



Weed control and use of tree shelters: improving restoration success of degraded north Patagonian forests

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Received: 5 April 2021 / Accepted: 19 March 2022 / Published online: 9 April 2022
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Abstract

Austrocedrus chilensis and *Nothofagus dombeyi* are endemic species of the Andean-Patagonian forests of Argentina. Both species grow in either pure or mixed stands. In the last decades, several *A. chilensis* stands have been degraded by different disturbances that have compromised their natural regeneration. Plantation of seedlings of both species may be an alternative to help restore ecological, scenic and productive characteristics of these stands. In this study, we determined, in degraded *A. chilensis* stands grown in a xeric ($\approx 690 \text{ mm}\cdot\text{yr}^{-1}$) and a mesic ($\approx 984 \text{ mm}\cdot\text{yr}^{-1}$) site without canopy cover, the effects of tree shelters, the presence/absence of neighboring herbaceous vegetation, and the interaction between these factors on the performance (i.e. survival and growth) of planted *N. dombeyi* and *A. chilensis* seedlings, during four growing seasons. Results showed that tree shelters improved survival of *N. dombeyi* in the mesic site, and improved survival of both species in the xeric site. The removal of neighboring herbaceous vegetation improved the survival and diameter growth of both species at the xeric site, and improved the diameter growth of both species at the mesic site. By applying these planting technologies, both species could be successfully used for restoring highly degraded *A. chilensis* stands at mesic sites, while it is more advisable to use *A. chilensis* at xeric sites under open sky conditions.

Keywords *Austrocedrus chilensis* · *Nothofagus dombeyi* · Tree shelters · Herbaceous competition · Enrichment planting

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Introduction

In any forest stand, when canopy cover becomes very sparse or even disappears due to natural or anthropic disturbances, the use of active restoration techniques may be necessary for recovering at least part of its former structure and functions (Whisenant 1999; Donoso et al. 2015; Urretavizcaya and Defossé 2019). Forest restoration has many environmental, social, and biological benefits. Among these benefits, there is an increasing appreciation for the importance of forests in reducing soil erosion, protecting biodiversity, improving carbon sequestration, and providing goods and services for society (Stange and Shea 1998). However, these restoration plans may not necessarily have, as a goal, to restore the forest exactly as it was in its former state prior to disturbance. One alternative to strict restoration is enrichment planting, which introduces valuable timber species in existing but degraded forests (Aide et al. 2000, International Tropical Timber Organization (ITTO) (2002), Martínez-Garza and Howe 2003, Paquette et al. 2006). This enrichment could successfully be used to increase the value of the forest, preventing their conversion to other land uses (Montagnini et al. 1997; Dalle et al. 2006; Paquette et al. 2009).

To ensure the establishment of desired species, restoration practices often require additional manipulation of the microsite where the seedlings are going to be planted to avoid or diminish any negative biotic or microenvironmental effects on plant establishment (Whisenant 1999; Veblen et al. 2004; Heinemann and Kitzberger 2006; Valenzuela et al. 2016, 2018). These negative effects are often caused by competition for light, soil water and/or nutrients by nearby herbaceous vegetation, or by the lack of nurse plants to protect the seedlings from excessive radiation and/or surrounding microenvironmental temperature fluctuations (Garau et al. 2008; Dinger and Rose 2009; Padilla and Pugnaire 2006; Maguire et al. 2009; Urretavizcaya et al. 2017; Caselli et al. 2021). In some situations, the removal of nearby herbaceous vegetation could improve the restoration success of planted seedlings (Davis et al. 1998; Benayas et al. 2005; Caselli et al. 2021). In others, and particularly during early stages of establishment, seedlings may be protected from extreme temperatures, dehydration, and excessive radiation by a nearby nurse shrub (Bertness and Callaway 1994; Keeley 1992; Chambers et al. 1999, Urretavizcaya and Defossé 2013, 2019). However, when nearby shrub vegetation is absent, this protection effect could be substituted by using artificial shelters (Bellot et al. 2002; Oliet et al. 2005; Chaar et al. 2008; Piñeiro et al. 2013; Valenzuela et al. 2016, 2018).

Several studies suggest that seedling growth and survival can be significantly increased with the protection given by tree shelters (Costello et al. 1996; Dubois et al. 2000; Weitekamp et al. 2001; Jacobs and Steinbeck 2001; Sweeney et al. 2002; Ponder 2003; Dorji et al. 2020). These responses have been attributed to an improvement of microclimatic conditions within the shelter environment (Potter 1988; Zastrowd and Marty 1991; Kjelgren et al. 1994; Peterson et al. 1994; Bergez and Dupraz 1997, 2000; Oliet and Jacobs 2007; Jacobs 2011). Tree shelters have been successfully used to establish trees for wood production, reforestation, landscape revegetation, and in urban environments (Burger et al. 1992; Buresti and Sestini 1994; West et al. 1999). However, tree shelter effects can be time, site and species-dependent (Potter 1988; Burger et al. 1992; Ward and Stephens 1995; West et al. 1999; Ponder 2003; Bellot et al. 2002; Famiani et al. 2007; Oliet and Jacobs 2007); and protection requirements of forest species may vary in the early stages of tree development, as was stated for *Austrocedrus chilensis* (D. Don) Pic. Ser. *et* Bizzarri, and *Nothofagus dombeyi* (Mirb.) Oerst, two important native species of North Patagonian forests (Caselli et al. 2018).

Austrocedrus chilensis and *N. dombeyi* forests have very important ecological, productive, and scenic values, but several natural and anthropogenic disturbances have undermined their tree quality and, mostly for *A. chilensis* pure forests, its natural regeneration capacity. In areas above 700 mm/year of precipitation, this species has been affected by a root disease caused by the pseudo-fungus *Phytophthora austrocedri* (Greslebin et al. 2007). This disease causes stand declining patterns and unpredictable mortality (Loguercio 1997; Greslebin and Hansen 2009). Forest density reduction caused by the disease could produce critical situations, inducing land use changes toward intensification of livestock activity or afforestation with exotic species, mainly due to the low forest value of the remaining degraded forest. However, when livestock grazing is not present, tree density reduction stimulates the natural regeneration of *A. chilensis*, and of *N. dombeyi* if nearby seed sources are available (Loguercio 1997; Amoroso and Larson 2010; Amoroso et al. 2012). This natural process suggests the possibility of leading active restoration of pure and sick *A. chilensis* stands into mixed *A. chilensis* and *N. dombeyi* stands, augmenting forest management options, and increasing its ecological and productive value (Loguercio 1997, Loguercio et al. 2018a, b, Caselli et al. 2021).

Nothofagus dombeyi is considered a light-demanding species (Müller-Using and Schlegel 1980; Donoso 1981; Dezzotti 1996; Amoroso and Larson 2010), and *A. chilensis* appears to be more shade tolerant (Veblen and Lorenz 1987; Veblen 1989; Kitzberger et al. 2000; Caselli et al. 2018). However, *N. dombeyi* affinity for open areas seems to be reduced in dry sites because its regeneration could be affected by extreme drought events, particularly in rocky soils with high slopes (Weinberg and Ramirez 2001, Suarez and Kitzberger 2008, 2010); also, its regeneration could be affected in places exposed to severe frost (Soto et al. 2009; Donoso et al. 2013). Previous studies showed that *A. chilensis* persists much longer below the canopy of pure and mixed forests, being also much more resistant to water deficit than *N. dombeyi* (Veblen et al. 1996; Suarez and Kitzberger 2008; Scholz et al. 2014; Caselli et al. 2018). Additionally, it has been shown that *A. chilensis* seedlings need some protection from excessive radiation and extreme temperatures, which can be provided by nearby nurse plants (Loguercio 1997; Villalba and Veblen 1997; Kitzberger et al. 2000; Rovere 2000; Letourneau et al. 2004; Urretavizcaya et al. 2012, Urretavizcaya and Defossé 2013).

Knowledge about how the use of tree shelters and removal of herbaceous vegetation can affect survival and growth of both *A. chilensis* and *N. dombeyi* is still scarce, and only a few experiments have been made. Urretavizcaya and Defossé (2013) showed that, for *A. chilensis*, tree shelters may have similar positive protection effects as nurse plants do. On the other hand, Caselli et al. (2021) showed that the removal of neighboring herbaceous vegetation could improve survival and growth of both species. Increasing the existing knowledge of these effects is important to make recommendations for the restoration of diseased pure *A. chilensis* stands. The objective of this study was to build knowledge about the performance of *A. chilensis* and *N. dombeyi* seedlings grown in severely degraded pure *A. chilensis* forests sites, which showed different environmental conditions, mainly related to their mean annual precipitation. We evaluated how (1) tree shelters and (2) neighboring herbaceous vegetation affected the survival and growth of seedlings of both species grown under the open sky (no canopy cover) at different environmental conditions: mesic ($\approx 984 \text{ mm.yr}^{-1}$) and xeric ($\approx 690 \text{ mm.yr}^{-1}$). We hypothesized that tree shelters favor survival of both species, especially in the xeric site; also, that removing nearby herbaceous vegetation may be beneficial for survival and growth of both species in either site.

Materials and methods

Study area

The Andean-Patagonian region of Argentina, where this study was carried out, presents a typical Temperate-Mediterranean climate with cold and wet winters, and dry and warm summers (Csb according Köppen and Geiger 1936). In addition, the study area presents a strong west- to east- precipitation gradient, where different vegetation assemblages prevail. Throughout this area, there are important types of the Andean-Patagonian forest, including pure and mixed *A. chilensis* and *N. dombeyi* forest stands. Both species have slightly different ecological requirements (Caselli et al. 2018), which allows a heterogeneity of structures to exist in their range of distribution. This comprises pure *N. dombeyi* forests in humid sites in the west to pure *A. chilensis* in dry sites, and mixed *N. dombeyi*-*A. chilensis* stands in intermediate zones (Loguercio et al. 2018a). The structure of mixed stands is usually stratified in two layers, with *N. dombeyi* dominating the upper layer and *A. chilensis* the lower layer (*Nothofagus dombeyi* can reach up to 40 m height while *A. chilensis* usually does not exceed 28 m in height) (Veblen and Lorenz 1987; Dezzotti 1996; Loguercio 1997).

In a representative area of *A. chilensis* natural distribution, we selected two sites, one presenting mesic environmental conditions (43° 11' LS, 71° 40' LW), and the other with xeric conditions (43° 12' LS, 71° 31' LW). Both sites are located in the Valle 16 de Octubre, at the southwest of Esquel town in Patagonia, Argentina. Both sites had an almost flat relief, with an altitude of 360 and 430 m.a.s.l. for the mesic and xeric site, respectively. The long-term average annual rainfall, 10 km to the east of the mesic site, is 984 mm (data from 1970 to 2019 recorded in the nearby INTA Trevelin Weather Station), and 3 km to the east of the xeric site, is 690 mm (data gathered from 1964 to 1988 in Nant y Fall Weather station, Albuinés 1998). In the study zone, the mean temperature of the warmest month (January) is 15.8 °C, and for the coldest month (July) is 3.0 °C (1970–2002 series for INTA Trevelin Weather Station).

The characteristic precipitation gradient of the Andean-Patagonian region and the mountain relief also determined the distribution of ice during glaciations, generating a sequence of west–east landscapes expressed by different geomorphological features. On the west, glacial erosion geofoms predominate, and on the east, accumulation geofoms predominate (Rabassa et al. 2000; Haller 2001). Pyroclastic deposits from volcanoes located in Chile, covered all this landscape during the Holocene (Auer 1950), which rapid alteration enabled the development of highly fertile soils (La Manna 2005). Both study sites have soils derived from volcanic ashes, with pH FNa values that indicate the presence of imogolite (amorphous aluminosilicate, Buduba 2006). However, in the area surrounding the xeric site, glacialfluvial deposits occur with high levels of clay almost at surface level, while in the area of the mesic site, the soils tend to be rockier, deeper, and better drained (La Manna 2005).

At the mesic site, the predominant vegetation is a diseased *A. chilensis* forest degraded by bovine and equine livestock, with some scattered *N. dombeyi* trees. At the xeric site, the predominant vegetation is composed also by *A. chilensis*, but this forest is less affected by *A. chilensis* disease and by livestock. The xeric site was affected by a wildfire during the summer of 1990. The above-mentioned disturbances produced landscape areas without canopy cover, where the experimental plots were installed.

At the mesic site, neighboring vegetation had high cover and was composed of herbs and grasses; the predominant species were mainly from the Poaceae family,

i.e. *Arrhenatherum elatius*, *Dactylis glomerata*, *Holcus lanatus*, *Phleum pratense*, and *Bromus sp.*; *Alstroemeria aurea* (Alstroemeriaceae) and *Blechnum penna-marina* (Blechnaceae) were also present. At the xeric site, the neighboring vegetation was mainly composed of herbs and grasses, similar to the mesic site. The predominant species were from the Poaceae family, i.e. *Holcus lanatus*, *Festuca sp.*, *Bromus sp.*, and *Poa sp.* There were also *Achillea millefolium*, *Osmorhiza chilensis*, *Maytenus chubutensis*, and *Carex sp.*

Mean temperature in the four growing seasons (from October to April in the Southern Hemisphere) of this study (from August 2016 to April 2020) was a little bit higher than the long-term average (INTA Trevelin Weather Station, series 1970–2015), while precipitation showed fluctuations, with periods of higher and lower records as compared to the long-term average, registering a lower precipitation in 2017, 2018 and 2019 (19, 14 and 19% lower than long-term average, respectively) (Fig. S1).

In November of 2016 at the mesic site, and in March of 2017 at the xeric site, we installed automatic data loggers (one for each site in a random plot), with soil temperature and moisture sensors placed at 15 cm soil depth in a horizontal position, without altering the neighboring vegetation (see Caselli et al. 2021). Mainly due to the west–east gradient of the region that induces different environmental conditions, there are differences in soil temperature and moisture between the mesic and the xeric site that could lead to differences in seedlings performance. The mesic site presented a minimum soil moisture value close to 10%, while the xeric site presented a minimum value under 5% (Fig. S2). In the xeric site, soil temperature at 15 cm soil depth reached almost 30 °C in summer, while in the mesic site it reached near 25 °C (Fig. S2).

For the soil characterization of the sites, at the beginning of the experiment, we took composite soil samples in each site from which the main physical–chemical properties of the soil were determined: pH in water, electrical conductivity, pH in NaF, organic matter, total N, available P, K, Na, Ca, Mg, S-Sulfates and cation exchange capacity. These samples were taken at four points equidistant from the corners of each of the three plots of each site (see Experiment design section), and then we took the media and the standard error per site (Table S1). The sites show similar pH in water, electrical conductivity, total N, Na, Ca and Mg content, and cation exchange capacity. The organic matter was higher at the mesic site, as is the pH FNa and S-Sulfates. At the xeric site, the content of P and K was higher than at the mesic site.

Characterization of plant material

Three-years-old *A. chilensis* and one-year-old *N. dombeyi* seedlings used in the experiment were produced from seeds of local origin with morphological attributes similar to those recommended as suitable for active restoration activities (Urretavizcaya et al. 2015) (Table 1). *Austrocedrus chilensis* seedlings were grown in a nursery using the traditional method of sowing seeds in a seed bed, in which the emerged seedlings remained for the first growing season. Then the seedlings were transplanted to 900 cm³ polyethylene bags, and remained outside the greenhouse for two years (3 yr old, or 1 + 2). *Nothofagus dombeyi* seedlings were produced in the greenhouse by fertilized-irrigation system and were grown in Dassplastic 24,250 trays (24 cavities, 250 cm³/cavity) for one year (1 yr old, or plug + 0).

Table 1 Morphological parameters of *A. chilensis* and *N. dombeyi* seedlings (mean and standard error) at the beginning of experiment (n = 30)

Parameter	<i>A. chilensis</i>	<i>N. dombeyi</i>
Root collar diameter (RCD, mm)	3.4 (0.07)	4.3 (0.10)
Height (H, cm)	16.6 (0.44)	56.6 (1.78)
Aboveground biomass dry weight (ADW, g)	3.0 (0.15)	3.4 (0.15)
Belowground biomass dry weight (BDW, g)	1.9 (0.12)	1.6 (0.11)
Slenderness index (H/RCD*10)	50.2 (2.0)	131.5 (3.9)
ADW/BDW	1.7 (0.05)	2.5 (0.12)

Experimental design

In each site (mesic and xeric), we selected an area of approximately 2000 m² without canopy cover at the edge of the existing forest. At each site, we planted *A. chilensis* and *N. dombeyi* seedlings, in the winter (August) of 2016, in three plots. In each plot, seedlings were planted in eight lines, with 12 plants of the same species in every line, four of *A. chilensis* and four of *N. dombeyi*. On each plot, we evaluated the effect of three factors: neighboring herbaceous vegetation removal (VR), the use of tree shelters (TS), and time (growing season) on seedling survival, root collar diameter (RCD), and height for each species and site, during the 2017–2020 period. The first two factors have two levels: with— VR and TS, and without—, No VR and No TS; and the third one has 4 levels: end of the first, second, third and fourth growing season (year 2017, 2018, 2019 and 2020, respectively). Each combination of levels of neighboring herbaceous vegetation removal and use of tree shelters (TS-No VR, No TS-VR, TSVR, and No TS-No VR) was applied to 1 random line per species in every plot.

The tree shelters consisted in white PET plastic tubes (Model: Patagonia, Manufacturer: Sujetatodo) of 12.5 cm in diameter and 60 and 30 cm in height, for *N. dombeyi* and *A. chilensis*, respectively. These tree shelters have a light transmission of 32%, and nine circular vents with a diameter of 1.5 cm distributed equidistant along the lower 25 cm. The height of 60 cm corresponds to the highest tree shelter available in the national market. These tree shelters were mainly designed to improve survival through protection against abiotic agents (i.e. solar radiation, wind), and not to protect plants from large herbivores browsing. Given the smaller size of the *A. chilensis* seedlings, and to maintain a similar relationship between the height of the plant and the tree shelter height in both species, the tree shelters of this species were cut at 30 cm in height, in the same way as Urretavizcaya and Defossé (2013) did. This size of tree shelter is enough to provide protection against the abiotic factors, as long as weed control was carried out without herbicides.

The neighboring herbaceous vegetation was manually removed to the root (trying to minimize disturbances to the surrounding soil), in a strip 1 m width, approximately 50 cm around the each target seedling, at the beginning of the growing season (October) and in midsummer (February), every year. During the first three growing seasons, RCD was measured in a sample of plants (first 6 plants of each row in every plot). In the fourth growing season the RCD was measured in all surviving plants. Height was measured for all plants throughout the experiment.

In both sites, we built perimeter fences around the plots because of the presence of cattle. However, in the mesic site, in 2019 the fence was broken down by a tree wind-blown, and the plants were damaged by the cattle. Because of this, 100% of plants of *N. dombeyi* without tree shelters and 89% of plants with tree shelters presented browsing damages. For

A. chilensis, the damage was lower, presenting damage 43% of the plants without tree shelters, and 63% of the plants with tree shelters. As the new shoots of both species are the only palatable plant parts for these animals, the browsing damage to each plant was then very limited. For its part, due to the lower palatability of *A. chilensis* and its lower shoots development, the damage in this species was even lower. In 2020, there was another accidental entry of cattle in the same place, but with less damage: 4 and 3% of *N. dombeyi* seedlings without and with tree shelters, respectively; and 21 and 43% of *A. chilensis* without and with tree shelters where affected. These damages have some effect on the final height reached by the plants in the mesic site, which could have been a little higher.

Statistical analyses

We analyzed seedlings RCD, height, and survival using linear mixed models in both sites and for both species separately. We considered neighboring herbaceous vegetation, tree shelters and time (year) as fixed effects, and the corresponding interactions among them. The random effects for all analyses were: plot ($n = 3$), subplot (seedling lines with the same treatment in each plot) and the seedling line. For growing analyses, the mixed models used allow considering each seedling as a sample unit. For survival temporal dynamics analyses, we compared the percentage of survival by line, transforming the data by arcsine to achieve the assumption of normality. For all analyses, we use autoregressive order 1 to model the correlation of data for every year (grouping by the plot, subplot, line, and observation). We made the comparison of the estimated models using the likelihood-ratio-test to find the best for each response variable (using the model with the lowest Akaike Information Criteria when $p \leq 0.05$ and the simpler when $p > 0.05$). For treatments comparisons, significance level was set at $\alpha = 0.05$. When there were significant differences, we performed means comparison using the least-significant-difference Fisher test. We performed all analyses with the statistical software Infostat (Di Rienzo et al. 2019). Infostat implements an interface with the R platform (R Core Team 2017) for the estimation of mixed models through the gls and lme processes of the nlme library (Pinheiro and Bates 2004; Di Rienzo et al. 2011). The interface with R was written in Delphi® and depends on R-DCOM (Di Rienzo et al. 2011).

Results

Survival

In the mesic site, *A. chilensis* survival was only affected by time (Table S2, Fig. 1). During the first two growing seasons (2017 and 2018), survival was similar, in 2019 it was significantly lower compared to the previous seasons, and finally in 2020 survival was significantly lower than in 2019, with a mean of 53%. In this site, *N. dombeyi* survival was significantly affected by tree shelters and time (Table S2, Fig. 1). Sheltered seedlings had significantly higher survival than seedlings without shelters. Survival was similar for the end of the second growing season (2018), compared with the first (2017) and the third (2019) growing seasons.

In the xeric site, *A. chilensis* survival was affected by neighboring herbaceous vegetation, tree shelters and time (Table S3, Fig. 1). During all the experiment, removal of neighboring herbaceous vegetation and the use of tree shelters were beneficial for *A. chilensis*

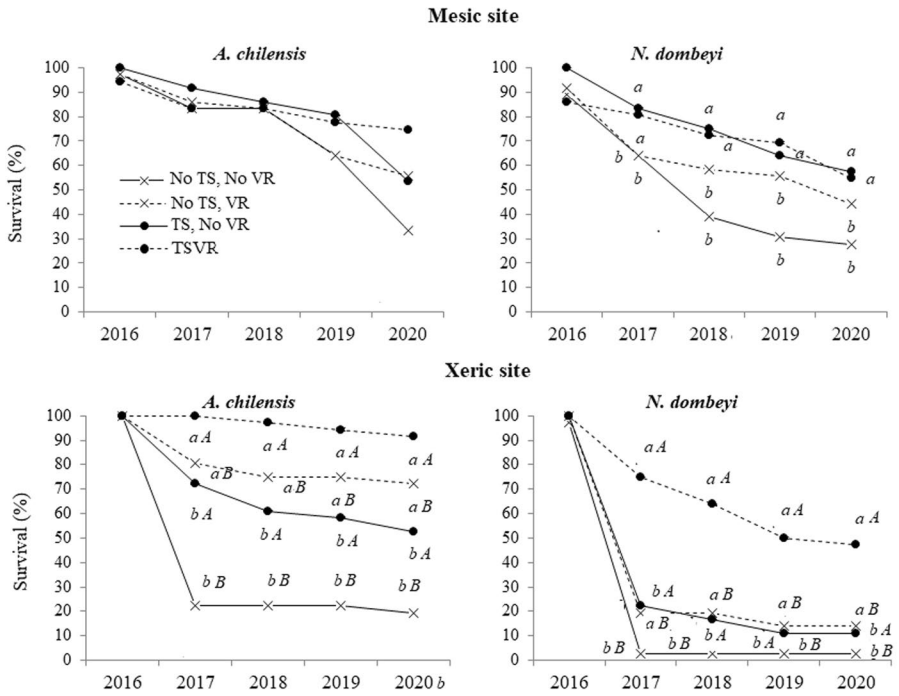


Fig. 1 Survival (period 2016–20) of *A. chilensis* (left) and *N. dombeyi* (right) growing at the mesic (above) and xeric (bottom) sites: neighboring herbaceous vegetation removal (VR), tree shelter (TS), tree shelter with neighboring herbaceous vegetation removal (TSVR), and without tree shelter, without neighboring herbaceous vegetation removal (No TS, No VR). Different letters indicate significant differences ($p \leq 0.05$): in the xeric site, uppercase indicates the effect of tree shelters and lowercase indicates the effect of the vegetation removal (comparisons between growing seasons are not shown)

survival. Survival was significantly higher at the end of the first growing season, compared with all the other growing seasons. In this site, *N. dombeyi* survival was affected by neighboring herbaceous vegetation and by tree shelters (Table S3, Fig. 1). During all the experiment, seedlings with vegetation removal and with tree shelters showed the highest survival.

Root collar diameter

In the mesic site, *A. chilensis* RCD was affected differently by neighboring herbaceous vegetation removal through time (Table S2, Fig. 2). At the end of the first growing season (2017), all seedlings had similar RCD (5.70 mm, SE=0.14), but later, seedlings with neighboring herbaceous vegetation removal showed the highest RCD (Fig. 2). In this site, *N. dombeyi* RCD was affected by neighboring herbaceous vegetation removal (Table S2, Fig. 2). Seedlings with neighboring herbaceous vegetation removal showed the highest RCD since the first growing season (Fig. 2).

In the xeric site, *A. chilensis* RCD was also affected differently by neighboring herbaceous vegetation and tree shelter through time (Table S3, Fig. 2). At the end of the first growing season the plants with tree shelters and vegetation removal were significantly wider than plants with tree shelters without vegetation removal. At the end of

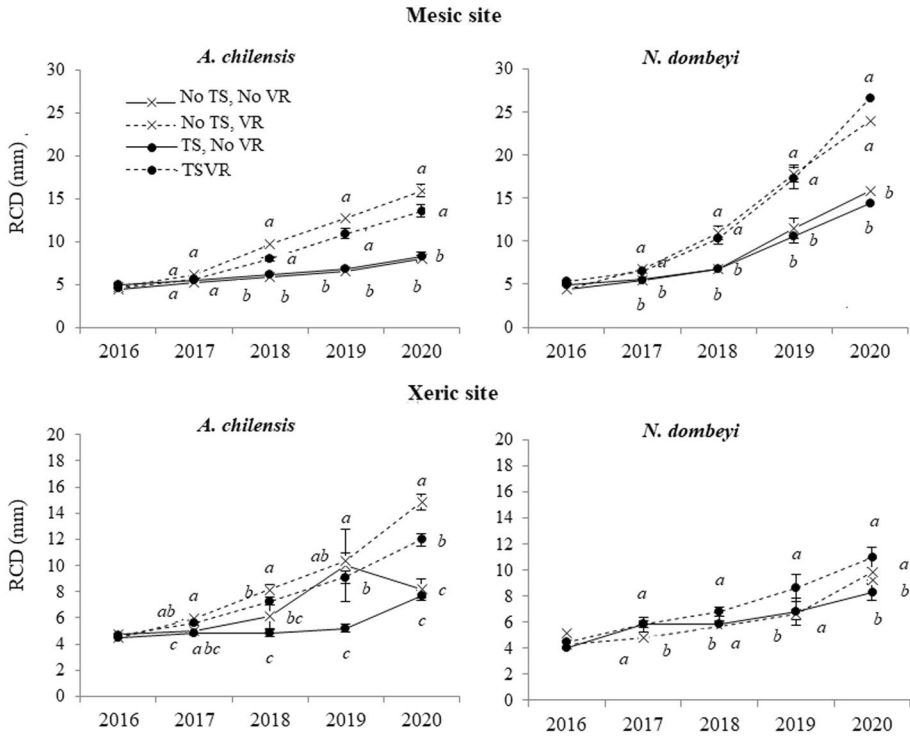


Fig. 2 Seedling’s root collar diameter (RCD) (mm) and standard error for the 2016–20 period of *A. chilensis* (left) and *N. dombeyi* (right), growing at the mesic (above) and xeric (bottom) site, neighboring herbaceous vegetation removal (VR), tree shelter (TS), tree shelter with neighboring herbaceous vegetation removal (TSVR), and without tree shelter, without neighboring herbaceous vegetation removal (No TS, No VR). For every year, different letters indicate significant differences ($p \leq 0.05$) between treatments (comparisons between growing seasons are not shown)

the second growing season (2018), seedlings with vegetation removal showed different RCD regardless of having tree shelters or not, being wider the plants without tree shelters (Fig. 2). In this year, seedlings without vegetation removal showed similar RCD with and without tree shelters, and the plants with vegetation removal had a wider RCD, independently of the use of tree shelters or not. In the third growing season (2019), seedlings with and without vegetation removal showed different RCD regardless of having tree shelters or not, being wider the plants without tree shelters in both cases. In this year, seedlings with tree shelters had different RCD regardless of having vegetation removal or not, being wider in the plants with vegetation removal. No significant differences were detected in the RCD of seedlings without tree shelters with or without vegetation removal (Fig. 2). The apparent improvement in the growth of the No VR-No TS seedlings in this season is based on the fact that it is the average between 2 plants only. In the fourth season, the diameter measurement method was changed from a sample to a census, so the data corresponds to the 7 living plants. For *N. dombeyi* seedlings at this site, it was not possible to compare RCD means for all factors, because of the lack of

living seedlings without tree shelters. During all the experiment, seedlings with vegetation removal showed the highest RCD (Table S3, Fig. 2).

Height

In the mesic site, height of *A. chilensis* was affected by neighboring herbaceous vegetation (Table S2, Fig. 3). *Austrocedrus chilensis* seedlings with neighboring herbaceous vegetation removal had the greater height since the first growing season. In this site, *N. dombeyi* height was only affected significantly by time (Table S2, Fig. 3), but also a tendency of an interaction of neighboring vegetation x time is showed ($p=0.0610$). At the end of the first growing season (2017), all seedlings had similar height (60.29 cm, SE = 1.80). Between the second and third (2019) growing seasons, seedlings height was similar, probably because most of the plants were browsed by cattle during 2019. At the fourth growing season (2020), seedling' height was significantly different from the previous growing season, even with the new browsing damage. Since the second growing season, a tendency of higher seedlings with neighboring herbaceous vegetation removal is evident. The unwanted effect

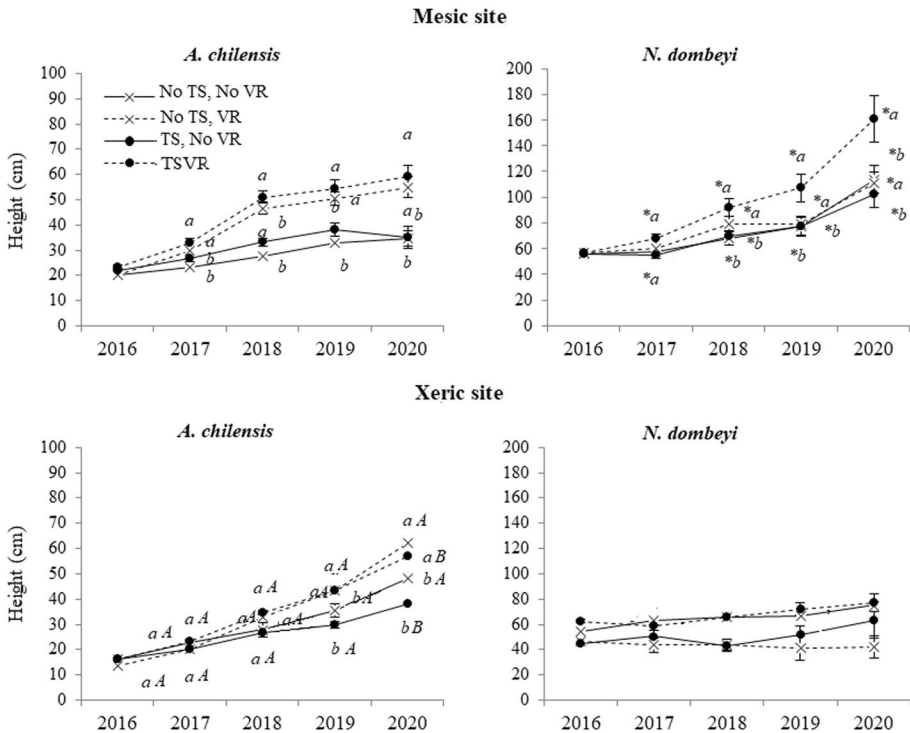


Fig. 3 Seedling's height (cm) and standard error for the 2016–20 period of *A. chilensis* (left) and *N. dombeyi* (right), growing at the mesic (above) and xeric (bottom) site: neighboring herbaceous vegetation removal (VR), tree shelter (TS), tree shelter with neighboring herbaceous vegetation removal (TSVR), and without tree shelter, without neighboring herbaceous vegetation removal (No TS, No VR). For every year, different letters indicate significant differences ($p \leq 0.05$): for *A. chilensis* in the xeric site, uppercase indicates the effect of tree shelters x time, and lowercase indicates the effect of vegetation removal x time (comparisons between growing seasons are not shown). *Corresponds to a tendency ($p=0.061$) of the effect of vegetation removal x time

of browsing may have homogenized the effects of the treatments applied to this species, so the height results in the mesic site cannot be considered completely conclusive.

The height of *A. chilensis* at the xeric site was affected differently by neighboring herbaceous vegetation and by tree shelter through the time (Table S3, Fig. 3). When comparing seedlings with and without vegetation removal, at the first and second growing seasons all seedlings had similar height, but later the plants with vegetation removal were taller. Comparing seedling height with and without the use of tree shelters, significant differences were recorded in the fourth season (2020) only, being the tallest plants those without tree shelters. In this site, and during all the experiment, *N. dombeyi* height was similar for all the seedlings (Table S3, Fig. 3).

Discussion

In this study we evaluated *A. chilensis* and *N. dombeyi* seedlings performance in common conditions present in degraded forests of *A. chilensis*. At the mesic and xeric sites, both species showed different responses associated with the use of tree shelters and the presence of neighboring herbaceous vegetation. Our hypotheses were partially proven because, at least until four years after the plantation, tree shelters favored survival of both species at the xeric site, and *N. dombeyi* survival at the mesic site. At the mesic site, neighboring herbaceous vegetation removal favored RCD and height of both species, but for *N. dombeyi* height, it was only a tendency. At the xeric site instead, while *A. chilensis* seedlings showed the greatest development with vegetation removal and no tree shelters, *N. dombeyi* only showed a positive vegetation removal effect on RCD.

Tree shelters and neighboring vegetation effects on survival

In humid sites, *N. dombeyi* has a clear affinity for open sites (Müller-Using and Schlegel 1980; Dezzotti 1996; Álvarez and Lara 2008; Amoroso and Larson 2010). However, under mesic and xeric conditions, it needs a certain degree of protection. On the other hand, it was stated that *A. chilensis* is able to bear better the environmental conditions that take place under the open sky, both in xeric and mesic conditions, in comparison with *N. dombeyi* (Caselli et al. 2021). This is evidenced in our study as tree shelters proved to have no effect on *A. chilensis* survival at the mesic site, and by the higher survival of *A. chilensis* compared to *N. dombeyi* in the xeric site. This behavior may be related to differences in the physiological mechanisms of both species. To avoid soil water stress by keeping some water in its tissues, *A. chilensis* closes its stomata in response to high evaporative demands (e.g., at midday), even under non limiting soil water availability (Gyenge et al. 2007). Nevertheless, as it has also been stated for other species, this strategy may imply the risk of photoinhibition or cell tissue damage because of overheating (Gyenge et al. 2007), and also starvation (McDowell et al. 2008). Under similar high evaporative demands, *N. dombeyi* seedlings have not shown this strategy; instead, this species increases its stomatal conductance (Read and Hill 1985; Zúñiga et al. 2006; Jiménez-Castillo et al. 2011), which could lead leaves to dehydration, abscission, and a later carbon starvation (Scholz et al. 2014). Our results suggest that the lack of protection, specially under moisture limiting conditions, could trigger physiological mechanisms that compromise seedling survival, as it was

also suggested for *A. chilensis* by Rovere (2000) and Caselli et al. (2018, 2021), and for *N. dombeyi* by Weinberger and Ramirez (2001) and Caselli et al. (2018, 2021).

In several studies and ecosystems, some authors have reported the benefits of tree shelters on survival and growth of forest species. These responses have been attributed to modified microclimatic conditions within the shelter environment (Potter 1988; Peterson et al. 1994; Bergez and Dupraz 1997, 2000; Clatterbuck 1999; Oliet and Jacobs 2007). Sheltered seedlings presented higher survival rates for many broadleaved and conifer species (Tuley 1985; Ward and Stephens 1995; Jacobs and Steinbeck 2001; Oliet et al. 2005; Puértolas et al. 2010; Valenzuela et al. 2018; Dorji et al. 2020). However, the effects could vary over time (Oliet et al. 2005) and due to the environmental conditions of the site (Oliet and Jacobs 2007). This is the case of *A. chilensis*, which survival was significantly promoted by tree shelters at the xeric site, but not at the mesic site. Since one of the potential advantages of tree shelters is their ability to keep moisture by capturing transpiration water that condenses inside the tubes (Potter 1991); these differences are probably based on the fact that the environmental conditions of the mesic site are not limiting for the development of this species seedlings under the open sky. In the xeric site instead, the environmental conditions would limit the establishment of the seedlings if they are not protected to desiccant factors, as provided by tree shelters or by nursery plants (Urretavizcaya and Defossé 2013, 2019).

Even so, using tree shelters only does not guarantee plantation success (Vallejo et al. 2012); therefore, the combination of various techniques might further increase seedling survival and growth (Baumgärtner 2012). It has been shown that herbaceous vegetation competition for soil moisture and nutrients can reduce survival of young trees (Dubois et al. 2000; Johansson 2004; Passaretti et al. 2020), especially in climates with seasonal water deficit (Davies 1985), such as Mediterranean types (Benayas et al. 2005; Navarro-Cerrillo et al. 2005). Thus, the removal of this type of vegetation could improve seedling survival. In our study, the driest conditions of the xeric site clearly showed the effect of neighboring herbaceous vegetation competition on the survival of both species. This behavior was expected as, in the driest sites, neighboring herbaceous vegetation competes with the target seedlings (Soriano and Sala 1984; Lee and Lauenroth 1994; Defossé et al. 1997; Davis et al. 1998), without providing shade as nurse plants do (Bannister et al. 2019). In fact, at this site, the soil moisture without herbaceous vegetation removal fell below 8% during February and March, a value that had been indicated as the lowest soil moisture limit for *N. dombeyi* seedlings survival under open sky conditions (Caselli et al. 2018). At the same time, it has been suggested that the net effects of competitive and facilitating interactions between plants vary along spatial and temporal gradients of abiotic stresses (Bertness and Callaway 1994; Holmgren et al. 1997). Thus, it was no surprising that, at the mesic site, we could not detect significant effects on survival of *A. chilensis* and *N. dombeyi* because of the neighboring herbaceous vegetation. This is showing that the soil moisture at a mesic site can be enough to sustain the life of both species seedlings and their neighboring herbaceous vegetation as well, although, woody seedling growth can be affected by this factor even at the mesic site.

Tree shelters and neighboring vegetation effects on growth

Although tree shelters can increase seedlings survival, they also may decrease RCD growth (Chaar et al. 2008). This effect was observed at the xeric site, where *A. chilensis* showed a negative effect of tree shelters in the RCD, which was significant from the second growing season and on for plants with vegetation removal, and only in the third growing season for

plants without vegetation removal. At this site, we could not evaluate the effect of tree shelters on *N. dombeyi* RCD because of the lack of living plants. Root collar diameter growth reduction in sheltered plants was reported in other studies (Tuley 1981; Smith 1983; Lantagne et al. 1990; Kjelgren et al. 1994; Burger et al. 1996; Piñeiro et al. 2013), and has been attributed to a different allocation of growth resources between root and shoot (Burger et al. 1997; Gerhold 1999; Jacobs and Steinbeck 2001; Oliet et al. 2005; Oliet and Jacobs 2007; Chaar et al. 2008). It has been stated that when plants grow inside the shelters, they accelerate height growth to reach available light at the expense of the RCD growth (Bardon et al. 1999; Sharew and Hairston-Strang 2005). But in our study the height of *A. chilensis* sheltered seedlings was not higher, and in fact, at the end of the fourth growing season, height was lower for sheltered seedlings. Oliet and Jacobs (2007) have indicated that sheltered seedlings invest in photosynthetic area mainly when water is not a limiting resource, which is not the case in ecosystems with summer water deficit, as in our xeric site. This would indicate that in our case, there would not be a change in the allocation of growth resources between root and shoot, but rather a decrease in general growth. This could be related to changes in the microenvironment that is generated within the tree shelter and that could be inducing the stomatal closure (Oliet and Jacobs 2007) that this species usually performs in unfavorable conditions, but further studies are needed to test this hypothesis.

Height of *N. dombeyi* seedlings was not affected by the use of tree shelters neither in the xeric site, and nor in the mesic site, at least until the second growing season (prior to the browsing effect). This result contrasted with those of several hardwood (Davies 1985; Tuley 1985; Gillespie et al. 1996; Bendfeldt et al. 2001; McCreary and Tecklin 2001; Dorji et al. 2020) and conifer species (Ward et al. 2000; Jacobs 2011), which had shown a pronounced positive impact on height with the use of tree shelters. It seems that our results agree with those of the authors who indicate that the net effect of tree shelters on plant growth appeared to be site- and/or species-dependent (Frearson and Weiss 1987; Potter 1988; Burger et al. 1992; Buresti and Sestini 1994; Ward and Stephens 1995; West et al. 1999; Ponder 2003; Famiani et al. 2007; Puértolas et al. 2010; Oliet and Jacobs 2007; Piñeiro et al. 2013). It should be mentioned, however, that the lack of effect of the tree shelters on *N. dombeyi* height in both sites, may be due to the fact that the shelters exceeded the initial height of the plants by a few centimeters only. In this sense, it was stated that the height growth advantage of sheltered seedlings appeared to be short-lived, because once seedlings emerged from tree shelters, height growth rates looked similar to that of the unsheltered seedlings (Lantagne 1995; Burger et al. 1996; McCreary and Tecklin 2001). Since *N. dombeyi* seedlings rapidly emerged from the tree shelters, they did not show the improvement in height growth that tree shelters can produce by stimulating apical dominance in the search of light (Lantagne et al. 1990; Jacobs 2004; Oliet et al. 2005), so this may be the reason why there were no effects of shelters on the seedlings' height. A similar mechanism could take place also for *A. chilensis* seedlings, explaining the lack of height growth stimulation of the tree shelters used. Nevertheless, this results contrast with those of Bellot et al. (2002), who reported for *Quercus coccifera* a higher growth in height when using tree shelters with 30 cm tall in comparison with shelters with 60 cm tall, in a Mediterranean site. These authors explain the differences by a best air circulation, which allowed to avoid the over warming that was observed in taller shelters.

On the other hand, given the height of the tree shelters in relation to the height of the plants, it was not possible to prevent the damage caused by cattle browsing in the mesic site (which had access to the plots when the fences were broken by falling trees in 2019 and 2020). Thus, it could be expected that the height achieved by this species at the mesic site would be somewhat greater, and even that some effect of the treatments applied could be

missed from the third growing season and onwards. Although preventing browsing damage was not the purpose of the use of tree shelters in this study, it has been such for other studies presenting positive effects of using taller devices for seedling browsing protection (Piñeiro et al. 2013; Dorji et al. 2020).

Moreover, reducing herbaceous competition can have positive effects on seedlings growth (Davis et al. 1998, Nilsson and Örlander 1999, Garau et al. 2000, Garau and Lemcoff 2001, George and Brennan 2002, Coll et al. 2004, Harper et al. 2005, Garau et al. 2008, 2009). It was stated that this effect comes mainly from reducing water competition, but also removing surrounding vegetation may have effects on nutrients availability (Harrington 1991; Dubois et al. 2000; Bannister et al. 2019). Furthermore, without herbaceous vegetation cover, the soil warms more quickly, reaching optimum temperatures for root development earlier; thus, seedling root systems may have access to soil water and nutrients earlier; this mechanism is particularly important for seedlings performance in sites with seasonal water deficit (Andersen et al. 1986). In our study, the main factor threatening the RCD growth of both species at both sites was the presence of neighboring herbaceous vegetation, indicating the competition that herbaceous vegetation can exert on woody seedlings in sites with and without seasonal water deficit.

Likewise, at both sites, *A. chilensis* seedlings showed an improvement in height growth when herbaceous vegetation was removed, while *N. dombeyi* seedlings only showed a tendency of a positive effect of herbaceous vegetation removal in the mesic site (influenced by the browsing damage from the third growing season and on). The lack of effect on height of *N. dombeyi* in the xeric site was striking because it was expected that competition of herbaceous vegetation would influence not only survival but also height development. It was stated in competition studies that height growth may be affected or not by herbaceous vegetation competition and sometimes a temporal difference may be found in the responses (Garau et al. 2009). No effect of neighboring herbaceous vegetation on height increment was found for *Eucalyptus regnans* (Messina 1990), and in the first year after plantation, for *Pinus resinosa* (Caldwell et al. 1995), while it had a significant impact on height growth of seedlings for up to 5 years after plantation of *Pinus banksiana*, *Pinus resinosa*, *Pinus strobus* and *Picea mariana* (Wagner et al. 1999). In the xeric site, it seems that the growth of *N. dombeyi* is more strongly tied to the environmental conditions, which result in limiting soil moisture and high temperature, than to the interaction with the neighboring herbaceous vegetation. In fact, the drier environment of the xeric site restrained in such a way the development of *N. dombeyi* that it showed a lower growth than *A. chilensis*. It was stated that growth rates of *N. dombeyi* seedlings are higher than those of *A. chilensis*, even at earlier ages (Loguercio 2005; Pafundi et al. 2016). However, our study showed that this difference can exist when seedlings are not exposed to dry conditions, in agreement with the findings of Caselli et al. (2018) in a nursery experiment with both species.

Implications for forest management and restoration

In this study, we were aimed at finding the proper field conditions to promote the establishment of planted *N. dombeyi* and *A. chilensis* seedlings in highly degraded (by either overgrazing and/or pests incidence) *A. chilensis* forests in mesic and xeric sites. Although our results are geographically limited to only one mesic and one xeric site, they suggest that in degraded forest lands it is recommendable to plant *A. chilensis* and *N. dombeyi* using tree shelters to improve survival rates, especially in xeric sites. When

tree shelters are not an option, it would be advisable to use nurse plants to give the necessary protection to the seedlings. Only in mesic sites, *A. chilensis* could have high survival rates under open sky conditions without any protection, but even in these sites using protections would be advantageous as in the future the effects of climate change could cause drier and hotter summers in the region, exposing plants to drying effects.

Neighboring herbaceous vegetation removal, in turn, is especially recommended in xeric sites, because it favors survival and growth, and in mesic sites, because it can favor growth. This removal should be done at least in the first four growing seasons, once or twice during the growing season, depending on the growth of the competing herbaceous plants. Also, given the trend observed in this study, it seems appropriate to accompany the use of tree shelters with the removal of neighboring herbaceous vegetation; otherwise, it could lead to reductions in growth.

As *A. chilensis* has greater capacity than *N. dombeyi* to tolerate the combination of high radiation and low soil moisture levels, in xeric sites under open sky conditions it will be more advisable to plant *A. chilensis* than *N. dombeyi*. Also, in these sites, *N. dombeyi* could be as productive as *A. chilensis*, while in mesic sites it can be much more productive. Although *N. dombeyi* may not perform well under open sky conditions in xeric sites, efforts for trying to establish both species to create mixed *A. chilensis*—*N. dombeyi* forests are still recommended, because of the multiple ecological and economic benefits of mixed versus pure forests (Scherer-Lorenzen et al. 2010; Kolstrom et al. 2011). In this sense, further research could focus on the effects of nursery plants on survival and growth of *N. dombeyi* under open sky-moisture limited environments. In all cases, the final goal should be contributing to enhancing the ecological, scenic and productive characteristics of degraded *A. chilensis* forests.

Finally, tree falls are common in diseased *A. chilensis* forests. Thus, it would be advisable to take this factor into account for site preparation and/or design of future restoration trials and experiences in sites where fences are needed because of the presence of cattle. The removal of standing dead trees that may damage the plants or fences with their fall should be done prior to planting, and then the state of the fences should be monitored periodically until the plants reach a safe height.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s11056-022-09912-2>.

Acknowledgements The authors wish to acknowledge Ivor Roberts and Alejandro Garzonio for allowing us to carry out this study in their lands. We wish to acknowledge Cristian Huisca, Tania Figueroa, Cristian Muñoz, Mailen Concha and Franco Millaman for their help on planting, maintenance of treatments and measuring. We also wish to acknowledge Melisa Rago for her help on neighbouring vegetation characterization and for her English revision. This work was supported by a grant of Applied Research Project (PIA) 14067 from Forestry Sustainability and Competitiveness Program of the Unit for Rural Change (UCAR, Argentina), and by a grant from CONICET (PUE-CIEFAP 4116/16). This research was carried out within the frame of a Postgraduate fellowship from National Scientific and Technical Research Council (CONICET, Argentina) to M. Caselli. Finally, we would like to thank the anonymous reviewers and associate editor for their detailed suggestions, which greatly improved our manuscript.

Authors' contributions MC: conceptualization, methodology, data collection, formal analysis, investigation, writing original draft, writing review and editing, visualization, project administration. FU: conceptualization, methodology, investigation, resources, writing review and editing, supervision, project administration, funding acquisition. GAL: conceptualization, methodology, investigation, resources, funding acquisition. LC: conceptualization, methodology. SG: data collection. Guillermo Emilio Defossé: conceptualization, resources, writing review and editing, funding acquisition.

Funding The Forestry Sustainability and Competitiveness Program of the Unit for Rural Change (UCAR) (Applied Research Project Grant PIA-14067, Argentina) supported this study. The Patagonian Andes Forest Research and Extension Center (CIEFAP), and the National Scientific and Technical Research Council (CONICET) of Argentina (grant-PUE CIEFAP 4116/16) provided additional funds. This research was carried out within the frame of a Postgraduate fellowship from National Scientific and Technical Research Council grant to Marina Caselli (CONICET, Argentina).

Availability of data and material Data and material are available.

Declarations

Conflict of 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.

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