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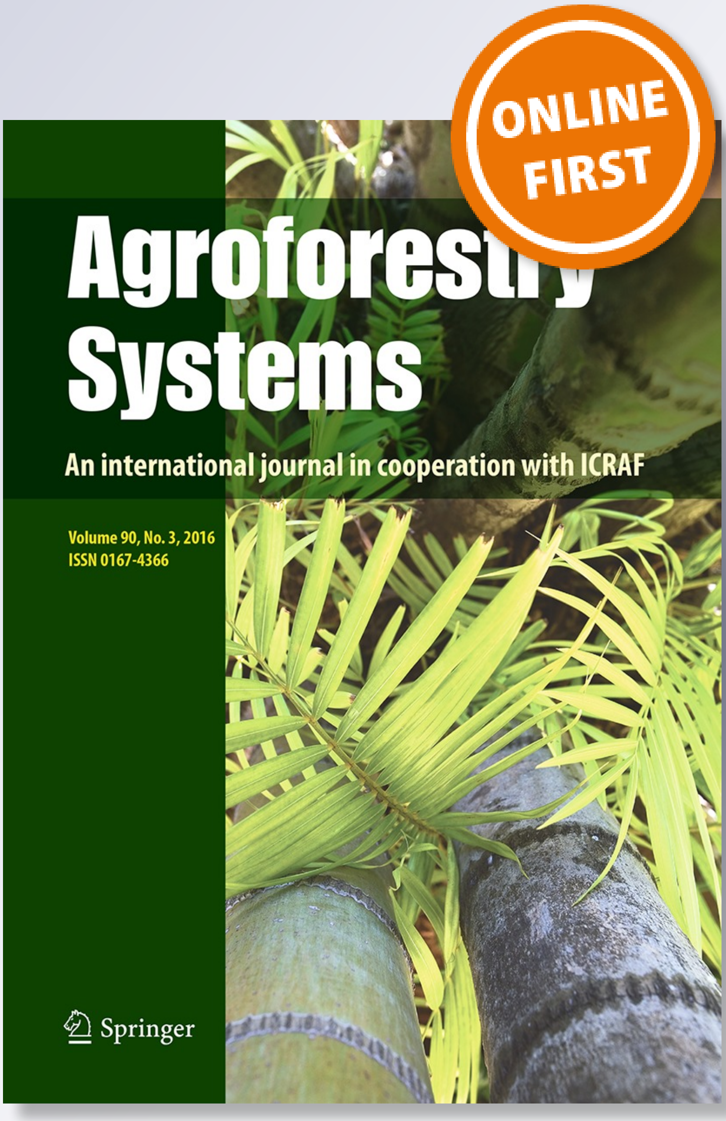

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Evaluation of plantation and early development of five alternatives to ponderosa pine in silvopastoral systems in northwest Patagonia, Argentina

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Abstract Previous studies of afforestation in Patagonia indicate that 30–50 % tree cover produces positive effects on the pasture. This coverage level is achieved by applying pruning and strong thinning to reduce the volume of timber production per area unit. From an economic standpoint, in order to not reduce the income level of the system, it is necessary to find tree species that could replace ponderosa pine (*Pinus ponderosa*) and maximize income per volume unit of wood. We evaluated the feasibility of implementation of five broadleaved tree species (native and exotic) with higher intrinsic wood quality than ponderosa pine. We tested the influence of tree cover generated by a framework of silvopastoral plantation on the increase in survival, regrowth and absolute increase in height, and compared ecophysiological variables (net photosynthetic activity, stomatal conductance, intrinsic water use efficiency) of different species to the status of a traditional plantation without tree cover. Additionally values of air temperature and relative humidity were registered under both cover conditions. Preliminary results support the conclusion that three of these five species could be considered as alternatives to ponderosa pine species for establishing silvopastoral systems with higher timber value. Our Based on the results, the use of tree cover generated under the current plantations of *P. ponderosa* could increase the success of the establishment of these species.

Keywords Forest diversification · *Sorbus torminalis* · *Ulmus pumila* · *Nothofagus obliqua*

Introduction

At global level, it is estimated that one billion hectares are used for agroforestry and silvopastoral systems. In Latin America and the Caribbean, these production systems may exceed 300 million hectares, involving different regions, crops, pastures and livestock with trees and shrubs (Frey et al. 2009). In Argentina, silvopastoral systems are implemented in native forests in order to mitigate the negative effects of livestock income due to the shift in the agricultural frontier (Carranza 2009). Additionally, these systems

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improve the return and economic stability of small and large forest producers whose activity is based on the plantation of exotic conifers and hardwoods (Colcombet et al. 2009).

In the Patagonian region of Argentina, silvopastoral systems are based on plantations of exotic conifers on natural grassland of the steppe-forest ecotone. Previous studies indicate that tree cover levels of 30–50 % must be maintained throughout the afforestation cutting cycle because the shading produced by the trees has positive effects on the water status of the natural grassland species, often leading to increases in their growth rates or production (Caballé 2013). Such coverage is obtained by applying a strong pruning and thinning, reducing the volume of timber production per unit area by 40 % compared to a pure timber plantation site (Davel et al. unpublished data). To prevent a decline in the income of silvopastoral systems in the region, it is necessary to find tree species that can replace conifers and maximize income per wood volume unit. For the inclusion of new species, it is required a better knowledge of their requirements and sensitivities in the Patagonian climate, which has hot and dry summers, and cool and rainy winters (Godoy et al. 2007).

The survival of many forest species in regions with marked abiotic stress (e.g., in the Argentine Patagonia), is generally correlated with the presence of nurse plants (Padilla and Pugnaire 2000). Under the shade of a nurse plant, air and soil temperatures are less extreme and the moisture content in the topsoil is usually greater than in open soils. The micro environmental conditions under the nurse plant improve the survival and/or growth rates of the species growing in association with it (Callaway and Pugnaire 1999).

Tree cover levels needed to maintain forage production of silvopastoral systems in Patagonia could be used as protection (nursing) for newly planted tree species. Only three conifer species are currently used in massive forestation in the Argentine Patagonia: ponderosa pine (*Pinus ponderosa* Dougl. Ex Laws.), douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco.), and lodgepole pine (*Pinus contorta* (Dougl.)), with an estimated area of approximately 95,641 hectares (DPF 2014). Eighty percent of these afforestations are ponderosa pine and cover a wide range of environmental conditions, from mesic to xeric sites. Douglas fir grows at wetter sites and lodgepole pine grows in xeric areas.

Ponderosa pine is the most widely used species in afforestation in Patagonia. In order to improve the economic return of silvopastoral systems, alternative species with higher value per wood volume unit, which could be planted in areas where ponderosa pine is currently grown, should be identified and evaluated.

Our objective was to evaluate the feasibility of planting five broadleaf tree species (native and exotic) with greater intrinsic wood value than *P. ponderosa* under two planting conditions: with and without a tree canopy generated by silvopastoral plantation. Our hypothesis was that current *P. ponderosa* plantations could provide protection (nursing effect) on newly planted forest species, favoring their development in the early stages, which is otherwise highly limited by the harsh environmental conditions of northwest Patagonia.

Materials and methods

Alternative species selection

Godoy and Deffosé (2004) suggested a number of promising species for plantations in Patagonia, of which we selected five: to evaluate: the exotics *Acer pseudoplatanus* (*A. p*), *Quercus robur* (*Q. r*), *Ulmus pumila* (*U. p*) and *Sorbus torminalis* (*S. t*) and the native *Nothofagus obliqua* (*N. o*). For species selection, we considered wood density greater than *P. ponderosa.* The five species were planted in the framework of the project “Patagonian Andean Silvopastoral Demonstration Area” (39°38′22″S, 71°10′04″W, Neuquén Province; Los Peucos ranch).

Planting trial

In September 2013, the species were planted using a complete randomized block design with a distance of 2 × 1.5 m, in two different types of coverage: under canopy cover of ponderosa pine (UC; afforestation with a density of 600 trees per ha; mean diameter at breast height of 19.3 cm and a basal area of 18 m^2/ha) and under open sky (OS). Blocks were nested within each condition, OS and UC. Thirty blocks in OS and 15 blocks in UC were established. The difference in the number of OS and UC blocks was because of the area occupied by afforestation, which allowed this spatial repetition. Five plots of three seedlings of the same species were randomly distributed within each block (450 and 225 plants for OS and UC respectively). The seedlings used in the assay were produced in nurseries in the region using traditional techniques, and transferred the field bare-root. After plantation, an individual 40 cm tall PVC protector was placed to prevent herbivore damage.

Recorded variables

During the 2013–2014 growing season (December 2013 after planting and April 2014 at end of the first growing season) and the beginning and end of the second growing season (December 2014 and March 2015, respectively), we recorded survival percentages (live plants per total seedlings) for each plot. Additionally, at the end of the second growing season, we recorded the absolute increase in height (cm) and the regrowth percentages (seedlings with apex mortality and presence of regrowth from basal buds) for all plants. The physiological state of the seedlings under both coverage treatments was evaluated in December of 2014. Net photosynthesis rate under saturated photosynthetically active radiation condition (*Asat*; μmol CO_2 m^{-2} s^{-1} at 1200 mol photons m^{-2} s^{-1}) was measured on five seedlings per species under each coverage condition. In addition, stomatal conductance (*gs*; H_2O mol m^{-2} s^{-1}) and the intrinsic water use efficiency (WUEi; *Asat*/*gs*) were determined by using an infrared gas analyzer (model LI-6400; LI-COR, Lincoln, NE, USA) with a 6400-02B LED radiation source. Measurements were performed on sunny days between 10:00 a.m. and 1:00 p.m. Each measurement was performed using a minimum waiting time of 180 s and a coefficient of variation of 3 %. Chamber temperature was configured to replicate the conditions of environmental temperature; leaf temperature was recorded by a thermocouple inserted in the chamber. The CO_2 partial pressure was set at 400 lmol mol^{-1}. The air flow within the chamber was set at 300 mol s^{-1}.

Air temperature and relative humidity in both treatments were recorded using the HOBO H8 Pro thermo hygrometers (Onset Computer Corporation; Bourne, MA, USA). Based on records obtained during the period of high atmospheric demand (January to April 2013), the vapor pressure deficit (VPD; kPa) was estimated three times a day (6 a.m., 10 a.m. and 2:00 p.m.) according to Ewers and Oren (2000). Rain fall of the studied seasons was recorded by a weather station (model HOBO Micro Station Data Logger, Onset Computer Corporation, Bourne, MA, USA). Additionally, the values of effective rainfall that reached the ground under the tree cover were estimated based on precipitation under open sky and considering interception percentages determined by Licata et al. (2010) for the tree cover conditions similar to those found Gin this study. On an average date (neither too hot nor too cool) of the growing season, soil moisture values in the top 15 cm of soil were recorded using TDR Hydrosense TM Model CD620 (Campbell Scientific) at 10 random selected points under each coverage condition.

Percentage of tree cover and the transmissivity (proportion of total radiation reaching the ground under the canopy) were determined by taking six digital hemispherical photographs at random points within the forest. The images were analyzed using the Gap Light Analyzer software (GLA 2.0, Simon Fraser University, Burnaby, British Columbia and Institute of Ecosystems Studies, Millbrook, New York). Canopy openings represented by portions of visible sky in a hemisphere seen from a fixed point at ground level were estimated.

Statistical analysis

Survival percentages of each recording date and regrowth percentages were analyzed using generalized linear mixed models considering as fixed factors Coverage with two levels (under tree coverage (UC) and open sky (OS)) and Species with five levels (*A. pseudoplatanus*, *N. obliqua*, *Q. robur*, *S. torminalis*, *U. pumila*), using a Binomial distribution. Block was a random factor nested within Coverage. Although the percentage of seedling survival was assessed on four dates over the two sampling seasons, the analysis was performed by date because the model including Time as a third factor of interest, together with the modeling of self-correlation between observations of one plot, has convergence problems. Absolute increase in height (AIH) of the seedling was adjusted to a linear mixed model (under Normal distribution) considering the same factors described above. When the interaction between both factors was significant, we compare the effect of Coverage for each species separately.

Because physiological state variables (*Asat*, *gs* and WUEi) and soil moisture were registered in randomly seedlings and soils points respectively under each cover condition, a completely randomized design was considered for its analysis. The level of significance used was 0.05.

In each cases in which the analyzed variables did not meet the assumptions of the models, transformations were applied. We utilized square roots and logarithms to transform the data.

The estimated percentage of tree cover and transmissivity values were used as qualitative variables for afforestation's characterization. All the analyses were performed using the Infostat V2015 software (Di Rienzo et al. 2015).

Results

The first evaluated growing season (October to April 2013–2014) was dry; cumulative rainfall during the period accounted for 65 % of the average historical value for the period between 1933 and 2011 (Fig. 1). The analysis of the hemispherical photographs indicated 41 % tree cover in the UC. Under these conditions, average total radiation reaching the ground was 67 ± 8 % of the total radiation received in open areas, and the canopy intercepts 12 % of rainfall reaching the ground. The atmospheric demand, evaluated from the VPD showed similar values under UC condition respect to OS condition during the down early morning hours (6 a.m.). During the morning/midmorning hours, VPD values were higher under OS condition than UC condition for months of higher atmospheric demand (January and February; Fig. 2; 10 a. m.). During the afternoon hour, differences in VPD between UC and OS showed the opposite pattern (Fig. 2).

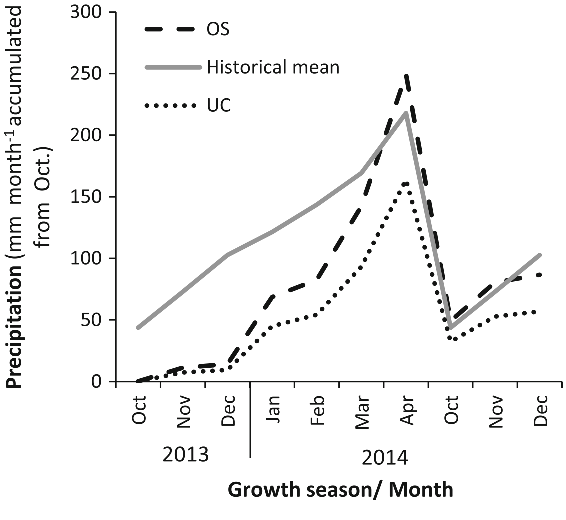


Fig. 1 Mean values for monthly accumulated precipitation for October to April in the 2013–2014 season and October–December 2014, for open sky (OS) and under *Pinus ponderosa* cover (UC estimated following Licata et al. 2010) and historical mean values (1933–2011) at Estancia Los Peucos, near the city of Junín de los Andes, Neuquén Province, Argentina

The top 15 cm of the soil profile, at the driest time in the growing season (February of 2015), mean soil moisture values were on average 5 % less in UC than in OS (3.2 ± 1.3 and 8.2 ± 0.7 % vol/vol respectively; $p \leq 0.05$).

Considering the percentage of seedling survival for the first date of register (December 2013), a significant interaction effect ($p \leq 0.0008$) was detected between Species and Coverage factors. Then, analyzing the contrast between coverages in each species, a significant difference between mean survival rates of *N. o* and *S. t* (marginally significant; relatively low *p* value) was detected, with seedlings under tree cover having higher mortality than those under open sky ($p \leq 0.0427$ and $p \leq 0.0841$, respectively). Even not showing statistical significance, *A. p* seedling mortality tended to be higher in OS than UC (Fig. 3).

For the second recording date (end of the first growing season, March 2014), no Species-Coverage interaction effect was found ($p_{\text{interaction}} \leq 0.7214$), with both factors showing statistical significance ($p_{\text{species}} \leq 0.0001$, $p_{\text{covergae}} \leq 0.0107$). Regarding Species effect, *U. p* and *S. t* had higher survival values than the other species. With regard to Coverage effect, OS seedlings had higher survival values than UC (Fig. 3).

Measurements performed in December 2014 (third recording date), showed a high mortality rate, principally in *A. p* and *N. o* (Fig. 3). On this date, an interaction effect between species and coverage was also detected ($p_{\text{interaction}} \leq 0.0136$). A significant effect of Coverage on mean survival rates for *U. p* and *S. t* was detected, in both cases with higher survival in UC than OS ($p \leq 0.0074$ and $p \leq 0.0404$, respectively). The same pattern was observed on the last recorded date (fourth recording date at the end of the second growing season, March 2015; $p_{\text{interaction}} \leq 0.0001$), showing significant higher means in survival rates in UC for species *U. p* and *S. t* ($p \leq 0.0001$ and $p \leq 0.0050$, respectively). Nevertheless, considering this recording

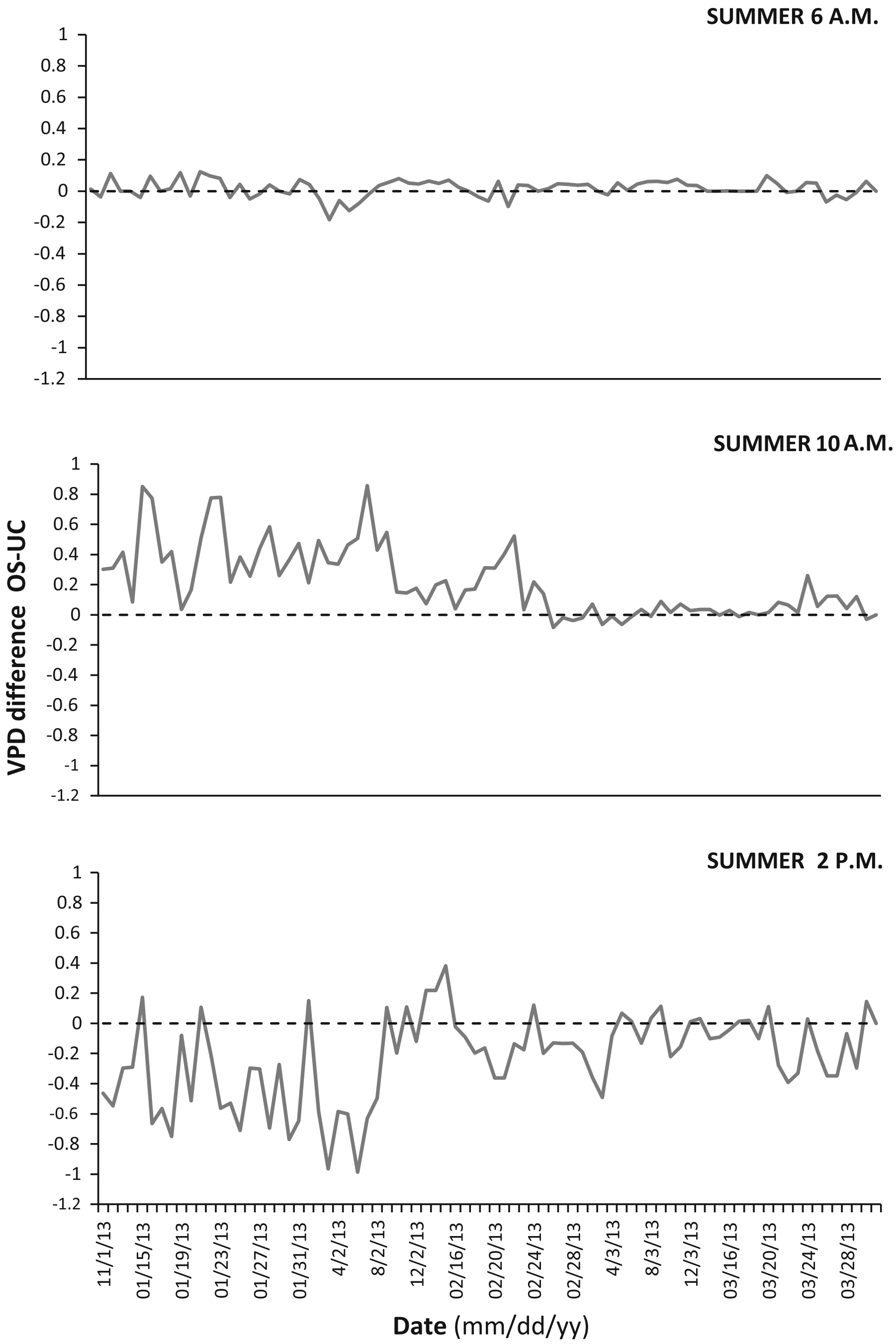


Fig. 2 Difference between the daily vapor pressure deficit (VPD) values between open sky (OS) and under *Pinus ponderosa* cover (UC) during three time ranges in January to March of the 2013–2014 season. Values higher than 0 on the *y* axis indicate greater deficit for OS, while values lower than 0 on the *y* axis show greater deficit values for UC

date, a slightly trend to higher values of seedling survival was observed in *A. p*, but not in *Q. r* or *N. o* in which seedlings under OS and UC conditions shows similar values of this variable.

The AIH measured at the end of the first growing season showed an interaction effect between Species and Coverage ($p_{\text{interaction}} \leq 0.0001$). A significant effect of Coverage for *Up* (marginally; relatively low p-value), *Q. r*, *N. o* and *S. t*, and non-significant effect for *A. p* ($p \leq 0.0607$; $p \leq 0.0076$; $p \leq 0.0174$; $p \leq 0.0001$ and $p \leq 0.7554$, respectively) were detected. The *U. p* and *Q. r* seedlings showed greater increase in height under OS than UC, whereas the opposite pattern was found for *N. o* and *S. t* (Fig. 4A).

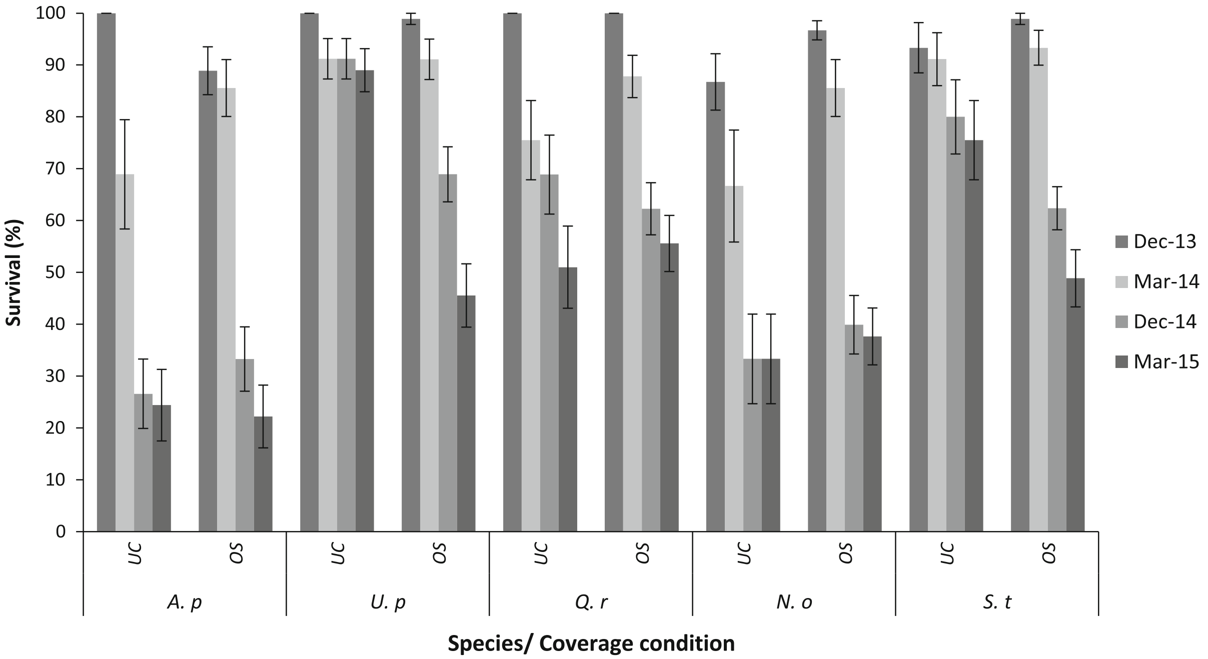


Fig. 3 Mean survival percentages for the four recording dates, initial post-plantation date (December 2013), end of the first growing season (March 2014), beginning of the second growing season (December 2014) and end of the second growing season (March 2015) (±SE), for the five forest species planted under the canopy of *Pinus ponderosa* (*UC*) and open sky (*OS*). Statistical differences between levels of the species factor and the cover treatment are discussed in the text. References: *A. p* = *Acer pseudoplatanus*; *N. o* = *Nothofagus obliqua*; *Q. r* = *Quercus robur*; *S. t* = *Sorbus torminalis* and *U. p* = *Ulmus pumila*; *UC* = under canopy and *OS* = open sky. Statistical differences among species and treatments and the interaction among factors are discussed in the text

Because of regrowth percentages, values were very low, as we decided to analyze this variable in a descriptively way. For this, we expressed this variable as the number of seedlings with regrowth over the number total planted seedlings per species and cover condition. As a trend, seedlings under OS condition showed higher values of regrowth than seedlings under UC condition (with mean values of 16 and 8 % respectively). At species level, *U. p* showed the highest values of this variable (19 %), followed by *Q. r* (15 %), *N. o* (14 %), *S. t* (12 %) and *A. p* (8 %) respectively (Fig. 4B).

In relation to eco-physiological variables, an interaction effect of Species and Coverage was observed in *Asat* ($p_{\text{interaction}} \leq 0.0366$; square root transformation). All the species, except *A. p*, presented higher values of *Asat* under OS condition than UC condition (Fig. 5A).

Stomatal conductance (log transformation) did not show interaction effect between Species and Coverage ($p_{\text{interaction}} \leq 0.1961$). However an effect of Species and Coverage was found ($p \leq 0.0001$ in both cases). At Species level, seedlings of *Q. r* and *A. p* showed lower mean values of this variable respect to the rest of the species. At coverage level, seedlings under OS condition showed higher values than seedlings under UC condition (Fig. 5B).

In relation to WUEi, there were differences between Species and levels of Coverage ($p \leq 0.001$ in both cases) without interaction between factors ($p_{\text{interaction}} = 0.1420$). At Species level, *A. p* showed the highest value compared with other species, followed by *S. t, U. p, Q. r* and *N. o*. This last species differ from *S. t*. At Coverage levels, seedlings under OS condition showed higher values than seedlings under UC condition.

Discussion

After two growing seasons (October to April 2013–2014 and 2014–2015), the nurse effect of tree

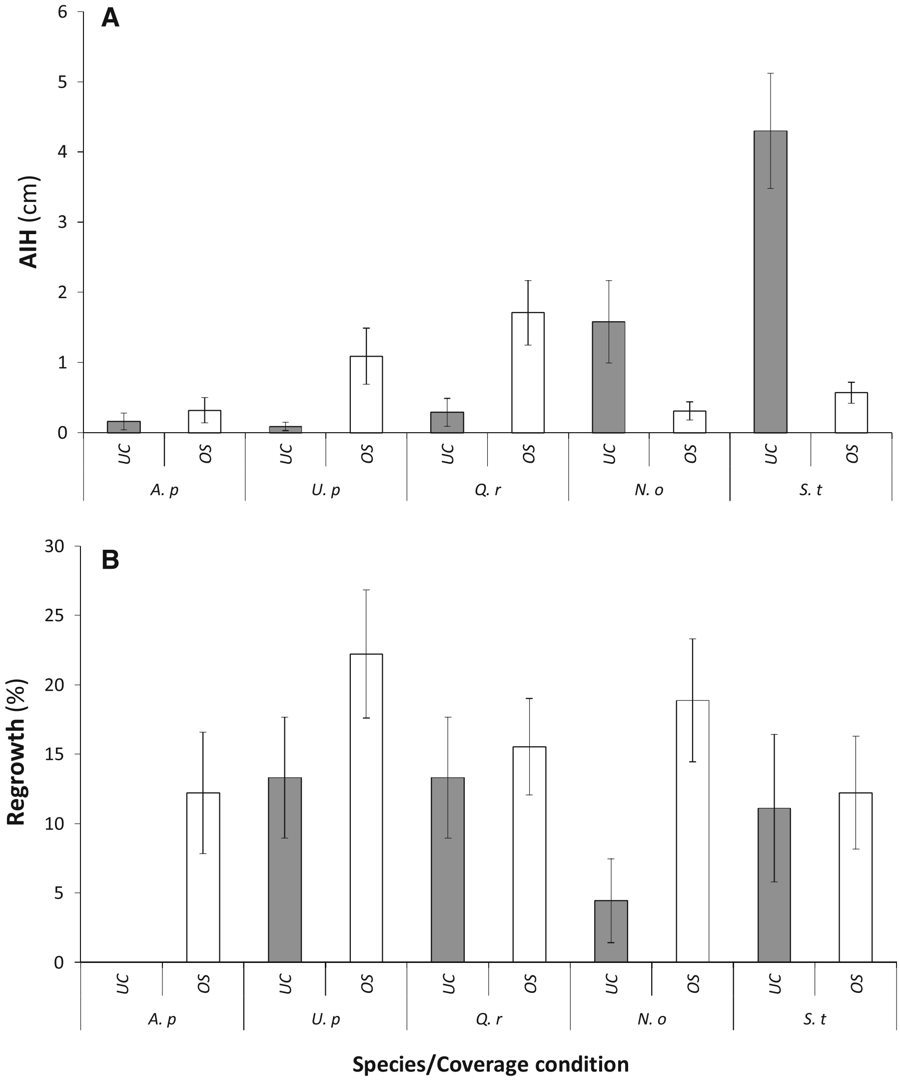


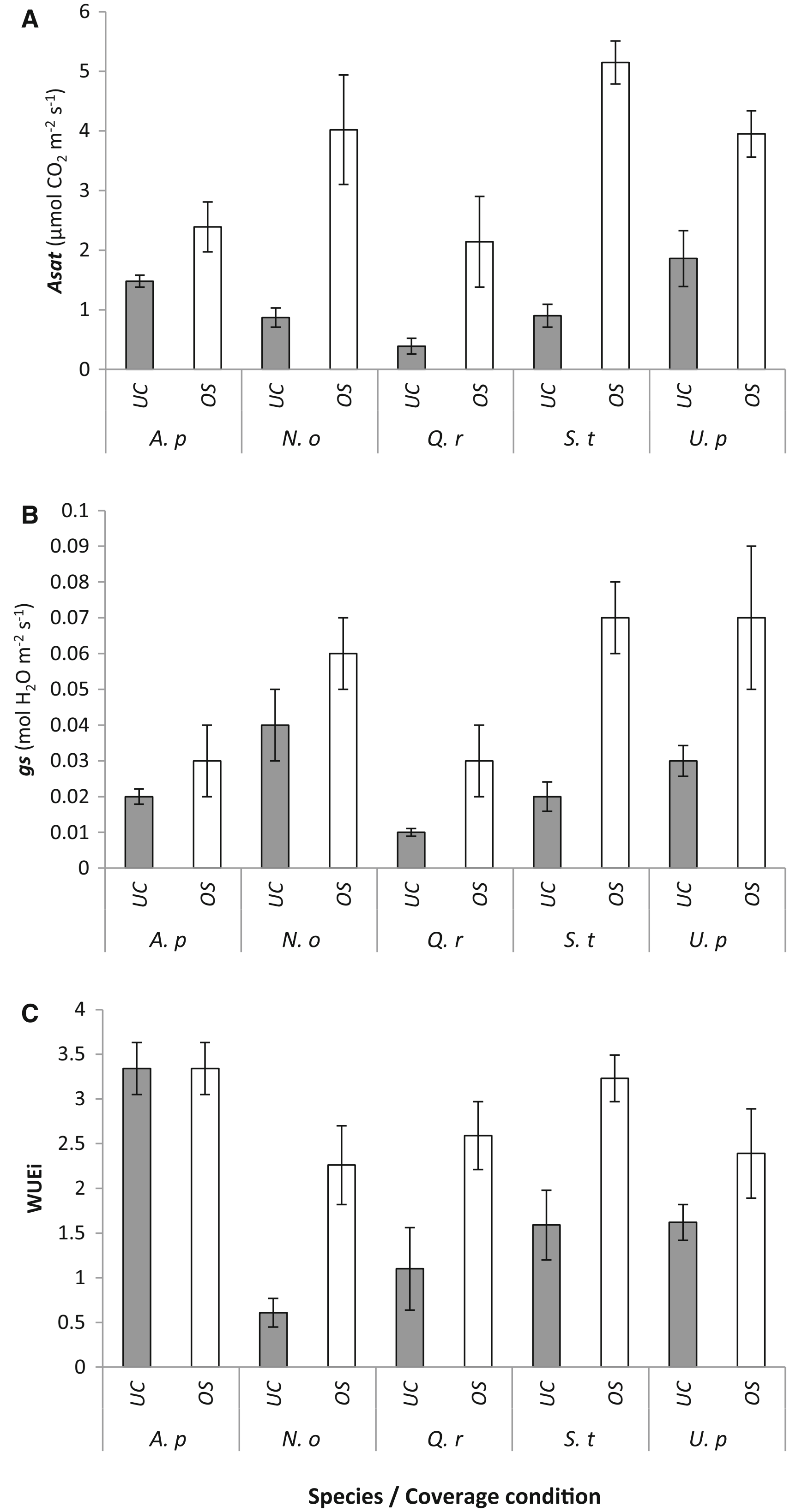
Fig. 4 Mean values (±SE) of: **A** Absolute increase in height (AIH, cm) and **B** Regrowth percentage per species under the two coverage conditions evaluated. References: *UC* = under canopy and *OS* = open sky. Statistical differences between species and treatments and the interaction among factors are discussed in the text. References: *A. p* = *Acer pseudoplatanus*; *N. o* = *Nothofagus obliqua*; *Q. r* = *Quercus robur*; *S. t* = *Sorbus torminalis* and *U. p* = *Ulmus pumila*; *UC* = under canopy and *OS* = open sky. Statistical differences among species and treatments and the interaction among factors are discussed in the text

cover on abiotic stress of summer reduced seedling mortality by 13 % compared to open sky condition (55 % vs. 42 % survival for UC and OS, respectively). While the quality of the plants we used may influenced the results of the study, the low rainfall values recorded during the study season caused 17 % seedling loss in UC and 8 % in OS during the first growing season and 5 % and 11 % respectively during the second growing season.

Three of the five species tested, (*A. p*, *U. p* and *S. t*) tended to be largely benefited by the tree cover, whereas *Q. robur* and *N. obliqua* had similar values under the different conditions. However, the positive effect of the tree canopy on survival decreased significantly during the winter.

Previous studies on silvopastoral systems in the region that quantified the overlap effect in the use of soil water resources for *P. ponderosa* and the grass species *Festuca pallescens* found strong competition between the two species at times of high deficit or particularly dry seasons (Fernandez et al. 2007, Caballé 2013). Under scenarios of high soil water availability, *P. ponderosa* uses deeper soil water layers.

Additional studies measuring soil water uptake by pines by means of sap flow also indicated that trees extract a high proportion of water from surface soil layers during periods of low water content (Licata et al. 2008). These studies in addition to the recorded rainfall interception by canopy may explain the lower


A
Asat (μmol CO2 m-2 s-1)
0
1
2
3
4
5
6
B
gs (mol H2O m-2 s-1)
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
C
WUEi
0
0.5
1
1.5
2
2.5
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4
UC
OS
A. p
N. o
Q. r
S. t
U. p
Species / Coverage condition

◀**Fig. 5** Mean values (±SD) for: **A** net photosynthesis at saturated photosynthetically active radiation (*Asat*; µmol CO_2 m^{-2} s^{-1}) and **B** stomatal conductance (*gs*; mol H_2O m^{-2} s^{-1}) and **C** intrinsic water use efficiency (WUEi; µmol CO_2 mmol H_2O^{-1}) per species under the two coverage conditions evaluated. References: *A. p* = *Acer pseudoplatanus*; *N. o* = *Nothofagus obliqua*; *Q. r* = *Quercus robur*; *S. t* = *Sorbus torminalis* and *U. p* = *Ulmus pumila*; *UC* = under canopy and *OS* = open sky. Statistical differences among species and treatments and the interaction among factors are discussed in the text

values of soil moisture recorded in UC condition, which also limits the growth of the planted species or causes an increase in seedling mortality after summer. The interaction between the lower radiation reaching the soil and changes in atmospheric demand under tree cover caused the reduction in rainfall intercepted by the canopy not to be linearly related to differences in the moisture content in the soil between UC and OS.

In this study, the fact that seedling mortality UC was higher in winter than in summer may be because of a lack of cold air movement and the concentration of frost. The roughness generated by canopy increases the thickness of the boundary layer and prevents air movement under canopy (Mason and Hughes 2001).

The estimated values of transmissivity did not appear to be limiting under the studied tree coverage level studied. However, the restriction in light generated by tree canopies had a negative effect on *Asat*, an effect which has been proven on adult individuals of numerous species (Larcher 2003), but not so evident at the seedling stage and as an almost short term response, as was found in this study during the first growing season.

There are few precedents to date that allow comparison between survival and growth rates of the studied species under tree cover or with the use of nurse plants in Patagonia. As a reference value, *P. ponderosa* initial survival after plantation (2–3 years after plantation) has a rate of mortality of 40–60 % of the planted seedlings (Rago pers. com.). To our knowledge, this is the first study in the region that considers physiological variables in the study species.

Regarding *Q. robur*, previous history of planting conducted at three sites in the region achieved a 49 % survival rate at only one of the sites after the first planting season (Godoy et al. 2007). This percentage could be considered acceptable, given that two of the sites had lower soil effective depth, which also limited the development of other species (Godoy et al. 2007). After this first season, oak seedlings merely survived, and low growth was observed for both stem diameter and seedling height.

In our study, *Q. robur* survival rates after the first growth season surpassed those percentages and had similar values after the second season. Similarly to the results reported by Godoy et al. (2007), absolute seedling height growth was low (at least for UC), probably because of the low rainfall during the evaluated seasons. However, the low growth in height is a characteristic of this species during initial years (Alvarez Alvarez et al. 2001). Littvay (2002) reported growth of 70–110 cm over four years in greenhouse assays (17.5–27.5 cm per year under suboptimal controlled conditions). *Q. robur* seedlings may prioritize root growth over total height or stem diameter growth in early stages of development. Notwithstanding, and taking into account the height analysis of adult trees studied in the region by other authors, optimal site qualities have been found (Schober 1985), in some cases exceeding the best quality sites that can be found in Europe. This case deserves special attention because of the fact that the trees were planted in steppe areas and sites with mean rainfall of approximately 900 mm per year, with excellent performance by the species, which adapted to the dry summer season. Thus, there are many potential sites for planting *Q. robur* in the region (Godoy et al. 2007).

Previous plantations assays with *S. torminalis* indicate that it adapts well to sites with 500 mm rainfall per year and can tolerate up to two months of summer drought (Dengler 1992, Mayer 1992; Montero et al. 2003). In Patagonia, it can survive under 400 mm rainfall per year condition, but is not suited to drought because the apical bud dies (Godoy et al. 2007). Von Schmeling (1994) reported that the average seedling height growth per year for *S. torminalis* is about 19–25 cm, depending on the site. Preliminary tests in Patagonia showed growth rates of 1 to 4 cm in the first growing season after plantation (Godoy et al. 2007). The survival percentages recorded in our study showed that *S. torminalis* could be considered as another species with potential for planting under study conditions. Absolute seedling height increases are consistent with the lowest values recorded in previous studies for the region. It is important to highlight that previous studies mentioned that, in places with sparse vegetation of bushes and grasses, *S. torminalis* seedlings growing under their protection were more vigorous than those that were not protected. This coincides with autecology descriptions in previous studies that mentioned that this species has "shade tolerant" behavior (Dengler 1992; Mayer 1992; von Schmeling 1994). Since it is a slow-growing species, its wood is one of the most valuable on the market. For this reason it is recommended to conduct further studies by planting this species in mixed stands in order to obtain, additionally to the product of fast growing species, a higher quality product. Our results are in agreement with previous studies that reported UC seedling survival rate to be 19 % higher than OS (Dengler 1992; Mayer 1992; von Schmeling 1994).

The *A. pseudoplatanus* demonstrates an excellent adaptation in wetter sites of Patagonia (Montero et al. 2003), since it can resist to summer drought, as it does in its region of origin. In juvenile stages, it can survive several years under field conditions, but to grow in height it needs plentiful light conditions (Dengler 1992). Low levels of precipitation plus lighting restrictions may play a major role in the establishment of this species. In our study, this species had the lowest survival values UC, probably because of poor initial quality of the seedlings utilized.

In the current study, mean seedlings survival for *U. p* was 70 %, which is higher than that reported in previous studies in the region where the lower seedling quality (few secondary roots) and the poor conditions remains until planting, strongly affecting survival (Godoy et al. 2007). Its survival rates remained high regardless of the effect of tree cover, showing the ability to maintain positive carbon fixation rates even at times of high abiotic stress. It may be the most tolerant to water stress of the species considered, and could grow at low-quality sites currently occupied by *P. ponderosa*. It was also the species which survival rates were most notably improved by tree cover.

In *N. obliqua*, stomatal control (which prevents water loss and maximizes carbon fixation), occurs when low water availability in soils is combined with high levels of atmospheric demand (Varela et al. 2010). Lower values of atmospheric demand (lower VPD) recorded under canopy cover (at least two times of day when VPD is higher) showed that this condition could be the most beneficial from the point of view of both water and radiation (Varela et al. 2010).

Although regrowth percentages recorded in this study were low (on average 12 %), it provided a survival strategy for all species (particularly *U. p* and *Q. r*). However if this strategy persist in time it conduce to a stem quality loss. It is important to highlight that for all the species considered, there was a trend to lower regrowth values UC. In three of the five species evaluated, survival under *P. ponderosa* coverage was over 50 %, even though rainfall was low during both study seasons. The plantation of valuable species under the study conditions is very promising and would be an important line of research for increasing the economic return of silvopastoral systems with *P. ponderosa*.

Conclusions

Our results allow to consider *U. pumila, S. torminalis* and, to a lesser extent, *N. obliqua,* as promising species as alternatives to *P. ponderosa*, when developing silvopastoral systems with species having higher wood value. Based on the results, the use of tree cover generated under the current plantations of *P. ponderosa* seems to increase the success of the establishment of these species. Future research is wanted to evaluated the plantation of these species along with the intensive thinning needed for silvopastoral management of *P. ponderosa* plantations.

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