



# Growth and yield of *Retrophyllum rospigliosii* pure plantations in the Colombian Andes

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## Abstract

Most reforestation in Colombia, especially in the Andean region, are monocultures of pines and eucalyptus with defined nursery and silvicultural packages. Planting native species would avoid the widespread controversy over reforestation with exotic species. Nevertheless, there are few studies that evaluate the growth and yield of native species and provide supported data to establish new projects. Here, we modeled the growth and yield of the native coniferous *Retrophyllum rospigliosii* in different areas of the Colombian Andes in terms of mean diameter ( $D$ ), height ( $H$ ), and volume ( $V$ ) as a function of age, based on longitudinal data from 115 research sample plots from three sites that were remeasured between 4 and 9 times for 20 years. We fitted the von Bertalanffy growth model for  $D$ ,  $H$ , and  $V$  through Bayesian generalized nonlinear mixed models to model tree growth. The adjustment of the models for the absolute growth of *R. rospigliosii* was 0.99, 0.99, and 0.97 for  $D$ ,  $H$ , and  $V$ , respectively. All models fulfilled all regression assumptions. Although the growth rates of *R. rospigliosii* differed between planted sites, *R. rospigliosii* plantations generally exhibited low growth and barely reached the sizes required for commercialization. These results suggest that the extensive use of *R. rospigliosii* in pure plantations is unlikely and discourages the massive propagation of *R. rospigliosii*.

**Keywords** Colombian pine · Tree growth modeling · Montane tropical forest · Commercial reforestation · Native and exotic species

## Introduction

Colombia contains 25% of all the tree species of the Neotropical biome. Colombia has 5776 woody tree species, which is similar to the Nearctic biome (North America, with 5216 tree species) and the Palearctic (Europe, Asia, Himalayas, North Africa, and the Arabian

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Peninsula; with 5964 tree species) (Beech et al. 2017). The largest concentration of plant biodiversity in Colombia is in the Andean region (Andrade 2011; Halffter 1992; Moreno et al. 2017; Rangel 2015). Some authors have suggested taking advantage of biodiversity by planting native species to avoid the widespread controversy over reforestation with exotic species (Carrere and Lohmann 1996; Le et al. 2012). Nevertheless, most reforestation in Colombia, especially in the Andes, are short rotation eucalypts and pines monocultures. They cover 90,495 ha and 25,438 ha, respectively (Martínez-Cortés et al. 2022; PROFOR 2017). Pine wood has been widely used both for sawmills and in long-fiber paper pulp. Eucalypts produce short-fiber cellulose and high-density boards (PROFOR 2017; Martínez-Cortés et al. 2022). Overall, these species have silvicultural packages, increased productivity, and short rotation periods depending on whether they are broadleaf ( $\approx 8$  y) or coniferous ( $\approx 18$  y) (Kanninen 2010; Liu et al. 2018).

Despite planting pure native species stands does not correspond to a natural forest, the use of native timber species can be valuable commercially. These species can generate economic, ecological, and social benefits simultaneously (Ball et al. 1995; Hagggar et al. 1998; Montagnini et al. 1995; Piotta et al. 2004). Thus, reforestation with native species could help to meet the current demand for wood products from natural forests, reducing their overexploitation. There are seven native coniferous species in Colombia, mainly from the Andean region (Bernal et al. 2015; Moreno et al. 2017; Veblen et al. 2005; Marín 1998). *Retrophillum rospiglosii* could be used for commercial reforestation for its potential use in cabinet making, construction, and pulp making (Cueva et al. 2013; Vásquez-Correa and Alcántara-Vara 2009; Portillo et al. 2019). Under natural conditions, this species attains a large size and has straight stems and few branches (Vásquez-Correa and Alcántara-Vara 2009; Cueva et al. 2013; Marín 1998). It can also be used for long fiber pulp, particle board, plywood, and the extraction of tannins (Torres 1983; JUNAC 1981; Arostegui and Sato 1970). Nevertheless, there is a lack of knowledge about appropriate silvicultural practices and the growth and yield expected per unit of area for this species (Cárdenas 2014).

*R. rospiglosii* grows naturally in Bolivia, Ecuador, Peru, Venezuela, and Colombia (Veblen et al. 2005; Mill 2016; see annex 1). Under natural forests in Colombia, it is found at 1700–3500 masl (Marín 1998; Mill 2016) and can reach up to 45 m in height and up to 2.5 m in diameter at 1.3 m above ground) (Lamprecht 1989; Luna 1981; Marín 1998; Mill 2016; Yaguana et al. 2012). *R. rospiglosii* grows in low-fertility soil, forming pure or mixed uneven-aged stands in late-successional forests (Marín 1998; Cueva et al. 2013). This species has been exploited intensely in the natural forests over the years (Arostegui and Sato 1970; Vásquez-Correa and Alcántara-Vara 2009), resulting in a progressive decrease in populations during recent years. According to the International Union for the Conservation of Nature (IUCN), *R. rospiglosii* is a vulnerable species (Cogollo et al. 2007; Gardner and Thomas 2013).

Despite the potential use of native species for commercial reforestation in the Andean region, few studies have evaluated the growth rates of these species. In this study, we used information from forestry plantations of *R. rospiglosii* established in the Andean region of Colombia remeasured regularly during the last 20 years. The objective of this study was to model the growth and yield patterns of *R. rospiglosii* in pure experimental plantations in mean diameter ( $D$ ), mean height ( $H$ ), and volume ( $V$ ) as a function of age.

## Material and methods

### Species and site description

Under natural conditions, *R. rospigliosii* usually grows in mixed stands as scattered trees in montane forest stands (Veblen et al. 2005). The populations of this species were generally associated with the tree families Lauraceae (*Ocotea* spp), Araliaceae (*Oreopanax* spp), Cunoniaceae (*Weinmannia* spp), Brunelliaceae (*Brunellia* spp), Clusiaceae, Myrtaceae, and Winteraceae (*Drimys* spp) (Marín 1998; Veblen et al. 2005). In exceptional conditions, this species can represent more than 40% of tree species in a stand (Rollet 1984) or even form almost pure stands (Marin 1998). The wood of this species has a density of approximately  $0.4 \text{ g cm}^{-3}$  and exhibits mechanical characteristics suitable for applications in cabinetmaking and construction, attributed to its tall stems and minimal branching (Torres 1988).

In Colombia, most *R. rospigliosii* plantations have been established in pure monospecific stands, and although there is a possibility of establishing mixed plantations with this species, there is no knowledge of its long-term monitoring. This study analyzed the information from the only three forestry plantations of *R. rospigliosii* (also known as *Nageia rospigliosii* and *Decussocarpus rospigliosii*) that were established and monitored along the Andean mountains of Colombia (Figure S2). These plantations are in three localities belonging to two Colombian departments (Table 1). They were established between 1998 and 1999 by two institutions, Smurfit Kappa Carton de Colombia and the National Federation of Coffee Growers of Colombia, to study the growth and silviculture of *R. rospigliosii*. The sites selected for the study were located near the lower limit of the species' distribution range (1755–1905 masl) and the soil corresponded to Andisols with taxonomy and physical–chemical characteristics like those of the closest natural forest where the species currently grows (Table S2). The seeds used in the studied plantations came from trees that grew in natural forests located in different Colombian municipalities in the departments of Antioquia, Cundinamarca, and Santander. Tree seedlings were produced under nursery conditions and were taken to the field once they reached 30 cm, approximately 6 months after germination. The plantations' density was 850–1111 trees  $\text{ha}^{-1}$  (see tree spacing, Table 1). The cultural treatments applied to the plantations included fertilization at planting time with a combination of 70 g of NPK and 15 g of sodium borate, 4 g boron (Borax), weeds control at the first stages of the plantation to suppress competing vegetation, and animal exclusion. No thinning has occurred since planting.

### Data sources

At each site, permanent sample plots (PSPs) were established in the *R. rospigliosii* plantations and remeasured periodically between 1998 and 2019 (Table 1). At the sites, La Suecia, Claridad, and Santa Isabel, 115 square PSPs,  $144 \text{ m}^2$  in size (16 trees per plot), were distributed systematically throughout the plantations with a sampling intensity of 11–36%. Tree diameter at breast height, 1.3 m above ground ( $d$ , cm), was measured with a diameter tape, and total height ( $h$ ) was measured with a vertex hypsometer to all trees within the sampling plots. Based on 50 data pairs of diameters at breast height and total volumes ( $v$ ,  $\text{m}^3$ ) in research sample plots established by the Colombian National Corporation for Forest

**Table 1** Main characteristics of the forestry plantation sites to study the growth and yield of *Retrophyllum rospigliosii* in the Andean region of Colombia

Site	La Suecia	Claridad	Santa Isabel
Municipality and department	El Tambo, Cauca	Popayán, Cauca	Fredonia, Antioquia
Latitude (N)	2°28'	2°26'	5°57'
Longitude (W)	76°48'	76°35'	75° 38'
Altitude (range, m asl)	1755	1905	1773
Mean annual precipitation (mm)*	2255	2224	2796
Monthly rainfall pattern	Bimodal	Bimodal	Bimodal
Mean annual temperature (°C)	19.4	15.1	17.0
Soil order	Andisol	Andisol	Andisol
Previous land use	Commercial plantation of <i>E. grandis</i>	Commercial plantation of <i>E. grandis</i>	Grazing land
Plantation type	Monospecific	Monospecific	Monospecific
Plantation area (ha)	3.7	1.0	6.6
Tree spacing (m × m)	3.0 × 3.0	3.4 × 3.4	3.0 × 3.0
Permanent sampling plots	30	25	60
Sampling intensity (% area)	11.7	36.0	13.1
Planting year	1999	1998	1998
Years of measurements	2001, 2003, 2004, 2006, 2008, 2009, 2010, 2016, 2018	2000, 2004, 2006, 2018	2001, 2003, 2006, 2008, 2015

Research and Development in 1994 (Cueva et al. 2013), we fit a simple allometric volume function to estimate the total volume of trees (Eq. 1, Figure S3).

$$\hat{v}_i = 0.0013 * d^{1.5541} \quad (1)$$

where  $v$  is the total volume per tree over bark ( $m^3$ ), and  $d$  is the diameter at breast height in cm.

Before fitting, Eq. (1) was logarithmically transformed into a linear function. The bias produced by this transformation was corrected by adding  $\frac{1}{2}$  of the mean square error (MSE) to the independent term of the linear (Zapata et al. 2001). The volume model reached  $R^2=0.78$  in coefficient of determination (Figure S3). The model met the regression assumptions of normality of residuals (Shapiro–Wilk test  $p$ -value=0.23,  $\alpha=0.05$ ) and homoscedasticity of residuals (Breusch-Pagan test  $p$ -value=0.78,  $\alpha=0.05$ ). Finally, we predicted the stand volume ( $V$ ,  $m^3 \text{ ha}^{-1}$ ) for each PSP by using Eq. (1).

## Modeling tree growth

We adjusted the widely used von Bertalanffy growth model to describe the yield of the forest stands (Vanclay 1994; von Bertalanffy 1957; Pretzsch 2010). In this case the mean diameter ( $D$ , cm), mean height ( $H$ , m), and volume per hectare ( $V$ ) (Eq. 2):

$$\widehat{Y(t)}_{ij} = A \cdot (1 - e^{-kt})^w \quad (2)$$

where  $Y(t)$  is any of the studied variables ( $D$ ,  $H$ , and  $V$ ),  $A$  is the asymptote of  $Y$ ,  $k$  is the intrinsic rate of organic growth, and  $w$  is a dimensionless parameter that models the shape of the growth curve and determines the degree of concavity and the inflection point of the curve (Inga and del Valle 2017).

Equation (2) was fitted for the response variables ( $D$ ,  $H$ , and  $V$ ) through a Bayesian generalized nonlinear mixed model (BGNMM), which incorporates prior knowledge into the model and avoids autocorrelation of errors produced by continuous and repeated measurements of all variables (Lee 2022). Models are considered a two-level structure that can be defined (plot and stand-level), according to (Xu et al. 2014), as:

$$Y_{ijt} = f(\phi_{ijt}(t)) + \varepsilon_{ijt}, i = 1, \dots, M, j = 1, \dots, M_i, t = 1, \dots, n_{ij}$$

where  $M$  is the number of stand sites,  $M_i$  is the number of plots within the  $i^{\text{th}}$  stand, and  $n_{ij}$  is the number of plots.  $Y_{ijt}$  is the growth measurement of  $H$ ,  $D$ , and  $V$  at the  $t^{\text{th}}$  age of the  $j^{\text{th}}$  plot taken from the  $i^{\text{th}}$  stand,  $\phi_{ijt}$  is the parameter vector,  $f$  is the Bertalanffy function to model tree growth, and  $\varepsilon_{ijt}$  is the within-group error. A Gaussian family was used for the distribution of the error. We fitted the model with 8158 observations from 1747 trees within 30 plots in La Suecia, 25 plots in Claridad, and 60 plots in Santa Isabel. The BGNMM (Eq. 2) incorporated random effects of both the plot and stand site. We evaluate model convergence both visually and by estimating ‘Rhat’. Rhat compares the convergence of the parameter estimates across the chains. Rhat values ideally should be between 0.9 and 1.05, indicating successful convergence and mixing. We estimated a Bayesian  $R^2$  using the ‘bayes\_R2’ function for each model to represent an estimate of the proportion of variation explained for new data. Additionally, we assess model fit visually by comparing observed data to simulated data from the posterior predictive distribution. We fitted all models using the package ‘brms’ (Bürkner 2017). We carried out all analyses in R (R Core Team 2024).

## Growth rates and lifespan

Predicted values were computed using the predicted random effects. Given the predicted values of  $Y$ , the current annual increment (CAI) was computed as  $CAI = \hat{Y}_t - \hat{Y}_{t-1}$ , where  $t$  is the stand age, and  $\hat{Y}_t$  is the predicted variable  $Y$  at time  $t$ . A continuous calculation of the von Bertalanffy model for the CAI, is the first derivative of Eq. (2), expressed in Eq. 3:

$$dY/dt = CAI = \frac{Ake^{-k(t)}(1 - e^{-k(t)})^{w-1}}{1/w} \quad (3)$$

Accordingly, the mean annual increment (MAI) was calculated as the ratio:  $MAI = \hat{Y}_t/t$ , and expressed according to the von Bertalanffy model as Eq. 4:

$$Y(t)/t = MAI = [A(1 - e^{-k(t)})^w]/t \quad (4)$$

As in Eq. (2), the time to reach the asymptote ( $A$ ) of  $D$ ,  $H$ , and  $V$  is infinity, an approximation within the finite time is the time to reach 99% of  $A$  in Eq. (2) ( $t_{99\%A}$ , Eq. 5) (Inga and del Valle 2017):

$$t_{99\%A} = \frac{\ln(1 - e^{(0.99A - w \ln A)})}{-k} \quad (5)$$

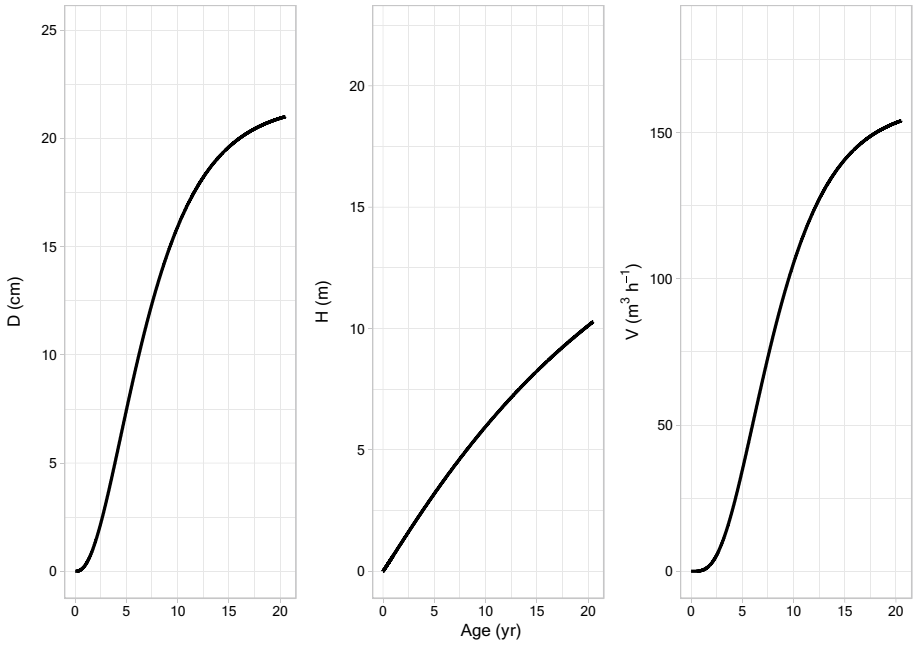
## Results

The BGNMM tree growth models of *R. rospigliosii* were fitted to the plantations located at three sites in the Andean region of Colombia (Figs. 1 and 2, Table 2 and S1). The statistical fit of the absolute growth that corresponded to model (2) of *R. rospigliosii* was 0.99, 0.99, and 0.97 (Bayesian  $R^2$ ) for  $D$ ,  $H$ , and  $V$ , respectively (Table 2). All models met the regression assumptions of residual normality, residual homoscedasticity, and residual independence.

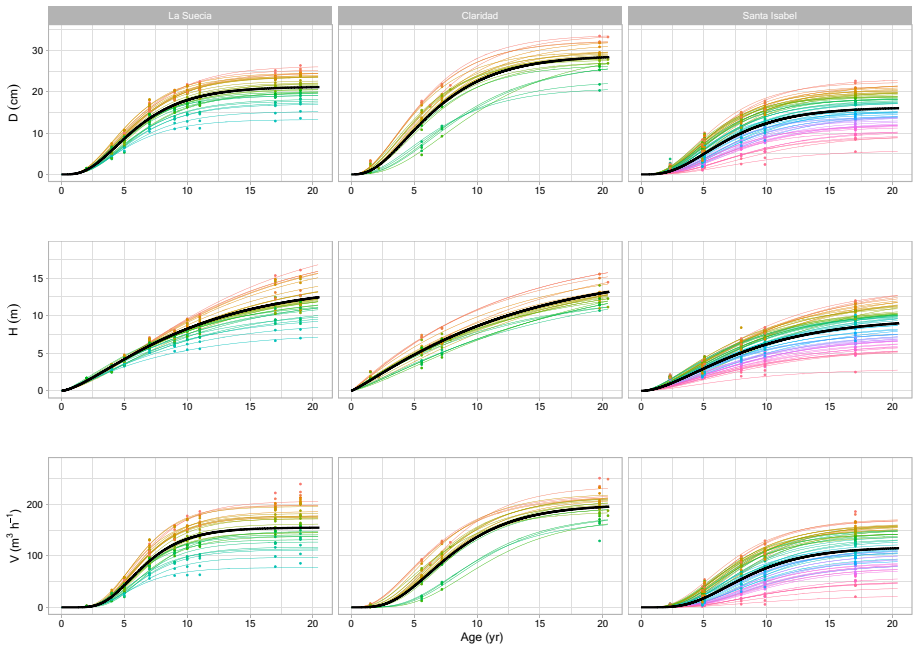
The parameter estimates for model (2) for  $D$ ,  $H$ , and  $V$  at all planted sites with *R. rospigliosii* were used to calculate growth rates and the time required by this species to reach 99% of the asymptotic  $D$ ,  $H$ , and  $V$  at all studied sites (Eq. 4, Table 3). Growth and growth rates of *R. rospigliosii* differed between planted sites during most of the life of the plantation (Figs. 2 and 3, Figures S3 and S4). This species achieved its maximum CAI and MAI (Eqs. 3 and 4) at very early ages. This is especially true for  $H$ , which reached its maximum CAI at only 2 y (Table 3, Fig. 3). *R. rospigliosii* also reached the 99% $A$  age ( $t_{99\%A}$ ) at relatively older ages: of 67, 125, and 110 years for  $D$ ,  $H$ , and  $V$ , respectively, and with low dimensions (21.6 cm in  $D$ , 18.1 m in  $H$ , and 159.4 m<sup>3</sup> ha<sup>-1</sup> in  $V$ ).

## Discussion

Forestry activities require robust forest growth models to determine the potential timber production for different areas and to establish management strategies (Vanclay 1994). Here, we described the growth of the only forestry plantations of *R. rospigliosii* in the Andean



**Fig. 1** Scatter plots and regression lines with 95% confidence intervals of the absolute growth in diameter ( $D$ ), height ( $H$ ), and volume ( $V$ ) of *Retrophyllum rospigliosii* in plantations in Colombia



**Fig. 2** Predicted lines of the absolute growth in diameter ( $D$ ), height ( $H$ ), and volume ( $V$ ) of *Retrophyllum rospigliosii* in stands of three sites in Colombia (black line represents mean growth)

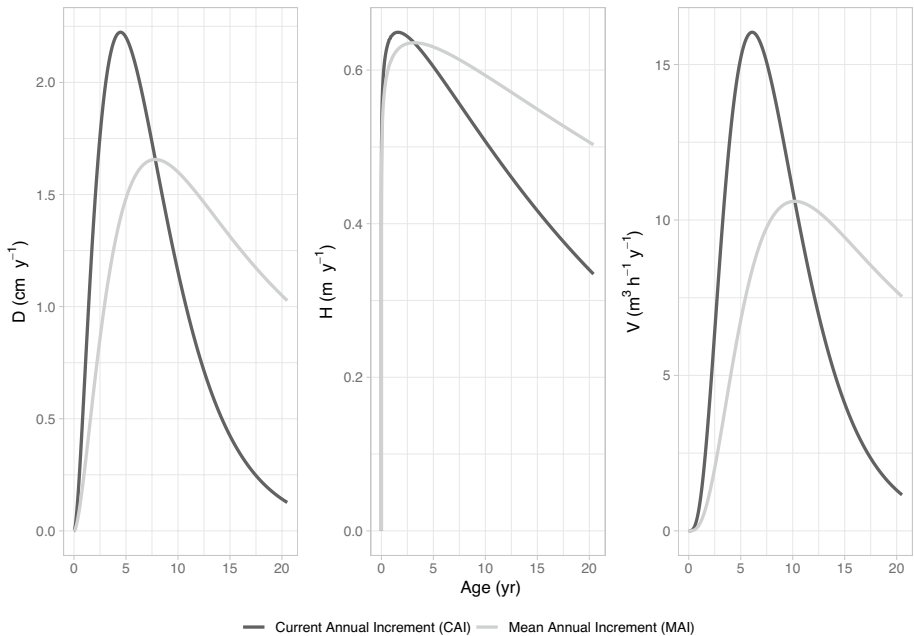
**Table 2** Summary of the Bayesian regression models of growth in diameter, height, and volume of *Retrophyllum rospigliosii* plantations in Colombia (all sites)

Model	Parameter	Estimate	Est. Error	<i>Rhat</i>	Bayesian $R^2$	RMSE
Diameter	<i>k</i>	0.23	0.02	1.00	0.99	6.72
	<i>w</i>	2.76	0.28	1.00		
	<i>A</i>	21.63	1.85	1.00		
	$\sigma$	0.95	0.00	1.00		
Height	<i>k</i>	0.04	0.00	1.00	0.99	3.29
	<i>w</i>	1.07	0.11	1.00		
	<i>A</i>	18.09	2.04	1.00		
	$\sigma$	0.90	0.00	1.00		
Volume	<i>k</i>	0.24	0.02	1.00	0.97	48.25
	<i>w</i>	4.36	0.43	1.00		
	<i>A</i>	159.41	13.80	1.00		
	$\sigma$	1.22	0.00	1.00		

**Table 3** Some silvicultural traits of the diameter, height, and volume of *Retrophyllum rospigliosii* plantations in Colombia, after 20 y of planting (all site models)

Model	Parameter	Value
Diameter	Asymptote (cm)	21.63
	$t_{99\% A}$ (years)	67
	Maximum <i>CAI</i> (cm yr <sup>-1</sup> )	2.24
	Age to reach maximum <i>CAI</i> (years)	4
	<i>MAI</i> (cm yr <sup>-1</sup> )	1.05
	Maximum <i>MAI</i> (cm yr <sup>-1</sup> )	1.68
	Age to reach maximum <i>MAI</i> (years)	8
	Age when diameter <i>CAI</i> =diameter <i>IMA</i> (years)	8
Height	Asymptote (m)	18.09
	$t_{99\% A}$ (years)	125
	Maximum <i>CAI</i> (m yr <sup>-1</sup> )	0.60
	Age to reach maximum <i>CAI</i> (years)	2
	<i>MAI</i> (m yr <sup>-1</sup> )	0.48
	Maximum <i>MAI</i> (m yr <sup>-1</sup> )	0.59
	Age to reach maximum <i>MAI</i> (years)	3
	Age when height <i>CAI</i> =height <i>IMA</i> (years)	3
Volume	Asymptote (m <sup>3</sup> ha <sup>-1</sup> )	159.41
	$t_{99\% A}$ (years)	110
	Maximum <i>CAI</i> (m <sup>3</sup> ha <sup>-1</sup> yr <sup>-1</sup> )	15.93
	Age to reach maximum <i>CAI</i> (years)	6
	<i>MAI</i> (m <sup>3</sup> ha <sup>-1</sup> yr <sup>-1</sup> )	7.69
	Maximum <i>MAI</i> (m <sup>3</sup> ha <sup>-1</sup> yr <sup>-1</sup> )	10.53
	Age to reach maximum <i>MAI</i> (years)	10
	Age when volume <i>CAI</i> =volume <i>IMA</i> (years)	10





**Fig. 3** Curves of current annual increments ( $CAI = dY/dt = f(t)$ , black line) and mean annual increments ( $MAI = D/t = f(t)$ , gray line) of diameter ( $D$ ), height ( $H$ ), and volume ( $V$ ) for *Retrophyllum rospigliosii* trees that grew in plantations in Colombia

region of Colombia. They were established and monitored using an extensive dataset covering information from two decades. We found that the BGNMM models adjusted for the growth data successfully. For all variables,  $D$ ,  $H$ , and  $V$ , the growth of *R. rospigliosii* in all the studied sites was slow and reached its maximum in  $CAI$  and  $MAI$  at very early ages. However, there were significant differences in growth among sites.

### Growth rates of *R. rospigliosii* and comparison with other species planted in Colombia

As it was previously suggested by Lonsdale et al. (2015), Bayesian models demonstrated their suitability for modeling forest growth parameters in this species (Fig. 1, Table 2). The models showed narrow confidence bands for mean values and accurate parameter estimators (Figs. 1, 2, Table 2). The growth curves generated with the BGNMM had biological meaning (Kiviste et al. 2002; Vanclay 1994), which showed sigmoid-shaped curves with inflection points that occurred for all variables at very early ages (Figs. 1, 2). This trend contrasted with the growth of this species in a natural forest. Dendrochronological studies in Peru showed a linear diameter growth trend up to 250 y (Becerra and Zevallos 2013).

Diameter increments reported for *R. rospigliosii* that grew in natural forests averaged  $0.33 \text{ cm yr}^{-1}$  and were at a maximum in the smaller diameter classes with values of  $0.48 \text{ cm yr}^{-1}$  (Luna 1981; Marín 1998). The increments found in this study were relatively higher. After 20 y of planting, trees reached an average of  $1.05 \text{ cm yr}^{-1}$  in  $D$ ,  $0.48 \text{ m yr}^{-1}$  in  $H$ , and  $7.69 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$  in  $V$  (Table 3). The estimated time to reach 99% of the asymptote

for *R. rospigliosii* was 67 y for *D*, 125 y for *H*, and 110 y for *V* (Table 3). The growth rates at which the plantations of *R. rospigliosii* reached the maximum *CAI* ( $dY/dt$ ) were very early (4, 2, and 6 years for *D*, *H*, and *V*, respectively). This fact implies that in the future, trees will accumulate additional sizes in terms of *D*, *H*, and *V*, at rates even lower than those observed currently.

Most of the native tree species planted in the mountains of Colombia outgrew *R. rospigliosii*. For instance, *Quercus humboldtii* and *Cedrela montana* exhibited diameter growth rates higher than  $1.0 \text{ cm yr}^{-1}$  and  $1.1 \text{ cm yr}^{-1}$ , respectively (Bare and Ashton 2016). *Cordia alliodora* that grew in plantations associated with coffee trees (*Coffea arabica*) at the age of 16 y had diameter growth rates of  $1.9\text{--}2.1 \text{ cm yr}^{-1}$  and height growth rates of  $0.9\text{--}1.3 \text{ m yr}^{-1}$  (Ospina et al. 2010). *Alnus acuminata*, another native species that is planted commonly in montane areas in monospecific, even-aged stands, and similar uses than *R. rospigliosii* attained 23.4 cm, 18.6 m, and  $255 \text{ m}^3 \text{ ha}^{-1}$  for mean *D*, *H*, and *V*, respectively in 25 y (del Valle and Gonzalez 1988) on the mean site index. Also, for *A. acuminata*, the mean height attained at 99% of the asymptote size was at the earliest age of 34 y. Thus, *A. acuminata* continued to grow at very high rates in mean diameter, height, and volume (del Valle and Gonzalez 1988). For these same three variables, at 20 y, *R. rospigliosii* reached 21 cm, 11 m, and  $153 \text{ m}^3 \text{ ha}^{-1}$  for mean *D*, *H*, and *V*, respectively (Table 3).

There is scanty literature available about the growth rates of other high mountain native species in monospecific, even-aged plantations that would allow us to compare with other tree species. Most of the literature of native species growing in these environments came from secondary forests that were under strong competition from other species. Additionally, there is no market in Colombia for native timber species that allow us to include prices to determine profitability of the different species. The financial viability of reforestation projects is necessarily influenced by forest yields, timber prices, and land costs (Samuelson 1995). We conclude that the low yields achieved by *R. rospigliosii* in even-aged monospecific plantations and difficulties to reach acceptable sizes for the sawmill industry show that this species is not very viable from a wood production perspective.

There is no other native coniferous species with wood-productive potential in Colombia. There are three exotic pine species well-adapted to the climatic, edaphic, and physiographic conditions of the high mountain areas of Colombia that are planted commonly for long-fiber wood production: *Pinus patula*, *Pinus tecunumanii*, and *Pinus maximinoi*. *P. patula* has been the most planted pine species in the Colombian highlands. Yet, it has been replaced gradually by the faster-growing *P. tecunumanii* and *P. maximinoi* (Hodge and Dvorak 2012). Several trials with these species in the highlands of Colombia showed *MAIs* in *D* at age 8 of  $2.4\text{--}2.7 \text{ cm yr}^{-1}$  and  $1.54\text{--}2.18 \text{ m yr}^{-1}$  in *H* (Hodge and Dvorak 2012). Trials close to 20 y carried out in Colombia showed that *P. patula* reached *MAIs* in *D* of about  $1.2 \text{ cm yr}^{-1}$  (Ospina et al. 2011) and *MAIs* in *V* of  $9\text{--}27 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$  (Cubbage et al. 2010; Lopez et al. 2010; Ramírez et al. 2020). These figures contrast with the *MAI* in *V* reached by *R. rospigliosii* of only  $7.69 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$  at 20 y (Table 3). Also, *Eucalyptus* spp are short fiber tree species growing in Colombia still faster than Pines. They attains *MAIs* in *V*, over  $30 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$  at the rotation age 8 y (Cubbage et al. 2010). Then, *R. rospigliosii* would not compete either with short-fiber or with the long-fiber tree species commonly planted in Colombia and in other tropical countries for pulp and paper.

As mentioned, *R. rospigliosii* reaches its maximum mean annual increment at a very young age (Fig. 3, Table 3). The biological rotation is usually defined as the age when the *MAI* in volume is maximized (Clutter et al. 1983; Vanclay 1994). In *R. rospigliosii* this occurs at only 10 y. At such an early age, the stand has about  $105.3 \text{ m}^3 \text{ ha}^{-1}$  and  $10.53 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$  of *MAI*. At age 10, the mean diameter reaches 16 cm. This diameter is lower

than the limit required by most commercial wood processing facilities (Moore and Cown 2015). Although virtually any size trees can be used as pulpwood, generally only trees over 18 cm in diameter are commercially sustainable for this use. This is because small logs generate important problems for handling and transport (Dykstra 2009). Additionally, the wood of *R. rospigliosii* presented difficulties in air drying because of the warping and cracking in the direction of the radius (Portillo et al. 2019). This wood was moderately susceptible to biodeterioration and to the attack of fungus that produces the blue stain (Arostegui and Sato 1970; Marín 1998). Therefore, it is not technically recommended for sawing. Some studies have suggested using *R. rospigliosii* wood in the pulp and paper industry (Vásquez-Correa and Alcántara-Vara 2009). In contrast to other Podocarpaceae species from Colombia that belong to the group of long fiber wood species (i.e., *Prumnopitys standleyi* and *Podocarpus oleifolius*) (Marín 1998), *R. rospigliosii* had fibers of about 2.3 mm in length (Vásquez-Correa and Alcántara-Vara 2009). However, fibers under 3 mm are considered short fibers (Richter et al. 2004).

The selected sites of this study were within the distribution limits of the species and relatively close to natural forests where the species occurs naturally. *R. rospigliosii* grows naturally in relatively low-fertility soils. However, a fertilization experiment found that the application of nitrogen, phosphorus, boron, and trace elements significantly increased the growth of this species (Ramírez et al. 2021). Thus, growth differences among sites may be related to soil fertility (i.e., differences in pH, cation exchange capacity, calcium, etc.). Table S2 presents the taxonomic classification of the Andisols of the three study sites and their main physical and chemical characteristics in the Ah horizons. In forestry, the quality of a site (SI) to produce wood is determined by the height of the dominant trees (top height of the 100–250 tallest trees per hectare) or the mean height at a certain age (Clutter et al. 1983). Using the mean height as the site index in the central panel of Fig. 2, we found that at 20 y, the site indexes (SI) of the studied plantations followed this order: Claridad (13 m) > La Suecia (12.5 m) > Santa Isabel (9 m). In the Ah horizon (humic horizon), the content of organic matter (%OM) and total nitrogen (%N) in the best SI (Claridad) was the lowest (11.2% OM and 0.72% N) compared with the other sites (Table S2). The other two sites had up to twice as much %OM and more %N. The Andisols in the humid tropical mountains have high contents of both %OM and %N, with very low bulk density (del Valle 1976; Roa-García et al. 2020). Claridad had about half the bulk density ( $0.44 \text{ g cm}^{-3}$ ) compared with Santa Isabel (Table S2). Thus, the lowest content of organic matter and total nitrogen means that organic matter decomposition and nitrogen mineralization are faster than at the other two sites. In Andisols of the high mountains of the Central Cordillera of the Colombian Andes, del Valle (1976) studied the relationship between the site index of *Cupressus lusitanica* with the nitrogen content in the Ah horizon and with the content of mineralized nitrogen by incubating soil samples at 20 °C for 15 d in 23 different stands. There was no statistically significant relationship between the growth of *C. lusitanica* and the %N total. But the mineralized N (sum of  $\text{NO}_3$ ,  $\text{NO}_2$ , and  $\text{NH}_4$ ) explained 58% ( $p < 0.01$ ) of the variance in the site index for this species. Therefore, nitrogen mineralization may have been higher at the Claridad site than at the other study sites. If we classify the fertility of the soils in the Ah horizon based on pH, P content, and the sum of the bases ( $\text{Ca} + \text{Mg} + \text{K} = \Sigma \text{ bases}$ ), Claridad also had the most fertile soil (pH = 5.5, P = 5 pmm,  $\Sigma \text{ bases} = 1.0\%$ ) (Table S2). Our fertility ranking followed this sequence from the most to the least fertile site: Claridad > Santa Isabel > La Suecia. There may be other physical variables of the soil, and the geomorphology not included in Table S4, that could limit the growth of *R. rospigliosii*. However, we discarded water availability

for three reasons: (i) the entire study area received high rainfall of 2170–2796 mm per year (Table 1), (ii) precipitation exceeded the potential evapotranspiration year-round (data not shown), and (iii) due to their low bulk density and their porous nature, these soils have a high water-holding capacity (Roa-Garcia et al. 2020).

Under natural conditions, in uneven-aged stands, the size of *R. rospigliosii* greatly exceeded 80 cm in diameter (Veillon 1962; Marín 1998). Veillon (1962) reported trees in the natural forests of Venezuela with total volumes of up to 5 m<sup>3</sup>. In contrast, the asymptotic volume in these plantations was only about 0.18 m<sup>3</sup> per tree (159.41 m<sup>3</sup> ha<sup>-1</sup>, Table 3). The large size attained by *R. rospigliosii* trees in natural uneven-aged mixed stands may indicate that this species was more productive due to reduced competition or facilitation processes (Pretzsch et al. 2017; Liang et al. 2016; Jactel et al. 2018). For instance, in a mixed experimental stand in Quindío (Colombia), where *R. rospigliosii* grew along with a *Eucalyptus* species (1111 trees per ha of which about 280 were *R. rospigliosii* and 831 were *Eucalyptus*), this species reached higher diameter, height and volume than that reported in this study for planted stands after 20 y (44 cm in *D*, 31 m in *H*, and 197 m<sup>3</sup> ha in *V*. Data not published). Our results indicate that pure plantations of *R. rospigliosii* did not exhibit the expected growth, contrasting with other native or exotic species commonly cultivated in Colombia for commercial purposes. Despite its limited potential for wood production, this species attains the largest sizes in diameter, height, and volume in the high mountains of Colombia. Thus, relict forests containing *R. rospigliosii* and the gigantic trees that persist should be preserved and recognized as monumental trees due to their profound aesthetic, cultural, and scientific values. Given the annual nature of the tree rings in this species (Escobar Chimbaco et al. 2023), this species stores valuable information about past climatic conditions of the tropical Andes that should be studied.

## Conclusions

Our findings indicated that *R. rospigliosii* plantations did not grow as well as expected compared to other native or exotic species commonly planted in Colombia. The low growth and the difficulty to reach adequate sizes for commercialization seem to prevent a long-term replacement of exotic species by the native *R. rospigliosii*. Given the vulnerability of this species, restoration and conservation programs should be a priority to maintain the few remaining relicts of forests where this species grows.

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## Declarations

**Conflict of interest** The authors declare no conflict of interest in connection with the work submitted.

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