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Mixed *Castanea sativa* plantations including arboreal companion species enhance chestnut growth and high-quality timber production

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ABSTRACT

Context: Chestnut (Castanea sativa Mill.) is an important tree species for its timber, which is widely used for multiple purposes, including the veneer industry. The species has an interesting productive potential in Chile and requires specific management strategies to produce valuable, high-quality logs. Although mixed plantations including companion species usually enhance timber quality of several trees, the performance of chestnut under different associations is not well known.
Aims: The objective of this study was to assess growth, survival, health, and timber quality of chestnut trees in several plantation types, including monoculture and mixtures with other companion trees and/or shrub.
Methods: Growth and survival measurements were taken periodically in pure chestnut and mixed plantations established in southern Chile for a 20-year period after planting. The mixed plantations tested were: a main forest species mixture (Castanea sativa Mill., Quercus rubra L., Quercus robur L. and Prunus avium L.); three mixtures including main forest species plus one arboreal companion species (Alnus glutinosa L., Gevuina avellana Mol. or Embothrium coccineum J.R. Forst. & G. Forst.); one including main forest species plus one shrub nurse species (Fabiana imbricata Ruiz & Pav.); and three mixtures including one of the arboreal companion species and the shrub. Timber quality variables were assessed at age 20, and health status was recorded at ages 7 and 20 in all plantations. Growth variables were analyzed using linear mixed models to assess plantation effect over time. Kaplan-Meier survival analysis and Log Rank Test were used to compare chestnut tree survival among plantation types. Quality timber variables were analyzed with a χ^2 test.
Results: Chestnut trees associated with arboreal main species (P. avium, Q. rubra, Q. robur) (Mix1) showed the best performance, with 10.1 % and 8.3 % higher height than average values of the other mixtures and the monoculture, respectively, and 19.1 % and 12.8 % higher diameter growth than across plantation types and monoculture average values, respectively. Mix1 had the highest average volume per tree (0.34 m^{-3}), at least 30 % higher than the average volume of pure and other mixed plantations. This mixture including only main species also exhibited the highest percentage of trees with high trunk length values of all plantation types. No pest or diseases were recorded on chestnut trees, and survival was high in all plantation types.
Conclusion: The impact of mixed plantations on growth and timber quality was evidenced at age 20. In particular, the association including arboreal companion species enhanced chestnut tree performance.

1. Introduction

Castanea sativa Miller is a precious species whose edible fruit has been used as a staple food since ancient times (from bread to the well-known *marron glace* sweets). It supplies firewood, charcoal (Kosňovská, 2013), wood products from short rotations (e.g. poles), high-quality timber produced in longer rotations (Bourgeois et al., 2004), and biomass. It has also been used in religious practices (Pollegioni et al., 2020). Chestnut timber has good technological characteristics; it is durable, dries well and is easy to work (except for vacuum

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impregnation), and has good luster and surface finishes. It is used for furniture, construction, veneers, floors, sculptures (Nava and Oliviero Rossi, 2021), musical instruments and cabinet-making (Borghini and Massafra, 2002), tools, firewood, and wickerwork. The chestnut wood industry demands defect-free logs of a minimum of 0.4 m in diameter and 1.4 m in length.

Chestnut cultivation began in the Early Bronze Age (Krebs et al., 2019), with evidence of clonal selection and grafting from the 15th century (Pollegioni et al., 2020). Residues of chestnut in necropolis and Roman cremation sites were associated with discards of by-products derived from management, such as pruning or coppicing (Costa-Vaz et al., 2020). With the expansion of the Roman Empire, chestnut was spread for the production of poles, which were used in the cultivation of vines and in mining Costa-Vaz et al., 2020. In the UK, chestnut has been included among the eight most important species for high-value timber production (Kerr and Evans, 1993), given its ease of establishment, fast growth rate, possibility of coppicing, wood quality and marketability (Everard and Christie, 1995).

Mixed plantations may contribute to product diversification, decreased phytosanitary risks, facilitated management (Jungers et al., 2021) and increased carbon stocks (Warner et al., 2022) and timber quality and productivity through a better use of light, water and nutrients (Pretzsch and Schütze, 2016). They may also increase landscape aesthetics (Grilli et al., 2016), water supply (Schäfer et al., 2019), growth stability (Knoke et al., 2008; Mohni et al., 2009; Aussenac et al., 2017), and provide habitat for wildlife (Duflot et al., 2021). Mixed plantations might also help mitigate disturbances due to climate change (Bauhus et al., 2017; Schäfer et al., 2019).

Sustainable forest production systems for high-value timber production may be built using mixed plantations, thereby contributing to an efficient soil use, and increased biodiversity and stability (Liu et al., 2018). In South America, the application of mixed plantations involving native species has also shown to be beneficial. Indeed, the potential for quality timber production through sustainable management has been suggested, additionally providing diversified goods and services (Piotto et al., 2004; Loewe et al., 2008a).

Even though biodiversity is known to support a wide range of forest ecosystem functions and services, the effects of mixed plantations can be neutral or even negative. For example, in Europe, diversity was found top enhance resistance to drought only in drought-prone environments; consequently, managing forest ecosystems for high tree species diversity does not necessarily improve adaptability to the more intense and frequent droughts predicted for the future (Grossiord et al., 2014). De Streel et al. (2022) reported no consistent species-mixing effect on drought resistance for *Fagus sylvatica* L. and *Pinus sylvestris* L. across sites, and Del Rio et al. (2017) confirmed that the species mixing positive effect in stabilizing productivity at the community level may be neutral or negative at the population and individual tree level.

Chestnut was introduced to Chile by European immigrants and become naturalized, presenting low genetic variability (Loewe et al., 2008b). Approximately 1,000 ha have been planted for timber production, with about one third being pure plantations and two thirds, mixed plantations (Benedetti et al., 2004; Loewe and González, 2006). Pure plantations are planted mostly at high density (1,111 trees ha^{-1}) and extensively managed (no pruning, late or no thinning, no soil tillage), with estimated productive cycles of 30–35 years (Benedetti et al., 2018). Mixed plantations have shown interesting results in terms of timber quality when associated with several conifers and broadleaved species, with straight, smooth, cylindrical stems with natural pruning, without epicormic shoots (Loewe et al., 2005). The timber produced in the country presents good technological characteristics, with no ring-shake defects having been found (Loewe et al., 1994). This defect causes significant economic losses in several countries (Fonti et al., 2002).

C. sativa is threatened by forecasted climate changes (Castellana et al., 2021), including warming, variation in seasonal rainfall patterns, and increased frequency and intensity of drought (IPCC, 2021), reducing the species functionality and stability, and affecting health status, including an increased vulnerability to ink disease (Gomes-Laranjo et al., 2006). Consequently, the consideration of chestnut as a future-proof tree has been questioned recently (Conedera et al., 2021). Thus, studying adaptation processes of the species becomes necessary (Castellana et al., 2021). Management of chestnut plantations under climatic variability calls for a better understanding of the types of plantations better suited to the species development.

Regarding timber quality, pure chestnut plantations present challenges derived from the high epicormic shoot re-sprouting along stems after pruning or thinning (Meier et al., 2012); therefore, mixed plantations could be a better option, particularly if the companion species are trees that boost stem growth, and/or shrubs that provide lateral shadowing, conditioning the species architecture.

The working hypothesis considered that chestnut mixed plantations with arboreal main species impact growth performance and timber quality. Other species could enhance growth without adding timber products (arboreal or shrub companion species). The species interactions could have positive, neutral or even negative effects on the target main species growth, survival and timber quality. The objective of this study was to assess growth, survival, health, and timber quality of chestnut trees grown in pure plantations and mixed with main species, and with companion arboreal and/or shrub species.

2. Material and method

2.1. Experimental trial

The experimental trial, involving several plantation types, was established in Los Lagos, southern Chile (39°50′S, 72°46′W), on a plain located 50 m from Calle Calle river, at 80 m asl (Fig. 1S). The climate in the area is rainy temperate, with 1,758 mm of rainfall distributed all year round and average temperature of 10.7 °C (Table S1). The soil origin is glacial and fluvial with deposition of large amount of sediments, with pH of 5.2 and 16.7 % of organic matter. Chemical analyses of composite soil samples from the site conducted in a certified laboratory reported deficiency of nitrogen, phosphorus, potassium, calcium, sodium, zinc and boron, and high content of iron, manganese and cupper. Since the experiment establishment, a semi-intensive management based on quality arboriculture principles (Loewe, 2003) has been applied, including soil preparation by ploughing and subsoiling in the planting line at 40 cm depth and fertilization at planting (doses for each plant: mono ammonium phosphate 100 g, sulphate of potassium and manganese 120 g, boronatrocalcite 20 g, zinc sulphate 20 g and calcium carbonate 250 g).

A randomized complete block design with three blocks was used as experimental setup to assess nine plantation types including chestnut (pure plantation and Mix1 through Mix 8, Table 1, Fig. 1). Mix1 consisted of a main species association including Chestnut + Cherry (*Prunus avium* Linnaeus, PA) + Red oak (*Quercus rubra* Linnaeus, QRu) + Oak (*Quercus robur* Linnaeus, QRo). Mix2, Mix3 and Mix4 included a companion arboreal species: Mix2: Mix1 + the *N*-fixing Black alder (*Alnus glutinosa* Linnaeus), Mix3: Mix1 + Chilean hazelnut (*Gevuina avellana* Molina), and Mix4: Mix1 + Notro (*Embothrium coccineum J.R.* Forster & G. Forster). Mix5 was an association including a companion shrub species: Mix1 + *Fabiana imbricata* Ruiz & Pavon (FI). Finally, three associations included both arboreal and shrub companion species: Mix6 (Mix2 + FI), Mix7 (Mix3 + FI) and Mix8 (Mix4 + FI). The species were mixed tree-by-tree, involving a one-row buffer of oaks around plots. Tree spacing was 8 × 8 m among main species, 4 × 4 m among main and secondary arboreal species; shrubs were located at 2.5 m from main species. All plantation types were established with one-year old seedlings, produced with local seed sources, in winter 2001 and then monitored for 20 years after plantation. The plot size for each mixture was 576 m^2 and included 4 to 16 chestnut trees per plot (Fig. 1). To determine the exact location of each tree and shrub species within each

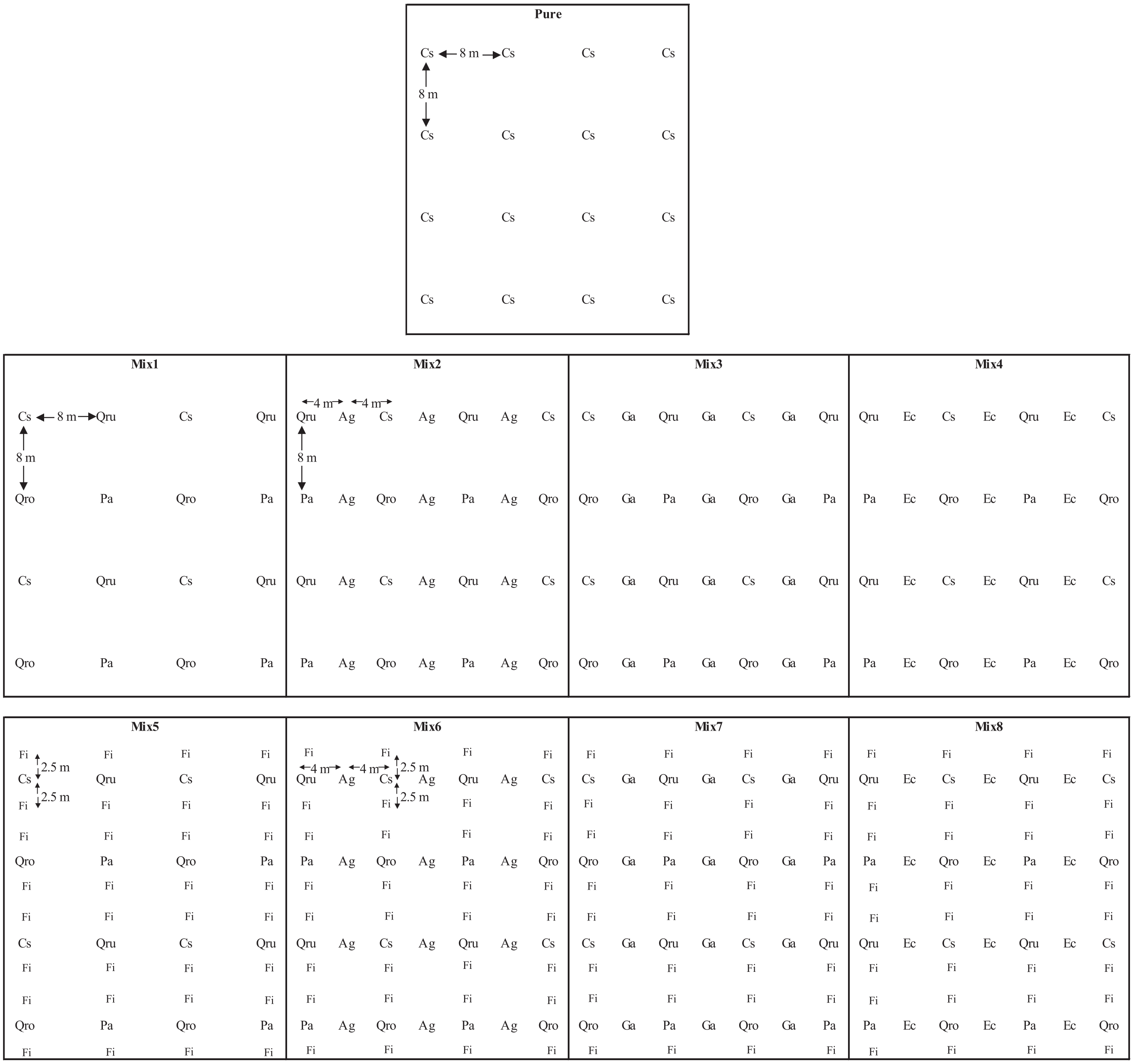

Fig. 1. Design of one block of the experimental trial Cs: *Castanea sativa,* Pa: *Prunus avium,* Qru: *Quercus rubra,* Qro: *Quercus robur,* Ag: *Alnus glutinosa*, Ga: *Gevuina avellana,* Ec: *Embothrium coccineum,* Fi: *Fabiana imbricata.*

Table 1
Species composition by plantation type (%).

Plantation type	**Species**							
	Main arboreal species				**Companion arboreal species**			**Companion shrub species**
	Castanea sativa	*Prunus avium*	*Quercus rubra*	*Quercus robur*	*Alnus glutinosa*	*Gevuina avellana*	*Embothrium coccineum*	*Fabiana imbricata*
Pure	100	0	0	0	0	0	0	0
Mix1	25	25	25	25	0	0	0	0
Mix2	14	14	14	14	44	0	0	0
Mix3	14	14	14	14	0	44	0	0
Mix4	14	14	14	14	0	0	44	0
Mix5	8	8	8	8	0	0	0	68
Mix6	7	7	7	7	20	0	0	52
Mix7	7	7	7	7	0	20	0	52
Mix8	7	7	7	7	0	0	20	52

mixture, a systematic design was used. At planting, there were differences in size of the main species seedlings (Table 2).

Mechanical weed control was applied at ages 2, 3, 4, 5 and 6, and formation pruning at ages 2, 3, 4, 5 and 6. A thinning is envisaged to be applied in 5–10 years.

2.2. Measurements

Height (m) and diameter at 1.3 m above the ground (DBH, cm) were the growth variables measured for each tree during winter of years 1, 2, 3, 4, 5, 6, 7, 12, 15 and 20. Volume at age 20 was calculated using the Smalian formula (de Miguel-Díez et al., 2022); the stem taper considered a decrease of 1.2 cm per meter of trunk length (Loewe et al., 1994). Timber quality was assessed by evaluating vigor, stem form, crown form and trunk length were assessed at the end of the study period.

Vigor was classified based on Lakatos and Mirtchev (2014), as follows: high vigor trees (those with no defoliation or leaf discoloration); medium–low vigor trees (those showing none or slight defoliation, and/or slight leaf discoloration, or trees showing moderate or severe defoliation or discoloration). Stem form was classified as straight (0); light buckled (curvature lower than the mean curvature, 1), heavy buckled (curvature higher than the mean curvature, 2), and deformed (several curvatures, 3), based on Kuehne et al. (2013). Crown form was measured as a function of apical dominance and classified as monopodial (one dominant apex, 0), forked (two codominant apexes, 1) and brushy (without any dominant apexes, 2). Chestnut trunk length was classified into three classes: short (<4 m), medium (4–6 m) and long (>6 m). Health records included detection of any symptom or presence of pest and diseases in each chestnut tree, and was assessed at ages 7 and 20. Presence of lichens on the trunk (0 = absence, 1 = presence) and lichen abundance (low (<30 %], medium (30–70 %] and high (>70 %)) were evaluated at age 20.

2.3. Statistical analyses

Height and DBH were analyzed using linear mixed models to assess the performance of the various plantation types regarding chestnut tree growth over time. The model included fixed effects of treatment (plantation type), age and treatment × age interaction. The temporal correlation was accounted for by explicitly modelling the variance–covariance matrix of error terms; the first-order continuous autoregressive model was selected to represent the correlation structure of measurements taken on the same chestnut tree (West et al., 2014). The initial height and diameter at collar height (DCH) were included as covariates to control potential differences among seedling sizes. The significance of the marginal fixed effects of the linear mixed models was tested by an F test. Log volume was analyzed at age 20 using an ANOVA model. Kaplan-Meier survival analysis and Log Rank Test (α = 0.05) were used to compare chestnut tree survival among treatments. Quality timber and lichen presence and abundance measurements were analyzed using a homogeneity of proportions χ^2 test (α = 0.05). InfoStat (Di Rienzo et al., 2022) and its interface with R (https://www.r-project.org) (package lme4) were used to run statistical analyses.

Table 2
Height and diameter at collar height (DCH) at planting of seedlings of the main species.

Seedling size (cm)	*Castanea sativa*	*Prunus avium*	*Quercus rubra*	*Quercus robur*
Height	29.1 ± 0.9	152.3 ± 2.6	67.1 ± 2.2	112.7 ± 1.4
DCH	1.5 ± 0.3	1.9 ± 0.03	1.1 ± 0.03	1.3 ± 0.03

Mean ± SE.

3. Results

Chestnut trees presented statistically significant differences for height (p < 0.0001) and DBH (p < 0.001) among plantation types; the plantation type × age interaction for DBH was also significant (p < 0.001). Average profiles for height and DBH for each plantation type, built from the predicted values of the fitted linear mixed models, are shown in Fig. 2; associations are shown separately for trees and shrubs.

Average chestnut tree height and DBH values at age 20 are shown in Tables 3 and 4, respectively. Height was on average 11.9 m, with significantly higher values in Mix1, which started to show a better performance after age 14. Height growth of chestnut trees in Mix4 and Mix6 was significantly lower than in other plantation types from age 14. Mix1 also showed the highest DBH performance of all plantation types after age 14 (Table 4, Fig. 2). At age 20, Mix4 had the lowest DBH, and all other mixtures and the pure plantation had an intermediate performance between Mix1 and Mix4. Diameter growth was 1.4 cm year^{-1} in Mix1 and 1.2 cm year^{-1} in the pure plantation. Height and DBH of the main arboreal companion species at the end of the study are shown in Table 5.

At age 20, chestnut trees presented no statistically significant differences for log volume (p = 0.0634) among plantation types (Table 6). Mix1 had the highest average volume per tree (0.34 m^{-3}), whereas the average volume of Mix4 and Mix6 was lower (0.15 and 0.20 m^{-3}, respectively).

Results of the Log Rank test applied to the survival curves estimated for chestnut trees revealed statistical differences (α = 0.05) among plantation types (χ^2 = 54.946, p < 0001) (Fig. 3). At age 20, survival of chestnut trees was 100 % in Mix1, Mix3 and Mix6; the lowest survival values were recorded in Mix8 (88.7 %), Mix2 and Mix4 (95.0 %), and Mix5 (98.0 %); monoculture survival was 99.0 %.

For all plantations, trees were highly vigorous, except for Mix8, where 20 % of trees showed low-medium vigor (Table 7). Regarding crown form, all trees were monopodial in all plantation types (Table 7). Stem form showed variability, but without statistical differences among plantation types (X^2 = 18.5, p = 0.7782) (Table 7). Trunk length showed statistical differences among plantation types (X^2 = 28.30, p = 0.0289), with Mix1 having the highest proportion (92 %) of chestnut trees with trunk length over 6 m (Table 7), whereas in the pure plantation that value was 56 %. Moreover, no pests or diseases were recorded in any chestnut tree at ages 7 or 20, with phytosanitary status being good in all plantations. Presence of lichens on the trunk was observed in all chestnut trees from all plantation types; no statistical differences were found for lichen abundance (X^2 = 11.87, p = 0.1569). However, no chestnut trees in Mix4, Mix5 and Mix6 had high abundance of lichens on the trunk.

4. Discussion

The performance of chestnut trees in pure and mixed plantations is scarcely known outside its native area. This study evaluates the behavior of chestnut trees for high-value timber production in different plantation systems, including arboreal and shrub companion species.

The plantation type × age interactions observed for height and DBH indicate that plantation type effects changed over time, with the effects of some plantation types increasing over the years. In particular, Mix1 showed increasing height and DBH growth after age 14. At age 20, the best performance was found for this association of main forest species, with the average height value being 10.1 % higher than the overall mean and 8.3 % higher than the pure plantation, and with DBH value being 19.1 % higher than the overall mean and 12.8 % higher than in the monoculture. Nunes et al. (2014) also found higher yield of *C. sativa* in association with the main species *P. menziesii* (Mirbel) Franco than in the pure plantation, while Sales and Monteiro (1998) reported that height growth patterns in *C. sativa* were not influenced by mixing with the same main species.

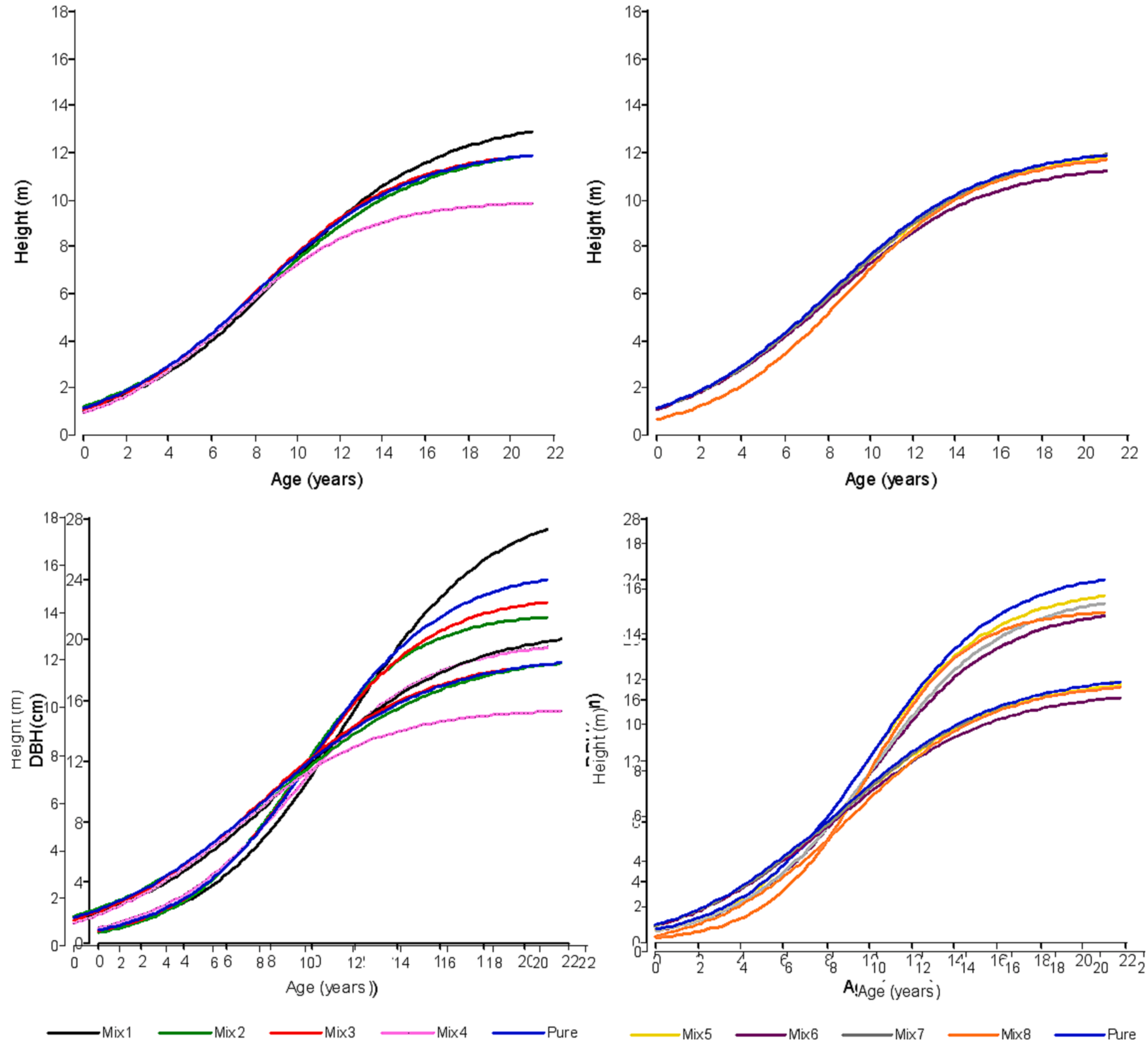

Fig. 2. Chestnut tree height (top) and DBH (bottom) growth curves for pure plantations and plantations mixed with companion arboreal species (left) and shrub species (right) in southern Chile. Mix1: *Castanea sativa* + *Prunus avium* + *Quercus rubra* + *Quercus robur*. Mix2: Mix1 + *Alnus glutinosa*. Mix3: Mix1 + *Gevuina avellana*. Mix4: Mix1 + *Embothrium coccineum*. Mix5: Mix1 + *Fabiana imbricata*. Mix6: Mix2 + *Fabiana imbricata*. Mix7: Mix3 + *Fabiana imbricata*. Mix8: Mix4 + *Fabiana imbricata*.

The average height growth across plantation types (0.6 m year^{-1}) was within the range of growth values reported for England, France, Italy and Spain (0.6–0.7 m year^{-1}) and higher than in Portugal (0.3 m year^{-1}, Nunes et al., 2014), Netherlands, Switzerland and Slovak Republic (0.4–0.5 m year^{-1}) (Manetti et al., 2001). In France, height growth rates were found to range from 0.4 m year^{-1} in poor sites to 0.9 m year^{-1} in the best sites (Lemaire, 2008).

Average DBH growth (1.15 cm year^{-1}) is in line with previous measurements taken in Chile (Loewe et al., 1994; Loewe et al., 2013). We observed a better performance than in France, where mean annual DBH growth at a similar age ranged between 0.56 cm year^{-1} without thinning and 0.75 cm year^{-1} in younger thinned plantations (Bourgeois et al., 2004). Our results are also better than records from Portugal both in pure and mixed plantations (0.46 cm year^{-1}, Nunes et al., 2014) and in Italy (0.73–0.84 cm year^{-1}, Amorini et al., 2000). These differences may be due to favorable climatic conditions in the study site, since Garcia-Barreda et al. (2021) reported positive correlations of DBH growth with water balance from the previous winter, and from end of spring and beginning of summer; and with mean minimum temperatures from autumn to mid-winter. Thus, the influence of climatic variables on chestnut growth should be studied also in non-native habitats.

After 2015 significant effects were observed; this pattern may be attributed to different factors. There is growing evidence that relationships between biodiversity and ecosystem functioning may become stronger over time, and that long-term experiments better mirror natural conditions, contributing to the understanding of such interactions (Guerrero-Ramírez et al., 2017). Mechanisms of partitioning and facilitation between species, referred to as complementarity (driving changes in the average relative yield in the mixture), selective processes that cause dominance of species with particular traits, and a sampling

Table 3
Height (m) of chestnut trees by plantation type.

Plantation type	Year									
	2001	2002	2003	2004	2005	2006	2007	2012	2015	2021
Pure	0.3 ± 0.2 a	1.9 ± 0.2 a	2.0 ± 0.2 a	2.4 ± 0.2 a	2.8 ± 0.2 a	3.6 ± 0.2 a	4.5 ± 0.2 a	8.5 ± 0.2 a	9.9 ± 0.2 a	12.1 ± 0.2b
Mix1	0.3 ± 0.3 a	1.8 ± 0.3 a	1.9 ± 0.3 a	2.4 ± 0.3 a	2.6 ± 0.3 a	2.9 ± 0.3 ab	4.2 ± 0.3 ab	8.6 ± 0.3 a	10.3 ± 0.3 a	13.1 ± 0.3 a
Mix2	0.3 ± 0.4 a	2.0 ± 0.4 a	2.2 ± 0.4 a	2.7 ± 0.4 a	2.9 ± 0.4 a	3.5 ± 0.4 a	4.3 ± 0.4 ab	8.2 ± 0.5 a	9.8 ± 0.4 a	11.9 ± 0.4b
Mix3	0.3 ± 0.3 a	1.8 ± 0.3 a	1.7 ± 0.3 a	2.2 ± 0.3 a	2.9 ± 0.3 a	3.7 ± 0.3 a	4.4 ± 0.3 a	8.6 ± 0.3 a	10.0 ± 0.3 a	12.1 ± 0.3b
Mix4	0.3 ± 0.4 a	1.5 ± 0.4 a	1.7 ± 0.4 a	2.4 ± 0.4 a	2.6 ± 0.4 a	3.4 ± 0.4 a	4.7 ± 0.4 a	7.7 ± 0.4 a	8.2 ± 0.4b	10.5 ± 0.4c
Mix5	0.3 ± 0.3 a	1.9 ± 0.3 a	1.8 ± 0.3 a	2.3 ± 0.3 a	2.8 ± 0.3 a	3.5 ± 0.3 a	4.3 ± 0.3 ab	8.2 ± 0.3 a	9.8 ± 0.3 a	11.9 ± 0.3b
Mix6	0.3 ± 0.4 a	1.9 ± 0.4 a	1.7 ± 0.4 a	1.8 ± 0.4 a	2.5 ± 0.4 a	3.4 ± 0.4 a	4.8 ± 0.4 a	7.9 ± 0.4 a	9.3 ± 0.4 ab	11.5 ± 0.4 bc
Mix7	0.3 ± 0.3 a	1.9 ± 0.3 a	1.8 ± 0.3 a	2.2 ± 0.3 a	2.8 ± 0.3 a	3.6 ± 0.3 a	4.5 ± 0.3 a	8.3 ± 0.3 a	9.8 ± 0.3 a	12.1 ± 0.3b
Mix8	0.4 ± 0.4 a	1.3 ± 0.3 a	1.1 ± 0.4b	1.4 ± 0.3b	2.1 ± 0.4 a	2.3 ± 0.4b	3.5 ± 0.4b	8.2 ± 0.4 a	10.1 ± 0.4 a	11.8 ± 0.4b
Mean	0.3 ± 0.0	1.8 ± 0.1	1.8 ± 0.1	2.2 ± 0.1	2.7 ± 0.1	3.3 ± 0.2	4.4 ± 0.1	8.3 ± 0.1	9.7 ± 0.2	11.9 ± 0.2

Mix1: *Castanea sativa* + *Prunus avium* + *Quercus rubra* + *Quercus robur.* Mix2: Mix1 + *Alnus glutinosa.* Mix3: Mix1 + *Gevuina avellana.* Mix4: Mix1 + *Embothrium coccineum.* Mix5: Mix1 + *Fabiana imbricata.* Mix6: Mix2 + *Fabiana imbricata.* Mix7: Mix3 + *Fabiana imbricata.* Mix8: Mix4 + *Fabiana imbricata.*
Mean ± SE. By column, different letters indicate statistical differences among plantation types.

Table 4
DBH (cm) of chestnut trees by plantation type.

Plantation type	Year					
	2005	2006	2007	2012	2015	2021
Pure	2.1 ± 0.6 a	3.8 ± 0.5 a	5.4 ± 0.5 a	14.6 ± 0.5 a	18.7 ± 0.5 ab	24.3 ± 0.6b
Mix1	3.0 ± 0.9 a	3.8 ± 0.9 a	5.5 ± 0.9 a	14.6 ± 0.9 a	19.9 ± 0.9 a	27.4 ± 0.9 a
Mix2	4.0 ± 1.3 a	4.4 ± 1.3 a	5.8 ± 1.3 a	15.0 ± 1.5 a	19.4 ± 1.3 ab	21.7 ± 1.1b
Mix3	2.3 ± 0.9 a	4.0 ± 0.9 a	5.6 ± 0.9 a	14.6 ± 0.9 a	18.4 ± 0.9 ab	22.6 ± 0.9b
Mix4	2.4 ± 1.3 a	4.5 ± 1.3 a	6.6 ± 1.3 a	13.5 ± 1.4 a	16.3 ± 1.3b	20.6 ± 1.3c
Mix5	2.4 ± 0.9 a	3.5 ± 0.9 a	4.9 ± 0.9 a	14.2 ± 0.9 a	17.9 ± 0.9 ab	22.9 ± 0.9b
Mix6	2.6 ± 1.3 a	3.9 ± 1.3 a	5.3 ± 1.3 a	13.8 ± 1.3 a	17.7 ± 1.2 ab	21.7 ± 1.2b
Mix7	1.9 ± 0.9 a	3.1 ± 0.9 a	4.8 ± 0.9 a	13.3 ± 0.9 a	17.0 ± 0.9b	22.5 ± 0.9b
Mix8	0.7 ± 1.2 a	1.2 ± 1.1b	3.4 ± 1.1 a	14.4 ± 1.4 a	18.6 ± 1.3 ab	23.1 ± 1.2b
Mean	2.4 ± 0.3	3.6 ± 0.3	5.3 ± 0.3	14.2 ± 0.2	18.2 ± 0.4	23.0 ± 0.7

Mix1: *Castanea sativa* + *Prunus avium* + *Quercus rubra* + *Quercus robur.* Mix2: Mix1 + *Alnus glutinosa.* Mix3: Mix1 + *Gevuina avellana.* Mix4: Mix1 + *Embothrium coccineum.* Mix5: Mix1 + *Fabiana imbricata.* Mix6: Mix2 + *Fabiana imbricata.* Mix7: Mix3 + *Fabiana imbricata.* Mix8: Mix4 + *Fabiana imbricata.*
Mean ± SE. By column, different letters indicate statistical differences among plantation types.

effect, have been theorized and tested in biodiversity experiments (Loreau and Hector, 2001). Complementary predicts that communities with higher functional diversity would have higher productivity (Ruiz-Benito et al., 2014), with a complementary resource use and improved soil nutrient availability.

In our study, no pests or diseases were identified, and climatic variables were the same for all plots and repetitions. The presence of an *N*-fixing species (*A. glutinosa*) in Mix2 and Mix6, which often boosts complementarity effects, did not positively affect growth; this result is probably due to the fast growth of the species, resulting in competition with the main species. Differences in canopy closure or canopy packing among pure and Mix1, and the more diverse treatments Mix2 to Mix8 may also be involved, derived from a higher plot density in the more complex mixtures. The inclusion of additional metrics to explain these mechanisms in future studies would help to identify specific mechanisms impacting chestnut performance in different plantation types.

According to Sales and Monteiro (1998), *C. sativa* responds well to competitive pressure from *Pseudotsuga menziesii*, showing a higher productivity, this result is explained by an intraspecific competition, which

Table 5
Height (m) and DBH (cm) of main arboreal species by plantation type at age 20.

Plantation type	*Prunus avium*		*Quercus robur*		*Quercus rubra*	
	Height	DBH	Height	DBH	Height	DBH
Pure	7.6 ± 0.5b	10.6 ± 1.0 a	13.1 ± 0.4 a	18.6 ± 0.8 a	14.7 ± 0.5 a	22.5 ± 0.9 ab
Mix1	10.0 ± 1.2 ab	14.0 ± 2.3 a	13.3 ± 0.9 a	21.0 ± 1.6 a	15.3 ± 0.9 a	24.1 ± 1.8 a
Mix2	10.3 ± 0.9 a	14.3 ± 1.7 a	12.4 ± 1.1 a	18.0 ± 2.1 a	14.4 ± 0.8 a	17.7 ± 1.5c
Mix3	7.6 ± 1.7 ab	10.9 ± 3.3 a	10.6 ± 0.7 a	16.4 ± 1.4 a	14.9 ± 1.1 a	18.4 ± 2.1 bc
Mix4	10.1 ± 1.1 ab	12.5 ± 2.1 a	12.1 ± 1.1 a	19.3 ± 2.1 a	13.6 ± 0.7 a	19.2 ± 1.4 abc
Mix5	8.2 ± 1.5 ab	10.2 ± 2.9 a	11.4 ± 0.7 a	15.7 ± 1.4 a	14.4 ± 1.1 a	21.8 ± 2.1 abc
Mix6	8.0 ± 0.8 ab	9.5 ± 1.6 a	12.3 ± 1.1 a	17.5 ± 2.1 a	13.5 ± 0.8 a	19.0 ± 1.5 abc
Mix7	7.1 ± 1.2b	7.7 ± 2.3 a	12.7 ± 0.8 a	19.2 ± 1.5 a	13.2 ± 1.1 a	18.6 ± 2.1 abc
Mix8	11.4 ± 1.0 a	16.1 ± 1.9 a	13.8 ± 0.9 a	21.5 ± 1.7 a	12.9 ± 0.8 a	18.6 ± 1.5 abc

Mix1: *Castanea sativa* + *Prunus avium* + *Quercus rubra* + *Quercus robur.* Mix2: Mix1 + *Alnus glutinosa.* Mix3: Mix1 + *Gevuina avellana.* Mix4: Mix1 + *Embothrium coccineum.* Mix5: Mix1 + *Fabiana imbricata.* Mix6: Mix2 + *Fabiana imbricata.* Mix7: Mix3 + *Fabiana imbricata.* Mix8: Mix4 + *Fabiana imbricata.*
Mean ± SE. By column, different letters indicate statistical differences among plantation types.

Table 6
Volume of chestnut trees by plantation type at age 20.

Plantation type	Volume (m^3 tree^{-1})
Pure	0.26 ± 0.10 a
Mix1	0.34 ± 0.04 a
Mix2	0.23 ± 0.07 a
Mix3	0.22 ± 0.02 a
Mix4	0.15 ± 0.06 a
Mix5	0.22 ± 0.04 a
Mix6	0.20 ± 0.00 a
Mix7	0.22 ± 0.05 a
Mix8	0.23 ± 0.02 a

Mix1: *Castanea sativa* + *Prunus avium* + *Quercus rubra* + *Quercus robur.* Mix2: Mix1 + *Alnus glutinosa.* Mix3: Mix1 + *Gevuina avellana.* Mix4: Mix1 + *Embothrium coccineum.* Mix5: Mix1 + *Fabiana imbricata.* Mix6: Mix2 + *Fabiana imbricata.* Mix7: Mix3 + *Fabiana imbricata.* Mix8: Mix4 + *Fabiana imbricata.*
Mean ± SE. Different letters indicate statistical differences among plantation types.

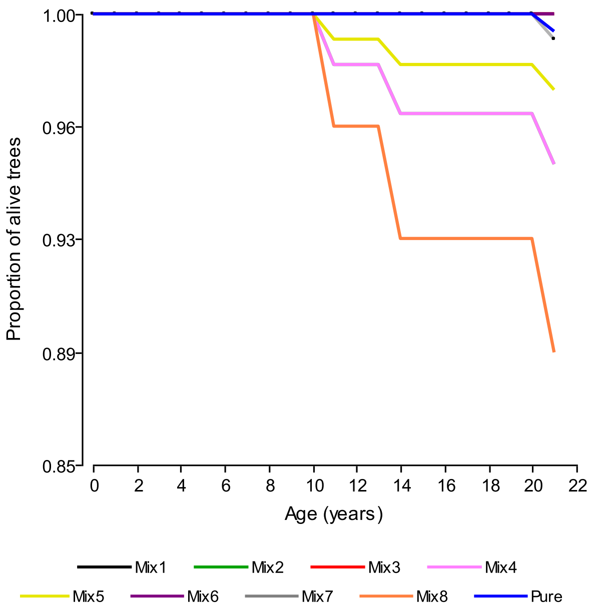

Fig. 3. Survival curves of chestnut trees by plantation type in southern Chile. Some mixtures are not visible, Mix1 and Mix3 are the same as Mix6, and Mix2 is the same as Mix4. Mix1: *Castanea sativa* + *Prunus avium* + *Quercus rubra* + *Quercus robur*. Mix2: Mix1 + *Alnus glutinosa*. Mix3: Mix1 + *Gevuina avellana*. Mix4: Mix1 + *Embothrium coccineum*. Mix5: Mix1 + *Fabiana imbricata*. Mix6: Mix2 + *Fabiana imbricata*. Mix7: Mix3 + *Fabiana imbricata*. Mix8: Mix4 + *Fabiana imbricata*.

could improve timber quality, as shown for other species (Burkardt et al., 2019). Future studies assessing the competition degree between chestnut and other species are therefore recommended.

Assuming a stable diameter growth and a minimum log diameter of 40 cm, according to our measurements, rotations of 29 years for Mix1 and 33 years for monoculture are estimated, similar to productive cycles suggested by Benedetti et al. (2018) in Chile, but shorter than in Europe (Kerr and Evans, 1993). The good performance of both plantation types could be associated with the lower plantation density than in other mixtures including arboreal or shrub companion species. Furthermore, the low selected plantation density, with main species and companion arboreal species being far away from one another, might have reduced the interactions between chestnut trees and other trees or shrubs so far. Distance could then be one major factor leading to the absence of effects.

Chestnut survival was high in all plantation types. In fact, three associations (Mix1, Mix3 and Mix6) had maximum survival (100 %); this result could be due to the high rainfall and low average temperature, conditions that are within the range considered optimal for chestnut development (Freitas et al., 2021). In fact, survival probabilities in poor and dry sites have been considered low (Conedera et al., 2021). Another explanation of the high survival recorded could be related to the planting time, since according to Radoglou et al. (2003), chestnut planted in mid-winter showed improved chances of survival due to an enhanced ability to partially resist water stress.

Another possible benefit from some associations to chestnut might be the reduction of phytosanitary risks (Zuppinger-Dingley et al., 2014). This effect might be important, since the species is sensitive to several pest and diseases (Freitas et al., 2021). However, we did not observe phytosanitary differences among plantation types, since health status of chestnut trees was excellent in all plantation types.

Several attributes have been used to characterize tree quality or suitability for timber production (Kuehne et al., 2013; Piagnani et al., 2018), with straightness being one of the most important in relation to timber quality (Frattegiani, 1996). Indeed, stem and crown form, and trunk length determine the economic result of the plantation at harvest. In our study, all trees had good stem and crown form, since the plantation is pruned periodically, limiting the possibility to test the impact of mixture composition on both variables.

We did not find the positive effect of nurse trees and shrubs on the percentage of straight trees reported for other species (Buresti-Lates, 1995). A simple association without companion species can produce chestnut timber of high quality and facilitate its cultivation; in fact, Mix1 produced longer trunks, representing a flexible silvicultural system. This result is in agreement with results from other studies that showed a positive effect of mixed plantation on chestnut timber quality when associated with conifers. For example, chestnut associated with *Pinus radiata*, *Pseudotsuga menziesii* and *Cupressus torulosa* David Don exhibited straight, smooth, cylindrical stems with natural pruning, and lower occurrence of epicormic shoots with respect to pure plantations (Loewe et al., 2005, 2013). Similar results were observed in chestnut associated with broadleaves such as *Quercus robur* and native species such as *Nothofagus alpina* (Poeppig & Endlicher) Oersted (Loewe et al., 2013). Future studies should assess timber quality performance of chestnut trees at later ages across plantations types.

Our findings showed that mixed plantations can also benefit growth and timber quality, which is economically relevant, as observed in other

Table 7
Percentage of chestnut trees for each stem quality variable and plantation type at age 20.

Variable	Plantation type								
	Mix1	Mix2	Mix3	Mix4	Mix5	Mix6	Mix7	Mix8	Pure
Vigor [%]									
High	92	100	100	100	100	100	100	83	100
Medium	8	0	0	0	0	0	0	17	0
Low	0	0	0	0	0	0	0	0	0
Stem Form [%]									
Straight	50	57	50	20	33	50	67	50	44
Light buckled	42	43	33	80	26	33	33	33	44
Heavy buckled	8	0	17	0	33	17	0	17	9
Deformed	0	0	0	0	8	0	0	0	3
Crown Form [%]									
Monopodial	100	100	100	100	100	100	100	100	100
Forked	0	0	0	0	0	0	0	0	0
Brushy	0	0	0	0	0	0	0	0	0
Trunk length [%]									
High	92	71	67	20	42	50	67	67	56
Medium	8	29	33	60	58	50	33	17	44
Low	0	0	0	20	0	0	0	17	0

Mix1: *Castanea sativa* + *Prunus avium* + *Quercus rubra* + *Quercus robur*. Mix2: Mix1 + *Alnus glutinosa*. Mix3: Mix1 + *Gevuina avellana*. Mix4: Mix1 + *Embothrium coccineum*. Mix5: Mix1 + *Fabiana imbricata*. Mix6: Mix2 + *Fabiana imbricata*. Mix7: Mix3 + *Fabiana imbricata*. Mix8: Mix4 + *Fabiana imbricata*.

studies in Chile (Siebert and Loewe, 2002; Loewe and González, 2006; Loewe et al., 2008b) and in other countries (Buresti-Lates, 1995; Binkley, 2003; Forrester et al., 2004, 2006; Gabriel et al., 2005; Hung et al., 2011). For example, in France, the inclusion of chestnut as a primary species in mixed plantations has improved stem form when associated with conifers (Bourgeois, 1992). In Italy, chestnut has been included in several mixed plantations to provide high-value timber production, and was classified as a medium growth species (Buresti-Lates and Mori, 2009). Finally, similar results were reported in Portugal and France (Bourgeois et al., 1991). We recommend studying the impact of different mixtures on wood density when thinning is performed. Furthermore, the ring shake defect, which is widely present in Europe (Fonti et al., 2002), could be investigated in mixed plantations, since it has not been detected in pure plantations in Chile (Benedetti and Subiri, 2000).

Our results regarding tree growth, survival, health, and timber quality highlight the potential of chestnut for forestry in Chile. The species may be especially attractive to small and medium-size landowners, who can produce nuts annually and obtain high quality timber at the end of the rotation. However, future studies addressing stand density, competition control, tree species selection and distribution within plantations could contribute to the achievement of high-quality timber.

5. Conclusions

The positive effects of some plantation types on chestnut growth and timber quality were evidenced in the long-term, at age 20. In particular, the association including arboreal main species, which will also generate timber products of commercial interest, resulted in bigger chestnut trees with longer trunks. The inclusion of *Embotrium coccineum,* a companion arboreal species, showed a detrimental effect on chestnut growth and timber quality. Mixed plantations including the shrub *Fabiana imbricata* did not improve chestnut tree performance.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foreco.2022.120742.

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