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Stone pine (*Pinus pinea* L.): an interesting species for agroforestry in Chile

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Abstract *Pinus pinea* is native to the Mediterranean basin, being an interesting species due to its high-value edible pine nuts (prices between €20 and €45 kg^{-1}), its ability to adapt to differing environmental conditions and its relative fast growth in Chile. The species was introduced to Chile more than one century ago by European migrants, who used it for dune stabilization, soil improvement and livestock shading. Agroforestry systems including stone pine and agricultural crops (forage oat and potatoes) and sheep grazing for mutton production were tested in two experimental plots located in El Carmen, Biobío region. The plots were evaluated during 5 years after planting. Crop yields were lower than the region average, reaching nearly 60% of national average yields of forage oat and 66–86% of potato. Forage production in these plots was not enough to sustain permanent grazing; however, sheep grazing in regulated periods contributes to mutton production. Grazing reduces weed and shrub growth, fire risk and the cost of periodic mechanical cleaning. Stone pine annual growth in height and diameter at collar height (ground level) were on average 50 and 2.5 cm, respectively, and was found to be a suitable species for agroforestry systems. Net present value was almost seven times higher in the agroforestry system than in pure stone pine plantations; therefore, this system can contribute to the local and national economy.

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Introduction

The current Chilean forest development model poses serious barriers to forest producers, both small and medium owners (SMOs) and small and medium enterprises (SMEs), with important socio-economic implications; indeed, with the exception of the three biggest forest companies, this sector involves over 19,000 SMOs and SMEs, and more than 810,000 hectares of plantations. An analysis performed by Loewe et al. (2015a) characterized SMOs socially and economically, finding them to be of low educational and low-income levels (66% earned less than US$ 330/month) and highlighting the need of SMOs and SMEs to incorporate innovations to the forest activity to improve their economic performance.

Besides a socioeconomic analysis, world trends in forestry indicate the importance of diversifying the forest activity (Pretzsch et al. 2016), considering species composition and geographical distribution; this is especially true for Chile, given the wide range of environments occurring across its territory.

Diversification also helps to limit biotic and abiotic risks, withstand economic risks and market fluctuations, and maximize site use (Seidel et al. 2013). Agroforestry allows agriculture and forestry diversification, and can be implemented with different species and in different settings according to specific conditions (Sotomayor and Barros 2016).

As stated by the director of FAO's Forestry Division (BBC 2014), agroforestry systems play a crucial role in the livelihoods of rural people by providing employment, energy, nutritious foods and a wide range of other goods and ecosystem services. Mixed systems provide rural sustainable development and enhance biodiversity while preserving landscapes; the use of conifers in these systems may expand the potential applications of agroforestry (Eichhorn et al. 2006). Reisner et al. (2007) identified regions in 32 European countries that are suitable for silvo-arable agroforestry, involving walnut (*Juglans regia*), cherry (*Prunus avium*), poplar (*Populus* sp.), stone pine (*Pinus pinea*) and *Quercus ilex*, confirming the species potential in combined productive systems.

The use of stone pine, a species native to the Mediterranean basin, has multiple environmental benefits, such as food source for fauna, watershed protection, dune and soil recovery, and erosion control. Stone pine is one of the nine most important species producing dried fruits in the world (Loewe and Delard 2016), its edible seeds, the pine nuts, which are the most expensive ones and have been used for millennia (Prada et al. 1997; Gil 1999; Badal 2001).

Stone pine was introduced in Chile more than a century ago by European immigrants, who used it for dune and soil improvement and livestock shading (Loewe and González 2003). The species provides an attractive option to Chilean producers, especially for the high value of its shelled nuts (Loewe and González 2007; Soto et al. 2008), with prices that have been increasing worldwide from €25 kg^{-1} in 2010 to €45 kg^{-1} in 2013, and also for the highly demanded biomass generated as by-product from its processing (Cruz 2008). Furthermore, the species is characterized by adaptation ability and relatively fast growth rate, which facilitate its management. Hence, it is also considered to be an option for small and medium landowners because it provides an annual income since the fruit productive age and it adapts to poor eroded areas (Loewe and Delard 2012).

The species is also easily integrated into agroforestry systems due to its plasticity and beauty, and the highly valued fruit in international markets. In fact, stone pine has been intercropped with agricultural crops in combined systems in Spain (Mutke et al. 2007). Furthermore, the use of grafted stone pine trees with high productivity clones becomes interesting in high intensity management systems, because of their increased pine nut production.

INFOR has investigated the species behavior in Chile for more than 25 years, aiming at developing techniques for its cultivation in this country, where conditions are suitable for stone pine growth. To assess and promote its cultivation in agroforestry settings, two experimental plots were established and implemented as mixed systems that combine pine nut production, agriculture and sheep rearing at different stages of crop development under a semi-intensive management system, using simple and affordable productive techniques. We hypothesized that agroforestry systems including stone pine would be feasible for SMO/SME and more profitable than the pure stone pine plantation.

We specifically aimed to compare two agroforestry systems that include stone pine in terms of: (1) growth (height, crown and trunk diameter) and vigor and stem form, (2) crop and sheep yields, and (3) technical and economic feasibility of mixed systems.

Materials and methods

Study site

Two plots that included stone pine nut plantations, agricultural crops and sheep grazing (Fig. 1) were established in El Carmen, Biobio region (36°56′S, 71°49′W), at 533 m a.s.l. The site is characterized by an annual rainfall of 1025 mm and average temperature of 12.4 °C; it is located in the stone pine Chilean distribution area, particularly in the South macrozone, which presents the best conditions for its growth and fruiting (Loewe et al. 2015b, 2016).

Plots are located on gentle slopes with deep volcanic soil that was cultivated before plantation establishment. The soil is homogeneous in both areas, with average neutral pH (6.4), high organic matter content (8.9%), no salt (EC 0.05 mmho cm^{-1}), low nitrogen (15 ppm), medium phosphorus (10 ppm) and

Fig. 1 Stone pine-based agroforestry system. Potato harvest at age 2 (upper); general view at age 3.5 (bottom)

high potassium (198 ppm) content. Micronutrient content is very low for boron and zinc (0.13 and 0.07 mg kg^{-1}, respectively), low for sulphur (0.5 mg kg^{-1}) and medium for copper, manganese and iron (0.65, 2.4 and 30 mg kg^{-1}, respectively).

Agroforestry systems established in both plots are presented in Table 1. Spacing pattern of stone pine trees differed between plots (5 × 5 m and 7 × 7 m), and total area amounted to nearly 5000 and 7000 m^2, respectively. Stone pine trees (1 year-old seedlings) were planted in winter 2010 and homogeneously managed using arboriculture techniques (Buresti et al. 2001), with the aim of maximizing pine nut production and timber production quality. Management included soil preparation, weed control, initial fertilization, formative pruning and irrigation.

Fertilization and irrigation during the first 5 years were calculated considering alternating agriculture crops requirements and plot density; the amount of fertilizer applied was 3020 and 2353 kg ha^{-1} in plots 1 and 2, respectively. Plots were irrigated 12 and 9 times, respectively (Table 1).

Data collection

Stone pine height and diameter at 1.3 m height (DBH) measurements were taken in winter during 5 years (2010–2015). To assess the fruit production entrance, we evaluated strobili and mature 3 year-old cone quantity from year 3 onward considering that in Chile reproductive maturity age of the species is reached earlier (from the age of 8 years onward) (Loewe et al. 2016) than in its native distribution area, where cone production starts at between 10 (Crawford 1995) and 20 years of age (Goor and Barney 1976). Stem form was observed at the end of the study period and was categorized according to straightness (1: straight tree; 2: partly curved; 3: strongly curved tree). Vigor was also categorized (1: vigorous; 2: medium; 3: low).

Statistical analyses

An ANOVA was performed to test differences in stone pine growth between plots at particular ages. Pearson's χ^2 test ($\alpha = 0.05$) was used to test homogeneity of proportion of qualitative variables (straightness, vigor).

The statistical analyses were conducted using the software INFOSTAT (Di Rienzo et al. 2015). Agriculture crops and sheep raising were evaluated using a descriptive comparative analysis.

Economic evaluation

In order to quantify the economics of the proposed systems, we compared two productive models: stone pine only for pine nuts, and stone pine for pine nut production in agroforestry system. Both models consider the use of non-grafted plants and semi-intensive management for cone production; the latter model also includes income and costs derived from the associated crop production and sheep raising.

Management considered weed control, irrigation during the first 8 years, annual fertilization during the whole rotation, one thinning at age 25, and pruning every 5 years. Costs are detailed in Table 2 and incomes in Table 3. The analysis considers a 1-ha plantation evaluated in a 60-year horizon with cone production increasing from 95 kg ha^{-1} at age 8 up to 8095 kg ha^{-1} at age 60, considering alternate bearing years (1 year of high production followed by two years of a halved cone production), and crop production up

Table 1 Description of the productive system and yield in stone pine agroforestry plots established in the piedmont of the Andes mountain range, Biobio Region, Chile

Plot	Rotation crop	Period	Frequency of irrigation/year (8 h duration each)	Fertilizer	Dose (kg ha^{-1})	Yield (kg ha^{-1})	Sheep grazing (No)
1 (5 × 5 m)	Oat forage[a]	Jul. 2010–Feb. 2012	None	Mix 5–33–12	320	Sheep feeding	15 during 10 days/month
	Potato[b]	Oct. 2012–Apr. 2013	6 (Dec.–Feb.)	Mix 5–33–12	2120	10,200	None
	Oat forage	Nov. 2013–Feb. 2014	None	Mix 5–33–12	320	Sheep feeding	15 during 10 days/month
	Pertmanent prairie (oat forage + rye grass[c])	March 2014–March 2015	6 (Dec.–Feb.)	Urea	260	Sheep feeding	30 during 2 days/month excluding February and March
2 (7 × 7 m)	Potato	Nov. 2010–Apr. 2011	5 (Dec.–Jan.)	Mix 5–33–12	1175	13,225	None
	Oat forage	Jul. 2011–Feb. 2012	None	Mix 5–33–12	294	2350 + sheep feeding	15 during 12 days/month
				urea	220		
	Oat forage	Apr. 2012–Jan. 2014	None	Mix 5–33–12	294	Sheep feeding	15 during 12 days/month
				Urea	150		
	Permanent prairie (oat forage + rye grass[d])	March 2014–Feb. 2015	4 (Nov.–Jan.)	Urea	220	Sheep feeding	30 during 4 days/month excluding February and March

[a]Oat forage (*Avena strigosa*)

[b]Potato (*Solanum tuberosum*)

[c]Rye grass (*Lolium multiflorum*)

[d]Oat forage (*Avena strigosa*) + rye grass (*Lolium multiflorum*)

Table 2 Costs and standards used in the economic evaluation

Activity	Yield	Unit	Unit value	Unit	Cost (US$/ha)
Weed control before plantation (total)					**72.3**
Labor	1	Day/ha	21.6	US$/day	17.3
Roundup	3	l/ha	6.9	US$/l	20.6
Simazine	3	kg/ha	11.5	US$/kg	34.4
Weed control after plantation (total)					**107.8**
Labor	2	Day/ha	21.6	US$/day	43.2
Roundup	7	l/ha	6.9	US$/l	48.0
Mixed	0.08	kg/ha	8.2	US$/40 g	16.5
Annual weed control					
Labor	4	Day/ha	21.6	US$/day	86.5
Deep soil preparation (40–50 cm)	1	Day/ha	86.5	US$/ha	86.5
Plantation (total)				US$/ha	**243.5**
Plant distribution	0.5	Day/ha	21.6	US$/day	10.8
Labor	6	Day/ha	21.6	US$/day	129.7
Stone pine plants	286	Plants/ha	0.36	US$/plant	103.0
Fertilization up to 15 years (total)					**152.2**
Labor	450	Plants/day	21.6	US$/day	13.7
Fertilizers (NPK)	150	g/plant	0.003	US$/g	138.5
Fertilization from 15 years onward (total)	250	g/plant	0.003	US$/g	**244.5**
Irrigation	6	Day/ha	21.6	US$/day	129.7
Production pruning up to age 24	100	Plant/day	21.6	US$/day	61.8
Production pruning from age 25	75	Plant/day	21.6	US$/day	41.2
Manual harvesting	0.2	€/cone kg			Varies with age
Cone picking from soil	3,200	kg/day	21.6	US$/day	Varies with age
Cone storage	0.04	US$/cone kg			Varies with age
Tools and materials					
Harvesting tool			28.8	US$/unit	Varies with age
bags			0.2	US$/unit	Varies with age
Administration	7.2	US$/month	12	month/ha	86.5
Unexpected expenses			28.8	US$/ha	28.8
Basic consumption	14.4	US$/month	12	month/ha	172.9

to 8 years after the establishment in the agroforestry system. Economic indicators obtained were net present value (NPV) at 8% interest rate and internal rate of return (IRR).

Results

Intercropped cultures

Obtaines crop yields (Table 1) were lower than the Biobio regional average (INE 2014b), amounting to 3910 kg/ha for forage oat and 15,450 kg/ha for potatoes; thus, in the first 3 years of these experimental agroforestry plots we achieved 60% and 66–86% of regional-level values, respectively. The tested crops had no negative impact on tree development.

Animal raising

At age 5, sheep production in plot 1, with trees spaced at 5 × 5 m, was equivalent to 3.7 sheep ha^{-1} year^{-1}, whereas in plot 2, with a lower tree density, it amounted to 4.4 sheep ha^{-1} year^{-1}. Interestingly,

Table 3 Income and standards used in the economic evaluation

Activity	Yield	Unit	Unit value	Unit	Income (US$/ha)
Crop production					
Potato (year 1)	11,712.0	kg/ha	0.4	US$/kg	4219.0
Sheep feeding (years 2–8)	4.1	Sheep/ha	1.0	US$/sheep (40 kg)	159.7
Cone production					
Cone production (year 8)	95.2	kg/ha	0.7	US$/kg	64.0
Cone production (year 12)	1904.8	kg/ha	0.7	US$/kg	1279.5
Cone production (year 20)	1904.8	kg/ha	0.7	US$/kg	1279.5
Cone production (year 30)	3571.4	kg/ha	0.7	US$/kg	2399.1
Cone production (year 40)	2381.0	kg/ha	0.7	US$/kg	1599.4
Cone production (year 50)	3095.2	kg/ha	0.7	US$/kg	2079.2
Cone production (year 60)	8095.2	kg/ha	0.7	US$/kg	5438.0

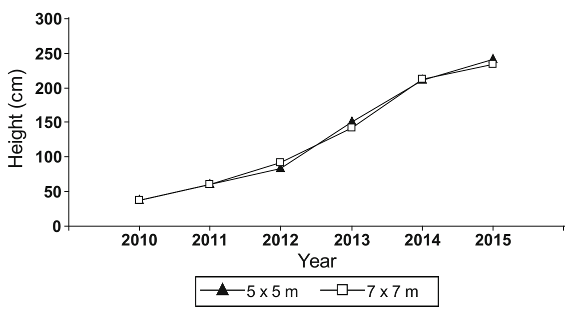

Fig. 2 Evolution of stone pine height

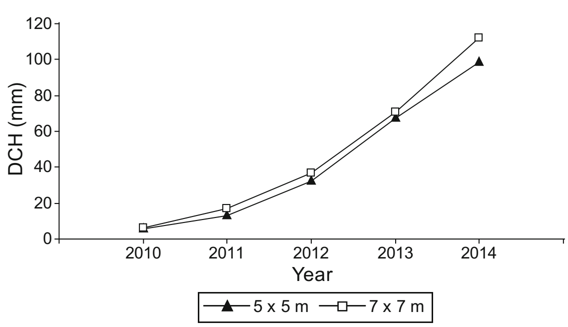

Fig. 3 Evolution of diameter at collar in stone pine

although sheep were introduced in the plantation since its establishment, no damage was recorded on trees.

Stone pine growth

Height evolution (Fig. 2) indicated a positive and sustained growth, which was similar in both plots. Annual growth was on average nearly 50 cm in both plots.

Diameter at collar height (DCH) (Fig. 3) had a sustained growth trend, and was significantly higher in plot 2, were tree density was the lowest; annual growth was 1.98 cm in the highest density plot (plot 1), and 2.24 cm in the lowest density one. DBH annual growth at age 5 reached 0.88 and 0.86 cm in plots 1 and 2, respectively.

The reported crown diameter values correspond to measurements of year 3, since 1 year later an intense formative pruning was done, which significantly reduced this parameter. Mortality was low (below 5%) in both plots.

Although stone pine trees were vigorous in both plots, we found significant differences. The highest percentage of vigorous trees was found in plot 1 (97%), being 87% in plot 2 (Table 4). In plot 1 no low vigor trees were observed, and in plot 2 that value was very low (1%).

Records of trunk straightness exhibited statistical differences between plots. The highest percentage of straight trees was found in plot 2, the one with lower density. In plot 1, most trees (54%) were curved, although higher density usually promotes a better form. Plot 2 also had the highest percentage of strongly curved trees (9%).

Cone production was evaluated from year 3, despite the short age of the plantation. At age 5, in plot 1 over 6% of trees had at least one strobilus (1 year-old conelet). Few trees started flowering in the second

Table 4 Stone pine growth and productivity variables in two agroforestry systems established in the piedmont of the Andes mountain range, Biobio Region, Chile

Variable	Plot 1 (5 × 5 m)	Plot 2 (7 × 7 m)
DCH[a] at age 4 (cm)	9.9 ± 1.7	11.2 ± 1.8*
DBH[b] at age 5 (cm)	4.4 ± 1.6	4.3 ± 1.6
Height at age 5 (m)	2.4 ± 0.04	2.5 ± 0.04
Crown diameter at age 3 (m)	0.93 ± 0.024	1.12 ± 0.024*
Survival at age 5 (%)	97.5	95.1
Percentage of trees with mature cones at age 5	0	1.3
Percentage of trees with strobili at age 5	6.3	0
Vigor (% of trees)		
Vigorous	97	87
Medium vigor	3	12
Low vigor	0	1
Straightness (% of trees)		
Straight	42	56
Curved	54	35
Very curved	4	9

Values correspond to Mean ± SE

Asterisk indicates statistically significant differences ($p < 0.05$)

[a]DCH: diameter at collar level

[b]DBH: diameter at breast height (1.3 m)

Table 5 Economic evaluation comparing the stone pine agroforestry system with a traditional pure stone pine plantation, both for cone production

Indicator	Stone pine pure plantation	Agroforestry system
NPV (US$/ha at 8% interest rate)	470	3282
IRR (%)	8.4	12.3

year, and some of those flowers developed and reached maturity at age five, given the 3.5-year cycle the fruit needs to reach completion.

Economic evaluation

The results of the economic evaluations (IRR and NPV at 8%) (Table 5) showed that the NPV was almost seven times higher in the agroforestry system (cones and crops) than in the pure stone pine plantation (US$ 3282 vs. US$470 ha^{-1}), and IRR rose from 8.4 to 12.3% in the agroforestry system.

Discussion

This study suggests that it is possible to associate stone pine cultivation with intercropped annual cultures and also with controlled grazing, with interesting tree development values, as it has been demonstrated for other fruit forest species (Chifflot et al. 2005), in particular with walnut (Loewe and González 2006) and cherry (Balandier and Dupraz 1999).

In the first 5 years since these experimental agroforestry plots were established, crop yields were lower than the average in the region in monoculture, reaching 60% for forage oats and 66 and 86% for potatoes in plots 1 and 2, where the available space for the intercropping was close to 70 and 80% of the total area, respectively. Additionally, sheep that fed directly in the field, which were not considered in this analysis to present a conservative scenario, should be added to the estimates.

At age 5, sheep production in plot 1, with trees spaced at 5 × 5 m, was 3.7 sheep ha^{-1} year^{-1}, whereas in plot 2, with a lower density, it amounted to 4.4 sheep ha^{-1} year^{-1}. Considering that mean production in medium quality pasture in Chile reaches 4 (3–5) reproductive sheep/ha (Claro 2009), our results in plots 1 and 2 represent 92 and 110% of country-level values, respectively.

Although forage production in these plantations was not enough to sustain permanent grazing, livestock from the farm grazed there during a limited number of days per month during 10 months each year, contributing to mutton production. Interestingly, although sheep were introduced into the plantation since its establishment, no damage was recorded on trees, since there was a strict control on forage availability and animal pressure.

The possibility to combine stone pine and animals was already pointed out by Agrimi and Ciancio (1994), who stated that grazing in open pineries could provide some income, even though in Europe the main species associated with livestock are chestnuts, poplars, hardwood plantations, Mediterranean oaks and fruit trees, but also pines (Pardini and Nori 2011), usually in coastal areas. Forage production in these plantations is not enough to sustain grazing, but livestock from nearby farms occasionally graze there; if grazing is periodical, it has several positive impacts on pine plantations, such as reducing growth of weeds and shrubs, fire risk and the cost of periodical mechanical or chemical cleaning. Soil fragmentation and nutrient enrichment through animal defecation during grazing has been reported, accelerating litter decomposition and nitrogen incorporation, and reducing pine needle accumulation and fire risk (Mancilla-Leyton et al. 2013). This effect of grazing is important given the increasing number of forest plantation fires and that forest plantations in Chile supply 98% of the timber used by the national industry (INE 2014a). Moreover, if there is a direct continuous regulation of livestock carrying capacity, trees would not be damaged, as it was observed in this study, and as previously pointed out by Anderson et al. (1988).

Regarding stone pine growth, our results are higher than those reported for the best growth macrozone for the species by Loewe et al. (2015b), located in the South of Chile, in which growth rate across ages and sites is 0.35 m year^{-1} in height and 1.50 cm year^{-1} in DBH. The higher growth values reported here could be due to the young age of the assessed plots, which is characterized by a fast growth is, and also to the positive effect of the association with crops, which were fertilized and irrigated during the first 5 years.

DBH and height at age 5 was similar in both plots despite the differences in fertilization dose and irrigation quantity, which were 28 and 33% higher in plot 1, respectively. The fact that 6.3% of 5 year-old trees in one of the plots have strobili, which should reach maturity at age 8 years given the long fruit development cycle (42 months), is remarkable, since in its native distribution area first cone production starts in trees of 10 (Crawford 1995) and 20 years of age (Goor and Barney 1976). This result indicates the overall beneficial effects of the system on tree reproductive development, and could be an advantage for traditional plantations with seedlings, which are significantly less expensive than grafted plants.

Forest management planning provides a framework to establish priorities, set objectives and devise strategies to deal with risks (Day and Pérez 2013). From the management point of view, this technical combination turned out to be a simple scheme, easy to follow by small and medium size landowners with limited capital and knowledge base.

The amount of fuels associated with forest management is very important for forest fire occurrence; in fact, it has been reported that a reduction of fuel biomass decreases the probability and intensity of wildfires (Peña and Pedernera 2004). Preventive forestry aims at reducing the number of fires, and more importantly, their size (Haltenhoff 2006). Accordingly, USDA (2006) noted that the decrease in stand density and understory and surface fuel loads are factors that explain historical fire rates. Hence, the efforts to prevent damage and losses in plantations aim at including measures also related to decreasing horizontal and vertical fuel continuity, contributing to the reduction of wildfire likelihood, minimizing losses and supporting actions for a rapid extinction if a fire occurs. The proposed agroforestry system then turns out to be not only a productive solution but also a management practice with foreseeable positive effects on reducing fire likelihood, given the important quantity of fuel reduction and continuity defined by the lower density and by the presence of animal grazing, while providing several benefits such as improved access, extra revenue and reduced fire hazards.

From an economic point of view, we found the combined system to be significantly more profitable than the stone pine monoculture oriented to cone production. Economic results can improve if the owner adds a primary elaboration to sell in-shell pine nuts.

Our results are in line with experiences reported in New Zealand. where it was found that the combined system was more profitable than pastoral, agriculture and plantation forestry individually (Arthur-Worsop 1984), and in Australia in pine agroforestry systems (Garland et al. 1984), besides environmental benefits reported fin South America, such as the strong influence exerted by trees in the creation of favorable microclimate within silvopastoral systems (Dube et al. 2013).

Furthermore, the agriculture/animal production during the first years generates income that in a traditional stone pine plantation is not available until sexual maturity is reached. Therefore, this important additional production is attractive not only due to its economic implications, but also because land owners need continuous annual income, which is an additional benefit of the tested system.

The duration of the associated animal and crop production under the present conditions is not well known and will depend upon crown development; however, according to the present analysis, the rain-fed forage and/or grazing, and irrigated potato and oat and rye grass pasture is expected to last over 8 years. After that age, a stone pine thinning will be necessary to keep the agroforestry systems as such.

The important technical and commercial gaps that affect forest SMOs and SMEs, characterized by a lack of options partly due to their fragmentation, could benefit from agroforestry systems designed to fit different situations, considering available capital, owner's goals, capacity of operative management, and market conditions. The preliminary results of the proposed agroforestry system are a relevant input for future policy design and implementation, since its adoption could be a way of enhancing the incorporation of SMOs and SMEs to a more sustainable forest activity, as recommended by Loewe and Venegas (2005). In particular, the associated productive system showed an economic performance that can justify a government subsidy for agroforestry system establishment and management in order to improve the rural economy.

Conclusions

Stone pine is a highly interesting species due to its high-value pine nuts, its relative fast growth rate, simple management and excellent phytosanitary performance in Chile, without any disease or pest having been recorded. It was found to be a species suitable for its establishment in combined agroforestry systems based on trees for both nuts and timber, intercropped with agricultural crops and animal grazing.

The annual income derived from crops and animals is relevant for the household economy, especially during the first years of tree development when they still are not fruiting.

Forage production in these plantations is not enough to sustain permanent grazing, but sheep grazing during certain programmed periods contributes to mutton production; in addition, periodic grazing reduces shrub growth, fire risk and the cost of periodical mechanical or chemical cleanings. No damage by animals was observed on trees.

The tested stone pine—agricultural crops—sheep grazing system showed a positive economic performance; given the socio economic limitations characteristic of this sector, these results could justify a government subsidy for agroforestry system establishment and management in order to improve the rural economy and SMOs and SMEs.

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References

Agrimi M, Ciancio O (1994) Italian Stone pine (Il pino domestico) (*Pinus pinea* L.). FAO Silva Mediterranea, Larnaca

Anderson GW, Moore RW, Jenkins PJ (1988) The integration of pasture, livestock and widely-spaced pine in South West Western Australia. Agroforest Syst 6:195–211

Arthur-Worsop, MJ (1984) An economic evaluation of agroforestry: the national viewpoint. In: Proceedings of a technical workshop on agroforestry. Ministry of Agriculture and Fisheries, Wellington, New Zealand, pp 61–70

Badal E (2001) La recolección de piñas durante la prehistoria en la Cueva de Nerja (Málaga). In: Villaverde V (ed) De neandertales a cromañones-el inicio del poblamiento humano en las tierras valencianas. Universidad de Valencia, Spain, pp 101–104 **(in Spanish)**

Balandier P, Dupraz C (1999) Growth of widely spaced trees. A case study from young agroforestry plantations in France. Agroforest Syst 43:151–167

BBC (2014) Eva Mueller: UN urges action on forest diversity. http://m.bbc.com/news/science-environment-27963330. Accessed 23 June 2014

Buresti E, Mori P, Ravagni S (2001) Arboricoltura da legno con il ciliegio: ridurre i rischi adottando la doppia pianta. Sherwood 73:11–16 **(in Italian)**

Chifflot V, Bertoni G, Cabanettes A, Gavaland A (2005) Beneficial effects of intercropping on the growth and Nitrogen status of young wild cherry and hybrid walnut trees. Agroforest Syst 66(1):13–26

Claro M (2009) Pequeñas explotaciones ovinas en la zona sur de Chile. http://es.slideshare.net/miclaro/pequeas-explotaciones-ovina-zona-sur-de-chile?related=1 Accessed 12 Sept 2015 (**in Spanish**)

Crawford M (1995) Nut pines. Yearbook, West Australian Nut and Tree Crops Association 19: 56–66

Cruz C (2008) La cascara de piñón ahorra el 30% más que el gas. http://www.elnortedecastilla.es/20080227/palencia/cascara-pinon-ahorra-20080227.html. Accessed 12 Aug 2011 (**in Spanish**)

Day JK, Pérez DM (2013) Reducing uncertainty and risk through forest management planning in British Columbia. For Ecol Manag 300:117–124

Di Rienzo JA, Casanoves F, Balzarini MG, Gonzalez L, Tablada M, Robledo CW (2015) InfoStat version 2015. Grupo InfoStat, FCA, Universidad Nacional de Córdoba, Argentina. http://www.infostat.com.ar

Dube F, Thevathasan NV, Stolpe N, Espinosa M, Zagal E, Gordon AM (2013) Selected carbon fluxes in *Pinus ponderosa*-based silvopastoral systems, exotic plantations and natural pastures on volcanic soils in the Chilean Patagonia. Agroforest Syst 87(3):525–542

Eichhorn MP, Paris P, Hderzog F, Incoll LD, Liagre F, Mantzanas K, Mayus M, Moreno G, Papanastasis VP, Pilbeam DJ, Pisanelli A, Dupraz C (2006) Silvoarable systems in Europe—past, present and future prospects. Agroforest Syst 67:29–50

Garland K R, Fisher WW, Greig PJ (1984) Agroforestry in Victoria. Technical Report Series (Victoria. Dept. of Agriculture) N° 93

Gil L (1999) La transformación histórica del paisaje: la permanencia y la extinción local del pino piñonero. In: Marín F, Domingo J, Calzado A (eds) Los montes y su historia, una perspectiva política, económica y social. Spain, pp. 151–185 (**in Spanish**)

Goor A, Barney C (1976) Forest tree planting in arid zones, 2nd edn. The Ronald Press Company, New York, US, p 504

Haltenhoff H (2006) Silvicultura Preventiva, para la prevención de incendios forestales en plantaciones forestales. Documento de Trabajo N° 452, 2° edition. Corporación Nacional Forestal. Santiago, Chile

INE (2014a) Variables de estado del medio ambiente [Online] http://www.ine.cl/canales/chile_estadistico. Accessed 29 April 2014 (**in Spanish**)

INE (2014b) Estimación de superficie, producción y rendimientos de cultivos anuales según región. Año agrícola 2013-2014. http://www.ine.cl/canales/menu/publicaciones/calendario_de_publicaciones/xls/tabulados_cosecha_ca_2013_2014.xls. Accessed 13 Feb 2017 (**in Spanish**)

Loewe MV, Delard RC (2012) Un nuevo cultivo para Chile, el Pino Piñonero (*Pinus pinea* L.). INFOR-CORFO, Santiago, Chile (**in Spanish**)

Loewe MV, Delard RC (2016) Producción de piñón mediterráneo (*Pinus pinea* L.). Manual N° 48. INFOR (**in Spanish**)

Loewe MV, González M (2003) Sicomoro, grevillea, roble rojo americano, pino piñonero, castaño, ruil y cerezo americano, alternativas para producir madera de alto valor. INFOR-FIA, Santiago, Chile (**in Spanish**)

Loewe MV, González OM (2006) Sistemas agroforestales con nogal común (*Juglans regia*), experiencias exitosas para zonas templadas. In: IV Agroforestry Latinoamerican Congress. Cuba (**in Spanish**)

Loewe MV, González M (2007) Pino piñonero: el potencial de su madera y fruto. Chile For 334:49–53 **(in Spanish)**

Loewe MV, Venegas V (2005) Escenarios y Desafíos del Desarrollo Forestal Chileno. In: Barrera A, Venegas V, Tomic T, Rojas H (eds) Economía del Conocimiento y Nueva Agricultura, pp. 265–289 (**in Spanish**)

Loewe MV, Vargas V, Ruiz JM, Alvarez A, Lobo QF (2015a) Creation and implementation of a certification system for insurability and fire risk classification for forest plantations. In: Proceedings of the large fires conference held in Missoula in May of 2014. USDA Forest Service proceedings RMRS-P-73, pp 141–149

Loewe MV, Delard RC, Balzarini M, Álvarez CA, Navarro-Cerrillo RM (2015b) Impact of climate and management variables on stone pine (*Pinus pinea* L.) growing in Chile. Agric For Meteorol 214–215:106–116

Loewe MV, Balzarini M, Álvarez A, Delard C, Navarro-Cerrillo RM (2016) Fruit productivity of Stone pine (*Pinus pinea* L.) along a climatic gradient in Chile. Agric For Meteorol 223:203–216. https://doi.org/10.1016/j.agrformet.2016.04.011

Mancilla-Leyton JM, Sánchez-Lineros V, Vicente AM (2013) Influence of grazing on the decomposition of *Pinus pinea* L. needles in a silvopastoral system in Doñana, Spain. Plant Soil 373:173–181

Mutke S, Calama R, Gordo J, Gil L (2007) El uso del pino piñonero como especie de frutal en sistemas agroforestales de secano. Cuadernos de la Sociedad Española de Ciencias Forestales 22:137–142

Pardini A, Nori M (2011) Agro-silvo-pastoral systems in Italy: integration and diversification. Pastoralism 1(1):26

Peña E, Pedernera P (2004) Silvicultura preventiva para combatir incendios forestales. Chile For 302:12–14 **(in Spanish)**

Prada MA, Gordo J, De Miguel J, Mutke S, Catalán G, Iglesias S, Gil L (1997) Las regiones de procedencia de *Pinus pinea* L. en España. Organismo Autónomo de Parques Naturales, Madrid, Spain (**in Spanish**)

Pretzsch H, del Río M, Schütze G, Ammer Ch, Annighöfer P, Avdagic A, Barbeito I, Bielak K, Brazaitis G, Coll L, Drössler L, Fabrika M, Forrester DI, Kurylyak V, Löf M, Lombardi F, Matovic B, Mohren F, Motta R, den Ouden J, Pach M, Ponette Q, Skrzyszewski J, Sramek V, Sterba H, Svoboda M, Verheyen K, Zlatanov T, Bravo-Oviedo A (2016) Mixing of Scots pine (*Pinus sylvestris* L.) and European beech (*Fagus sylvatica* L.) enhances structural heterogeneity, and the effect increases with water availability. For Ecol Manag 373:149–166

Reisner Y, De Filippi R, Herzog F, Palma J (2007) Target regions for silvoarable agroforestry in Europe. Ecol Eng 29:401–418

Seidel D, Leuschner C, Scherber C, Beyer F, Wommelsdorf T, Cashman MJ, Fehrmann L (2013) The relationship between tree species richness, canopy space exploration and productivity in a temperate broad-leaf mixed forest. For Ecol Manag 310:366–374

Soto D, Gysling J, Loewe V (2008) Antecedentes del Mercado Internacional de Piñones de Pino. Ciencia e Investigación Forestal 14(3):599–623 **(in Spanish)**

Sotomayor A, Barros S (eds) (2016) Los Sistemas Agroforestales en Chile. Instituto Forestal, Chile, p 456

USDA (2006) Wildland Fire and Fuels Research and Development Strategic Plan: Meeting the Needs of the Present, Anticipating the Needs of the Future. U.S. Department of Agriculture, Forest Service, Research and Development, Washington, DC, p 50