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A review of silvopastoral systems in native forests of *Nothofagus antarctica* in southern Patagonia, Argentina

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Abstract Silvopastoral systems in *Nothofagus antarctica* (ñire) forest have become an economical, ecological and productive alternative in Patagonia. Southern Patagonia's experience over the past 12 years with silvopastoral systems is reviewed. The productivity and nutritive value (crude protein content and dry matter digestibility) of the understorey grassland were dependent on the interaction of environmental (mainly soil water availability and light intensity) and management factors under the trees and in turn determined animal performance. A method developed for carrying capacity estimation at the paddock level was based on the potential aboveground net primary production, and values ranged from 85 to 2200 kg DM ha^{-1} year^{-1}. Planned thinning in secondary forest stands provides wood production and also improves the undestorey DM production by increasing incoming radiation. Within a management plan, a stand's water stress conditions as well as the use of Reineke's stand density index are proposed to assist in determining thinning intensities. Livestock production is the main annual income of silvopastoral systems where cattle and mixed livestock production (cattle + sheep) is the main activity. Animal performance at the whole farm scale is presented by comparing traditional extensive grazing management with an adaptive silvopastoral management that included strategic separation in homogeneous areas (grass steppe, forest and riparian meadows), stocking rate adjustment to grassland net primary production and the protection of regeneration from herbivores browsing. Data from litter decomposition, nutrient cycling and carbon storage studies also are presented. Finally, aspects related to the criteria and indicators to assess ñire forest's sustainability under silvopastoral use along with biodiversity conservation issues are presented.

Keywords Livestock grazing · Silviculture · Sustainability · Carbon · Nutrients

Introduction

Southern Patagonia includes two provinces (Santa Cruz and Tierra del Fuego) with an area of 265,206 km^2 and extends from latitudes 46°S–52° 30′S. The southern beech, ñire (*Nothofagus antarctica* (G. Forster) Oerst.), one of the main deciduous native species in this area, covers 342,094 hectares (Collado

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2009; Peri and Ormaechea 2013). These forests occur naturally in different habitats such as poorly drained sites at low elevations, exposed windy areas with shallow soils, depressions under cold air influence or drier eastern sites near the Patagonian steppe (Veblen et al. 1996). Silvopastoral systems combine trees and grasslands or pastures under grazing in the same unit of land and have become an economical, ecological and productive alternative land management practice in Patagonia. This provides diversification of farm income, either directly from the sale of timber and animals and/or indirectly by the provision of stock shelter and beneficial effects on soil conservation. There are ecological and economic interactions (positive and/or negative) between the woody, non-woody and animal components of the systems. Approximately 90 % of ñire native forest in Southern Patagonia has been used as silvopastoral systems (Collado 2009; Peri and Ormaechea 2013). This sustains mainly sheep and cattle production and provides a range of wood products including poles, firewood and timber for rural construction purposes (Peri 2005). In recent years, management plans or legislation to maximize the forest's sustainable benefits has been proposed (Peri et al. 2009a). The proposal involves developing a management plan for native ñire forests under a silvopastoral use that includes, for example, forestry inventories, silvicultural practices, adjustment of stocking rate according to pasture assessments and strategies to achieve forest regeneration. Also, guides for environmental quality conservation are included, such as an adequate road density plan, biodiversity maintenance and conservation of water quality in streams.

The aim of this review is to summarize the silvopastoral systems research carried out in a temperate region of Southern Patagonia over the period 2002–2014.

Understorey component

The productivity and nutritive value of a pasture in a silvopastoral system are dependent on the interaction of environmental and management factors under the trees and in turn determine animal performance. For grasslands under a defined light regime, the main determinants of growth are temperature, water, nitrogen and regrowth duration (Peri et al. 2006a). The main aspects of the incoming radiation, which are modified by trees and affect dry matter (DM) production of the understorey, are the light intensity and light quality (Peri et al. 2007). The extent of the effects of the environmental and management factors on DM production and pasture nutritive value depends on the seasonal changes and development of trees over time.

Dry matter production

Understorey dry matter (DM) production in ñire silvopastoral systems largely depends on the interaction of soil water availability and light intensity reaching the sward (Peri 2005; Peri et al. 2005a). Under moderate water stress conditions, a negative exponential relationship exists between DM production and the light reaching the pasture canopy, e.g., yields decreased from 2800 kg DM ha^{-1} in the open (100 % transmittance) to 500 kg DM ha^{-1} in severe shade (5 % transmissivity) (Peri 2005) (Fig. 1). Under water-limiting conditions, trees in silvopastures may reduce soil moisture by creating a rain shadow, direct interception of rainfall and root competition. The proportion of fine roots (≤2 mm diameter) of ñire trees are mostly concentrated in the 10–50 cm soil depth, which is also where 95 % of pasture species roots are distributed (Peri et al. 2006b; Peri 2011). Although tree and pasture roots compete for water whenever soil moisture drops below field capacity, under severe water stress conditions, moderate shade benefits pasture growth, e.g., pasture production increased from 5 to 47 % transmissivity and then reached a maximum value of 1400 kg DM ha^{-1} around 50–60 % transmissivity (Fig. 1). In these dry conditions, intermediate crown cover may conserve soil moisture by reducing evapotranspiration from pastures through a reduction in canopy temperature and stomatal closure and mainly by reducing the wind speed within the stand. In general, wind speed (of great importance in Patagonia) is reduced in *Nothofagus* forests (up to 80 % compared with adjacent open areas) with greater crown cover (Bahamonde et al. 2009). The response of understorey dry matter production to the openness of the original overstorey canopy cover by thinning varied from 300 ± 150 kg DM ha^{-1} for moderate thinning to 1400 ± 250 kg DM ha^{-1} for intensive thinning in better sites (Peri 2009c, d).

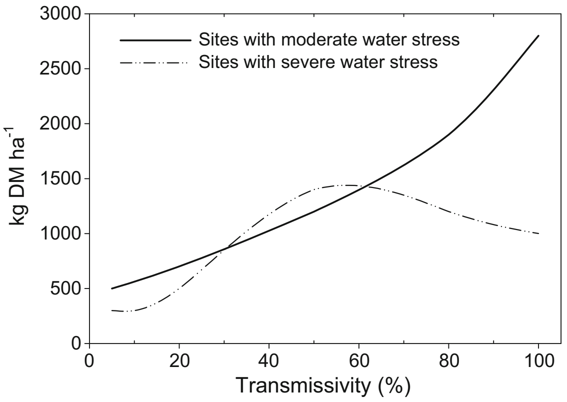

Fig. 1 Mean dry matter (DM) grass understorey production in ñire silvopastoral systems under different light intensities (determined by a gradient of crown cover) and adjacent open areas (100 % transmissivity) in Southern Patagonia. Severe water stress sites had a mean soil volumetric water content (VWC) in the top 250 mm less than 18 % during the main growing season (October–April), and moderate water stress sites had a soil VWC >18 %

Rapid assessment of pasture mass: Ñirantal Sur method

Determining stocking rates is one of the most important decisions in developing a grazing plan in silvopastoral systems. In Southern Patagonia (Santa Cruz and Tierra del Fuego provinces), a method has been developed for carrying capacity estimation in *N. antarctica* forests under silvopastoral use at a paddock level (Peri 2009a, b). This method, called the "Ñirantal Sur" or "Saint George" method, is based on estimates of potential aboveground net primary production (PANPP) for different forest conditions and date of use (spring or biomass peak, summer, autumn and winter), weighted by the area of each homogeneous forest unit. Estimates of PANPP for grasslands are based upon measurements of standing crop biomass by destructive harvests. Linear and nonlinear regressions and empirical relationships were generated based on a database of 900 DM cuts from pure and homogeneous ñire stands. The model was developed from data collected over a large gradient of environmental variables and broad geographic distribution (46°03′24″–54° 21′47″SL) during the period of 2003–2007 (Peri 2009b). This method is easy to use because it only requires three field measurements for PANPP estimation (Table 1): crown cover (CC), site class (SC) expressed as the mean height of dominant trees and wood debris cover (D). PANPP ranged from 85 (grassland grown in a SC III forest, CC of 5–30 % and D of 30–50 % in winter) to 2200 kg DM ha^{-1} year^{-1} (grassland grown in a SC I forest, CC of 5–30 % and D of 5–10 % in spring). An independent validation ($n = 20$) indicated that this method accounted for 83 % of the variation in PANPP. Therefore, this new grassland assessment method was shown to be adapted for *N. antarctica* ecosystems and also provides an objective technique to avoid overestimating carrying capacity.

Pasture nutritive value

Crude protein

The vegetation in the silvopastoral systems where pasture nutritive value was evaluated is dominated by *Carex andina* (20–30 %), *Poa pratensis*, *Phleum commutatum*, *Dactylis glomerata*, *Bromus setifolius*, *Agrostis flavidula*, *Deschampsia flexuosa* and *Festuca pallescens* with a mean historical stocking rate of 0.57 ewe ha^{-1} year^{-1}. In general, mean annual undestorey crude protein concentrations (CPs) in four sites of ñire forest under silvopastoral use in Southern Patagonia ranged from 8.2 to 12.2 % (Peri et al. 2005b). In these ecosystems, mean values of CP percentage increased from 9.9 % in open pastures to 11.2 % under severe shade (10 % transmissivity) although this response varied with site quality (site by shade interaction; $p < 0.05$). The increase in CP percentage as PPFD declined may be attributed to either a decrease in photosynthates, with a consequent rise in nitrogen concentration, or to an increase in soil organic matter mineralization under trees that provided more nitrogen for grass uptake. Forage CP percentage decreased during the summer period when water stress was severe (Bahamonde et al. 2012a), and dry conditions are known to retard both pasture uptake and soil mineralization of N during the season (Whitehead 1995). In Bahamonde et al.'s research, forage CP generally was greatest under moderate shade on higher quality sites, but in low quality sites CP was greatest under severe shade (site quality X light intensity interaction; $p < 0.05$). Similarly, Wilson (1996) reported that an increase in CP content in grasses with shade level must be related to the growing medium or soil because the increase in CP of several pasture grasses was not detected in shaded plants growing in a solution culture.

Table 1 Mean potential aboveground net primary production (PANPP) (kg DM ha^{-1} year^{-1}) (± standard deviation) of grassland under silvopastoral use growing at different conditions of *Nothofagus antarctica* forests [site class (SC), crown cover (CC), wood debris cover (D)] and date of use (spring or biomass peak, summer, autumn and winter) in Southern Patagonia

	Spring (Nov–Dec)			Summer (Jan–Feb)			Autumn (Apr–May)			Winter (June–Aug)		
	Debris 5–10 %	Debris 10–30 %	Debris 30–50 %	Debris 5–10 %	Debris 10–30 %	Debris 30–50 %	Debris 5–10 %	Debris 10–30 %	Debris 30–50 %	Debris 5–10 %	Debris 10–30 %	Debris 30–50 %
SC I												
CC 5 a 30 % ($n = 110$)	2200 ± 500	1850 ± 425	1620 ± 380	1630 ± 370	1370 ± 315	1195 ± 280	1430 ± 325	1200 ± 275	1050 ± 240	770 ± 175	645 ± 150	565 ± 130
CC 30 a 60 % ($n = 105$)	1200 ± 350	1055 ± 370	955 ± 275	935 ± 275	820 ± 290	745 ± 215	805 ± 230	705 ± 235	640 ± 185	455 ± 135	400 ± 140	360 ± 105
CC >60 % ($n = 90$)	750 ± 285	680 ± 230	580 ± 160	605 ± 230	550 ± 185	470 ± 130	510 ± 195	442 ± 150	375 ± 105	315 ± 120	285 ± 95	240 ± 65
SC II												
CC 5 a 30 % ($n = 101$)	1100 ± 370	990 ± 310	870 ± 235	780 ± 260	705 ± 220	620 ± 165	615 ± 205	555 ± 170	485 ± 130	308 ± 105	275 ± 85	245 ± 65
CC 30 a 60 % ($n = 108$)	745 ± 285	655 ± 245	565 ± 190	545 ± 205	480 ± 180	415 ± 140	430 ± 165	380 ± 140	325 ± 110	245 ± 95	215 ± 80	185 ± 60
CC >60 % ($n = 92$)	340 ± 130	310 ± 140	270 ± 115	260 ± 100	235 ± 105	205 ± 90	205 ± 80	185 ± 85	160 ± 70	135 ± 50	125 ± 55	110 ± 45
SC III												
CC 5 a 30 % ($n = 102$)	390 ± 125	345 ± 130	280 ± 90	265 ± 85	235 ± 80	190 ± 60	195 ± 60	175 ± 60	145 ± 45	115 ± 35	105 ± 40	85 ± 30
CC 30 a 60 % ($n = 107$)	485 ± 210	430 ± 185	375 ± 110	370 ± 160	325 ± 140	285 ± 85	265 ± 110	240 ± 100	200 ± 60	170 ± 75	150 ± 65	130 ± 40
CC >60 % ($n = 85$)	280 ± 160	250 ± 130	220 ± 85	220 ± 125	200 ± 100	175 ± 65	190 ± 105	170 ± 90	150 ± 50	130 ± 75	115 ± 60	100 ± 35

Site class I mean height of dominant trees >12 m; *site class II* mean height between 7 and 12 m; *site class III* mean height <7 m; *n* number of dry matter cuts for each group of crown cover and site classes (*n* total 900 cuts)

Organic matter digestibility

Forage organic matter digestibility (OMD) displayed both strong seasonal fluctuation and significant response to shaded conditions (Peri and Bahamonde 2012). Values for OMD ranged from 43.7 to 78.5 % and were lowest in the dry summer period at sites without trees (Fig. 2). In an analysis of microclimatic factors affecting mean annual OMD, photosynthetic photon flux density (PPFD) in the 400–400 nm waveband and relative humidity had little effect, while mean soil volumetric water content (VWC) in the top 30 cm and air and soil temperature were the main factors explaining OMD variation for grasses leaves (Table 2). Although shading usually reduces the total non-structural carbohydrate of grasses, but has variable (positive and negative) effects on cell wall content and composition, lignin and in vitro digestibility of plant dry matter (Wilson 1988). Furthermore, studies of shading effects on forage digestibility typically are confounded by changes in temperature. High temperatures have been shown to increase lignification and reduce forage quality (Henderson and Robinson 1982).

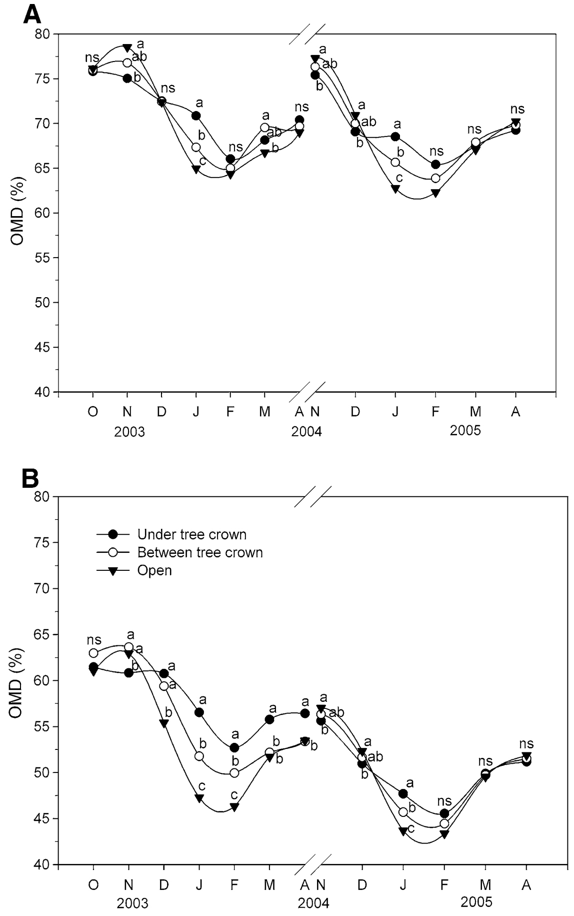

Fig. 2 Understorey organic matter digestibility (OMD %) over time for three shade conditions at two contrasting silvopastoral sites (**a** Catalana station, 54°10′50″LS, 67°16′02″LO, MAT: 4.3 °C, MAP: 430 mm; **b** Tres Marías station, 51°19′05″LS, 72°10′47″LO, MAT: 5.8 °C, MAP: 320 mm) in ñire forest (Southern Patagonia, Argentina): open (100 % transmissivity), between tree crowns (~50 % transmissivity) and under trees (~25 % transmissivity). *Different letters* within a date indicate significant differences based on the Tukey test at 0.05 probability

Linear relationship ($y = -4.8x + 78.5; p < 0.001; R^2$ 0.84) between OMD % and site classes (1–5) indicated the highest values in the best forest sites. In conclusion, the environmental variables that determined the productive capacity of the forest (clime, soil) also affected the OMD values of the understorey grasses.

Improved pasture in ñire silvopastoral systems

One method to improve forage availability in ñire silvopastoral systems (despite their limited local precipitation) is to introduce highly productive forage species. Legumes are especially important because of their central roles as a source of nitrogen and in providing high-quality forage for grazing animals. Peri et al. (2005b) reported that the level of pasture production that can be achieved in silvopastoral systems from mixed improved pastures increased by ~20–35 % depending on light availability, and clover made up 32 % of the annual dry matter produced in the open adjacent sites. In understorey pasture improved with *Trifolium repens* (white clover), the total DM production did not differ between open and 70 % transmissivity sites but was greater than in pastures grown under 20 % transmissivity (Peri et al. 2012a). With rotational grazing clover survived well, contributing between 33 and 41 % of the total annual yield, although leguminous cover declined substantially under severe shade. In these ecosystems, maximum white clover growth rate occurred in January with values of 7.5, 9.4 and 12.9 kg DM ha^{-1} day^{-1} for 20, 70 and 100 % transmissivity, respectively. While pasture CP decreased according to low light intensity due to a decrease in clover cover, digestibility was influenced only by soil water content at the upper

Table 2 Coefficient of determination (R^2) from simple linear regression between the organic matter digestibility (OMD) and main environmental variables

Site	PPFD	MAT	MST	RH	VWC
Cancha Carrera[a]	0.002 ns	−0.46***	−0.48***	0.130*	0.61***
Tres Marías[b]	0.001 ns	−0.30***	−0.43***	0.040 ns	0.39***
Catalana[c]	0.002 ns	−0.33***	−0.30***	0.012 ns	0.19**
Indiana[d]	0.005 ns	−0.24**	−0.25**	0.01 ns	0.20*

PPFD photosynthetic photon flux density, *MAT* mean annual temperature, *MST* mean soil temperature, *RH* relative humidity, *VWC* mean soil volumetric water content at 0–30 cm depth) at different locations in Southern Patagonia

Linear regression significance, * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; *ns* not significant

[a] Location: 51° 13′21″LS; *72°15′34″LO (Santa Cruz province); *site class IV: mean height of dominant trees 6–8 m; *mean annual temperature (MAT): 6.1 °C; *mean annual precipitation (MAP): 360 mm

[b] Location: 51°19′05″LS, 72°10′47″LO (Santa Cruz), site class V: < 6 m, MAT: 5.8 °C, MAP: 320 mm

[c] Location: 54°10′50″LS, 67°16′02″LO (Tierra del Fuego province), site class II: 10–12 m, MAT: 4.3 °C, MAP: 430 mm

[d] Location: 54°21′47″LS, 67°27′05″LO (Tierra del Fuego), site class II: 10–12 m, MAT: 4.8 °C, MAP: 480 mm

20 cm depth (Peri et al. 2012a). These results highlighted the adaptation of white clover to ñire silvopastoral systems and their value for improving the quality of natural pastures.

Simulation model of dry matter production and crude protein of grasses under silvopastoral use

Because of a silvopasture system's complexity, determining the effects of multiple interacting factors on system outputs can be challenging, and this is further compounded by the "results" changing over time. To improve the understanding of these processes, a tool that integrates existing information using a system approach is required, i.e., this requires studying the relationships between variables connected to each other through causal relationships, including feedbacks between variables (Haraldsson 2000). This systemic approach also allows describing the dynamic (change over time) of the variables and/or relationships (Haraldsson and Sverdrup 2004). Simulation models are appropriate for this purpose and have been developed with STELLA Systems dynamics software to estimate forage DM production and CP in *N. antarctica* silvopastures (Bahamonde et al. 2014). The model considered environmental variables (air and soil temperature, air humidity, soil moisture, site quality, crown cover) and was focused at a stand level of homogeneous, even-aged ñire forest under Southern Patagonia conditions. Model estimates were compared with yield and nutritive value data from several studies, and weak but significant linear correlations were found for DM ($R = 0.52$; $p < 0.001$, average underestimation 22 %) and CP ($R = 0.47$; $p < 0.001$, average overestimation 24 %) (Fig. 3). Also, in that work simulations of different situations related to the management of the ñire forest under silvopastoral use were carried out. These simulations were coherent with empirical data in regard to the environmental and stand management variables that affect the DM and CP of the understory and suggest that the model is a reasonable first estimator for guiding management decisions of understory grasses in ñire forests.

Tree component

Large-scale canopy disturbance in *N. antarctica* forests occurs mainly as a result of blowdown (at a small gap scale) and to a lesser extent due to snow damage or fires associated with human activities. This results in abundant regeneration (e.g., 100,000 seedlings ha^{-1} less than 1 m tall, up to 20 years of age) followed by self thinning due mainly to light competition resulting in a final stand density of 200–350 trees ha^{-1} at mature stages (more than 180 years of age). For silvopastoral systems, planned thinning in secondary forest stands may reduce the time required to yield products of a desired quality, concentrate growth on selected trees, increase wood production by

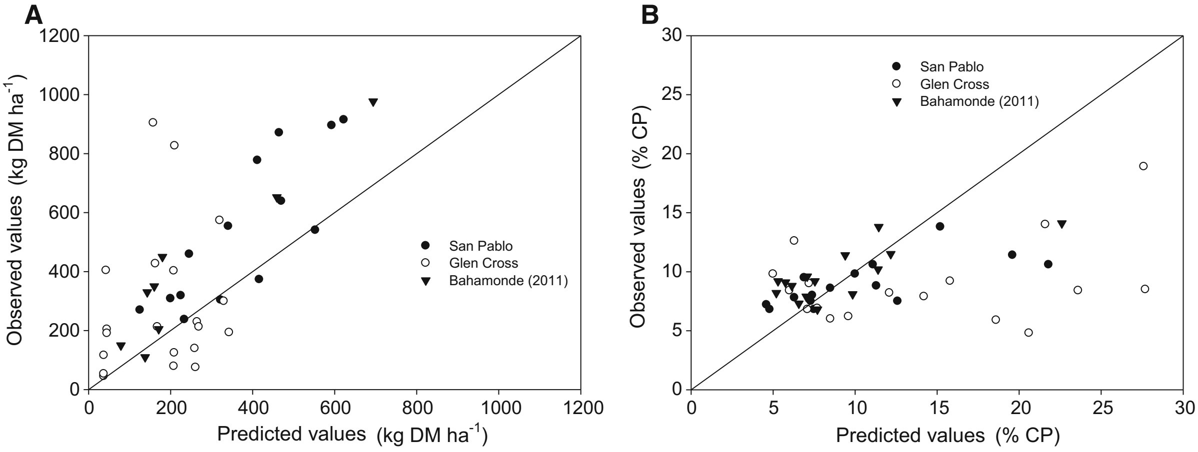

Fig. 3 Observed versus predicted values of dry matter production (**a**) and crude protein (**b**) of grasses growing at different *N. antarctica* forest in Patagonia. The *line* represents the 1:1

utilizing trees that would die in the absence of thinning and also improve the undestorey DM production (and consequently increase animal production) by increasing incoming radiation. In this context, information from provincial inventories indicated that there are approximately 21,480 ha in Santa Cruz province (13.5 % of total forest area) and 108,430 ha in Tierra del Fuego province (59 % of total forest area) of natural forests with high canopy cover (>70 %) with potential for thinning (Collado 2009; Peri and Ormaechea 2013).

Regeneration

Since there are positive and negative interactions among trees and livestock, proper silvopastoral system practices aim to encourage the positive interactions to ensure tree regeneration for long-term viability (Peri et al. 2009a). One of the main ecological indicators that defines the success of some forestry proposals is the implementation of effective natural forest regeneration practices that ensure the maintenance of the tree layer (Martínez Pastur et al. 2009). The seedling stage constitutes the earliest and most critical stage of the tree life cycle. Moreover, it defines the capacity of forest ecosystems to remain in time and space. Under natural conditions there are several limitations for forest regeneration, from the flowering stage until seedlings establish and survive (Jordano et al. 2008; Soler et al. 2013). These limitations may be intensified in those forests impacted by productive activities. Studies regarding regeneration limitations usually emphasize either seed limitation or establishment limitations because of the reduction of suitable microsites (Clark et al. 1999). Regarding the first component, *N. antarctica* forests in Southern Patagonia produce millions of seeds each year, through cyclical masting periods (Cuevas 2000), with high variability among stands and years with high temporal (e.g., year to year) and spatial (e.g., stand level) variation (Bahamonde et al. 2011, 2013a; Soler et al. 2013). In Santa Cruz and Tierra del Fuego strong interannual variation of seed production has been recorded in forests with silvopastoral use, ranging from 1–40 million to 1–56 million seeds ha^{-1}, respectively. In Santa Cruz, such production does not differ from that of unmanaged primary forests, where the maximum value recorded reached 52 million seeds ha^{-1}. In Tierra del Fuego, fruiting as well as seed production was more successful in unmanaged forests, likely because of the reduction of the basal area in silvopastoral stands. About 40–50 % of *N. antarctica* seeds produced are empty, which greatly reduces the natural potential for installation at early stages of the regeneration process. Also, the percentage of viable seeds is very low and ranged from only 8.5–29 % of full seeds in Santa Cruz and 11–30 % in Tierra del Fuego. Canopy opening in silvopastoral systems also appears to modify biotic and abiotic factors of *N. antarctica* forests (Bahamonde et al. 2009; Soler et al. 2013), thus influencing the microsite quality for seedling installation and survival. In natural *Nothofagus* forests, small canopy disturbances (gaps) stimulate the growth of seedlings established on the forest floor (Rebertus and Veblen 1993) by increasing resource availability (e.g., solar radiation, soil moisture, nutrient dynamic) (Heinemann et al. 2000). However, canopy opening in silvopastoral systems generates more drastic changes in the original overstory (e.g., 50 % canopy openness), and therefore the success of natural regeneration could be negatively affected. Recent studies carried out in *N. antarctica* forests of Santa Cruz showed that higher seedling installation occurred in forests with silvopastoral use compared to primary unmanaged forests. Installation rates ranged from 10 to 270 thousand seedlings ha^{-1}, with the highest values in the best quality sites. But commonly at the end of the growing season, the survival rate was almost zero. In rare cases, survival (35–75 %) has been recorded during the first year of installation, but no seedlings survived the second year. In contrast, in Tierra del Fuego the minimum number of installed seedlings in primary unmanaged forests ranged from 200,000–270,000 ha^{-1} compared to 100,000–175,000 seedlings ha^{-1} in forests with silvopastoral use. First year survival rates ranged from 15 to 38 %, creating a well -stablished seedling bank: total seedling densities after 4 years of monitoring varied from 54,000 seedlings ha^{-1} in primary unmanaged forests to 93,000 seedlings ha^{-1} in silvopastoral stands.

Survival of seedlings and saplings depends on the species' ecophysiological traits. *N. antarctica* is considered less shade tolerant than other closely related species such as *N. pumilio* (Peri et al. 2009b). This provides competitive advantages when these trees grow in open areas. A recent study in Tierra del Fuego demonstrated the success of seedling establishment and survival at the sapling stage in managed stands, indicating the advantage of *N. antarctica* for the implementation of silvopastoral systems (Soler et al. 2013). On the other hand, there is a significant impact of domestic livestock on tree regeneration. In experimental enclosures in silvopastoral systems of Tierra del Fuego, seedling densities were three times higher (295,000 ha^{-1}) than in unprotected sectors (102,000 ha^{-1}). In another experiment in Santa Cruz, using individual tree protectors on advanced regeneration resulted in greater mean annual growth of protected than unprotected saplings (10.4 vs. 0.4 cm height), mainly after the second year of enclosures installation. Minimizing the damage (e.g., browsing, trampling) on natural regeneration in silvopasture (Reque et al. 2007; Peri et al. 2009c; Peri and Ormaechea 2013) is essential for sustainable management of *N. antarctica* forests.

Nothofagus antarctica also has a great (though less known) ability to resprout from stumps under natural conditions (Steinke et al. 2008). This presents a reproductive advantage over the other *Nothofagus* species and provides another option for forest regeneration under silvopastoral use. In some natural conditions (e.g., peatlands), stump regrowth is the only means of regeneration for *N. antarctica* (Donoso et al. 2006). Vegetative reproduction is a key mechanism of persistence for those species facing natural or anthropic disturbances that cause partial loss of aboveground biomass (e.g., thinning, browsing damage; Vesk 2006). Sprouts originating from established plants have well-developed root systems and canopies that develop rapidly. In a thinning experiment in *N. antarctica* forests of Santa Cruz, stumps sprouted 1 year after thinning by forming groups of large thin branches. Mean and maximum lengths of regrowth were 11 and 25 cm, respectively (Bahamonde et al. 2013b). Similarly, vegetative reproduction in Tierra del Fuego has been observed mostly in forests with silvopastoral use (25 % of the seedling bank) with 6 cm year^{-1} of mean height growth (Soler et al. 2012).

Knowledge of natural regeneration of *N. antarctica* provides evidence for the ecological advantages of implementing silvopastoral systems with this forest species in South Patagonia. The climatic particularities for each region (e.g., precipitation range) should be considered during management planning. Also, protecting advanced natural regeneration (e.g., individual enclosures, plot fences) is essential to ensure the maintenance of the tree component. Further monitoring and long-term knowledge of regeneration processes will allow us to determine whether the quantity and quality of young trees surviving within managed forests are enough to ensure the sustainable silvopastoral production in South Patagonia forests (Peri et al. 2006c).

Silviculture and wood production

Intermediate treatment schedules have been proposed previously for ñire forests, and several thinning trials have been established to date. Within natural ñire forests managed for silvopastures, Peri et al. (2009a) proposed two thinning intensities depending on water stress conditions and stand site qualities. Under severe water stress conditions (drier sites near the Patagonian steppe) where dominant trees reach a total final height between 4 and 8 m, a moderate thinning intensity leaving at least 50–60 % of canopy cover is recommended. Usually this remaining crown cover provides protection from desiccating strong winds, improving the microclimatic conditions for understorey production, tree regeneration and plant biodiversity conservation. In contrast, for stands growing in better sites (final height of dominant trees >8 m) with a higher annual precipitation regime (>350 mm year^{-1}) and deeper soils (>0.5 m depth), more intensive thinning is promoted leaving a 30–40 % of canopy cover. Another important consideration of silviculture practices in these forests under silvopastoral use is to ensure the continuity of tree strata in the long term. One of the major obstacles for successful establishment and growth of seedlings is browsing by herbivores (such as rabbits, hare and livestock) and competition with grasses for light. In several areas of ñire forest under grazing, tree regeneration was completely damaged and tree dynamics were interrupted (Peri and Ormaechea 2013). In this context, trees may be protected as individual specimens or as small groups (where trees form a feature as a group rather than as individual specimens) by using individual tree guards or small fences (Peri et al. 2009c; Ormaechea and Peri 2010). We suggest protecting about 250 seedlings ha^{-1} for dry sites and 150 seedlings ha^{-1} in sites with better conditions until regeneration trees reach >2 m height.

Tree growth in natural unmanaged forest is greatly influenced by the landscape, where higher site quality stands occupy the moister environments with deeper soils, mainly close to *N. pumilio* forests. The lower site quality stands are found in areas of heavy wind exposure or in the ecotone with the steppe in the drier areas. The diameter growth is also influenced by the vertical structure, and dominance significantly affects this variable. The annual diameter growth of dominant trees in high quality sites can reach to 0.37 cm year^{-1}; in lower site classes, 0.22 cm year^{-1} is more typical (Fig. 4). In the same way, dominant trees grow more rapidly (0.22–0.37 cm year^{-1}) than the suppressed trees (0.14–0.22 cm year^{-1}) along the site quality gradients.

Some regional forest management plans have used Reineke's Stand Density Index (SDI) to assist in defining thinning intensities for varied canopy covers (Ivancich et al. 2009). SDI is a relative measure of stand density in single-species and even-aged stands. SDI_{25} represents the equivalent number of trees per hectare at a standard of 25 cm quadratic mean diameter. Density and diameter data from 266 ñire

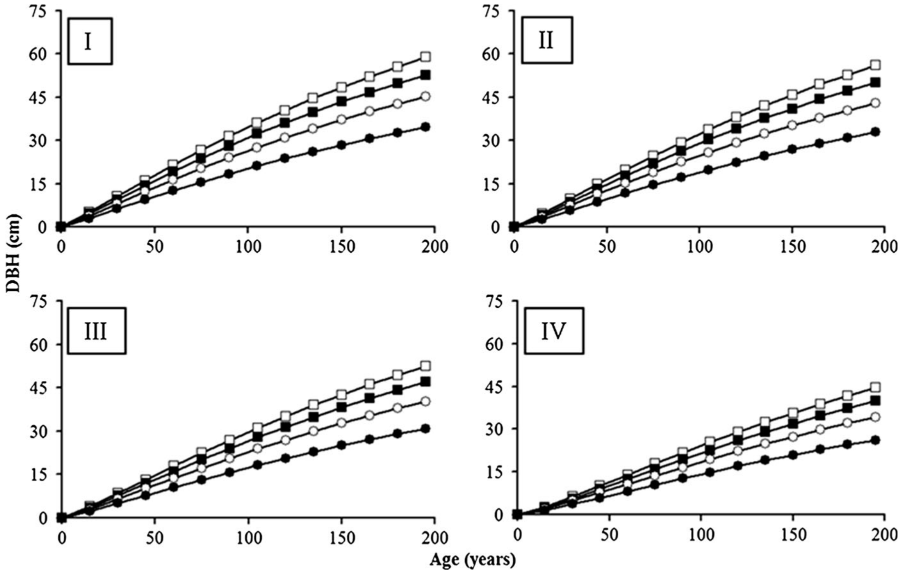

Fig. 4 Diameter growth model classified by site quality of the stands (I = $SI_{50} > 9.3$ m, II = $SI_{50} > 7.2$ and ≤ 9.3 m, III = $SI_{50} > 5.1$ and ≤ 7.2 m, IV = $SI_{50} \leq 5.1$ m) and crow class of the trees (dominant = *white squares*, co-dominant = *black squares*, intermediate = *white circles*, suppressed = *black circles*)

forest inventory plots in Santa Cruz and Tierra del Fuego were fitted to a model of maximum relative density. The SDI_{25} was 1435 trees ha^{-1} based on the equation: $\log_{10}N = \log_{10}897000 - 2 * \log_{10}QMD$, where N is the number of trees per hectare and QMD is the quadratic mean diameter of the trees. A new density model then was fitted for different canopy covers; the model was based on the stand density equation and a previously developed model that estimates stand crown cover (CC %) using stand basal area (BA) (m^2 ha^{-1}) and an independent variable ($CC\ \% = 99.45 * 1 - e^{-0.0264*BA}$; $R^2 = 0.95$) (Peri 2009a). This final model predicts the parameter used in an equation to estimate the SDI for a particular QMD at any canopy cover. This model simplifies data collection during the forest inventories; only stand density and basal area measures are required to estimate the thinning intensity needed for a given crown cover. This model is independent of stand age and site quality and could be applied at several forested landscapes in Southern Patagonia.

As part of the PEBANPA network (biodiversity and ecological long-term plots in Southern Patagonia), permanent plots (1 ha) were established in 2008 in a young, pure, even-age *N. antarctica* stand (41 ± 6 years old, 4055 ± 48 trees ha^{-1}, DBH = 5.2 ± 1.8 cm, BA = 29 ± 5.8 m^2 ha^{-1}, $SI_{50} = 7.2$ m) located in Santa Cruz province (51°13′20″SL, 72°15′24″WL). Peri et al. (2012b, 2013) reported that thinning (final stocking of 1551 ± 35 trees ha^{-1}, crown cover 40 %) for silvopastoral use increased the mean tree DBH growth rate by approximately 40 % compared with the control treatment. The total over bark volume growth rate at the stand level was 4.3 ± 0.65 and 3.7 ± 0.43 m^3 ha^{-1} year $^{-1}$ for the thinned and control stands, respectively. In Tierra del Fuego province, a trial was established in 2009 with two thinning intensities in an area of 5 ha of pure even-aged *N. antarctica* forest growing at a good site quality ($SI_{50} = 12.3$ m) in Cape San Pablo Ranch (54°15′45″SL, 66°49′44″WL), leaving a stand without intervention as a control treatment (Ivancich et al. 2010, 2012). In each treatment, five permanent plots were established. In the low-intensity thinning treatment (18 m^2 ha^{-1} remaining BA), 53 % (±15.9 %) of BA was harvested, decreasing stand density from 2.793 ± 448 to 681 ± 48.3 trees ha^{-1}, but tree size was increased from 13.4 ± 1.0 to 18.3 ± 1.7 cm QMD. After thinning, the crown cover was 66.5 and 53.0 % for low and high intensity, respectively. The high intensity thinning treatment left 12 m^2 ha^{-1} remaining BA; 65 ± 9.1 % of the original BA was removed. Stand density was decreased from 2.183 ± 834 to 345 ± 63 trees ha^{-1}, and tree size was increased from 14.3 ± 1.9 to 21.2 ± 1.3 cm QMD. Individual tree growth was measured annually in these permanent plots. Mean diametric increment was 0.34 ± 0.05 and 0.40 ± 0.02 cm $year^{-1}$ for low- and high-thinning intensities, respectively. This contrasted with 0.19 ± 0.02 cm $year^{-1}$ for the control. The mean volumetric growth at the stand level was 3.92 ± 0.88 and 3.12 ± 0.2 m^3 ha^{-1} year $^{-1}$ for low- and high-thinning intensity, respectively, in comparison with 4.86 ± 1.01 m^3 ha^{-1} year $^{-1}$ in the control. These growth increments reported for *N. antarctica* for silvopastoral use were lower than those reported by Peri et al. (2002) in which volume growth of 67-year-old *N. pumilio* forests increased by 83 and 65 % over control treatments with light and heavy thinning, respectively, in a high-quality site ($SI_{60} = 23.2$ m). These growth increments also were lower than those reported by Martínez Pastur et al. (2001) in which pure *N. pumilio* stands grown in site quality II–III had maximum growth of 12.7 m^3 ha^{-1} $year^{-1}$. In the same plots, the overstorey dynamics were monitored using hemispherical photos and Gap Light Analyzer software (Martínez Pastur et al. 2011) and significant variations occurred over time and treatment (Fig. 5). The effectiveness of the cuttings were determined over time by analyzing the evolution of leaf area index (LAI), crown cover and solar radiation transmission. During the first 5 years after thinning, while crown cover in the control treatment decreased (−1.5 %), heavy and light thinning increased (6.0 and 8.9 %, respectively). Long-term monitoring also has allowed us to quantify the impact of biotic factors on tree growth. For example, during the third year, a heavy insect (*Ormiscodes amphimone*) attack occurred that was higher in the heavy thinning treatment than the others.

These results highlight the importance of establishing permanent plots that cover different thinning treatment (intensity) options across a site quality gradient to fully evaluate the growth responses of *N. antarctica* stands. Long-term plots are essential to determine the economic feasibility of the intermediate treatments, define baselines and impacts of different silvicultural treatments and provide monitoring

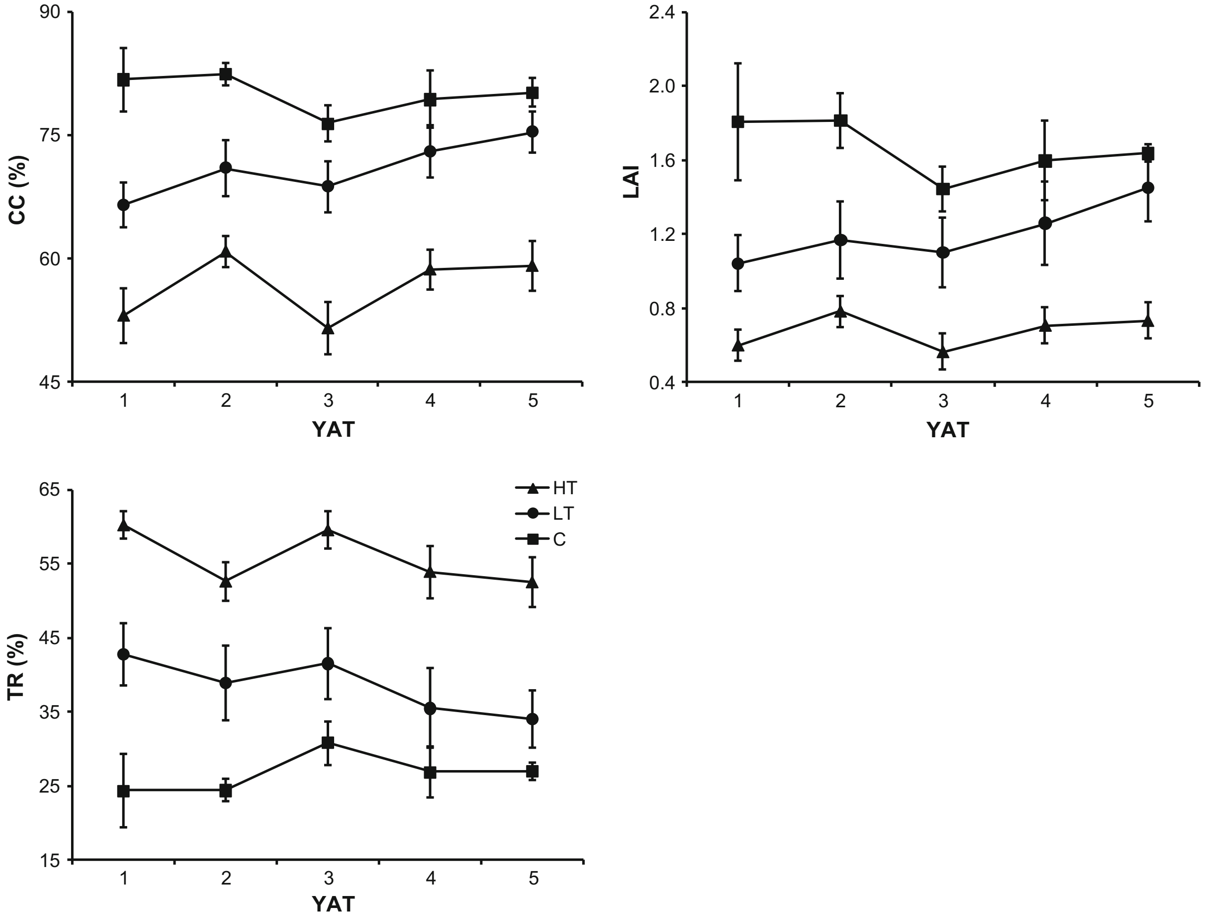

Fig. 5 Overstorey dynamics after thinning (YAT = years after thinning) in heavy thinning (HT), light thinning (LT) and control stands (C) for crown cover (CC), leaf area index (LAI) and percentage of total radiation that reach to the forest floor (TR)

methodologies. These plots also are useful to demonstrate different forest management practices and to train professionals.

The volume of harvested logs in mature *N. antarctica* forests under silvopastoral use and the sawn-timber yield (plank, board, strut, strip and strip board) after processing in a typical regional sawmill have been measured in Tierra del Fuego (Martínez Pastur et al. 2008). The timber (cut at the base bole and minimum diameter of 20 cm) was extracted with skidders to the piling zone (loading truck bay), where logs (3–5 meters long) were obtained for the sawmill. The individual log volume varied between 0.9 and 2.9 ± 0.3 m^3. Because of the high number of defects in the low-quality logs, the mean conversion factor of the logs (ratio of sawn wood over log volume) was 18 %. Sawmill conversion efficiency for ñire timber was lower than that reported for *N. pumilio* timber (mean conversion factor 41 %) in the same type of sawmill (Martínez Pastur et al. 2000). Conversion efficiency not only affects sawmill profits, but is also important to extend existing supplies of standing timber. Therefore, to improve the productivity and profitability of ñire silvopasture systems, the sawmill industry will need to adapt to the wood resource, diversify its sawn product stream and find ways to add value to these commercial products. Developing uses and markets for the high percentage of small diameter logs produced from ñire forests is a priority. Economical and value-added uses for small diameter timber can help offset forest management costs in ñire silvopastoral systems and provide economic opportunities for stakeholders. However, large-scale chip generation is not possible in Tierra del Fuego province because the exportation of this product is forbidden and there is no local industry that consumes chips. The practicability of this process (without chip production) that maximizes the value of harvesting volumes from ñire silvopastoral systems should include high-value products used for furniture, flooring and millwork (windows, doors, paneling cabinetry, moldings and other custom woodwork).

Animal component

The total number of landholdings with ñire forest and the proportion of these on an area basis were estimated by the overlap of provincial GIS cadastre and forest inventory (Peri and Ormaechea 2013). In Santa Cruz, 55 % of the ranches practicing silvopasture at a large scale have less than 10 % ñire forest cover. In Tierra del Fuego 64 % of ranches have between 10 and 50 % of their land areas covered with ñire forest (Ormaechea et al. 2009). The average size of these properties in Santa Cruz province is 21,553 ha and in Tierra del Fuego is 18,050 ha, although the largest station is 160,000 ha.

Personal surveys were used to determine the main livestock characteristics and management practices of the provinces. Cattle (mainly Hereford breed) and mixed livestock production (cattle + sheep) are the main activities, often with low stocking rates (0.60–0.65 sheep ha^{-1}) and low lambing rates (74–76 %).

More than 75 % of the landholdings used winter low-altitude ranges (*invernadas*) and summer high-altitude ranges (*veranadas*) (Table 3). Grassland assessment methods to estimate carrying capacity have been used on only 6 % of ranches with ñire forests. The main criteria defining stocking rates included personal experience, range conditions and historic stocking rates. Thus, ranch managers mainly make grazing management decisions based on subjective criteria and previous experience. Also, only a few ranches (<17 %) make land divisions to achieve homogeneous grazing according to vegetation types. Usually, vast areas with few paddocks restrict the potential for managing grazing. Throughout the region, land managers use paddocks with ñire forest mainly during breeding season or maintenance or without specific objectives. Shelter provided by paddocks with ñire forest was perceived as an important advantage mainly in Santa Cruz province; main limitations include inaccessibility, herding difficulties and high animal losses.

Animal production

Livestock production is the main source of annual income in silvopastoral systems, but the reduction of light induces changes in the nutritive value and sward structure (height, bulk density, botanical composition) and distribution of morphological components within the canopy that may have an important influence on daily herbage intake and performance. Sheep (Peri 2008) and cattle (Peri et al. 2006d) gains were compared when animals grazed pastures improved with cocksfoot and white clover under two contrasting canopy covers (CC = 30 and 60 %) and two post-grazing pasture masses (optimum and low) in ñire silvopastures. The experiments were conducted in a temperate, subhumid climate with a long-term average rainfall of 660 mm. All thinned material was removed. Polled Hereford heifers (14 months old, mean weight 264 ± 32 kg) and Corriedale ewes (4 years old, mean weigh 42 ± 5 kg) were used in short duration (30-day) grazing studies at the time of maximum biomass production (December). Stocking rate adjustments were based on similar pasture allowances between treatments. Mean allowance was 3.1 and 7.9 kg DM hd^{-1} day^{-1} for ewes and heifers, respectively. Live weight gains (LWG) did not differ ($p > 0.05$) between crown cover treatments for either sheep or cattle at the optimum post-grazing forage mass (Table 4), although pasture bulk densities (calculated as pre-grazing mass * plant height) were slightly lower in the more shaded stand (CC = 60 %). Although LWG did not differ between the CC treatments, pre-grazing mass in the 30 % crown cover silvopastoral system allowed a higher stocking rate and consequently a greater LWG per hectare (3.8 vs. 2.4 kg ha^{-1} day^{-1} for sheep and 29.8 vs. 17.1 kg ha^{-1} day^{-1} for cattle under optimum post-grazing mass). The greater total gain on CC 30 % pastures was attributed to the greater pasture growth rate, pre-grazing mass and bulk density, which allowed higher stocking rates and pasture intake. In addition, there was a strong influence of post-grazing herbage mass on LWG (both on a per-animal and per-hectare basis). LWG was decreased 50–80 % for animals grazing pastures managed for low post-graze herbage mass (Table 4).

Table 3 Livestock management and stakeholders' perceptions of ranches with ñire forest in Santa Cruz and Tierra del Fuego provinces

		Santa Cruz	Tierra del Fuego
Grazing management practice utilized (%)	Summer–winter ranges	77	78
	Rotational[a]	16	16
	Year-round	7	6
Percentage (%) of ranches that apply rangeland assessment[b]		6	6
Main criterion for determining stocking rate by stakeholders (%)	Historic stocking rate	19	47
	Personal experience	26	25
	Range condition	19	16
	Animal condition	13	3
	Rangeland assessment	6	3
	Annual precipitation	3	3
	No specific criterion	13	3
Percentage of ranches that makes divisions to achieve homogeneous grazing according to vegetation types (%)		6	16
Intended use (%) of paddocks with ñire forest	Without specific objective	42	40
	Breed or maintenance	42	16
	Calving	10	22
	Variable	3	19
	Fattening	3	3
Stakeholders' perception (%) related to advantages of paddocks with ñire forest	Shelter	39	38
	Good grass (quality and quantity)	13	12
	Do not know/Do not answer	48	50
Stakeholders' perception (%) related to limitations of using paddocks with ñire forest	Inaccessibility, animal lost or herding difficulties	32	7
	Lack of grass biomass	6	3
	Fleece contamination	3	0
	No specific criterion	59	90
Percentage (%) of ranches that apply forestry practices		6	3

[a] Refers to management systems that allow paddocks to rest at least one season every 2 years

[b] Refers to rangeland assessments conducted at least one time every 2 years or more frequently

Low post-grazing residuals decrease sward quality (with decreases in green leaf content and OMD %) and DM intake, consequently reducing animal production (Thompson and Poppi 1990).

To achieve animal production targets in silvopastoral systems, a grazing manager must know the relationship of animal gain to pasture allowance (pre-grazing herbage mass) and quality, which are functions of stand crown cover (thinning intensities) and residual pasture mass. However, an accounting at the whole-farm level is essential when designing grazing prescriptions at a field scale in order to improve animal production, ecosystem conservation objectives and the modes of adaptation of farm management strategies (Gibon 2005; Peri 2012a). Silvopasture systems should be studied at the whole farm scale to develop an understanding of the diversity of livestock farmer decision-making and to assess the economical and/or environmental impacts of change in grassland use in reference to grazing management practices. Thus, a study was carried out to compare traditional extensive grazing management (TGM) with adaptive silvopastoral management (ASM) that included strategic separation of homogeneous areas (grass steppe, forest and riparian meadows) and stocking rate adjustments based on grassland net primary production. The ASM

Table 4 Pasture and animal gain parameters in ñire-based silvopastures managed for optimum or lower than optimum post-graze forage mass in Southern Patagonia

Treatment	Pre-gazing mass (kg DM ha^{-1})	Pasture height (cm)	Bulk density (mg DM cm^{-3})	CP (%)	Post-gazing mass (kg DM ha^{-1})	Individual LWG (kg day^{-1})	LWG/ha (kg ha^{-1} day^{-1})
Sheep							
CC 30 %	2850 ± 341	24.2 ± 5.1	0.971	11.2 ± 0.9	543 ± 134	0.098a	3.81a
					374 ± 42	0.041b	1.02d
CC 60 %	2050 ± 330	29.7 ± 4.2	0.825	15.3 ± 1.4	439 ± 76	0.102a	2.43b
					290 ± 74	0.048b	1.84c
Cattle							
CC 30 %	3060 ± 341	22.8 ± 6.0	0.965	10.6 ± 1.1	843 ± 134	1.39a	29.8a
					305 ± 33	0.20b	10.3c
CC 60 %	1949 ± 330	31.7 ± 3.7	0.855	13.4 ± 1.8	864 ± 76	1.48a	17.1b
					298 ± 52	0.55b	2.3d

CP crude protein content, *LWG* liveweight gain, *CC* crown cover

system was managed for increased animal production at the ranch level and the protection of regeneration from browsing herbivores (hare and livestock) by using individual tree guards (Ormaechea et al. 2010, 2011). The trial (2008–2009) was conducted under real production conditions in the forest-grass steppe in Santa Cruz province. Grassland assessment in all paddocks (300–5000 ha) was carried out in both management treatments before animals entered the systems. The ASM group grazed only a forested paddock between June and September and a riparian meadow paddock during January. Each management treatment had a group of 1000 ewes. During the pre-lamb shearing, we weighed 300 fleeces of each group and at the end of the annual season the lambing rate and the weight of 300 lambs was measured. No differences in individual animal performance between grazing managements were measured (Table 5). Lambing rate and fleece weight for ASM sheep had slightly higher values compared with TGM, probably because of the reasonable stocking rate used and the effective use of the forest and the riparian meadow grasses in moments of high quality compared with the rest of the areas. In addition, the forest provided protection from cold winds and snowstorms. This advantage was probably the reason for winter weight loss reduction for the ASM group (Table 5). However, the main impact of the adaptive silvopastoral management provided was an improvement in animal productivity on an area basis. Thus, lamb, meat and wool production in ASM per hectare increased by 30–40 % compared with TGM.

Studies of animal distribution using global positioning system (GPS) technology provide important information for grazing plans since they allow long-term, uninterrupted monitoring of grazing animals at low cost. Ormaechea et al. (2012a) determined the preferred environments used by sheep using GPS collars. Spatial positions (50,000+ records) were monitored from February 2009 to January 2010, and the environmental preference for each major vegetation type in paddocks was calculated using the program Havistat v2 beta 2.1 (Montenegro and Acosta 2008) and Ivlev's electivity index (IEI) (Ivlev 1961). The percentage of use by animals of each vegetation type was related to paddock area. The IEI takes values between 1 (highly preferred) and −1 (completely avoided). It is 0 when the fraction of feeding time equals the fraction of area covered by the respective vegetation type (random grazing). Ewes clearly preferred the forest environment, which was associated with better thermal conditions and good forage quantity and quality. Thus, in those paddocks with mixed vegetation types (ñire forest, riparian meadows and grass steppe), the forest environment had an IEI between 0.23 and 0.63, and sheep used 65–73 % of the vegetation types in these areas. In contrast, sheep avoided the riparian meadow environment during waterlogged periods (spring) and frozen soils (winter), and the IEI ranged between −0.02 and −0.24.

Table 5 Main site characteristics and animal performance (mean ± standard deviation) at a ranch level of a traditional extensive grazing management and an adaptive silvopastoral management over 2 years of measurements (2008–2009) in the forest-grass steppe region, southwest of Santa Cruz province, Patagonia

	Traditional extensive management	Adaptive silvopastoral management
Number of paddocks	3	5
Paddocks mean size (ha)	2470	1140
Forage allowance (kg DM ha^{-1})	301 ± 12.5	367 ± 20.9
Stocking rate (ewes ha^{-1} $year^{-1}$)	0.3 ± 0.02	0.9 ± 0.20
Winter weight loss (kg)	12.4 ± 8.0	10.1 ± 8.9
Lambing rate (%)	84.9 ± 11.9	86.9 ± 4.9
Lamb weight (kg)	33.5 ± 1.9	27.6 ± 5.1
Lamb production (lamb ha^{-1})	0.25 ± 0.02	0.41 ± 0.01
Meat production (kg ha^{-1})	8.25 ± 0.2	11.35 ± 1.8
Fiber diameter (µm)	28.5 ± 0.4	28.5 ± 0.7
Fleece weight (kg)	4.0 ± 0.1	4.3 ± 0.4
Wool production (kg ha^{-1})	1.10 ± 0.01	1.55 ± 0.07

Table 6 Cattle grazing schedules for traditional grazing management (TGM) and an integral silvopastoral intensive management (ISIM) at the ranch level in Tierra del Fuego province, Patagonia

Grazing period	Main vegetation type	Number of paddocks	Paddock area (ha)	Pasture allowance (kg MS/ha)	Stocking rate (animal/ha)
ISIM					
Oct–Dec	Ñire forest (rotational grazing)	9	20	800	1.3 (6.9)[a]
Jan–March	Riparian meadow (rotational grazing)	6	40	1580	0.9 (4.1)[a]
April–Sep	Ñire forest and meadow	1	800	710	0.2
Traditional					
Oct–March (summer ranges)	Ñire forest and meadow	1	470	1045	0.3
April–Sep (winter ranges)	Ñire forest and meadow	1	1200	650	0.08

[a] Stocking density in subdivisions within paddocks shown in parentheses

Similarly, Peri et al. (2012c) compared the cattle production of a TGM system with an integral silvopastoral intensive management (ISIM) system under real production conditions at San Pablo Ranch (54°15′46″SL, 66°59′41″WL) in Tierra del Fuego province. While ISIM included strategic separation in homogeneous areas (forest and riparian meadows), short rotation grazing and stocking rate adjustment matched to grassland net primary production, TGM consisted of winter and summer extensive grazing paddocks (Table 6). We followed the convention that defoliation frequency is more important than defoliation intensity for proper grazing management. Each management treatment had a group of 160 Hereford heifers (initial LW = 185 kg ± SEM), and the live weight gain was evaluated in different seasons. In general, while the individual live weight gain was higher with TGM (except in autumn), cattle production on an area basis was higher in the ISIM treatment (0.20 vs. 0.91 kg ha^{-1} day^{-1}) (Fig. 6). Parasitological studies also indicated no infection problems.

Analysis of the positioning data indicates greater homogeneity of land use and greater forage utilization occurred in smaller paddocks under intensive management during the growing season (Ormaechea et al. 2012b). Distances walked daily by cattle did not differ

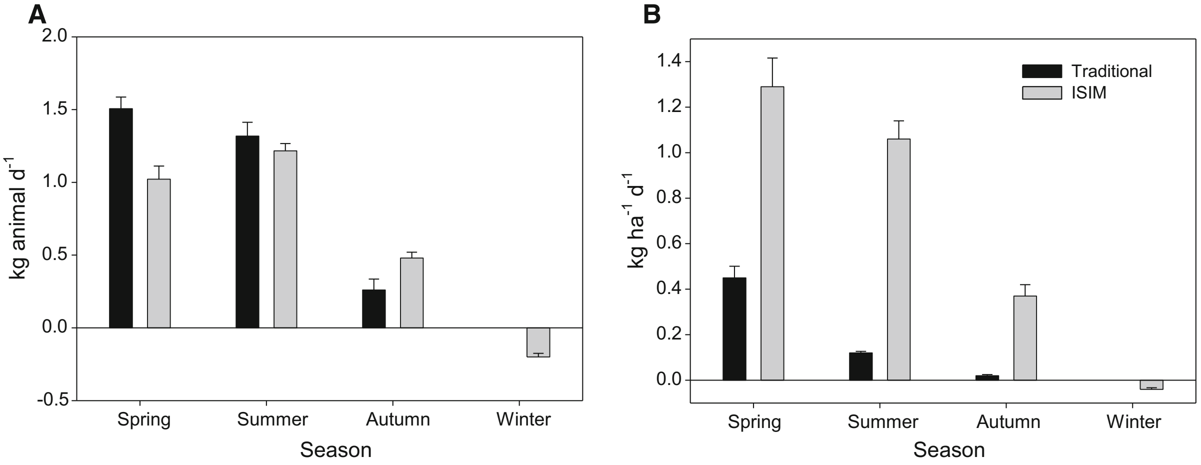

Fig. 6 Cattle liveweight gains per individual animal (**a**) and per hectare (**b**) (mean ± standard deviation) at the ranch level of traditional grazing management (TGM) and an integral silvopastoral intensive management (ISIM) in Tierra del Fuego province, Patagonia

between seasons and management grazing systems (paddocks with different size vegetation types); animals in ISIM explored less area compared with TGM. Cattle grazing under ISIM used 50–90 % of the paddock area, while animals in the TGM used less than 25 % of the paddock area.

These types of studies provided important information about extensive sheep and cattle grazing production throughout a year at a ranch level. The separation of homogeneous areas into discrete units coupled with more intensive grazing management in silvopasture systems offers promise for ranchers in Southern Patagonia. However, further studies about variables associated with the animals and forages are needed to provide proper recommendations for intensive management in meadow-forest ecosystems in the region.

Carbon storage

There is increasing interest in research that improves our understanding of carbon (C) sequestration. This interest is partly driven by Article 3.4 of the Kyoto Protocol of the United Nations Framework Convention on Climate Change, which allows countries to count sequestration as a contribution to reducing greenhouse gas emissions (IPCC 2001). Data on C storage in forests are essential for understanding the importance of rapidly increasing levels of CO_2 in the atmosphere and its potential effect on global climate change. Also, estimates of native forest C storage under different management practices are required for estimating regional and national greenhouse gas balance. In Southern Patagonia, mean maximum annual temperature is predicted to increase by 2–3 °C by 2080 between 46 and 52° 30′ SL (Kreps et al. 2012). If realized, such an increase will have significant effects on Patagonian ecosystems. In this context, secondary indigenous forests are considered efficient C sink ecosystems. Stand age, site quality and crown classes all affect the magnitude of C pools in both forest above- and below-biomass and forest floor pools (Peri et al. 2005c, 2006d, 2008a, 2010). It is important to emphasize that roots in these forest ecosystems can contribute up to two times more biomass and C storage than above-ground components in young growth phases. Few studies exist on above- and below-ground pools of C storage in Patagonian *Nothofagus* forests and the consequences of different disturbance and management regimes. In this context, forest ecosystem pools and fluxes of C are strongly affected by forest management. Peri et al. (2010) and Peri (2011) showed that C storage in the tree components (leaves, stems, branches, roots, rots) and forest floor changes as a result of different forest structures, which is determined by the proportion of crown classes, development stages (age) and the site quality where trees grow. Above- and belowground C sequestration for different components of trees and pasture (green and dead leaves, pseudostem and coarse and fine roots) and the C storage in the floor litter and different horizons of mineral soil (from 0 to 0.6 m depth) in *N. antarctica* silvopastoral systems at three site classes are shown in Table 7. Mean stand density was 175 ± 20 trees ha^{-1} (80 % dominant trees and 20 % co-dominant trees) in the mature development stage (190 ± 15 years). In these ecosystems, the C concentration was higher in tree rot (55 %) and lower in the dead leaves of pasture (40 %). The C concentration decreased from 51 % in floor litter to 0.5 % in mineral soil at 0.6 m depth in the low site quality stand. At the silvopastoral stand level, the total C stored ranged from 148 to 252 Mg C ha^{-1}, with approximately 85 % in soil, 12 % in trees and 3 % in pasture (Table 7). Belowground biomass represented an important C storage pool in the ecosystem with mean values of 7.7–9.3 and 1.7–4.6 Mg C ha^{-1} for tree and pasture root components, respectively. While total C accumulation in trees growing on the best quality site (37.5 Mg C ha^{-1}) was sapwood > coarse roots > heartwood > bark > small branches > fine roots > rotten wood > leaves; the order of C accumulation for trees growing in a low site quality (20.3 Mg C ha^{-1}) the total C accumulation followed the order coarse roots > heartwood > sapwood > bark > small branches/fine roots > rotten wood > leaves (Table 7). This is consistent with Dube et al. (2011) who reported that the C storage of a *Pinus ponderosa* silvopastoral system (224 Mg C ha^{-1}) in Chilean Patagonia was more efficient than in tree plantations or natural prairie.

Table 7 Carbon content (Mg C ha^{-1}) of different components of *Nothofagus antarctica* silvopastoral systems growing at three sites classes (SC) in Southern Patagonia

System component	SC V	SC IV	SC III
Soil			
Litter	4.4	7.4	8.2
Organic horizon (0–03 m)	9.4	13.6	16.0
Mineral horizon (0.03–0.1 m)	12.2	17.6	18.4
Mineral horizon (0.1–0.3 m)	44.3	81.3	85.9
Mineral horizon (0.3–0.6 m)	55.9	98.6	104.3
Total soil	126.2	218.5	232.8
Trees			
Leaves	0.2	0.5	0.7
Small branches	0.6	1.0	2.4
Sapwood	4.1	7.3	10.4
Heartwood	5.0	8.2	7.3
Bark	1.7	3.7	4.1
Rotten wood	0.4	0.5	1.3
Fine roots	0.6	0.1	2.0
Coarse roots	7.7	8.7	9.3
Total trees	20.3	30.1	37.5
Pasture			
Green leaves	0.2	0.5	0.9
Dead leaves	0.05	0.1	0.2
Pseudostem	0.2	0.4	0.7
Roots	1.3	2.5	2.8
Total pasture	1.7	3.5	4.6
Total silvopastoral system	148.2	252.1	274.9

Site class III: stands where the mean total height of dominant mature trees (H) reaches 10.2 m, site class IV: $H = 7.8$ m, site class V: $H = 5.3$ m

Litter decomposition

Maintaining nutrient cycles over time is a key aspect that determines the sustainability of a forest. These cycles may be modified by management practices that involve the use of different forestry systems (Chapin et al. 2002). However, the effect of silvicultural practices on nutrient cycling may be different depending on the species composition and structure of the forest, its age and the environmental conditions driving its processes (Begon et al. 2006). In the particular case of organic matter decomposition (OMDe) the complexity is similar. It is well known that the OMDe is controlled by the chemical composition of the litter, soil organisms and environmental conditions (Swift et al. 1979). Similarly, special attention should be paid to the potential modification of N cycling, because is considered the most limiting element in temperate forests (Fisher and Binkley 2000). Thus, it is desirable to know how the silvicultural practices carried out to improve forage production in silvopastoral systems may influence litter decomposition and nutrient dynamics, e.g., Caldentey et al. (2001) reported higher litter decomposition in thinned *N. pumilio* forest (50 % crown cover) compared to unmanaged forest (80–90 % crown cover) in Chilean Patagonia. In Southern Patagonian ecosystems, the OMDe of ñire leaves increased with canopy openness from 20 to 30 % under and between crowns, respectively, after 480 days (Bahamonde et al. 2012b; Fig. 7). Similarly, senescent grass decomposition was slower under tree crowns in the forest when compared

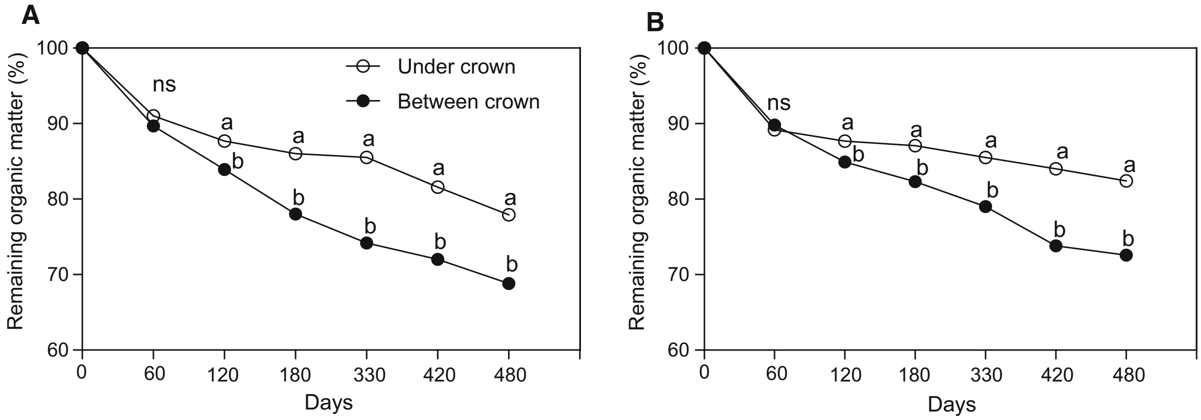

Fig. 7 Variation of the remaining organic matter (as a percentage of the initial weight) over time (start October 2005) of tree leaves under two levels of radiation in *N. antarctica* forests growing at site class IV (**a**) and V (**b**). *Different letters* in a same date indicate significative differences ($p < 0.05$); *ns* no significant

with decomposition in an adjacent area without trees, respectively (27 vs. 38 %; Fig. 8). These results suggest that a higher intensity of thinning in these forests (for silvopastoral use) also may increase the decomposition of the herbaceous stratum.

In practical terms, these results may be translated into differences in the time (years) that decomposing material remains in the soil as almost original material. For example, under high tree cover it could take between 23 and 27 years to decompose 99 % of the organic matter in ñire leaves, while in intermediate crown coverage (between trees) that time could be reduced to 15–17 years. The same pattern was found for the decomposing grasses. When the environmental factors driving this process in silvopastoral systems of ñire forests were analyzed, Bahamonde et al. (2012b) found that the main factor was the total transmitted radiation for both decomposing materials (ñire and grass leaves) (Table 8).

Bahamonde et al. (2012b) highlighted the importance of the radiation level, which implies an important influence of tree removal on decomposition rates. This agrees with Austin and Vivanco (2006) who reported that solar radiation effects on litter decomposition can be both direct (photodegradation processes) and indirect (facilitating the action of microorganisms). Peri et al. (2008b) also found that thinning and removing ñire trees for silvopastoral use caused a 35–50 % decrease in litterfall to the forest floor, which would reduce the potential nutrient return to the understory. Litter in these disturbed forests is subject to a higher rate of decomposition, which could accelerate nutrient cycling and further decrease the accumulation of litter along with other fine and coarse debris (Frangi et al. 1997).

Bahamonde et al. (2012b) also evaluated the mineralization-immobilization dynamic in decomposing leaves of ñire and grasses. Nitrogen, P and Ca were mineralized during the first stage of the decomposition (60 days) and immobilized after that, while K was immobilized over the entire study period (480 days). This pattern of nutrient dynamics was similar at different crown coverages in the studied sites.

In two *N. antarctica* forests under silvopastoral use, $NH4^+$ was the predominant form (75 %) of total extractable N in soils (Bahamonde et al. 2013c). Net N mineralization varied between the cover and dates; in lowest quality sites, mineralization did not differ among tree cover levels, but in the moderate quality site mineralization was lower without tree crown cover.

When environmental factors were correlated to N mineralization, simple linear regression analysis showed that the volumetric soil moisture was the only parameter that explained variation in N mineralization at the studied sites, although this relationship was weak ($p < 0.05$; $R^2 = 0.13$).

Nutrient accumulation in silvopastoral systems

Information about biomass and nutrient accumulation in different tree components is essential to evaluate the importance and impact of management practices (silviculture, silvopastoral systems, harvesting) on

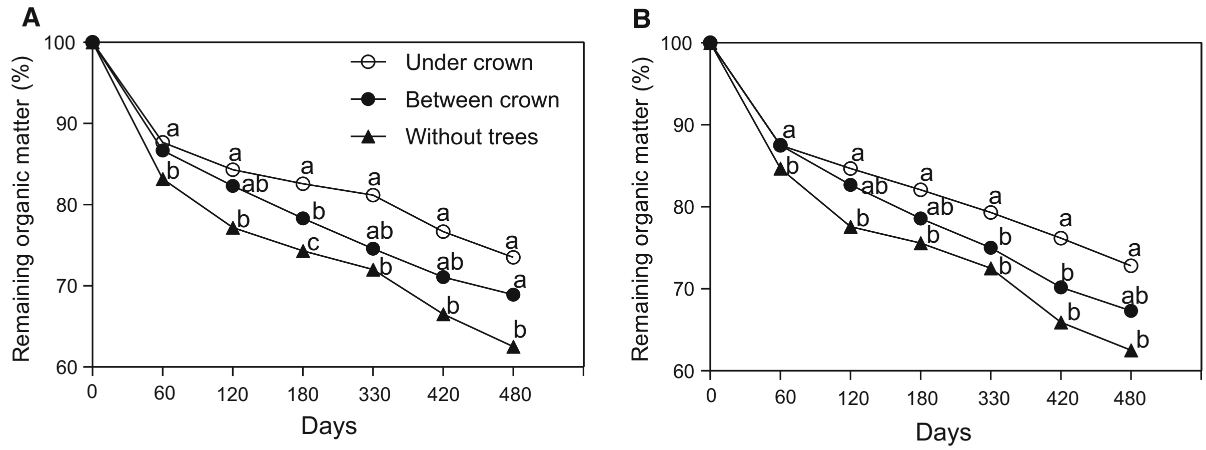

Fig. 8 Variation of remaining organic matter (as a percentage of the initial weight) over time (start October 2005) of grass leaves under three levels of radiation in *N. antarctica* forests growing at site class IV (**a**) and V (**b**). *Different letters* in a same date indicate significative differences ($p < 0.05$); ns: no significant

Table 8 Simple linear regression between decay constants (k) and main environmental variables

Environmental variable	Grass leaves		*N. antarctica* leaves	
	Significance[†]	R^2	Significance[†]	R^2
Total transmitted radiation	**	0.61	**	0.49
Average air temperature	**	0.40	**	0.41
Average soil temperature	**	0.40	**	0.40
Volumetric soil moisture	ns		ns	
Air relative humidity	**	0.30	*	0.27

[†] Significance, linear regression significance, * $p < 0.05$, ** $p < 0.01$, *ns* no significant. R^2 coefficient of determination $k = \frac{-\ln(X_1/X_0)}{t}$, where x_0 y x_1 are the initial and final weight (g) of each period, respectively, t is the time expressed as a fraction of the year, and "ln" is the natural logarithm

site productivity, mineral fertility, bio-element recycling and long-term effects on the mineral balance (Santa Regina 2000). *N. antarctica* is adapted to a range of site qualities and conditions; trees growing on low quality sites tend to have greater root biomass, while more resources are distributed to aerial parts on better sites (Peri et al. 2006d, 2008a, 2010; Gargaglione et al. 2010, 2013).

Site quality also affects nutrient concentration; old dominant trees in better sites have about 2.5 times of Ca, N, K, P, S and Mg than dominant trees on lower quality sites (Gargaglione et al. 2013). The lowest nutrient content in worse sites was due to both less biomass accumulation and nutrient concentration in all tree components (Peri et al. 2006d, 2008a). Another factor that modifies nutrient amounts in *N. antarctica* trees is the crown class condition. As this species is not shade tolerant, the position of the tree in the canopy has important effects on nutrient accumulation. For example, in a site class III (tree height 10 m), the differences in nutrient content per tree between old dominant and suppressed trees ranged from 1.6:1 for N to as much as 18:1 for P. The greater content was due to the bigger crowns and root systems of dominant trees, which allowed them to acquire more light and underground resources compared to suppressed trees that grow below the canopy.

Thinning trees to create silvopastures reduces the nutrient amounts retained in the biomass of the ecosystem, mainly by removing trees from the stand and by changing the proportions of crown classes (dominant, codominant, intermediate and suppressed trees). The average difference in aboveground nutrient content between silvopastures and forests in site class

Table 9 Nutrient amounts (kg ha^{-1}) in *Nothofagus antarctica* forests under two uses (primary forest and silvopastoral system) with two contrasting site qualities in Southern Patagonia, Argentina

	N	P	K	Ca	S	Mg	N	P	K	Ca	S	Mg
	Primary forest SC III						Primary forest SC V					
	(400 tree ha^{-1} D: 40 % C: 30 % I: 20 % S: 10 %)						(440 tree ha^{-1} D: 36 % C: 27 % I: 13 % S: 14 %)					
Leaves	46.4	4.4	12.6	15.4	4.7	4.8	15.8	2.0	3.5	8.9	1.5	1.9
Branches	53.1	6.1	20.0	74.7	8.0	7.3	13.2	1.8	4.7	22.5	2.2	3.8
Trunk	385.6	26.5	65.6	74.0	32.4	42.3	59.3	10.6	29.3	59.9	8.0	9.5
Bark	106.4	3.5	43.2	296.4	15.5	8.6	18.6	1.4	4.9	117.6	4.0	4.8
Roots	96.4	59.0	83.2	446.5	38.6	32.8	65.7	37.3	47.6	70.4	18.2	16.6
Total	688.0	99.5	224.7	906.9	99.2	95.9	172.6	53.1	90.0	279.3	33.9	36.6
Silvopastoral system SC III							Silvopastoral system SC V					
(180 tree ha^{-1} D: 70 % C: 25 % I: 5 %)							(200 tree ha^{-1} D: 60 % C: 40 %)					
Leaves	24.9	2.5	6.8	7.6	2.6	2.6	9.2	1.3	2.4	5.7	1.0	1.2
Branches	30.5	3.9	12.1	39.8	4.6	4.4	8.2	1.1	2.7	12.7	1.3	2.4
Trunk	229.5	15.5	37.5	38.6	19.11	23.9	40.1	7.3	20.2	42.1	5.6	6.1
Bark	62.1	2.1	25.1	162.6	9.0	5.8	12.6	0.9	3.2	80.1	2.7	3.2
Roots	60.3	36.6	51.1	250.8	22.7	19.8	46.5	26.4	33.7	49.9	12.9	11.7
Grasses	31.1	4.2	27.9	6.7	1.3	2.8	5.0	0.8	4.9	1.5	0.2	0.5
Total	438.4	64.7	160.5	506.1	59.4	59.3	121.5	37.8	67.0	192.0	23.6	25.2

In site class (SC) III, dominant trees reached 9 m height; in SC V, trees averaged 5.3 m height

D percentage of dominant trees at stand level, *C* codominant, *I* intermediate, *S* suppressed trees

V and site class III was 40 and 60 %, respectively, despite site class V having more stems ha^{-1} (Table 9). The nutrients accumulated by understorey grasses did not compensate for the nutrients lost by removing trees. In both sites, leaves and small branches accounted for significant proportions of the total stand nutrients. Because these components (structures with low lignin contents) usually have rapid turnover in the ecosystem, thinning practices should aim to leave fine material (mainly leaves, small branches and bark) on the site to limit nutrient removal and to avoid a decline of long-term yields. Furthermore, the nutrient supply to understory grasses over the long term may be supported by mineralization of tree roots following harvest. This effect may be greater in low quality sites given greater partitioning to roots relative to above-ground biomass (Table 9).

Biodiversity

The vascular plant biodiversity in *N. antarctica* forests is greater compared with other *Nothofagus* forests (Speziale and Ezcurra 2008). The species assemblages in ñire forests vary along their latitudinal distribution range and with habitat conditions, such as humidity, with different characteristic species from North to South, and from xeric to humid environments. In Tierra del Fuego Province, 28 species of vascular plants were observed in the understory (Lencinas et al. 2008a), along with 251 species of insects (Lencinas et al. 2008b) and 18 species of birds (Lencinas et al. 2005). In Santa Cruz Province, 225 species of vascular plants, 112–165 species of insects and 10–21 species of birds were observed (Gallo et al. 2005; Peri and Ormaechea 2013; Peri and Paz 2013). In *N. antarctica* forests in Sothern Patagonia, the most frequent species are *Berberis buxifolia*, *Chiliotrichum diffussum*, *Carex andina*, *Deschampsia flexuosa*, *Empetrum rubrum*, *Galium aparine*, *Osmorhiza chilensis*, *O. depauperata*, *Cotula scariosa*, *Acaena ovalifolia*, *A. magellanica* and *Vicia magellanica.* Among birds, the main species are *Aphrastura spinicauda* Gmelin, *Pygarrhichas albogularis* King. and *Turdus falcklandii* King. *Nothofagus* forests are considered an endemic zone for mammals, with 36 endemic species and 12 endemic genera (Patterson 1993), including several species of rodents, foxes and bats. However, information about their specific assemblage in forests along the complete range of *N. antarctica* distribution is lacking. Likewise, several exotic and/or invasive species are usually found in *N. antarctica* forests, whether accidentally or intentionally introduced, including plants, insects and mammals. For example, *Holcus lanatus*, *Poa pratensis* and *Dactylis glomerata* provide forage for grazing, *Taraxacum officinale* is a widely distributed and naturalized weed, and *Hieracium pilosella*, *H. praealtum* and *Vespula germanica* are aggressive invaders, *Castor canadensis* is an ecosystem engineer, and *Mustela vison* is a competitive predator.

Nothofagus antarctica forests are usually immersed in a landscape spatial matrix that alternates among rangelands, peat-lands and other *Nothofagus* forests, with dominance of open or forested environments depending on the geographic zone. Biodiversity is partially shared among these environments, e.g., 79–93 % of their vascular plant species are usually common to all environments of the landscape matrix, with low values of exclusive vascular plant species in *N. antarctica* forests (7 % of vascular plant richness), and their composition is quite similar to *N. pumilio* forests and grasslands (Lencinas et al. 2008a). Similar proportions were observed for insect and bird diversity, with 36–95 % of common species and 5 % of exclusive ones for insects (Lencinas et al. 2008b) and 67–78 % of common species and 22 % of exclusive species for birds (Lencinas et al. 2005). The existence of species that only occur in *N. antarctica* forests denotes the importance of this unique environment, which is usually undervalued because of the lack of natural provincial and national reserves that preserve wildlife habitat (Rusch et al. 2004).

Nothofagus antarctica forests are among some of the last remaining pristine wilderness areas on the planet (Mittermeier et al. 2003). However, several human-related influences have incrementally modified their original structure and natural dynamic, e.g., livestock, harvesting and beaver activities, which influence the entire forest system and modify the biodiversity levels at the understory, soil and canopy levels. Variations in forest structure, through modifications in overstorey canopies, generate differences in richness and relative abundance of different organisms (Fig. 9), which could be minimal for understory vascular plant, insect and bird richness and bird density, or very important as in vascular plant cover or insect abundance. Livestock use in *N. antarctica* forests usually reduces the biodiversity in terms of both richness and relative abundance. This decrease is mainly due to the loss of species sensitive to animal trampling and disturbance as well as selective grazing of more palatable species. The severity of these effects also could be masked by incoming species, which could generate similar values of richness (Lencinas et al. 2014).

Bioindicators may be used to provide early warnings regarding environmental changes (environmental indicator) to monitor a specific ecosystem stress (ecological indicator) or to indicate levels of taxonomic diversity at a site (biodiversity indicator) (McGeoch 1998). Bioindicators may also be used for conservation prioritization using spatial comparisons of site value and for site monitoring of ecosystem recovery or response to management. This information is required to set up explicit recommendations to preserve (or minimize impacts to) natural ecosystems and very sensitive or endangered species. *Threchisibus antarcticus* (Coleoptera) (Lencinas and Martínez Pastur 2010) and *Neochelanops michaelseni* Simon (Pseudoscorpionida) are promising species as bioindicators and under study in the PEBANPA network.

Furthermore, a sustainable management will be one that reconciles the productive needs and requirements of the local people with the conservation of native forests. In Southern Patagonia, guides for environmental quality conservation are needed within a management plans for native ñire forests under silvopastoral use (Rusch et al. 2004; Peri et al. 2009a). Maintaining terrestrial habitats surrounding wetlands is critical to the management of natural resources because of their importance as feeding and nesting sites for wildlife for the conservation of water quality in streams and providing substantial benefits as habitat or dispersal corridor. For this, buffer zones to protect wetland and riparian habitats can be maintained by preserving a core terrestrial habitat from 15 to 60 m from the edge of aquatic sites. Also, for biodiversity maintenance and conservation at a landscape or ranch level, creating a complete array of forest successional stages and structures, including sectors with old-growth forest conditions that retain standing dead trees and fallen logs, is recommended. Coarse woody debris also should be left because it plays a substantial role in several ecological processes

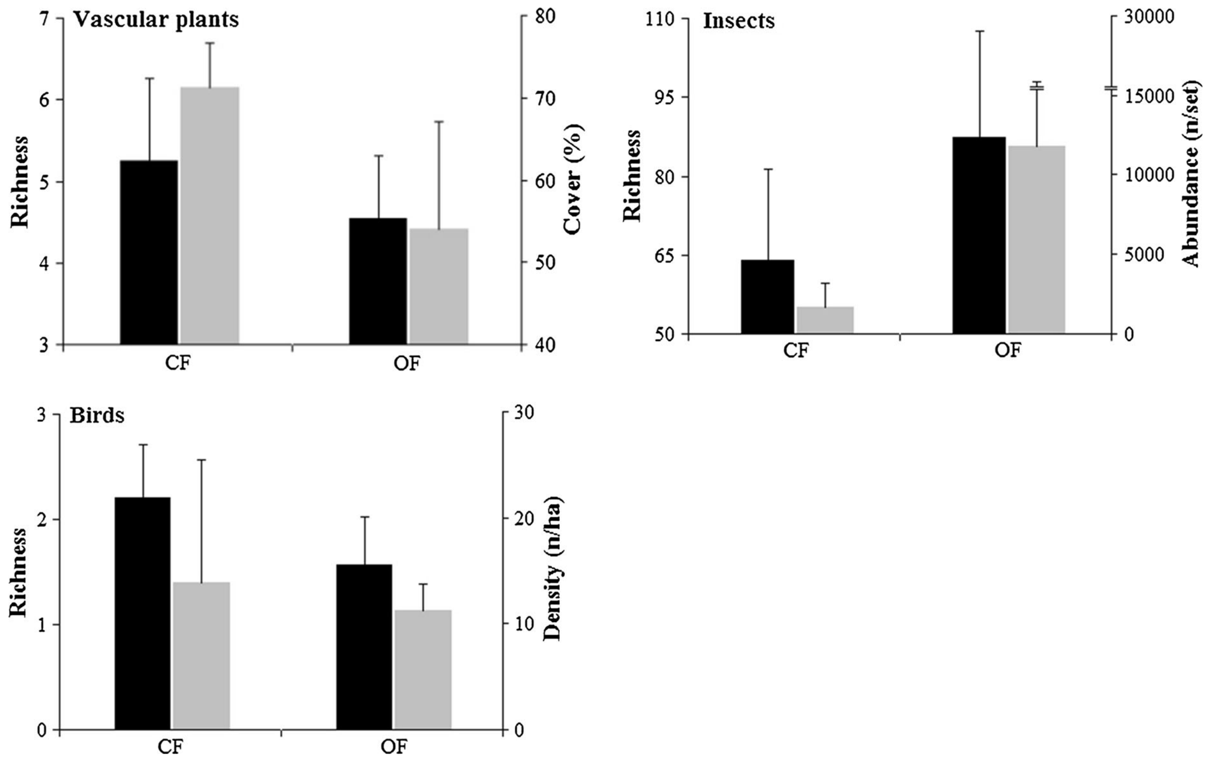

Fig. 9 Biodiversity variations in *Nothofagus antarctica* forests in vascular plants (richness and cover), insects (richness and abundance) and birds (richness and density) for different forest structures (*CF* closed primary forests, *OF* opened silvopastoral forests)

in forest ecosystems and because a large number of organisms (fungi, insects) are dependent on decaying wood for nutrients or habitat (Franklin et al. 1987).

Criteria and indicators to assess ñire forest's sustainability under silvopastoral use

The Santa Cruz government has a statutory responsibility to ensure that native forests are sustainably used within silvopastoral systems. Provincial regulations also require that a Regional Forest Plan and long-term forest policies are developed. To maximize the forest's sustainable benefits for society, Peri (2012b) developed indicators of sustainable management of *N. antarctica* forests. Multi-criteria methods were used to integrate different perspectives regarding environmental, social and economic aspects of the forest's management (Mendoza and Prabhu 2000). Starting with a range of internationally accepted criteria and indicators (C&I), a local set of C&I was developed to assess the ñire forest's sustainability. The relative importance of the C&I and the degree to which sustainability was being achieved through each of the indicators were assessed using a survey completed at a series of workshops attended by a range of stakeholders from government (technicians, professionals and bureaucrats from government or city council planning, conservation, natural resources administration and tourism offices), industry (wood processing workers, consultants, large and small company owners and ranchers), people working for environmental non-governmental organizations, teachers (high school, natural resources and university lecturers) and the community in general. The final product contained 4 criteria, 11 groups and 55 indicators (Table 10; Peri 2012). Thus, 9 indicators of criterion 1 focus on the legal, institutional and economic framework for forest conservation and sustainable management; 17 indicators of criterion 2 measure the maintenance and enhancement of long-term multiple socioeconomic benefits (employment, manufacture and consumption of forest products, education and research, and community needs). The focal point of the 10 indicators of criterion 3 is related to the maintenance of ñire forest

Table 10 Relative importance of criteria and groups for sustainable use of ñire forest under silvopastoral systems in Santa Cruz province, Southern Patagonia, Argentina

Level in the hierarchy	Criterion and groups text	Criterion level weights (%)	Group level weights (%)
Criterion 1	Legal, institutional and economic framework for ñire forest conservation and sustainable management	31	
Group A	Legal framework		37
Group B	Institutional framework		33
Group C	Economic framework		30
Criterion 2	Maintenance and enhancement of long-term multiple socioeconomic benefits to meet the needs of society	26	
Group A	Employment		28
Group B	Silvopastoral forest products consumption and production		26
Group C	Education and research		25
Group D	Community needs		21
Criterion 3	Maintenance of ñire forest ecosystem integrity (including productivity, biodiversity, health)	22	
Group A	Biodiversity		53
Group B	Protection		47
Criterion 4	Planning, monitoring and assessment of the ñire forest resource use	21	
Group A	Long-term regional plan		51
Group B	Short to medium-term silvopastoral plans		49

ecosystem integrity (including productivity, biodiversity, health) under silvopastoral use, and criterion 4′s 19 indicators deal with planning, monitoring and assessment of the ñire forest resource use. At the group level, the institutional framework was assessed as substantially more important (37 %) than the other two groups in criterion 1. The employment (28 %) group of indicators was the most important in criterion 2. Both groups of criteria 3 and 4 were evenly weighted.

An overall sustainability score (Fig. 10) for the whole set of C&I (calculated using the weighted results from the assessment) indicates that stakeholders perceive current management limited (1.72) when rated on a sustainability scale of 1–5 (where 1 represents a loss of sustainability/ecosystem provisioning and 5.0 is far from this threshold value). These results provide a reference point for future change of ñire forest use in Santa Cruz province. The sustainability scores and weightings at group and criterion levels (Fig. 10) can be used to focus efforts on improving the poorest performing groups of indicators. Criterion 4 had the lowest mean score (1.23), and criterion 3, biodiversity and protection, showed the best performance (2.34). Groups of indicators with the lowest scores (less than 1.3) were legal and economic frameworks within criterion 1, and long-term regional and short-term management plans (criterion 4). In general, the forest ecosystem integrity and conservation indicators were evaluated as performing reasonably well. The results also show that the key areas needing effort are in the policy, planning and resource administration of the forest.

Finally, the most important factors affecting sustainable management of ñire forest under silvopastoral use were selected, by choosing indicators with a mean individual sustainability score less than or equal to 1.2, and at the same time considering the performance of groups of indicators (Table 11).

Conclusions

Silvopastoral systems in ñire forest that combine trees and grasslands or pastures under grazing on the same unit of land are an economical, ecological and socially productive alternative to traditional management systems in Southern Patagonia. Understanding of the

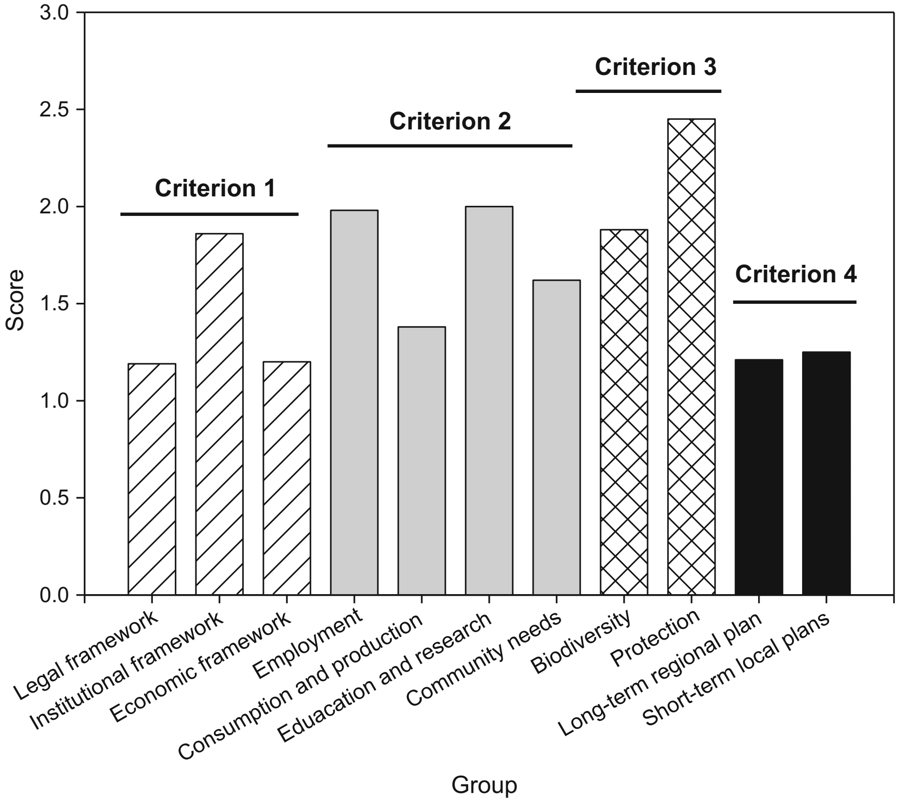

Fig. 10 Criterion and group scores calculated as the mean of their indicators for silvopastoral systems in ñire forest in Santa Cruz province (Southern Patagonia). High scores represent a performance closer to sustainability

Table 11 Top six lowest scoring indicators of silvopastoral forest use in Santa Cruz province

Number	Indicator text	Group	Score
1.2	Extent to which the legal framework supports the conservation and sustainable management of forests under silvopastoral use	Legal framework	1.06
2.8	Investments in forest management under silvopastoral use are carried out (thinning, environment planning, livestock plan, etc.). Access to financial support (application for credit) for stakeholders to improve the productive system including investments in timber technology	Forest products consumption and production in silvopastoral systems	1.08
4.2	Silvopastoral forest management planning and its implementation takes into account economic variables (costs, investments, revenue), as well as the results of the environmental and social impact assessments	Long-term regional plan	1.08
4.7	There is a regional land use plan that reflects the different forested land uses promoting its integral use and gives attention to ecosystem services such as carbon fixation and biodiversity	Long-term regional plan	1.09
4.9	Periodic monitoring is conducted to assess the effectiveness of the measures employed to maintain or enhance the applicable conservation attributes	Long-term regional plan	1.10
4.14	The silvopastoral forest management has a monitoring system for correct implementation. Data collection includes productive, economic and social variables	Short-term management plan	1.11

different system components (animal management and performance, trees and silviculture, productivity and nutritive value of understorey grassland) of these systems, as well some processes such as litter decomposition, nutrient dynamics and carbon storage, has increased greatly over the past 12 years. The productivity and nutritive value of understorey grassland are dependent on the interaction of environmental (mainly soil water availability and light intensity) and management factors (thinning and grazing management) under the trees and in turn determines animal performance. Successful forestry proposals require effective establishment of natural regeneration of forest species to ensure the maintenance of the tree layer. The separation of homogeneous areas into discrete units coupled with more intensive grazing management in silvopasture systems offers promise for ranchers. Ñire silvopastoral systems are efficient C sinks, and ensuring that native forests are sustainably used within silvopastoral systems is a high priority. To that end, Southern Patagonia must further develop polices and plans that support appropriate management plans and monitoring activities for both the timber industry and pastoralists. In addition, an economic assessment based on realistic production estimates and values is required to encourage the development of silvopastoral systems that could also offer benefits, such as erosion control, timber production and biodiversity conservation.

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