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Novel Yield Model of *Pinus patula* Schltdl. & Cham. Growth near the Ecological Limit in Northwestern Peruvian Andes

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Abstract: Forest plantations with exotic species in the northwestern Peruvian Andes have brought different ecosystem benefits. The wood productivity in this Páramo region is directly related to the great availability of water from abundant rainfall compared to other regions of the semi-arid Andes. To address the lack of information on forest inventories of plantations in the Páramo region, this study used annual growth rings (dendrochronology) to build new models of tree growth and wood productivity and compared 22-year-old *Pinus patula* plots with thinning and unthinning treatments. Our results show that late thinning, removing 63% of stem density in the 15th year, does not have significant effects on the diameter increase or stand-level productivity. For these plantations, we propose a management rotation of 21 years with a first thinning treatment (35%) at 5 years and a second thinning treatment (50%) at 12 years. Production at 21 years is expected to be between 194.6 m^3 ha^{-1} and 504.6 m^3 ha^{-1} for stands with low and high wood productivity, respectively. Tree-ring studies are potentially useful for monitoring forest plantations and provide an alternative method for forest managers who use allometric equations to predict silvicultural treatments and to propose management guides for plantations.

Keywords: biological rotation age; tree-ring; Páramo; forest management; thinning application

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1. Introduction

Páramos are high-altitude grasslands that occur in equatorial America between 3000 and 5000 m [1,2]. Patches of upper montane forests, dominated by *Polylepis*, occur at altitudes up to 3500–4000 m above sea level [3]. An open discussion still exists regarding the extent to which Páramo grasslands should be considered former forest lands or natural grasslands [4,5]. In the context of forest ecosystem rehabilitation [6,7], the planting of alien tree species has been reported to favor the regeneration of secondary forest species, leading to increased diversity levels in comparison to unforested control sites [8,9]. Although, in some cases, the planting of alien tree species can alter hydrological regimes, modify soil nutrients, or change local biotic communities [10].

During late 1960s, the Peruvian government established an international cooperation agreement to promote socioeconomic development in the Department of Cajamarca, Northwestern Peruvian Andes, named the Granja Porcón project [11]. Since 1974, this agreement has promoted a massive afforestation process on private and communal lands for logging production and wood pulp [11,12]. Between 1982 and 1989, a 3500-hectare pilot industrial afforestation was installed in the Northwestern Peruvian Andes, located in the Páramo region [13,14]. As in other afforested areas of the Páramo in the Peruvian Andes, such as in Venezuela, Colombia, and Ecuador [15], the plantation's forest productivity and ecosystem services are still scarcely studied (but see [12,14,16–18]).

There are ongoing discussions in the Páramo region about afforestation and its possible influence on the net losses of water for irrigation or area losses for native grassland regeneration [19,20]. The Granja Porcón project is one of the most successful forest plantation models in the region [11,12]. This project is known for its territorial management model that has contributed to the strengthening of the local market, through a social enterprise that guarantees labor stability, gender equality, and distribution of profits between economic, social, and environmental dimensions [18]. The Granja Porcón forest represents a wood resource transformed in situ with added value for local communities using tree species such as *Pinus patula* Schiede ex Schltdl. & Cham. and *Pinus radiata* D. Don. [12,14]. In addition, the forest provides valuable ecosystem services such as tourism and non-timber forest products, including mushrooms [11,13,14,18,21,22]. Furthermore, despite the alteration of the native landscape, pine forests have halted soil erosion and reduced the pressure to obtain wood from relict natural forests [14].

Exotic pine plantations such as *P. patula* are widespread in the Andean region of South America [16]; however, there are no studies from the Páramo region on the production [20] or management [21] of exotic pine plantations. *P. patula* is a native species of the subtropical regions of Mexico. It grows at latitudes between 16° N and 24° N, at altitudes between 1500 and 3100 m a.s.l., and in sites with annual precipitation from 600 to 2500 mm [23]. In Granja Porcón, the production of wood in some areas planted with high-quality clones imported from Zimbabwe can reach volumes of 410–560 m^3 ha^{-1} [24]. The success of *P. patula* plantations, despite the growth of trees near their ecological limit (7° S, 3000–4000 m a.s.l.), is due to the amount of basin precipitation. Here, basin precipitation is >1000 mm/year compared to 100–700 mm/year of rain in most of the semi-arid Peruvian Andes [12]. The growth projections for *P. patula* in this region were based on 20-year cutting cycles with thinning starting at year six [11,13,17]. However, this plan was not fulfilled in many of the plots projected for felling [25], and only some permanent plots received continuous monitoring [26]. In addition, forest inventories carried out to adjust the growth models have been poorly developed or are not readily available (but see [14,27]).

Growth monitoring within and between trees depends on periodic forest inventories that can be difficult to assess annually [28]. Tree-ring-based studies (dendrochronology) are a potential alternative that can reduce data gaps on the growth of exotic plantations in the Andean regions [29]. Tree-ring analysis has the advantage of offering annual resolution and high sensitivity to analyze different growth parameters (e.g., diameter, volume, density, and biomass) that are usually considered to evaluate management and production responses [29–36]. The results of these analyses are also useful for adjusting future cutting cycles and silvicultural treatments [37].

In the present study, we analyze the annual growth of *P. patula* near its ecological limit in the Northwestern Peruvian Andes using tree-ring measurements. The objectives were: (1) to evaluate the growth of *P. patula* at the stem and stand levels by comparing thinned plots with unthinned plots, (2) to provide an alternative method for forest managers who use allometric equations to predict silvicultural treatments, and (3) to propose a management guide for *P. taeda* plantations in the Peruvian Páramo regions for future productive plantations.

2. Materials and Methods

2.1. Study Area and Experimental Design

The experimental area was located in the Agrarian Cooperative "Granja Porcón" Farm, Cajamarca Department, Northwestern Peru (Figure 1A). Cajamarca is mainly a rural department that is considered to be one of the poorest areas in Peru despite the high economic growth that mining has brought to the region [18]. The area is characterized as a very humid Montane Tropical forest (under the Holdridge classification), with average annual rainfall and temperature measuring 1625 mm and 10 °C, respectively (Figure 1B). The soil is classified as cambisol [38] derived from volcanic rocks (61%) and sandstones (35%) [14]. The dominant plant formation is "Páramo", characterized by grass species such as *Agrostis tolucensis*, *Stipa brachyphylla*, *Calamagrostis tarmensis*, *C. macrophylla*, *C. rigescens*, and *Festuca* sp., among others [24]. Natural tree vegetation is preferentially located near watercourses (e.g., *Alnus acuminata*, *Polylepis racemosa*) [14,24].

More than eight thousand hectares of pine, consisting mainly of *Pinus patula* and *Pinus radiata*, were planted in a triangular system at 3 m spacing (1283 trees ha^{-1}) between 1983 and 1995 [13,24]. The first project was "Proyecto Ploto de Forestación—PPF" with 3572 hectares of pine planted between 1983 and 1989, followed by a second project named "Proyecto Forestal Industrial de la Sociedad Paramonga" with 4124 hectares of pine planted between 1989 and 1993 [24]. In this study, two *P. patula* stands were selected based on their initial moderate–good potentiality of use for timber production forest areas in the Tropical Peruvian Andes [11]: (i) the Cushuro area (7°00′ S, 78°40′ W; 3460 m a.s.l.; slope 35%) including 10.5 ha of *Pinus taeda* trees and (ii) the Enterador area (7°00′ S, 78°40′ W; 3561 m a.s.l.; slope 20%) including 9.2 ha of *Pinus taeda* trees with a selective thinning treatment that removed 63% (smaller *P. patula* trees) of the stand density (trees ha^{-1}) in the 15th year (June 2005).

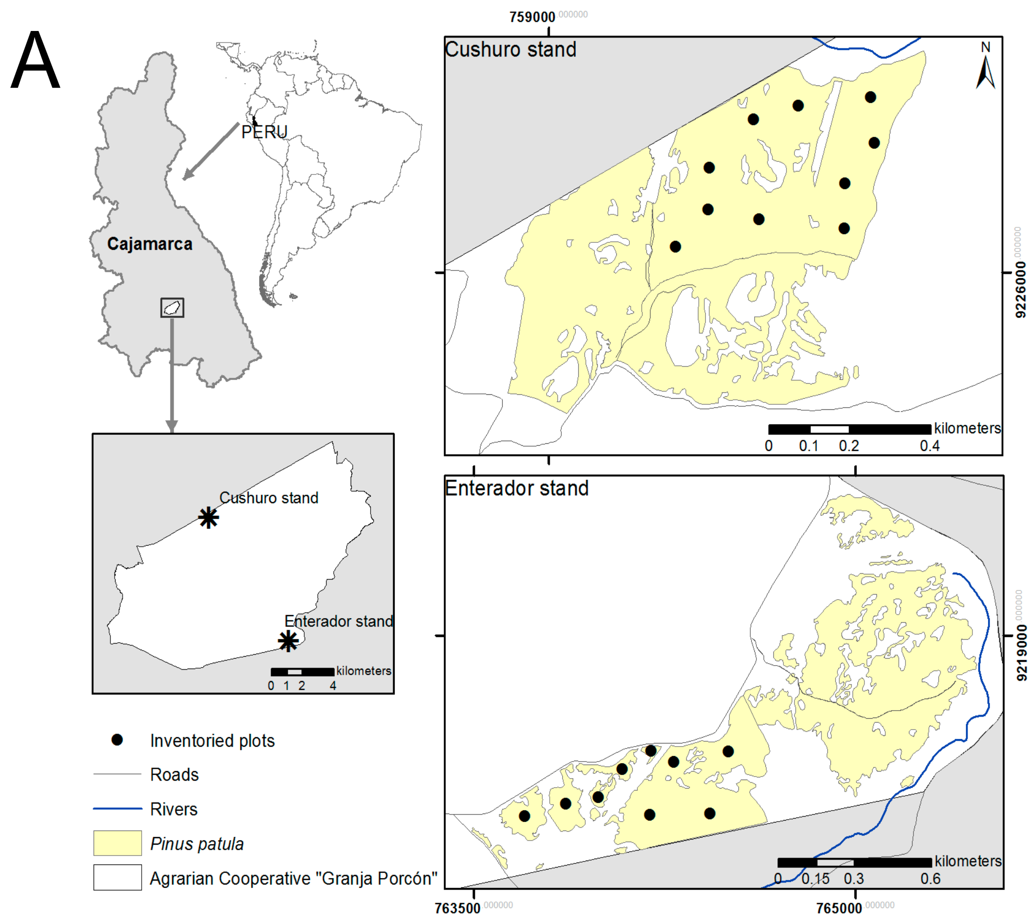

Figure 1. *Cont.*

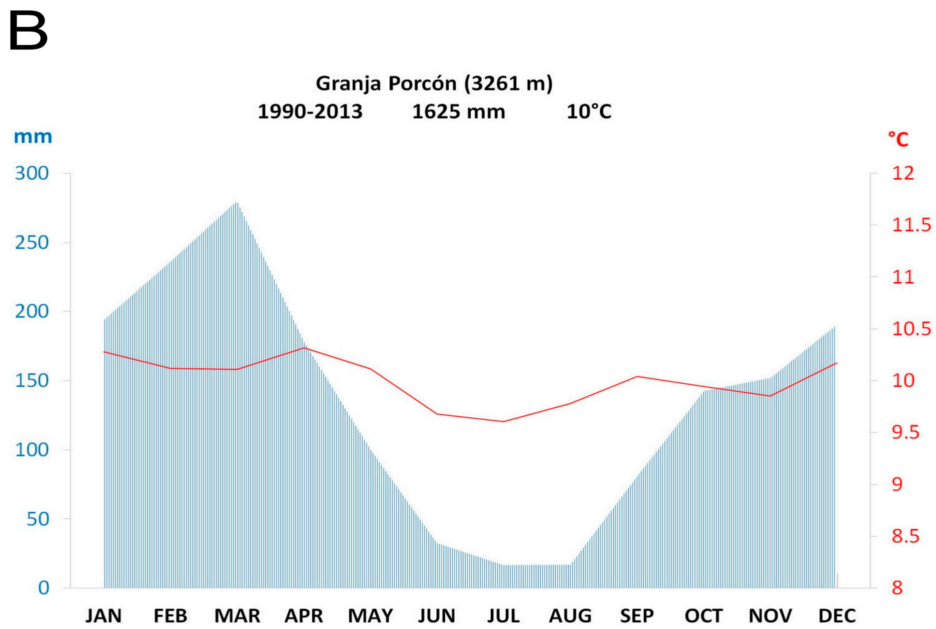

Figure 1. (**A**) Location of Cushuro's unthinned area and Enterador's thinned area and (**B**) climate variability (1990–2013) [39].

2.2. Wood Sample Collection and Preparation

For the inventory, a coefficient of variation of 21% was considered based on the diameter at breast height (DBH, 1.3 m) of felled trees registered in the most recent management plan of the company [25], with an admissible relative error of 10% and a plot size of 500 m^2 [40]. Ten and nine experimental plots were randomly allocated for the Cushuro and Enterador areas, respectively (Figure 1A). In all plots, the DBH and total heights of the trees were measured using a diameter tape and Bitterlich relascope, respectively, which were then used to establish diameter classes and average heights. The characteristics of the sampled stands are summarized in Table 1.

Table 1. Characteristics of the sampled stands. Growth data based on measurements taken outside of the bark. Standard deviations are provided in brackets.

Stand Name	Age (Years)	Stand (*n* of Plots) *	Density (Trees ha^{-1})	Mortality (%)	Basal Area (m^2 ha^{-1})	Volume (m^3 ha^{-1})	Average DBH (cm)	Average Total Height (m)
Cushuro	22	Unthinned (10)	1140	11	98	631.56	30.5 (6.8)	22.8 (2.1)
Enterador	22	Thinned (9)	380	8	43	270.18	37.6 (4.7)	20.5 (1.6)

* Sampling strategy [40]: $n = \frac{t^2CV^2}{E^2+\frac{4CV^2}{N}}$, where: n = number of sample plots in the stand; t = Student's t, in the forest inventory t = 2 for a probability of 95%; CV = coefficient of variation; E = maximum permissible relative error (10% for maximum reliability inventories); N = number of 500 m^2 plots that make up the stand.

Thirty-five *P. patula* trees classified as dominant and representative of each stand (based on the mean wood volume from the inventory) were selected. The number of *P. patula* trees was established with a 95% confidence level ($Z\alpha$ = 1.96) and with an acceptable sampling error limit of 10% (e = 0.1) (Table 2). Four core samples per tree were taken at breast height using an increment borer of 0.5 mm in diameter [41]. The increment cores were glued onto a wood support and polished with sandpaper (120–600 grains $inch^{-2}$) to distinguish the annual tree ring boundaries. The wood cross-sections were scanned, and the tree ring widths were measured using the software Image Pro-plus v. 4.5 (0.001 mm precision).

Table 2. *P. patula* sample trees (February 2013) based on outside bark volume from inventoried data (January 2013). Standard deviations are provided in brackets.

Diameter Classes	Unthinned				Thinned			
	Inventoried Trees	Volume of Inventoried Trees (m^3)	Cored Trees (*n*)	Volume of Cored Trees (m^3)	Inventoried Trees	Volume of Inventoried Trees (m^3)	Cored Trees (*n*)	Volume of Cored Trees (m^3)
(−∞, 10)	6	0.028 (0.01)	0	-	0	-	0	-
[10, 20)	26	0.159 (0.06)	2	0.167 (0.06)	0	-	0	-
[20, 30)	223	0.393 (0.11)	9	0.381 (0.06)	10	0.371 (0.09)	2	0.375 (0.05)
[30, 40)	282	0.666 (0.14)	17	0.66 (0.04)	105	0.638 (0.11)	21	0.642 (0.05)
[40, 50)	37	1.034 (0.19)	2	1.111 (0.05)	56	0.893 (0.12)	11	0.913 (0.04)
[50, ∞)	0	-	0	-	2	1.339 (0.08)	0	-
Total	574	0.554 (0.24)	35	0.579 (0.32)	173	0.711 (0.19)	35	0.65 (0.26)

The number of cored trees (n) was calculated using the equation [42]: $n = \frac{N.SD^2 Z\alpha^2}{e^2(N-1)+SD^2 Z\alpha^2}$, where: N = number of inventoried trees; SD = standard deviation of outside bark volume; $Z\alpha$ = score for confidence level (95%); e = sampling error. Outside bark volume of trees (V in m^3) was calculated using the equation [43]: $V = \frac{\pi}{40000}\left[d_b d_t + \frac{(d_b-d_t)^2}{2r+1}\right]H$, where: d_b = diameter at the trunk base (cm); d_t = diameter at the trunk top (cm); H = total trunk height (m); r = taper factor (0.5, paraboloid). The diameters and heights were measured using a Bitterlich relascope.

2.3. Stem Analysis

The annual tree rings of the cores were synchronized and visually cross-dated to confirm the stand age. The dating accuracy sampled was checked with the computer program COFECHA [44]. Then, the annual diameter increment of *P. patula* trees was reconstructed using the thickness measurement of each annual tree ring. In the sequence, the wood volume increment was adjusted using the equation [34]:

$$V_i = a + bDBH^c TRW^d \quad (1)$$

where: V_i = inventoried wood volume in the 10th, 15th, and 22nd years; DBH = tree diameter in year t; and TRW = tree ring width in year t. This model was used to calculate the volume of trees at different ages (m^3 year^{-1}), which was considered for the subsequent stand analysis using the Chapman nonlinear model (see Section 2.4). The stem diameter and height distribution and the DBH and volume growth curves of *P. patula* trees were also obtained for both the unthinned and thinned stands.

2.4. Stand Analysis

The diameter and wood volume cumulative growth of *P. patula* for each stand were fitted using the Chapman nonlinear model [45–48]:

$$GV_t = a\left(1 - e^{(-bt)}\right)^c \quad (2)$$

where: GV_t = growth variable in year t; GV = diameter (DBH) (cm) or volume (V) (m^3; calculated using Equation (1)); and a, b, and c = parameters.

Based on the modeled individual tree growth data, the current (CAI) and mean (MAI) annual diameter and wood volume increment for each *P. patula* stand were obtained using:

$$CAI\_GV_t = GV_t - GV_{t-1} \quad (3)$$

$$MAI\_GV_t = \frac{GV_t}{t} \quad (4)$$

The biological rotation age (BRA) of *P. patula* trees was estimated by intersecting the current and mean annual wood volume increments. The potential thinned ages were also interpreted using the growth increment curves of DBH and volume.

Then, the current annual increment (CAI) of the basal area and wood volume per hectare was calculated using:

$$CAI\_GVh_t = 0.001(SD_{trees}\,\frac{m\%_t}{100}\,\frac{T\%_t}{100}\,(GVh_t - GVh_{t-1})) \tag{5}$$

where: CAI_GVh_t = growth variable per hectare in year t; GVh = basal area (m^2 ha^{-1}) or volume (m^3 ha^{-1}); SD_{trees} = stand density (1283 trees ha^{-1}); $m\%_t$ = % of stand density after mortality in year t; and $T\%_t$ = % of stand density after thinning in year t. Furthermore, the relationship between the volume increment per hectare (m^3 ha^{-1} $year^{-1}$) and the basal area (m^2 ha^{-1}) was analyzed.

2.5. Wood Production Simulation

For the wood production simulation, the calculated tree wood volume per hectare (m^3 ha^{-1}) data was used to propose a management guide for *P. patula* near its ecological limit by readjusting the parameters of the Chapman nonlinear model 2. The management guide was proposed, based on the forest management practices applied in *P. patula* plantations in the Andes regions [14,16,29], using the following parameters: initial density (1283 trees ha^{-1}); mortality (9%); first thinning at 5 years (35%); second thinning at 12 years (50%); and final density (380 trees ha^{-1}). The fitting analysis for items 2.3–2.6 was performed using the software Origin 2018 [49].

3. Results

3.1. Stem Growth

More than one half of the stem height frequencies of *P. patula* trees in the unthinned stand showed a displaced distribution for heights ≥ 20 m, whereas in the thinned stand, almost 50% of the stems had heights between 18 and 22 m (Figure 2A). The stands of unthinned and thinned *P. patula* trees showed more than 50% of their diameter frequencies between 20 and 40 cm and between 30 and 40 cm, respectively (Figure 2B). The unthinned plots had trees with smaller diameters but higher heights than the trees from the thinned plots, which measured 30.5 cm and 22.8 m compared to 37.6 cm and 20.5 m, respectively (Table 1).

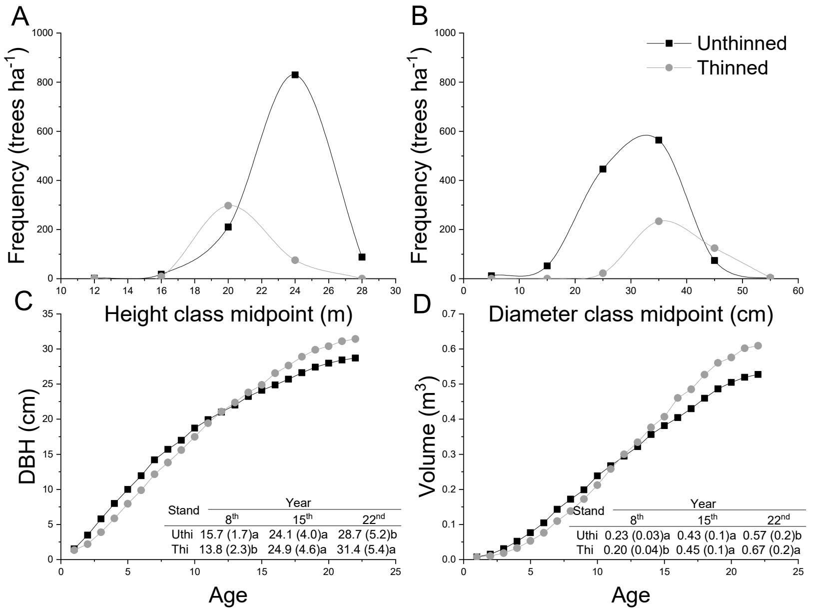

Figure 2. (**A**) Stem diameter, (**B**) height frequency, (**C**) DBH, and (**D**) wood volume of 22-year-old *P. patula*. The lower right corner shows the DBH and volume pairwise comparison (Tukey test) in different years. Different letters (a, b) indicate statistically significant differences between the thinned and unthinned plots in years 8, 15, and 22 ($p < 0.05$).

The cumulative DBH (Figure 2C) and wood volume (Figure 2D) curves of the unthinned (NThi) and thinned (Thi) *P. patula* trees showed significant growth differences in the 8th (NThi higher than Thi) and 22nd year (Thi higher than NThi). No growth differences were observed in the 15th year.

3.2. Stand Growth

A comparison of the unthinned and thinned stands indicated that the *P. patula* trees from the 22-year rotation did not show differences of up 56% (55 m^2 ha^{-1}) and 57% (361.38 m^3 ha^{-1}) in stand basal area or wood volume, respectively.

Regarding the wood production of 22-year-old *P. patula* trees, the unthinned stand produced 98 m^2 ha^{-1} and 632 m^3 ha^{-1}, whereas the thinned stand produced 43 m^2 ha^{-1} and 270 m^3 ha^{-1} (Figure 3A,B and Table 1). Higher mortality was observed in the unthinned stands (11%) compared to the thinned stands (8%) (Table 1). The mean annual increment of the basal area was the same for both stands (3.4 m^2 ha^{-1} $year^{-1}$), whereas the mean annual increment of volume was slightly higher for the unthinned stands (24.8 m^3 ha^{-1} $year^{-1}$) compared to the thinned stands (23.6 m^3 ha^{-1} $year^{-1}$).

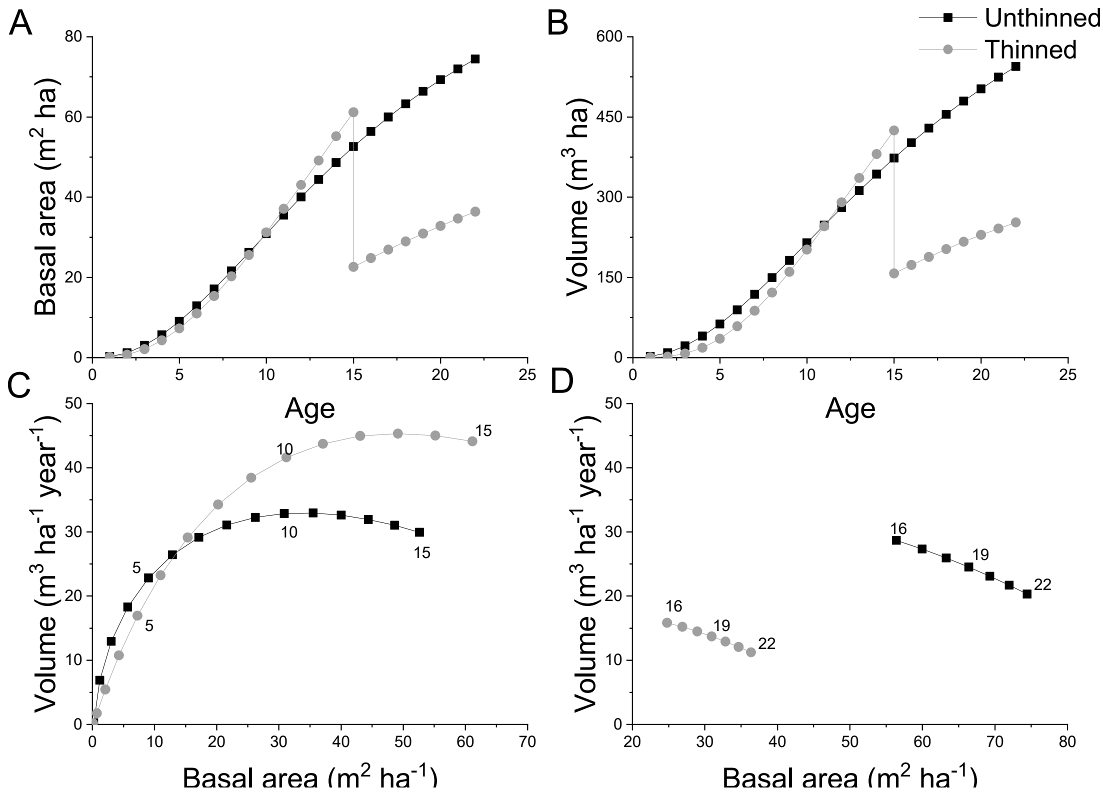

Figure 3. (**A**) Basal area and (**B**) wood volume per hectare in relation to tree age; the relationship of wood volume annual increment and basal area (**C**) before and (**D**) after thinning application in the 22nd year for *P. patula* trees. Symbols represent years for each stand.

The CAI wood volume of *P. patula* trees increased up to 29.9 m^3 ha^{-1} $year^{-1}$ in the unthinned stands and up to 44.1 m^3 ha^{-1} $year^{-1}$ in the thinned stands until the 15th year of the thinning application (Figure 3C). The CAI wood volume also increased up to 20.3 and 11.2 m^3 ha^{-1} $year^{-1}$ between the 16th and 22nd year (Figure 3D) in the unthinned and thinned stands, respectively. The results also showed that the CAI volume decreased in both stands when the basal area reached 20 m^2 ha^{-1}, but the decrease was more significant in the unthinned stands at 8 years (Figure 3C). No significant differences in the increment pattern were found after thinning (Figure 3D). After the 15th year-thinning application, the CAI volume curve decreased by 8.4 m^3 ha^{-1} in the unthinned stands and by 4.6 m^3 ha^{-1} in the thinned stands between the 16th year and the 22nd year (Figure 3D). The maximum wood volume of *P. patula* trees was 32.9 and 45.32 m^3 ha^{-1} for the unthinned and thinned stands in the 11th and 13th year, respectively (Figure 3C).

The intersection of the current (CAI) and mean (MAI) curves was reached at five and nine years for DBH and 18 and 22 for wood volume in the unthinned and thinned stands, respectively (Figure 4). The DBH increment at the CAI–MAI intersection was higher for the unthinned stands (2 cm) compared to the thinned stands (1.83 cm) (Figure 4). The wood volume at the CAI–MAI intersection was higher for the thinned stands (0.026 m^3) compared to the unthinned stands (0.022 m^3) (Figure 4). The DBH of trees at the biological rotation age (BRA) of the *P. patula* trees, represented by the CAI–MAI volume intersection, was 26.6 cm (18th year) and 31.42 cm (22nd year) for the unthinned and thinned stands, respectively. The unthinned stands reached a maximum DBH increment per tree (2.17 cm) at three years and a maximum volume increment per tree (0.029 m^3) at 11 years (Figure 4A). For the thinned stands, the maximum DBH (2.06 cm) and volume (0.038 m^3) increment per tree were reached at five and 13 years, respectively (Figure 4B).

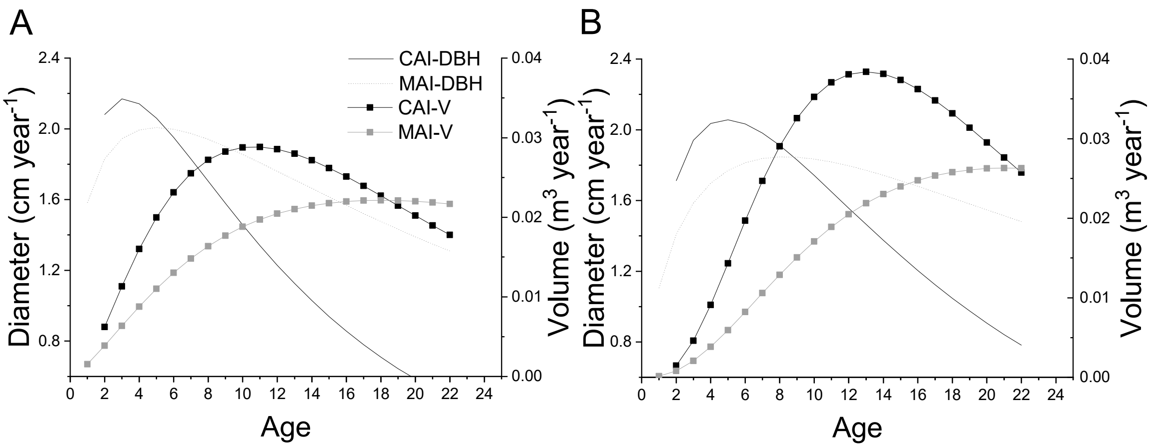

Figure 4. Current (CAI) and mean (MAI) annual diameter and wood volume increments of *P. patula* trees: (**A**) unthinned and (**B**) thinned stand.

3.3. Allometric Equation Using Tree-Ring Parameters

The model (Equation (1)) used to estimate the wood volume of *P. patula* trees at different ages (Section 2.3), based on the TRW and DBH obtained by dendrochronological methods, was significant ($p < 0.01$) for the scaling parameters *a* (intercept), *b* (slope), and *c* (associated with DBH). The model was not significant ($p = 0.52$) for the parameter *d* (associated with TRW) (Table A1 and Figure A1). The model explained 95% (Adj. R^2) of the variation in wood volume at different ages by the TRW and DBH, and the RMSE was 10% of the mean (Table A1). The value of the coefficient of determination, r^2, was 0.95 and the error of the mean, Sx, was 0.04 m^3 (Figure A1C). The residuals showed a random distribution along the fitted values, which indicated that the regression model specifies an adequate relationship between the observed and estimated wood volume at different ages (Figure A1D).

The Chapman nonlinear Equation (2) [48] explained 87% and 88% (Adj. R^2) of the observed variation in cumulative DBH and 74% and 73% in cumulative volume of the unthinned and thinned stands, respectively (Figure A2 and Table A2). All equations were significant for the scaling parameters *a*, *b*, and *c* ($p < 0.0001$). The value of the RMSE and mean percentage error for DBH were 3.18 cm and 17% and 3.45 cm and 18% for the unthinned and thinned stands, respectively. The value of the RMSE and mean percentage error for tree volume were 0.09 m^3 and 39% and 0.12 m^3 and 44%, for the unthinned and thinned stands, respectively. The residuals of the data estimated using Equation (2) showed a heteroscedastic pattern, where increases were observed with higher tree DBH and volume values at >20 cm and >0.35 m^3, respectively (Figure A2).

The DBH and wood volume simulations of three growth classes of *P. patula* trees identified that Equation (2) was significant ($p < 0.001$) for all parameters (Table 3). The simulation for each growth class (Table 3) showed improvements in the statistics compared to the fit cumulative tree DBH and volume of the unthinned and thinned stands (Table A2). The RMSE of the growth equations varied between 1.68 and 2.13 cm for DBH and between 0.04 and 0.08 m^3 for volume. The mean percentage error varied between 8.94% and 13.15% for DBH and between 17% and 23% for volume. The adequacy of Equation (2) for each growth class was confirmed by the random residual distribution along the estimated DBH and volume (Figure A3). However, slight decreases were observed with higher DBH and volume values of C1 > 16 cm and >0.25 m^3, C2 > 25 cm and >0.5 m^3 and C3 > 25 cm and >0.6 m^3, respectively (Figure A3).

Table 3. Parameters and fit statistics for Equation (2) that was used to estimate the cumulative diameter and wood volume of three growth classes of *P. patula* trees. C1: 15–24 cm; C2: 25–34 cm; C3: 35–45 cm.

Model	Growth Variable	Growth Class	Parameter	Estimate	SE	*t*-Value	*p*-Value	Adj. R^2	Fit Statistics RMSE	|E|%
Equation (2)	DBH	C1	a	23.560	0.674	35.0	<0.0001	0.91	1.95 cm	13.15
			b	0.134	0.014	9.4	<0.0001			
			c	1.365	0.120	11.4	<0.0001			
		C2	a	37.961	0.746	50.9	<0.0001	0.97	1.68 cm	8.94
			b	0.090	0.005	20.0	<0.0001			
			c	1.382	0.042	33.2	<0.0001			
		C3	a	50.482	2.400	21.0	<0.0001	0.97	2.13 cm	9.23
			b	0.087	0.010	9.1	<0.0001			
			c	1.518	0.101	15.1	<0.0001			
	Volume	C1	a	0.417	0.049	8.5	<0.0001	0.79	0.05 m^3	22.86
			b	0.100	0.022	4.6	<0.0001			
			c	2.502	0.443	5.6	<0.0001			
		C2	a	0.845	0.045	18.9	<0.0001	0.95	0.04 m^3	17.02
			b	0.095	0.008	12.5	<0.0001			
			c	3.109	0.205	15.2	<0.0001			
		C3	a	1.376	0.166	8.3	<0.0001	0.94	0.08 m^3	18.56
			b	0.102	0.018	5.6	<0.0001			
			c	3.556	0.582	6.1	<0.0001			

SE standard error, RMSE root mean square error, |E|% mean percentage error.

3.4. Growth Simulation

Based on the proposed 21-year plantation management guide, the basal area and wood volume of *P. patula* trees per hectare for each growth class were, respectively: 25.4 m^2 ha^{-1} and 194.6 m^3 ha^{-1} for C1; 44 m^2 ha^{-1} and 316.1 m^3 ha^{-1} for C2; and 68.3 m^2 ha^{-1} and 504.6 m^3 ha^{-1} for C3 (Figure 5A,B). The basal area and wood volume of *P. patula* trees at final cutting for each growth class were, respectively: 14 m^2 ha^{-1} and 113.9 m^3 ha^{-1} for C1; 27.4 m^2 ha^{-1} and 203 m^3 ha^{-1} for C2; and 44.6 m^2 ha^{-1} and 333.2 m^3 ha^{-1} for C3. The cutting cycle included two partial productions at the 5th (35% stand density) and 12th (50% stand density) year thinning, which measured, respectively: 2.5 m^2 ha^{-1}–16.4 m^3 ha^{-1} and 9 m^2 ha^{-1}–64.3 m^3 ha^{-1} for growth class C1; 2.8 m^2 ha^{-1}–16.7 m^3 ha^{-1} and 13.8 m^2 ha^{-1}–96.3 m^3 ha^{-1} for growth class C2; and 3.5 m^2 ha^{-1}–21.3 m^3 ha^{-1} and 20.3 m^2 ha^{-1}–150.1 m^3 ha^{-1} for growth class C3. These values were calculated based on the best experimental conditions (see Sections 2.4 and 3.3) and Páramo regional information [13,16].

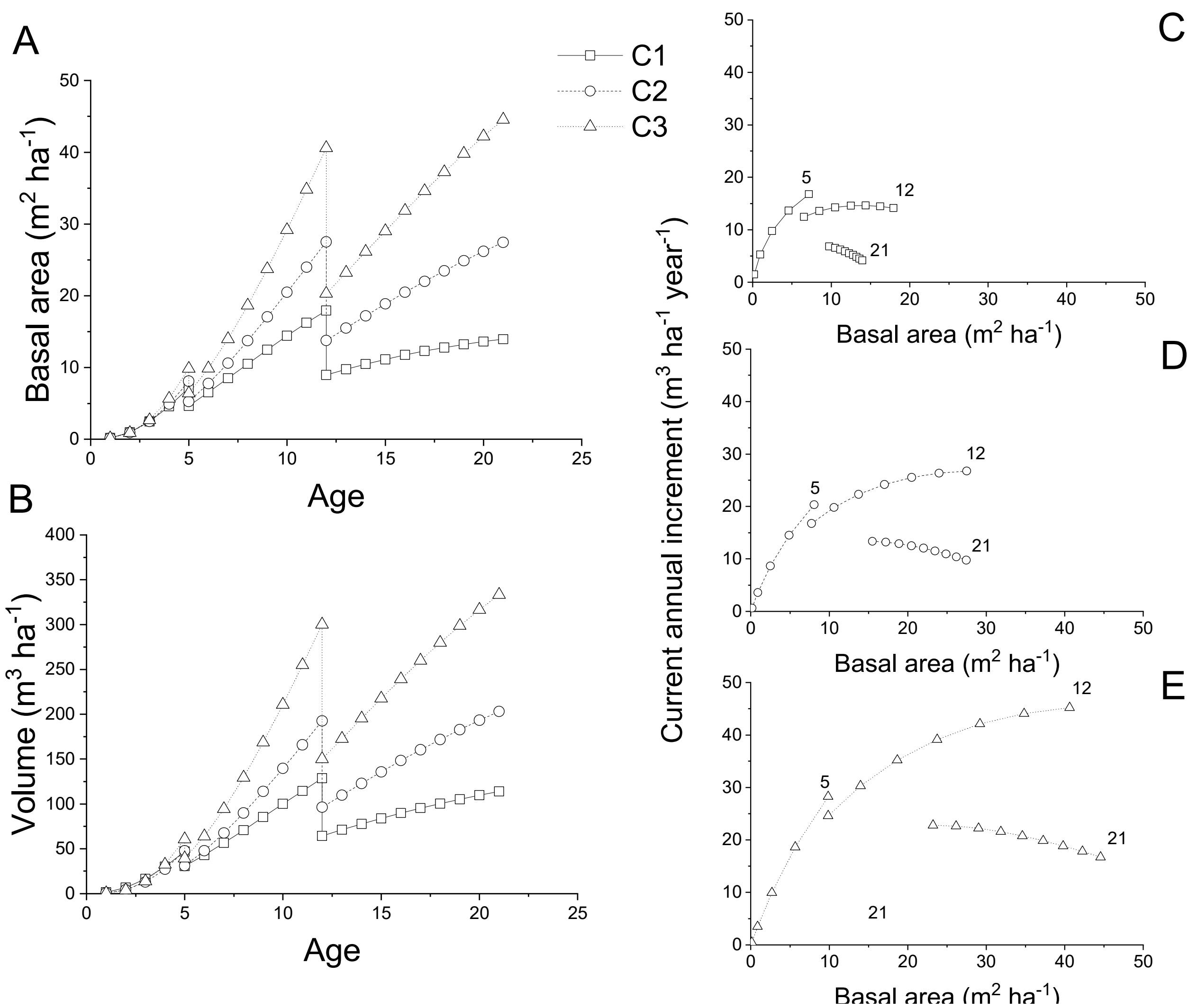

Figure 5. *Pinus patula* trees (**A**) basal area and (**B**) wood volume per hectare for three growth classes modeled for a 21-year-cutting cycle (1283 trees ha^{-1} initial stand density; thinning applied in the 5th, and 12th year; 380 trees ha^{-1} final stand density) and relationship of wood volume annual increment and basal area (**C**–**E**). (**C**) C1: 21.6, (**D**) C2: 30.3, and (**E**) C3: 38.7 cm DBH trees at cutting cycle.

The site production capacity for each growth class was: 1.2 m^2 ha^{-1} year^{-1} and 9.3 m^3 ha^{-1} year^{-1} for C1 (Figure 5C); 2.1 m^2 ha^{-1} year^{-1} and 15 m^3 ha^{-1} year^{-1} for C2 (Figure 5D); and 3.3 m^2 ha^{-1} year^{-1} and 24 m^3 ha^{-1} year^{-1} for C3 (Figure 5E). Significant differences in the CAI volume increment pattern, after the first thinning, were found (Figure 5C–E). After the 5th year thinning application, when the basal area reached 7.1 m^2 ha^{-1}, 8.1 m^2 ha^{-1} and 9.9 m^2 ha^{-1} for C1, C2, and C3, respectively (Figure 5C–E), the CAI volume curve between the 6th and 12th years increased by 1.7 m^3 ha^{-1} for C1, 10 m^3 ha^{-1} for C2, and 20.6 m^3 ha^{-1} for C3. After the 12th year thinning application, the CAI volume curve between the 13th and 21st years decreased by 2.7 m^3 ha^{-1} for C1, 3.6 m^3 ha^{-1} for C2 and 6.1 m^3 ha^{-1} for C3. The maximum wood volume of *P. patula* trees was 16.8, 26.7, and 45.2 m^3 ha^{-1} for C1, C2, and C3 in the 5th, 12th, and 12th year, respectively (Figure 5C–E).

4. Discussion

4.1. Stem Growth

The growth of 22-year-old *P. patula* trees showed differences in the distribution of height frequency as an effect of thinning treatment after removing 63% of the stem density.

Similar results have been reported in 14-year-old *P. patula* plantations treated with low thinning intensity, removing 35% of stems [50], and high thinning intensity, removing between 55 to 70% of stems [51]. Our results showed that most of the trees in the unthinned stands presented a non-normal height distribution with heights higher than 20 m, whereas trees in the thinned stands presented normal distributions with a mean value of around 20 m. Our results agree with previous studies indicating that thinning reduces intraspecific competition for sunlight, water, and nutrients between trees, which causes the trees to decrease their primary growth in height and increase secondary growth in diameter [52–54].

Regarding tree diameter, a normal distribution of frequency was observed for both stands with a mean value of approximately 30 cm in the unthinned stands and 35 cm in the thinned stands. Trees in the thinned stands started with lower growth than in the unthinned stands. However, after thinning the trees, mean growth increased by 3 cm and 0.10 m^3 compared to the trees in the unthinned stands. This positive effect on growth in diameter and volume of trees meets one of the objectives of thinning to produce trees with a larger trunk and higher DBH [16,54]. Studies on the response to thinning of *P. patula* plantations by removing 30% of the stems showed similar results with a mean increase in diameter growth of up to 3.9 cm [50] and up to 0.12 m^3 per tree [51].

The increase in diameter and volume indicated that the two variables are strongly correlated and present similar trends and responses in growth after silvicultural treatment is applied to the spacing regimes of *P. patula* in Peruvian Andes [50,55]. On the other hand, the impact on the height growth of the remaining trees in the thinned stands depends on the genetic improvement conducted on the trees [50,55–57] and not necessarily on the silvicultural management (but see [58]).

4.2. Stand Growth

Improved stand growth or productivity is a result of the application of intensive management practices distributed throughout the rotation cycle of plantations (for example, fertilization, understory vegetation control, and spacing control, among others) [50,52,55,59]. At the end of the 22-year rotation cycle, it was observed that the thinning treatment, removing 63% of the tree density in year 15, produced an increase of 1.5% in basal area and a decrease of 4.4% in volume in the thinned stands compared to the unthinned stands. In the Granja Porcón, the low efficacy of the thinning treatments applied to increase wood production was previously pointed out by Jonard et al. [14]. The authors mentioned that the intensities and periodicity of the thinning application limited the gain in diameter growth and, therefore, in the productivity of the different stand conditions. As was observed in Cardoso et al. [55], the ability of a tree to respond to late thinning (in the 12th and 17th year for a 24-year *Pinus taeda* rotation cycle) is significantly reduced when the relative density index values are higher than 60%, which results in lower levels of production increases and suggests prescribing a clear-cut.

Despite the fact that trees from the same seed sources were installed in areas with similar geographic and climate conditions in both contemporary stands [11], the relationship between volume (production) and basal area (growth condition) showed differences after the 5th and 7th years. This suggests that there are differences in site quality (such as soil fertility) and other microclimatic factors in each area [55,60], and consequently, a particular silviculture treatment can be applied to each stand, depending on the desired productivity [14]. Furthermore, using dendrochronology to monitor and follow the relationship between volume and basal area also allows for verifying the ability of the stand to respond to silvicultural treatments and the effects on production [30]. In our study, the application of thinning at 15 years did not present significant effects on the stand development because it was applied when the volume per basal area curve had exceeded its maximum value and presented a decreasing pattern.

Our results also showed that the intersection of CAI and MAI curves was reached at five and 18 years for DBH and volume, respectively, in the unthinned stands. In contrast, this intersection was reached at 9 and 22 years, respectively, in the thinned stands.

The growth responses analyzed using the CAI and MAI curves showed that silvicultural treatments (e.g., fertilization and thinning) cause a rapid decline in the increment curves in the treated stands and accelerates the intersection of the CAI and MAI growth curves [29,30,61–63]. As previously pointed out, despite the similar growing conditions in both stands, it is possible that the site quality, which determines the mortality and the initial growth of trees [55], had more influence on the late intersection of the CAI and MAI curves in the thinned stand than did the late age thinning application [64]. In summary, late thinning had less of an effect on the increment because an unthinned or improperly thinned stand cannot respond to the treatment and cannot contribute to the acceleration of diameter growth [54].

4.3. Allometric Equations for P. patula

Volume and biomass models are usually obtained from field diameter surveys or historical diameter reconstructions using inventories [14,27,34,65]. Tree-ring-based studies have the advantage of offering an annual resolution and long timescale of diameter increment information and, therefore, could be used to produce reference annual basal area, volume, or biomass production estimations (Figures A1–A3; Tables A1 and A2; [29,30,34,37,66]). This method is suggested to evaluate plantations where historical data obtained from inventories are scarce [29,34,67], as in the case of the Granja Porcón area [26].

The tree-ring-based estimation of the volume increment for *P. patula* presented acceptable statistics (Table A1). The model explained 95% (Adj. R^2) of the volume, and the error was 10% of the mean. Our results were slightly better than those obtained in previous estimations using inventory values of a 30-year-old *P. patula* plantation in the Granja Porcón with a thinning treatment of 38% density removed in the 10th year [27]. The inventory-based model used by Villar Cabeza et al. [27] explained between 86% and 98% of the volume and presented an error of 13% of the mean. Although, the statistics of our volume estimation were slightly worse than the values obtained by an inventory-based model used to fit the data from contemporary natural stands of a *P. patula* plantation in Hidalgo, Mexico [65]. The model applied by Santiago-García et al. [65] explained 96% and 98% of the volume and presented an error of 7% and 3% of the mean for 18- and 20-year-old *P. patula* trees, respectively.

The volume increment models, based on inventory data of DBH and height, were significant ($p < 0.01$) for the three scaling parameters [27,65]. Our model fitted as a function of DBH and TRW, with random weighting parameters, was not significant ($p = 0.52$) for the scaling parameter associated with TRW. The low significance of this parameter suggests that it must be fixed for the application of this model (e.g., [34]). Despite the low significance of the TRW parameter, the adequacy of the model was confirmed by the plot of the standardized residuals (Figure A1). Furthermore, the error of 10% related to the use of the allometric model of volume growth was lower than the 13% error found by Bouriaud et al. [34], who worked with 22 *Picea abies* L trees between 14 and 117 years old.

Regarding the cumulative DBH and volume, 87% and 73% (Adj. R^2) of the observed variation data, respectively, were explained by the Chapman model (Equation (2)). The model presents an error of 17% and 39% of the mean DBH and volume, respectively. The statistics of our fit were slightly worse than the estimation of 86% of the volume with an error of 9% of the mean as obtained by the Chapman and Richards model used to fit data from 25-year-old *P. patula* trees of Colombia [16]. The low adjustment values may be due to the high intraspecific variability that exists between the trees of the studied plots [14]. Therefore, the separation by diameter classes was necessary to increase the adjustment values, recalculate the parameters, and reduce the problems with intraspecific variability (e.g., [14]). After separation into diameter classes, improvements were observed in the fit statistics where the model explained between 91% to 97% and 79% to 95% (Adj. R^2) of the DBH and volume, respectively, and their errors were between 9% to 13% and 17% to 23% of the mean, respectively. The improvements in the adequacy of the model were also confirmed by the plot of the standardized residuals (Figure A3).

4.4. Management Guide

The proposed 21-year management rotation for *P. patula* trees (Figure 5) is in line with that generally practiced for this tree species in the Páramo region for a 20- to 25-year rotation [14,16,29]. Our guide maintains the triangular system with a spacing of 3 m (1283 trees ha^{-1}) for the pine plantation [13]. This planting density allows better use of space compared to pine trees planted at a spacing of 3 × 3 m (1111 trees ha^{-1}) [14]; both systems showed good results for logging production [14,16].

Based on our results, the simulated mortality of *P. patula* trees was 9%. This mortality is lower than that reported by previous studies in the area, which found values of up to 29% [17]. However, our mortality estimate is in line with the ~10% mortality reported in the Colombian Andes [16] and the ~12% mortality reported in the Ecuadorian Andes [68]. In general, the mortality of 15- to 30-year *P. patula* plantations observed in the Páramos was higher than the 4.8% reported in Mexico [65], the 3–13% reported in Malavi [50], and the <10% reported in Ethiopia and South Africa [69].

In general, tree growth is lower at higher altitudes [16]. Thus, when planning the application of thinning treatments, a manager must consider the altitudinal range and the rainfall regime of each location in order to obtain the best evolution of the average diameter of the remaining trees [14]. For altitudes between 1800 and 4000 m a.s.l. in the Ecuadorian Andes [68], trials in Páramo regions have reported the best tree growth between 2500 and 3000 m a.s.l. [16]. According to Llerena et al. [12], the success of *P. patula* plantations in Granja Porcón, growing between 3000 and 4000 m a.s.l., is due to the 1625 mm of precipitation that the basin receives. Furthermore, Jonard et al. [14] mentioned that the productivity of *P. patula* stands is higher for soils with parent material composed partially or entirely of volcanic rock compared to those made of sandstone, and this productivity tends to be higher for stands located below 3450 m altitude. In these conditions, Jonard et al. [14] suggested that the first thinning for *P. patula* in the Granja Porcón plantations must be carried out at younger ages and with a shorter time interval between the first and second thinning (three years instead of six). The authors also mention that the progressivity of the interventions allows for obtaining more regular radial increases while limiting the risks of stand instability and soil erosion.

In the present study, the management guide proposed a first thinning treatment (35%) at 5 years for *P. patula,* based on the occurrence of maximum CAI–DBH for the best condition (Figure 4B). Ospina et al. [16] recommended the first plantation thinning at 7 years when the maximum CAI–BA is reached, removing between 25% to 35% of stems, to increase space and decrease competition between trees. A total volume of 54.4 m^3 ha^{-1} of wood extracted from the three diameter classes (Figure 5) can be used in pulp for paper and in boxes for transporting food, as well as in pallets, chipboards, and fence posts [16]. The second thinning, removing 50% of stems, is suggested for 12-year *P. patula* trees based on the maximum CAI–V (Figure 4), which is similar to that recommended by Ospina et al. [16] for plantations of *P. patula* in Colombia growing between 1800 and 2800 m a.s.l. with a rainfall regime between 1000 and 2000 mm. In other regions of the Argentine Andes, in plantations of *P. patula* growing between 700 and 1200 m a.s.l. with a rainfall regime between 750 and 1200 mm, only one commercial thinning at age 10–12 was suggested, just before the BA–CAI curve declines [29]. A total volume of 310.7 m^3 ha^{-1} of wood extracted from the three diameter classes (Figure 5) can be used for post, rafters, beams, tongue and groove board, boards, and furniture [16].

The expected production of a 21-year rotation *P. patula* plantation is 194.6 m^3 ha^{-1} for the C1 growth class, 316.1 m^3 ha^{-1} for the C2 growth class, and 504.6 m^3 ha^{-1} for the C3 growth class (Figure 5B), considering C1, C2, and C3 *P. patula* plantations with low, medium, and high wood productivity, respectively. Our production simulation showed better results than the 277 m^3 ha^{-1} estimated by Villar Cabeza et al. [27] for a 30-year rotation *P. patula* plantation of the Granja Porcón. The results were also better than the 187–190 m^3 ha^{-1} estimated by Valle-Carrión et al. [68], for a 16–19-year rotation *P. patula* plantation in Ecuador. However, the plantation classified as high wood productivity is still considered less productive compared to the 593 m^3 ha^{-1} reported by Ospina et al. [16] in the Colombian Andes.

5. Conclusions

The main highlight of the present study is the simulated growth of *P. patula* at a stem and stand level considering the readjustment of the selected model using the DBH and volume classes. The improvement observed in the statistics of the models indicates that the management plans must consider monitoring growth classes that can be associated with specific timber products.

Decision-making for the next rotation cycle of *P. patula* in the Granja Porcón, or in other Andean areas with similar geographic characteristics and weather conditions, should consider these predictors by growth classes that were obtained from the collection of historical data during the first cycle.

Furthermore, we suggest that the site quality must be evaluated using tree height [55,60] and that the response to silvicultural treatments can be evaluated based on the relationship between volume and basal area using tree rings [30]. We also suggest testing earlier and more dynamic thinning in low-production areas, for example, by attempting to shorten the interval between the first and second treatments [14,68]. Likewise, a tree-ring-based analysis must be tested in areas with an insufficient inventory of historical data [29]. The combined effect of this monitoring is expected to optimize the production of *P. patula* (and other alien and natural species) in the South American Páramos.

Author Contributions: Conceptualization: D.R.O.-R. and J.R.-A. Methodology: D.R.O.-R., J.R.-A., S.B.D. and M.C. Resources: S.B.D. and M.C. Sample collection and preparation: D.R.O.-R. and S.B.D. Sample analysis: D.R.O.-R. and M.C. Data analysis: D.R.O.-R., A.H., R.S.-S. and M.T.-F. Writing: D.R.O.-R., J.R.-A., M.C. and M.T.-F. Reviewing: A.H., R.S.-S. and S.B.D. Editing: D.R.O.-R., A.H. and R.S.-S. Supervision: J.R.-A., M.C. and M.T.-F. All authors have read and agreed to the published version of the manuscript.

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Appendix A

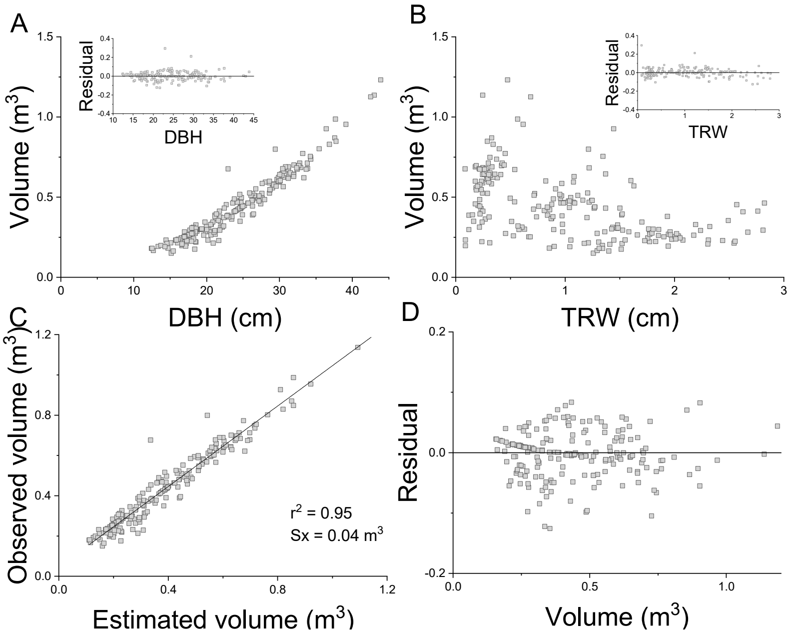

Figure A1. Volume of *P. patula* at different age and independent variables DBH (**A**) and RW (**B**) of fitted Equation (1) and their residuals, analyze included both stands. Regression between the observed and estimated volume (**C**) and their residual (**D**).

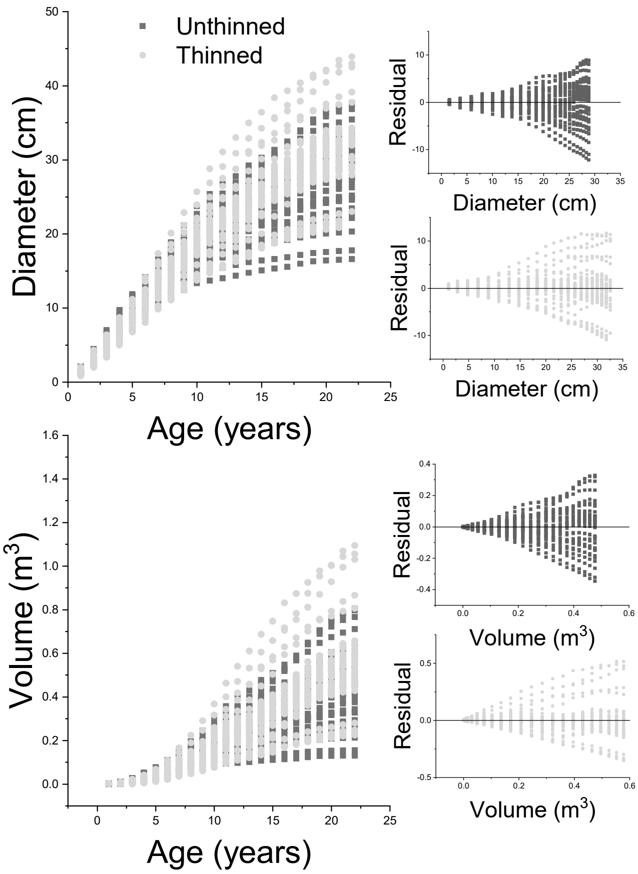

Figure A2. Cumulative DBH and wood volume of unthinned and thinned stands of fitted Equation (2) and their residuals.

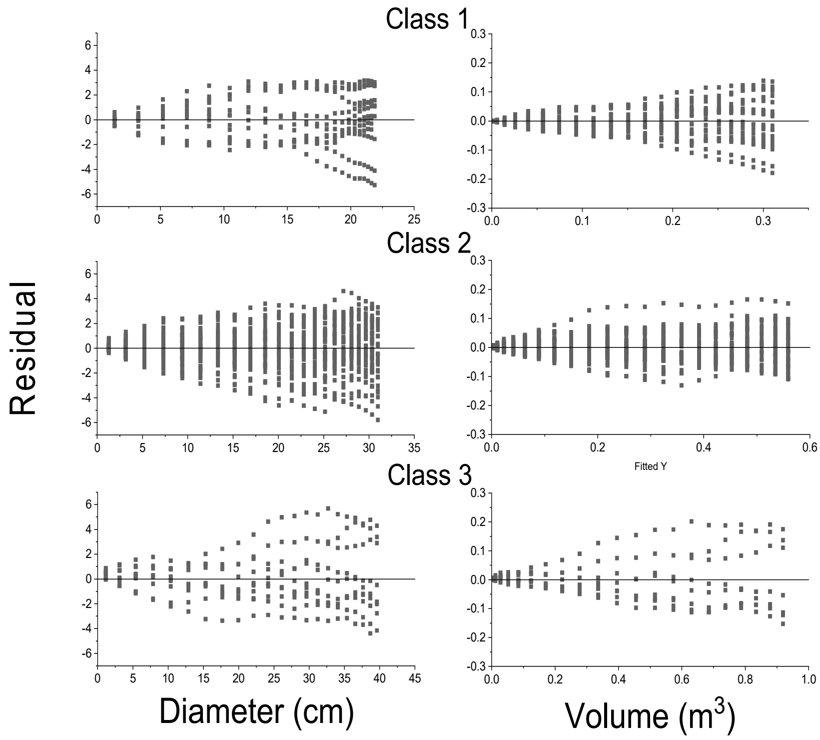

Figure A3. Residuals of cumulative DBH and wood volume of three growth class of *P. patula* trees fitted by Equation (2). Class 1 (C1): 15–24 cm; Class 2 (C2): 25–34 cm, Class 3 (C3): 35–45 cm.

Table A1. Parameters and fit statistics for Equation (1) to estimate volume increment of *P. patula*.

Model	Parameter	Estimate	SE	*t*-Value	*p*-Value	Adj. R^2	Fit Statistics RMSE (m^3)	∣E∣%
Equation (1)	a	0.00541	0.00271	2.19	<0.01	0.95	0.04602	10.45
	b	0.00091	0.00036	2.53	<0.01			
	c	1.88575	0.10142	18.59	<0.0001			
	d	0.00674	0.01055	0.64	0.52			

SE standard error, RMSE root mean square error, ∣E∣% mean percentage error.

Table A2. Parameters and fit statistics for model Equation (2) to estimate the cumulative trunk diameter and wood volume of *P. patula* unthinned (Nthi) and thinned (Thi) trees.

Model	Growth Variable	Parameter	Stand	Estimate	SE	*t*-Value	*p*-Value	Adj. R2	Fit Statistics RMSE	∣E∣%
Equation (2)	DBH	a	Nthi	33.427	1.174	28.5	<0.0001	0.87357	3.18 cm	17.20
		b		0.101	0.011	9.6	<0.0001			
		c		1.303	0.089	14.7	<0.0001			
		a	Thi	42.116	2.346	18.0	<0.0001	0.88812	3.45 cm	18.23
		b		0.082	0.010	8.0	<0.0001			
		c		1.433	0.101	14.3	<0.0001			
	Volume	a	Nthi	0.692	0.090	7.7	<0.0001	0.74606	0.09 m^3	39.09
		b		0.090	0.019	4.6	<0.0001			
		c		2.486	0.396	6.3	<0.0001			
		a	Thi	0.848	0.114	7.4	<0.0001	0.72868	0.12 m^3	44.39
		b		0.107	0.021	5.0	<0.0001			
		c		3.790	0.741	5.1	<0.0001			

SE standard error, RMSE root mean square error, ∣E∣% mean percentage error.

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