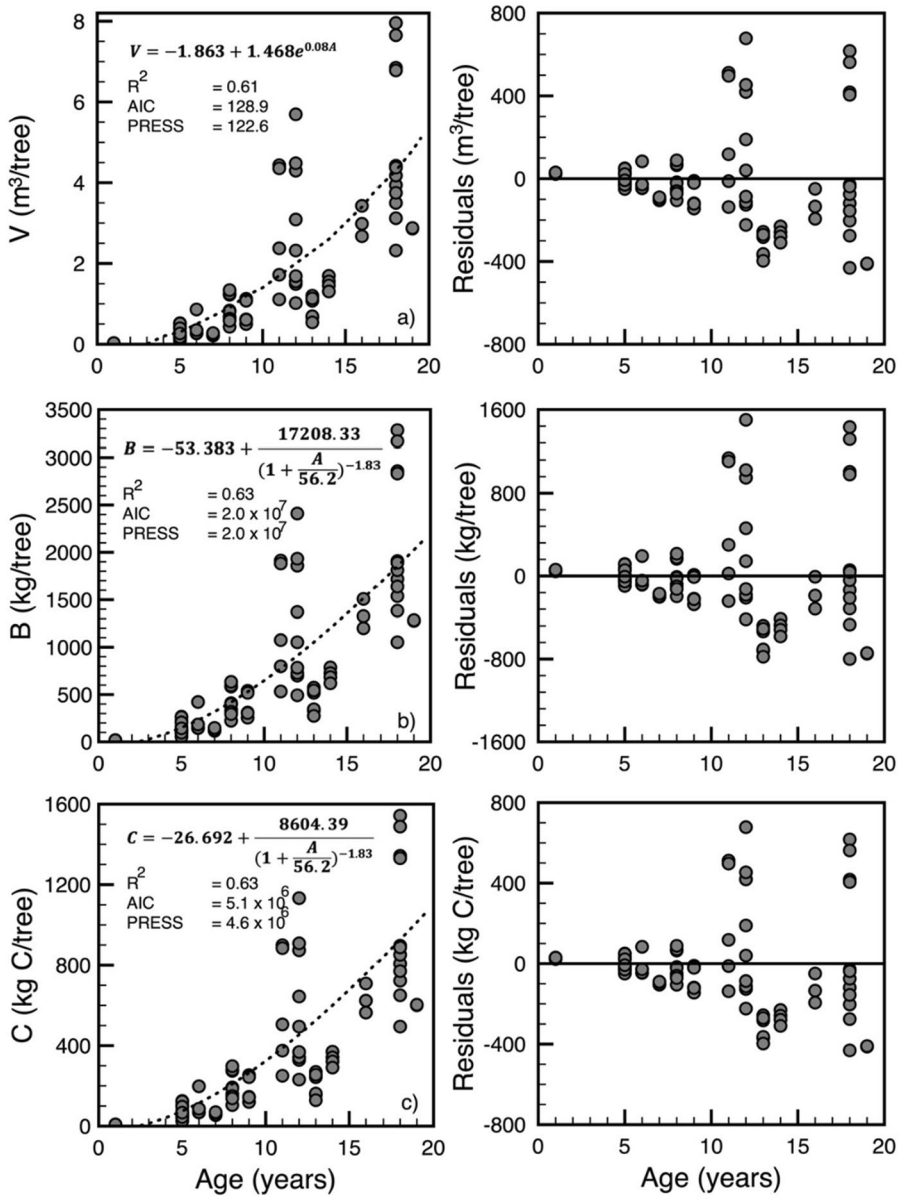


Fig. 2 Best-fit models of volumetric growth and accumulation of aboveground biomass and carbon, with corresponding residual plots, for *Cordia alliodora* in agroforestry systems with coffee in Líbano, Tolima, Colombia. **a** V: total timber volume; **b** B: total aboveground biomass; **c** C: carbon in total aboveground biomass; A: age (years); R^2: coefficient of determination; AIC: Akaike's Information Criterion; PRESS: predicted residual error sum of squares

and Hernández et al. (1997) at the same age. Somarriba and Beer (1987) reported diameters up to 66 cm of around 32 years in the same type of production system in the region of Turrialba, Costa Rica. These studies confirm that *C. alliodora* continues to grow at an age greater than 20 years, although at a lower rate, which has implications for management and profitability of this production system.

The growth of *C. alliodora* varies depending on the site and the management of the associated crop, differing between production systems such as forests, pure plantations or agroforestry systems (Somarriba and Beer 1987; Current et al. 1998; Valdivieso et al. 1998; Somarriba et al. 2001; Parresol and Devall 2013). Current and mean annual increases in dbh and total height obtained by this study were also higher than those reported in plantations of *C. alliodora* in Colombia (Van der Poel 1988), and in AFS with cacao, coffee, sugarcane and pastures in Costa Rica (Somarriba and Beer 1987). Somarriba et al. (1995) report increases of 6.4 cm/year and 4.5 m/year at 2.4 years in cocoa

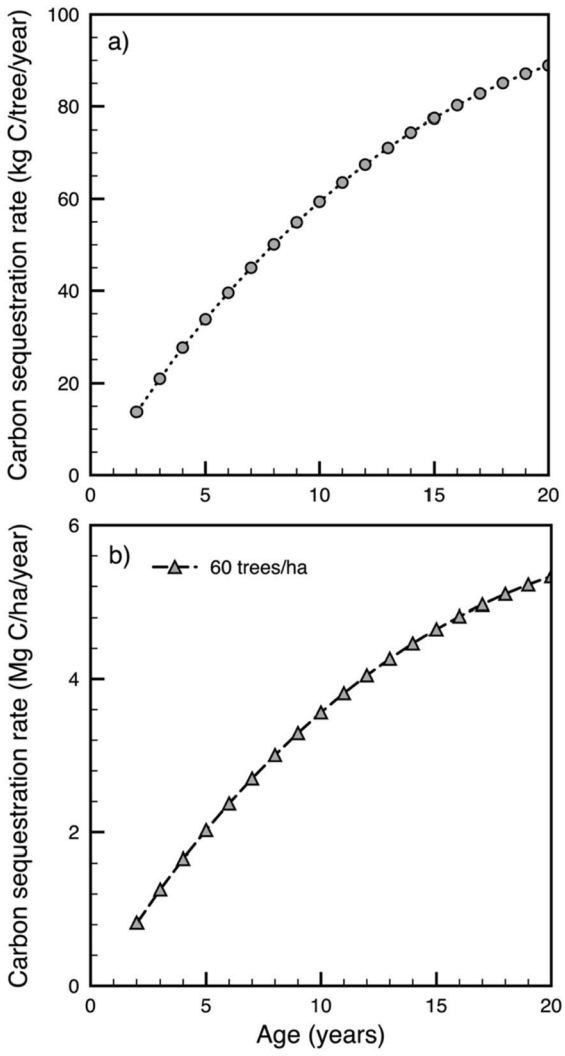


Fig. 3 Carbon sequestration rate (current annual increment) **a** of individual trees and **b** stands at a density of 60 trees/ha of *Cordia alliodora* in agroforestry systems with coffee in Líbano, Tolima, Colombia

AFS in Puerto Viejo, Talamanca, Costa Rica; while Rosero and Gewald (1979) estimated increases of 0.9 cm/year and 0.2 m/year in 15 to 17-years-old trees in associations with coffee cultivation in the Atlantic zone of Costa Rica. Peak growth occurs at an age slightly higher than the findings of Montero and Mellink (1987) and Somarriba et al. (2001), who consider that the greatest increases of the species are obtained mainly in the first four years. The higher growth and carbon sequestration rates in this study may be due to the high fertility of these Andisol soils.

Volumetric growth was maximized in trees close to 20 years of age (0.60 m^3/tree/year), which indicates the feasibility of maintaining the trees in the field for a longer period, so that larger sawlog dimensions can be produced (Somarriba and Beer 1987). These increases exceed those reported by Rosero and Gewald (1979), Glover (1981) and Hernández et al. (1997) in Colombia and Costa Rica. Valdivieso et al. (1998) estimated that *C. alliodora* (68 trees/ha) can reach 0.87 m^3/tree at 6 years (59.2 m^3/ha and MAI = 9.6 m^3/ha/year) in AFS with cocoa and banana. Somarriba et al. (2008) reported in AFS with 56 trees/ha in Talamanca (Costa Rica) a value of 59.3 m^3/ha in cacao plantations, while for 51 trees/ha it was 54.1 m^3/ha in banana plantations (with a periodic annual increment of 4.0 and 6.3 m^3/ha/year, respectively). These values that are largely surpassed by the timber stocks achieved at those same densities in the present study (276–303 m^3/ha, with a MAI of 13.8—15.1 m^3/ha/year). Somarriba and Beer (1987) state that this species can be maintained longer in the field and achieve total volumes of 298 to 690 m^3/ha for densities of 68 to 290 trees/ha of *C. alliodora* at 34 years in AFS (MAI of 8.8 and 20.4 m^3/ha/year, respectively). Although comparisons are difficult due to differences in climate, soils and management, the volumetric growth of *C. alliodora* in Líbano is high, but within the estimates of other authors at higher tree densities. Larger logs usually command higher market prices per cubic meter (Ramírez et al. 2020; Wanneng et al. 2021), which represents a high advantage of this species.

As with volumetric growth, carbon sequestration was maximized in trees of older age (20 years) and size (dbh = 62.6 cm) (88.9 kg/tree/year). This indicates the possibility of maintaining individuals of this species longer in the AFS, so that more carbon is sequestered, the permanence of carbon in the biomass is increased, and more emission reduction credits, and greater profitability are achieved (Waldén et al. 2020). This practice would bring positive impacts, as Andrade et al. (2014b) state that timber species contribute approximately 66% of carbon sequestration in AFS with coffee in this same study area.

By modeling carbon sequestration, it was estimated that *C. alliodora*, at a density of 60 trees/ha, can sequester 260 Mg CO_2/ha over the 20 years (a mean

sequestration of 13.0 Mg CO_2/ha/year = 3.5 Mg C/ha/year), without considering below-ground biomass (additional 18–21%). Pocomucha and Alegre (2013) state, as do these findings, that the age of the AFS and tree density significantly affect the carbon stock potential. In this same study area (Tolima, Colombia), carbon sequestration rates have been estimated for *C. alliodora* in the order of 1.1 to 4.9 Mg C/ha/year in cocoa plantations and 4.4 Mg C/ha/year in coffee plantations; while in plantations 1.2 Mg C/ha/year is reported (Andrade et al. 2013, 2014b; Patiño et al. 2018). In contrast, Aristizábal et al. (2002) found lower values in Caldas, Colombia in AFS with cocoa and banana and densities of 200 trees/ha (4.3 Mg C/ha/year). The same occurs in Costa Rican AFS: Segura (2005) estimated 2.1 and 2.8 Mg C/ha/year in cocoa plantations with 100 and 150 trees/ha, respectively; while Ávila et al. (2001) estimated between 0.3 and 2.2 Mg C/ha/year in cocoa AFS with 156 trees/ha and wooded pastures with 370 trees/ha, respectively. The inclusion of *C. alliodora* in coffee plantations would change the magnitude of the carbon footprint in this production system, transforming them from net GHG (greenhouse gases) emitters (− 5.7 Mg CO_2/ha/year) to net CO_2 sequesters (14.2 Mg CO_2/ha/year) (Andrade et al. 2014b), achieving carbon neutrality (Birkenberg and Birner 2018) and its economic and market benefits (Birkenberg et al. 2021). This means that the potential carbon offset by *C. alliodora* was 19.9 Mg CO_2/ha/year (Andrade et al. 2014b) compared to 13.0 Mg CO_2/ha/year in this study, whose differences are explained by tree densities.

Conclusions

The non-linear regression models obtained in this study allowed us to evaluate the growth and carbon sequestration of *C. alliodora* in coffee plantations in the municipality of Líbano, Tolima. These models are a tool for the silvicultural management of these agroforestry systems and are a support to maximize timber production and atmospheric CO_2 sequestration.

The maximum volumetric, biomass and carbon growth at 20 years would indicate that it is possible to maintain these trees in these agroforestry systems for longer, so that they achieve larger logs, sequester more carbon for longer and achieve a greater permanence of carbon in the biomass. This would mean a very important win–win strategy for the promotion of these production systems.

The high carbon sequestration rates (2.7 to 8.0 Mg C/ha/year), for more than 20 years, are an indicator of the importance of these production systems for climate change mitigation. In the same way, the inclusion of *C. alliodora* would make a conversion in the carbon footprint, from being a net emitter of GHG to a net fixer of atmospheric CO_2. This species could be used in emission reduction projects or in carbon neutral coffee production.

Acknowledgements The authors express their gratitude to the Central Research Committee of the Universidad del Tolima for the financing of research project No. 260210, within the framework of which the present study was developed. To the Federación Nacional de Cafeteros en Líbano, Tolima, and mainly to the coffee growers of the study area, for allowing access to their farms for the experimental development of the study and for providing the necessary information. To Laura Melo and Daniel Machado, we express our most sincere gratitude for supporting the data collection in the field.

Author contributions HJA, MAS and JCS contributed to the conception and design of the study. Material preparation, data collection and analysis were performed by HJA and MAS. The first draft of the manuscript was written by HJA and all authors commented on earlier versions of the manuscript. All authors read and approved the final manuscript.

Funding Open Access funding provided by Colombia Consortium.

Declarations

Conflict of interest Hernán J. Andrade has been invited as Guest Editor for a next issue of Agroforestry Systems on "Agroforestry Systems in Latin America". Authors declare they have no financial interests.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

References

Adesuyi FE, Akinbowale AS, Olugbadieye OG, Jayeola K (2020) Fitting non-linear models for tree volume estimation in strict nature reserve, South-West, Nigeria. Trop Plant Res 7(1):6–13

Albrecht A, Kandji ST (2003) Carbon sequestration in tropical agroforestry systems. Agric Ecosyst Environ 99:15–27. https://doi.org/10.1016/S0167-8809(03)00138-5

Andrade HJ, Segura MA (2016) Dinámica de la sombra de *Cordia alliodora* en sistemas agroforestales con café en Tolima. Colomb Agron Costarric 40:77–86

Andrade H, Segura M, Somarriba E, Villalobos M (2008) Valoración biofísica y financiera de la fijación de carbono por uso del suelo en fincas cacaoteras indígenas de Talamanca, Costa Rica. Agroforestería En Las Américas 46:45–50

Andrade HJ, Figueroa JM, Silva DP (2013) Almacenamiento de carbono en cacaotales (*Theobroma cacao*) en Armero - Guayabal (Tolima, Colombia). Sci Agroaliment 1:6–10

Andrade HJ, Marín LM, Pachón DP (2014a) Carbon fixation and shade percentage in coffee (*Coffea arabica* L.) production systems in Líbano, Tolima. Colom Bioagro 26:127–132

Andrade HJ, Segura MA, Canal DS, Feria M, Alvarado JJ, Marín LM, Pachón D, Gómez MJ (2014b) The carbon footprint of coffee production chains in Tolima, Colombia. In: Oelbermann M (ed) Sustainable agroecosystems in climate change mitigation. Wageningen Academic Publishers, The Netherlands. https://doi.org/10.3920/978-90-8686-2_3

Andrade HJ, Segura MA, Somarriba E (2022) Above-ground biomass models for dominant trees species in cacao agroforestry systems in Talamanca, Costa Rica. Agrofor Syst 96:787–797. https://doi.org/10.1007/s10457-022-00741-y

Aristizábal J, Guerra A, Gutierrez B, Romero M (2002) Estimación de la tasa de fijación de carbono en el sistema agroforestal nogal cafetero (*Cordia alliodora*) - cacao (*Theobroma cacao* L) - platano (*Musa paradisiaca*). Universidad Distrital

Ávila G, Jiménez F, Beer J, Gómez M, Ibrahim M (2001) Almacenamiento, fijación de carbono y valoración de servicios ambientales en sistemas agroforestales en Costa Rica. Agrofor En Las Américas 8:32–35. https://doi.org/10.1016/j.amjsurg.2012.05.035

Beer J, Muschler R, Kass D, Somarriba E (1998) Shade management in coffee and cacao plantations. Agrofor Syst 38:139–164. https://doi.org/10.1023/A:1005956528316

Beer J, Harvey C, Ibrahim M, Harmand JM, Somarriba E, Jiménez F (2003) Servicios ambientales de los sistemas agroforestales. Agrofor Américas 10:37–28

Birkenberg A, Birner R (2018) The world's first carbon neutral coffee: lessons on certification and innovation from a pioneer case in Costa Rica. J Clean Prod 189:485–501. https://doi.org/10.1016/j.jclepro.2018.03.226

Birkenberg A, Narjes ME, Weinmann B, Birner R (2021) The potential of carbon neutral labeling to engage coffee consumers in climate change mitigation. J Clean Prod 278:123621. https://doi.org/10.1016/j.jclepro.2020.123621

Chait G (2015) Café en Colombia: servicios ecosistémicos, conservación de la biodiversidad, in: Sistemas Agroforestales. Funciones Productivas, Socioeconómicas y Ambientales. Serie técnica. Informe técnico 402. CATIE, Colombia/Costa Rica, pp 349–361

Current D, Rossi LM, Sabogal C, Nalvarte W (1998) Comparación de la potencial del manejo de la regeneración natural con asocio agroforestal y plantaciones puras para tres especies: estudios de caso en Brasil. Perú y Costa Rica, Valdivia, Chile

Detlefsen G, Somarriba E (2012) Producción de madera en sistemas agroforestales de Centroamérica. Serie técnica. Manual técnico/ CATIE; no . 109, Turrialba, CR

Detlefsen G, Somarriba E (2015) Producción agroforestal de madera en fincas agropecuarias de Centroamérica, in: Editorial CIPAV, Cali, C. (Ed.), Sistemas Agroforestales. Funciones Productivas, Socioeconómicas y Ambientales. Serie técnica. Informe técnico 402. CATIE, Colombia/Costa Rica, pp 21–44

Detlefsen G (1988) Evaluación del rendimiento de (*Coffea arabica*) cv. Caturra bajo diferentes densidades de *Cordia alliodora* y *Erythrina poeppigiana* plantados en un diseño sistemático de espaciamientos.Tesis de maestría, IICA -CATIE, Costa Rica

Dixon RK (1995) Agroforestry systems: sources of sinks of greenhouse gases? Agrofor Syst 31:99–116. https://doi.org/10.1007/BF00711719

Doyog ND, Lumbres RIC, van Weerd M, Baoanan ZG (2021) Non-linear tree height (h-d) model development and forest resource productivity assessment of Diguyo limestone forest within Northern Sierra Madre Natural Park. Philip J Sci 150(6A):1517–1530

Dzib B (2003) Manejo, secuestro de carbono e ingresos de tres especies forestales de sombra en cafetales de tres regiones contrastantes de Costa Rica. Tesis de Maestría, CATIE, Costa Rica

Farfán F (2012) Árboles con potencial para ser incorporados en sistemas agroforestales con café. Bogotá, Colombia, p 88

Farfán F (2014) Agroforestería y sistemas agroforestales con café. Manizales, Caldas (Colombia), p 342

Farfán F, Urrego J (2004) Comportamiento de las especies forestales *Cordia alliodora*, *Pinus oocarpa* y *Eucalyptus grandis* como sombrío e influencia en la productividad del café. Cenicafé 55:317–329

Glover N (1981) Coffee yields in a plantation of *Coffea arabica* car. caturra shaded by *Erythrina poeppigiana* with and without *Cordia alliodora*. Centro Agronómico Tropical de Investigación y Enseñanza, CATIE. Serie técnica. Informe técnico No. 17, Turrialba, Costa Rica

Graves A, McCarter PS (1990) *Cordia alliodora*. A promising tree for tropical agroforestry, Tropical forestry papers no. 22. Oxford Forestry Institute. Department of Plant Sciences, England

Hammer Ø, Harper DAT, Ryan PD (2001) PAST: Palentological Statistics software package for education and data analysis. Paleontol Electrón 4(1):9

Hernández O, Beer J, Von Platen H (1997) Rendimiento de café (*Coffea arabica* cv Caturra), producción de madera (*Cordia alliodora*) y análisis financiero de plantaciones con diferentes densidades de sombra en Costa Rica. Agroforestería en las Américas 4, 8–13.

Instituto de Hidrología, Meteorología y Estudios Ambientales [IDEAM] (2010) Cambio climático en Colombia [WWW Document]. URL http://www.derechoambientalcolombiano.org/Assets/PDFs/ICDA-Generalidades_CC_Ideam.pdf

Holdridge LR (1967) Life zone ecology. Tropical Science Center, San José, Costa Rica, p 206

Houllier F, Leban JM, Colin F (1995) Linking growth modelling to timber quality assessment for Norway spruce. For Ecol Manage 74(1–3):91–102. https://doi.org/10.1016/0378-1127(94)03510-4

Jaimez R, Araque O, Guzman D, Mora A, Espinoza W, Tezara W (2013) Agroforestry systems of timber species and cacao: survival and growth during the early stages. J Agric Rural Dev Trop Subtrop 114(1):1–11

Liegel L, Stead J (1990) Cordia alliodora (Ruiz & Pav .) Oken, Capá prieto, Laurel, in: Burns R, Honkala B (Eds.), Silvics of North America. United States Department of Agriculture (USDA), Forest Service, Agriculture Handbook 654, Washington, D.C., pp 270–277

Montagnini F, Nair PK (2004) Carbon sequestration: An underexploited environmental benefit of agroforestry systems. Agrofor Syst 61:281–295. https://doi.org/10.1007/s00339-016-9647-0

Montagnini F, Cusack D, Petit B, Kanninen M (2004) Environmental services of native tree plantations and agroforestry systems in Central America. J Sustain for 21:51–67. https://doi.org/10.1300/J091v21n01_03

Montagnini F, Somarriba E, Murgueitio E, Fassola H, Eibl B (2015) Sistemas agroforestales. Funciones productivas, socioeconómicas y ambientales. Serie técnica. Informe técnico 402. CATIE, Colombia/Costa Rica

Montero C, Mellink W (1987) Productividad inicial de algunas asociaciones agroforestales en San José del Guaviare, Colombia. Bogotá CONIF Informa 7:5–18

Nair P (1993) An introduction to agroforestry, 1st edn. Springer, Netherlands, p 489

Oelbermann M, Voroney RP, Gordon AM (2004) Carbon sequestration in tropical and temperate agroforestry systems: A review with examples from Costa Rica and southern Canadá. Agric Ecosyst Environ 104:359–377. https://doi.org/10.1016/j.agee.2004.04.001

Ospina C, Hernández R, Sánchez F, Rincón E, Carlos R, Godoy A, Medina J, Obando D (2010) El nogal cafetero *Cordia alliodora* (Ruiz y Pavón) Oken, Guías silviculturales para el manejo de especies forestales con miras a la producción de madera en la zona andina colombiana. Cenicafé, p 49

Intergovernmental Panel on Climate Change [IPCC] (2006) Tierras forestales, in: Eggleston H.S., Buendia L., Miwa K., N.T. and T.K. (eds) (Ed.), 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Published: IGES, Japan, p 93

Parresol BR, Devall MS (2013) Patterns of diametric growth in stem-analyzed laurel trees (*Cordia alliodora*) in a Panamanian forest. Southwest Nat 58:170–178

Patiño S, Suárez LN, Andrade HJ, Segura MA (2018) Captura de carbono en biomasa en plantaciones agroforestales en Armero-Guayabal, Tolima, Colombia. Rev Investig Agrar Ambient 9:121–132

Pocomucha V, Alegre J (2013) La interacción de carbono almacenado en sistemas agroforestales de cacao (*Theobroma cacao* L.) en Huánuco. Perú Investig Amaz 3:36–43

Van der Poel P (1988) *Cordia alliodora* (Ruiz & Pavon) Oken: Experiencias en Colombia. Serie de documentación No. 15. Convenio CONIF-HOLANDA, Bogotá, Colombia

Ramírez L, Orrego SA, Restrepo HI (2020) Financial analysis of potential Pinus patula plantations in Antioquia, Colombia. Rev Fac Nac Agron Medellín 73(2):9227–9242. https://doi.org/10.15446/rfnam.v73n2.82833

Rapidel B, Allinne C, Cerdán C, Meylan L, Virginio E, Avelino J (2015) Efectos ecológicos y productivos del asocio de árboles de sombra con café en sistemas agroforestales, in: Sistemas Agroforestales. Funciones Productivas, Socioeconómicas y Ambientales. Serie técnica. Informe técnico 402. CATIE, Colombia/Costa Rica, pp 5–19

Righi C, Bernardes M, Lunz A, Pereira C, Neto D, Favarin J (2007) Measurement and simulation of solar radiation availability in relation to the growth of coffee plants in an agroforestry systems with rubber trees. Árvore 31(2):195–207

Rosero P, Gewald N (1979) Crecimiento del laurel (*Cordia alliodora*) en cafetales, cacaotales y potreros en la zona atlántica de Costa Rica pp 211–214

Salgado J (2012) Producción de madera en sistemas agroforestales con café, in: Detlefsen, G., Somarriba, E. (Eds.), Producción de Madera En Sistemas Agroforestales de Centroamérica. Serie técnica. Manual técnico/ CATIE; no . 109, Turrialba, CR, pp 145–160

Schroeder P (1994) Carbon storage benefits of agroforestry systems. Agrofor Syst 27:89–97. https://doi.org/10.1007/BF00704837

Segura MA (2005) Estimación del carbono almacenado y fijado en sistemas agroforestales indígenas con cacao en la zona de Talamanca. Turrialba, CR, Costa Rica, p 139

Segura MA, Andrade HJ (2012) Huella de carbono en cadenas productivas de café (*Coffea arabica* L.) con diferentes estándares de certificación en Costa Rica. Rev Luna Azul 35:60–77

Sit V, Poulin-Costello M (1994) Catalogue of curves for fitting. Biometrics Information. Handbook No. 4. Ministry of Forest Research Program. British Columbia. P 110

Somarriba E (1990) Sustainable timber production from uneven-aged shade stands of *Cordia alliodora* in small coffee farms. Agrofor Syst 10:253–263. https://doi.org/10.1007/BF00122915

Somarriba E (1992) Revisiting the past: an essay on agroforestry definition. Agrofor Syst 19:233–240. https://doi.org/10.1007/BF00118781

Somarriba E, Beer J (1987) Dimensions, volumes and growth of *Cordia alliodora* in agrforestry systems. For Ecol Manage 18:113–125

Somarriba E, Meléndez L, Campos W, Lucas C (1995) Cacao bajo sombra de maderables en Puerto Viejo. Manejo, crecimiento y producción de cacao y madera. Turrialba, Costa Rica, Talamanca, Costa Rica, p 72

Somarriba E, Valdivieso R, Vásquez W, Galloway G (2001) Survival, growth, timber productivity and site index of *Cordia alliodora* in forestry and agroforestry systems. Agrofor Syst 51:111–118. https://doi.org/10.1023/A:1010699019745

Somarriba E, Suárez A, Calero W, Botina A, Chalaca D (2008) Aprovechamiento, rendimiento maderable y carbono perdido en los residuos de *Cordia alliodora* de regeneración natural en cacaotales (*Theobroma cacao*) y bananales (*Musa* AAA cv. Gros Michel) de Talamanca. Costa Rica Agrofor Am 46:34–39

Soto-Pinto L, Anzueto M, Mendoza J, Ferrer GJ, de Jong B (2010) Carbon sequestration through agroforestry in indigenous communities of Chiapas. México Agrofor Syst 78:39–51. https://doi.org/10.1007/s10457-009-9247-5

Staver C, Guharay F, Monterroso D, Muschler RG (2001) Designing pest suppressive multistrata perennial crop systems: shade grown coffee in Central America. Agrofor Syst 53:151–170

Swamy SL, Puri S (2005) Biomass production and C-sequestration of *Gmelina arborea* in plantation and agroforestry system in India. Agrofor Syst 64:181–195. https://doi.org/10.1007/s10457-004-1999-3

Valdivieso R, Somarriba E, Galloway G, Vázquez W, Kass D (1998) Crecimiento del laurel (*Cordia alliodora*) en sistemas agroforestales de Talamanca, Costa Rica y Chinguinola, Panamá. Agrofor Am 5:17–18

Waldén P, Ollikainen M, Kahiluoto H (2020) Carbon revenue in the profitability of agroforestry relative to monocultures. Agroforest Syst 94:15–28. https://doi.org/10.1007/s10457-019-00355-x

Wanneng P, Ozarska B, Phimmavong S, Belleville B, Davidson B (2021) Timber trading and pricing of plantation grown teak (*Tectona grandis* Linn.F) in Laos. Small-Scale for 20:569–584. https://doi.org/10.1007/s11842-021-09481-w

Winjum JK, Dixon RK, Schroeder PE (1992) Estimating the global potential of forest and agroforest management practices to sequester carbon. Water Air Soil Pollut 64:213–227. https://doi.org/10.1109/JCN.2000.6596716

Yang J, Song X, Cao M, Deng X, Zhang W, Yang X, Swenson NG (2021) On the modelling of tropical tree growth: the importance of intra-specific trait variation, nonlinear functions and phenotypic integration. Ann Bot 127(4):533–542. https://doi.org/10.1093/aob/mcaa085

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.