Eur J Forest Res (2015) 134:113–124
DOI 10.1007/s10342-014-0837-z

ORIGINAL PAPER

Litterfall and nutrients return in *Nothofagus antarctica* forests growing in a site quality gradient with different management uses in Southern Patagonia

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Received: 13 February 2014 / Revised: 31 July 2014 / Accepted: 1 August 2014 / Published online: 14 August 2014

Abstract We evaluated the annual litterfall and nutrients return in primary forests of *Nothofagus antarctica* growing at three different site classes (SC) (III, IV and V) and compared two of these forests with adjacent stands under silvopastoral use (thinned 40 years ago), in Patagonia, Argentina. Traps were installed in each stand and sampled monthly during the litterfall over 10 years. Sample from the five stands was ground for further analyses of nutrients (N, P, K, Ca, Mg and S). The litterfall varied significantly between SC, but not between years, from 1,306 to 1,972 kg ha^{-1} in the best site. The nutrients return from litterfall did not change neither between site classes and years in most nutrients. Comparing primary forests with silvopastoral stands, in SCIV, significant differences among uses occurred for litterfall production and nutrients return, being higher in primary forest. While, in SCV, the litterfall and nutrients return practically did not change among uses. The results showed the incidence of site quality and forest use on the litterfall and nutrients return in *N. antarctica* forests.

Keywords Native forest · Silvopastoral system · *Nothofagus antarctica* · Nutrient cycling

Communicated by Aaron R. Weiskittel.

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Introduction

Nothofagus species dominate the temperate forests of southern Argentina and Chile (Veblen et al. 1996), being the deciduous *Nothofagus antarctica* (G. Forster) Oerst. (ñire, ñirre) the species with the broader ecological amplitude (Donoso et al. 2006). In southern Argentinean Patagonia (Santa Cruz and Tierra del Fuego provinces), the ñire forests cover an area of 431,000 ha (Collado 2001; Peri and Ormaechea 2013), occurring in contrasting environmental conditions such as poorly drained sites with high precipitations, exposed windy areas with shallow soils or drier sites in the limit with the Patagonian steppe (Veblen et al. 1996). This diversity of soil and climate where the ñire forests grow determines different site qualities, where the most productive sites combine the best weather conditions, topography and soil characteristics (Skovsgaard and Vanklay 2008). This implies differences in wood productivity, final dominant trees height, carbon accumulation rates, seeds production, understory biomass and partitioning of nutrients (Lencinas et al. 2002; Peri et al. 2010; Bahamonde et al. 2011, 2012a; Gargaglione et al. 2013) being higher in better site qualities. On the other hand, 70 % of these forests in Southern Patagonia have been used as silvopastoral systems (Collado 2001; Peri and Ormaechea 2013), where silvicultural practices such as thinning are common to increase understory forage production. The implications of these practices have been studied in different productive and ecological issues of ñire forests, such as diversity of understorey (Quinteros et al. 2010), forage production (Bahamonde et al. 2012a), seed regeneration (Bahamonde et al. 2013a; Soler et al. 2013) and litter decomposition (Bahamonde et al. 2012b). Well known is the role of the litterfall in the process of the recycling nutrients and organic matter in forest ecosystems as the main source of mineral and carbon return to the soil. However, the knowledge about the incidence of silvicultural management of ñire stands on the litterfall and potential nutrients return over time still unknown. Caldentey et al. (2001) found that the litterfall and nutrients return were decreased approximately 50 % in a *N. pumilio* primary forest compared to the same forest thinned with a shelterwood system in Magallanes (Chile) during 1 year of measurements. Similarly, Mansilla (2012) informed a decline of litterfall and nutrients in *N. pumilio* forests in Tierra del Fuego, which were thinned 1 or 10 years earlier compared to primary forest in the same site, but these differences were suppressed when compared the primary forest with a thinned 50 years earlier stand. In this context, the objective was to answer the following questions: (1) Does the differences in site quality correlate with the annual litterfall and therefore with the potential nutrients return? (2) Does the thinning practices for silvopastoral use decrease the litterfall and nutrients return in *N. antarctica* forests? (3) Is the effect of thinning practices equal in different site qualities stands? (4) Is the litterfall stable over time in these forests? Considering these questions, we hypothesized: (1) The annual litterfall and nutrients return in primary forests of *N. antarctica* will be higher in the stands growing in better site classes independently of the years; (2) The annual litterfall and nutrients return for a same site class will be major in the primary forests compared to adjacent thinned stands under silvopastoral use.

Materials and methods

Study sites

The study was conducted in five pure *N. antarctica* stands in the southwestern of the Santa Cruz province (Patagonia, Argentina). Three stands are primary forests with not previous management growing at three different site qualities (Ivancich et al. 2011): site class III (SCIII) where the mean total height of dominant mature trees (*H*) reached to 11.7 m (51°13′21″SL–72°15′44″WL), site class IV (SCIV) where H reached to 8.0 m (51°13′22″SL–72°15′32″WL) and site class V (SCV) representing a marginal site in the limit with the Patagonian steppe reaching a *H* of 5.0 m (51°19′05″SL–72°10′47″WL). The other two stands are located adjacent to the SCIV and SCV, respectively, but these were thinned 40 years ago. This allows the comparison between primary forest and silvopastoral use in the same site quality. The average age of the dominant trees in height ranged between 80 and 90 years.

The climate in the region is cold temperate humid with mean annual air temperatures between 5.5 and 8.0 °C, and precipitation (rain and snow) with a range between 400 and 800 mm year^{-1} (Soto 2004), with a gradient west–east, which implies that the stands in SC V have lower precipitations and higher wind speed (Bahamonde et al. 2009). The soils were classified as mollisols-haploxerolls according to USDA classification and had 0.8 m depth.

Stands characterization

Stands were characterized with three circular plots of 500 m^2 randomly distributed. In each plot, total number of trees, frequency of crown classes (dominant, codominant, intermediate and suppressed), diameter at breast height (DBH) and total height were measured. To calculate the total volume of trees, the equation proposed by Lencinas et al. (2002) was used.

Litterfall and nutrients return

To quantify litterfall production, four traps of 1 m^2 were installed 1 m above the ground in each stand randomly distributed in the primary forests and regularly separated in the silvopastoral stands. The traps were sampled monthly during the period of maximal litterfall at these latitudes (February–May) (Caldentey et al. 2001; Frangi et al. 2004) during a continuous period of 10 years (2004–2013). The traps remained in the field throughout the year to avoid underestimation of litterfall due to falling debris during the rest of the year. The collected material was carried to the laboratory in plastic bags, and then, samples were separated in three components: leaves, small branches (<2 cm diameter) and miscellaneous material (mainly seeds, flowers, immature fruits and bark residues). Each component was weighted (±0.01 g) after drying in a forced draft oven to constant weight at 60 °C. From the samples taken in 2006, 2008 and 2012, subsamples of leaves from the five stands were ground in a mill containing 1 mm stainless steel screen for further analyses of nutrients (N, P, K, Ca, Mg and S). Also, in 2008, subsamples of small branches and miscellaneous material from the primary forest stands were ground and then analyzed. N was determined by semi-micro Kjeldahl, while P, K, Ca, S and Mg were determined with a plasma emission spectrometer (Shimadzu ICPS-1000 III, Japan).

For each stand, the mean annual litter production per unit area (kg ha^{-1}) was calculated by summing the monthly litterfall values. To estimate the quantity of each nutrient that return to the soil, the weighted average was calculated according to nutrient concentration and the amount of each litterfall component.

Data analysis

Exploratory testings were carried out to verify the compliance with the assumptions of normality, homoscedasticity and independence of data for each evaluated situation. While the Shapiro–Wilk test was performed to verify the normality of the data, the Levene test was used to verify homoscedasticity. The independence was verified by analyzing residuals from graphs. Dasometric characteristics of each study stand were analyzed by analysis of variance (ANOVA). To evaluate the incidence of site class on litterfall production and nutrients return, the three primary forest stands were analyzed with ANOVA for repeated measurements with site class as an inter-subject factor and each year as an intra-subject factor. To compare the litterfall and nutrients return between uses, silvopastoral and primary forest stands were analyzed at two site classes through ANOVA for repeated measurements with site class and use as inter-subject factors and each year as an intra-subject factor. These analyses were selected because litterfall and therefore nutrients return values are not independent of time. This type of analysis has been shown to be appropriate for these cases (Gurevitch and Chester 1986). Tukey tests were performed to test differences among factors when F-values were significant ($p < 0.05$). To avoid misinterpretations, multiple comparisons were made when the interaction between factors were significant (Willems and Raffaele 2001).

To evaluate the effect of different dasometric parameters on the litterfall production and its nutrients return, linear and nonlinear regressions were done with the dasometric parameters as independent variables in all the five studied stands for the 10 evaluated years.

Results

Dasometric parameters and nutrient concentrations

As was expected, primary forest stands presented significant differences in the height of dominant trees, determined by its site classes according to the classification proposed by Ivancich et al. (2011) (Table 1). Also, there was a gradient in basal area, and therefore in total volume, according to the site class. Similarly, there were significant differences in most of the dasometric variables when the different uses (primary forest vs silvopastoral) were compared for the same site class.

Nutrient concentrations in the leaves did not vary among stands, neither for site class nor in the stand use (Table 2). However, in the other components, there were differences between SC depending on a particular nutrient. Thus, the concentration of P and K in miscellaneous were higher in SCV, while the concentrations of Ca, S and Mg in the same component were lower in SCV.

Litterfall and nutrients return in primary forests growing at three different site classes

The total litterfall varied significantly between SC, but not between years (Table 3), being lowest in the SCV stand (average = 1,306 kg ha^{-1}; range 559–1,954 kg ha^{-1}), with not differences between SCIII (average = 1,972 kg ha^{-1}; range 1,555–2,324 kg ha^{-1}) and SCIV (average = 1,891 kg ha^{-1}; range 1,254–2,238 kg ha^{-1}) stands (Fig. 1). On the other hand, the percentages of different components (leaves, small branches and miscellaneous) did not show variation between SC (Table 3). Nevertheless, the proportion of leaves and small branches were different between years with not significant interactions in SC (Tables 3, 4), while the percentage of miscellaneous did not vary significantly between years, but showed a significant interaction between

Table 1 Main dasometric parameters of *N. antarctica* stands growing at different site classes and uses in Southern Patagonia

Site class	Use	DH (m)	Crown cover (%)	Density (trees ha^{-1})	DBH (cm)	BA (m^2 ha^{-1})	Dom (%)	Cod (%)	Int (%)	Sup (%)	TOBV (m^3 ha^{-1})
III	PF	11.7a	75a	746a	32.0a	63.6a	26b	25b	26a	23b	418a
IV	PF	8.0b	85a	895a	24.8b	57.8a	33ab	23b	27a	17b	276b
IV	SP	8.0b	52b	418b	28.3ab	47.0b	37a	25b	19b	19b	218b
V	PF	5.0c	80a	962a	19.8b	43.5b	21b	28b	22ab	29a	141c
V	SP	5.0c	50b	357b	25.7b	19.8c	43a	38a	14b	5c	78c

Site classes according to Ivancich et al. (2011)

PF primary forest, *SP* silvopastoral use, *DH* height of dominant trees, *DBH* diameter at breast height, *BA* basal area, *Dom* dominant trees, *Cod* codominant trees, *Int* intermediate trees, *Sup* suppressed trees, *TOBV* total over bark volume

Different letters in a same column indicate significant differences ($p < 0.05$)

Table 2 Nutrients concentration and statistical differences in different components (*L* leaves, *SB* small branches, *MM* miscellaneous material) of litterfall in *N. antarctica* forests growing at different site classes and uses (*PF* primary forest, *SP* silvopastoral use)

Site class (SC)	Use (U)	Component	N (%)	P (ppm)	K (ppm)	Ca (ppm)	S (ppm)	Mg (ppm)
III	PF	L	0.92 (0.6)	1,279 (310)	3,076 (1,777)	10,307 (431)	783 (435)	2,062 (106)
		SB	0.75 (0.2)	548 (37)	2,420 (239)	15,787 (1,671)	522 (104)	1,030 (131)
		MM	1.12 (0.1)	871 (62)	2,588 (102)	13,400 (970)	788 (48)	1,226 (52)
IV	PF	L	0.74 (0.3)	1,508 (404)	3,102 (1,688)	11,327 (1,210)	1,108 (989)	2,365 (309)
		SB	0.79 (0.1)	619 (39)	2,652 (137)	12,526 (751)	542 (20)	1,344 (55)
		MM	1.09 (0.2)	859 (93)	3,468 (548)	14,064 (265)	718 (56)	1,277 (39)
IV	SP	L	0.79 (0.3)	1,267 (243)	2,887 (1,343)	9,747 (1,086)	694 (159)	2,338 (299)
V	PF	L	0.63 (0.2)	1,565 (706)	1,644 (995)	9,239 (470)	570 (219)	2,233 (390
		SB	0.83 (0.1)	770 (220)	3,335 (568)	8,319 (1,234)	487 (72)	970 (107)
		MM	1.23 (0.2)	1,142 (151)	3,844 (264)	3,800 (15)	625 (52)	709 (63)
V	SP	L	0.77 (0.4)	1,544 (170)	2,865 (1,673)	9,610 (1,010)	734 (321)	2,220 (355)
Statistical differences								
SC		L	ns	ns	ns	ns	ns	ns
		SB	ns	ns		**	ns	**
		MM	ns	*	*	***	*	***
U		L	ns	ns	ns	ns	ns	ns
SC × U		L	ns	ns	ns	ns	ns	ns

Site classes according to Ivancich et al. (2011). Numbers in parentheses are the standard deviation of the mean

ns not significant

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

Table 3 Repeated-measures ANOVA for total litterfall, and percentages of leaves, small branches and miscellaneous, measured at three site classes, and 10 years in primary *N. antarctica* forests

Source	*df*	Total litterfall *F* (p)	% leaves *F* (p)	% Small branches *F* (p)	% miscellaneous *F* (p)
Between subject effects					
Site class (SC)	2	10.07 (<0.001)	3.98 (0.063)	3.18 (0.097)	3.11 (0.100)
Within subject effects					
Year (Y)	9	0.60 (0.792)	6.37 (0.036)	3.98 (<0.001)	0.69 (0.430)
Interactions					
SC × Y	18	0.83 (0.658)	2.91 (0.112)	1.67 (0.067)	7.91 (0.013)

SC and years (Table 3). The percentage of leaves, small branches and miscellaneous in all SC and years averaged 68.1, 14.2 and 17.7 %, respectively.

The potential return of nutrients from the litterfall did not show differences between site classes in most of the evaluated nutrients (Table 5), except S that had lower return value in CSV (Table 5; Fig. 2). Also, there were not significant differences in nutrients return neither among years and the interactions between SC and years (Table 5).

Litterfall and nutrients return in primary and under silvopastoral use forests growing in different site classes

Total litterfall did not vary significantly neither between site classes or years, but presented significant differences between uses (primary vs silvopastoral stands) (Table 6). However, as the interactions were significant among SC and year, and among SC and use (Table 6), multiples comparisons provide more detailed information. In SCIV, significant differences among uses occurred in four of the ten evaluated years, being always higher in primary forest (Fig. 3a). Ten-year average values showed significant differences between uses with 1,891 and 827 kg ha^{-1} for primary forest and silvopastoral use, respectively. On the other hand, in SCV, there were only significant differences during the year 2013 with lower litterfall in the silvopastoral stand (Fig. 3b). The 10-year average in these SC did not change significantly between uses, with values of 1,221 and 1,053 kg ha^{-1} for primary forest and silvopastoral use, respectively.

When the proportion of each component was analyzed, the proportion of leaves, small branches and miscellaneous

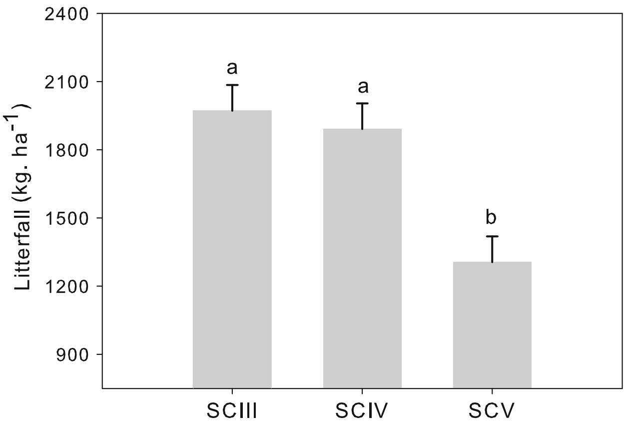

Fig. 1 Average litterfall of 10 years in three primary *N. antarctica* forests growing at different SC. *Different letters* among columns indicate significant differences among SC ($p < 0.05$). *Bars* represent the standard error of the mean

Table 4 Percentages of different components of litterfall in *N. antarctica* forests measured during 10 years

Year	Leaves (%)	Small branches (%)	Miscellaneous material (%)
2004	78.7a	10.6b	10.7
2005	57.0b	12.3b	30.7
2006	77.3a	9.7b	13.0
2007	72.6a	11.6b	15.8
2008	67.9ab	15.5ab	16.6
2009	72.6a	15.3ab	12.1
2010	70.5ab	13.7b	15.8
2011	60.7b	20.7a	18.6
2012	61.2b	15.2ab	23.6
2013	67.3ab	14.7ab	22.0

The values of each year represent the average of the 3 stands growing at different site classes

Different letters in a same column indicate significant differences among years ($p < 0.05$)

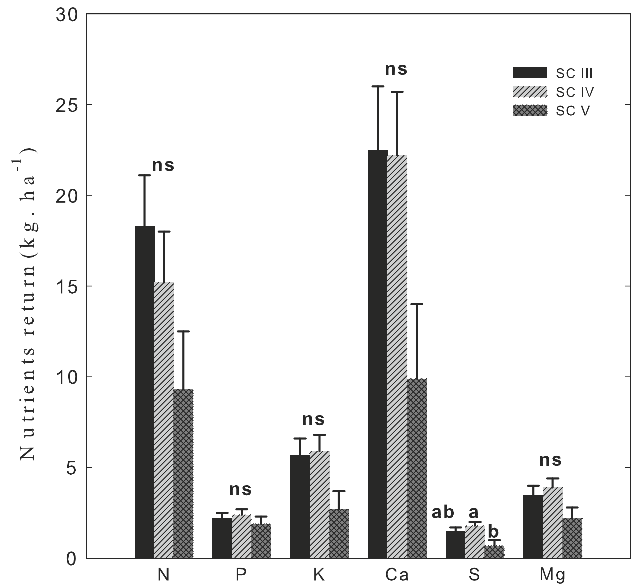

Fig. 2 Average nutrients return from litterfall of 10 years in three primary *N. antarctica* forests growing at different SC. *Different letters* between column for a same nutrient indicate significant differences among SC ($p < 0.05$). *ns* not significant differences. *Bars* represent the standard deviation of the mean

significantly varied between SC and years, but not between uses (Table 6). However, the interactions were significant, and the multiples comparisons resulted more appropriate. Considering the average of 10 years and uses, the percentage of leaves represented the 74 and 58 % for SCIV and SCV, respectively. In SCIV, there were significantly differences among uses during 2 years with higher percentage of leaves in the silvopastoral use (Table 7), while in SCV, lower percentage of leaves were measured in SP use during 2 years (Table 8). The small branches percentage varied between uses only 1 year in SCIV with higher value in the primary forest (Table 7). Similarly, in SCV, the proportion of small branches was higher in the primary forest 1 year, but in another year was higher in the silvopastoral stand (Table 8). There were not significantly differences in percentage of miscellaneous among uses in SCIV (Table 7), but in SCV, during 4 years, the proportion of miscellaneous was higher in the SP stand (Table 8). Finally, it was notable the low proportion of leaves and high percentage of miscellaneous in SCV during 2005.

Table 5 Repeated-measures ANOVA for nutrients return from litterfall estimated at three site classes, and 10 years in primary *N. antarctica* forests

Source	*df*	N *F* (p)	P *F* (p)	K *F* (p)	Ca *F* (p)	S *F* (p)	Mg *F* (p)
Between subject effects							
Site class (SC)	2	2.26 (0.167)	0.57 (0.589)	3.45 (0.083)	3.40 (0.085)	5.86 (0.027)	2.16 (0.178)
Within subject effects							
Year (Y)	9	1.42 (0.197)	1.67 (0.113)	1.22 (0.295)	1.67 (0.603)	1.12 (0.354)	1.17 (0.340)
Interactions							
SC × Y	18	2.18 (0.072)	1.66 (0.069)	0.88 (0.136)	1.56 (0.208)	1.21 (0.343)	1.54 (0.219)

Table 6 Repeated-measures ANOVA for total litterfall, and percentage of leaves, small branches and miscellaneous measured at two site classes, two uses (primary forest and silvopastoral use) and 10 years in *N. antarctica* forests

Source	*df*	Total litterfall *F* (p)	% leaves *F* (p)	% small branches *F* (p)	% miscellaneous *F* (p)
Between subject effects					
Site class (SC)	1	0.86 (0.376)	47.01 (<0.001)	19.07 (0.001)	29.31 (<0.001)
Use (U)	1	6.57 (0.028)	0.02 (0.880)	4.54 (0.059)	4.14 (0.072)
Within subject effects					
Year (Y)	9	1.89 (0.063)	16.90 (<0.001)	8.33 (0.016)	34.33 (<0.001)
Interactions					
SC × U	1	3.48 (0.092)	11.05 (0.009)	1.92 (0.196)	11.51 (0.008)
SC × Y	9	5.88 (0.036)	14.59 (<0.001)	0.73 (0.412)	27.74 (<0.001)
U × Y	9	7.71 (0.020)	1.38 (0.212)	0.38 (0.553)	2.13 (0.036)
SC × U × Y	9	4.25 (0.066)	2.28 (0.025)	6.27 (0.031)	2.56 (0.012)

The main effects of the treatments and their interactions on nutrients return depended on the evaluated element (Table 9). Thus, while only Ca and S return significantly varied among SC, only N and K return did no change with the forest use. From multiple comparisons, two completely different patterns were found in the two studied site classes. In SCIV, most of years nutrients return was significantly higher in primary forest (Table 10), with the only exception of Mg there where in 6 years, there was no significant difference among uses. In contrast, in SCV, there were not differences in nutrients return among uses for any of the evaluated elements or years, with the only exception for P return in 2013 that was higher in the primary forest (Table 11).

Influence of dasometric parameters on litterfall production and nutrients return

When we analyzed the five stands of ñire during 10 years, most of the evaluated dasometric parameters showed a direct correlation with the litterfall and nutrients return (Table 12). The basal area better explained the variability of litterfall and nutrients return, with the exception the P return, which was mainly associated to trees density (Table 12). On the other hand, DBH presented the lower explanatory potential for all the evaluated variables.

Discussion

Dasometric parameters and nutrient concentrations

The structure of the stands was associated mainly to the site class of the stands and the use of these forests in different ways. When the primary forests were compared according to its site class, the higher differences among them were dominant height, DBH, basal area and volume, which is expectable considering that this classification is based on the stand productivity (Ivancich et al. 2011). When we compared the use of the forests in the same site class, the main differences were obtained in crown cover, tree density and basal area for both site classes, and also the percentage of trees in different crown classes and volume in the SCV. These dissimilarities were the result of thinning management to increase the light availability in the herbaceous stratum, as was proposed to manage the ñire forests as silvopastoral system in Southern Patagonia (Peri et al. 2009). The nutrient concentrations in leaves were in the range of the reported for others South American *Nothofagus* (Caldentey et al. 2001; Frangi et al. 2005; Decker and Boerner 2006) and other previous studies in *N. antarctica* (Mazzarino et al. 1998; Diehl et al. 2003; Bahamonde et al. 2012b) with no differences among site classes or uses. Similarly, the others components presented similar nutrient concentrations as the previously informed in another ñire forests (Peri et al. 2006).

Litterfall and nutrients return in primary forests growing in three different site classes

To start, we have to mention an extraordinary event occurred in the stands, both primary forest and silvopastoral use, in SCV, during the year 2005. These stands were attacked by defoliating insects, which we could not identify. However, considering that we measured during 10 years, when we compared the global results, there were not changes if we excluded or not that year in the analyses; therefore, the year 2005 still included in the work.

Values of litterfall obtained in this study are in the range reported by others studies in *Nothofagus* forests of the region, e.g., in *N. pumilio* (another deciduous species) forest of similar dasometric characteristics (Caldentey et al. 2001), lower than those reported for *N. antarctica* in Tierra del Fuego in a stand growing in a better site quality stand (14 m dominant height trees) (Frangi et al. 2004), and higher than data reported by De Paz et al. (2013) in ñire

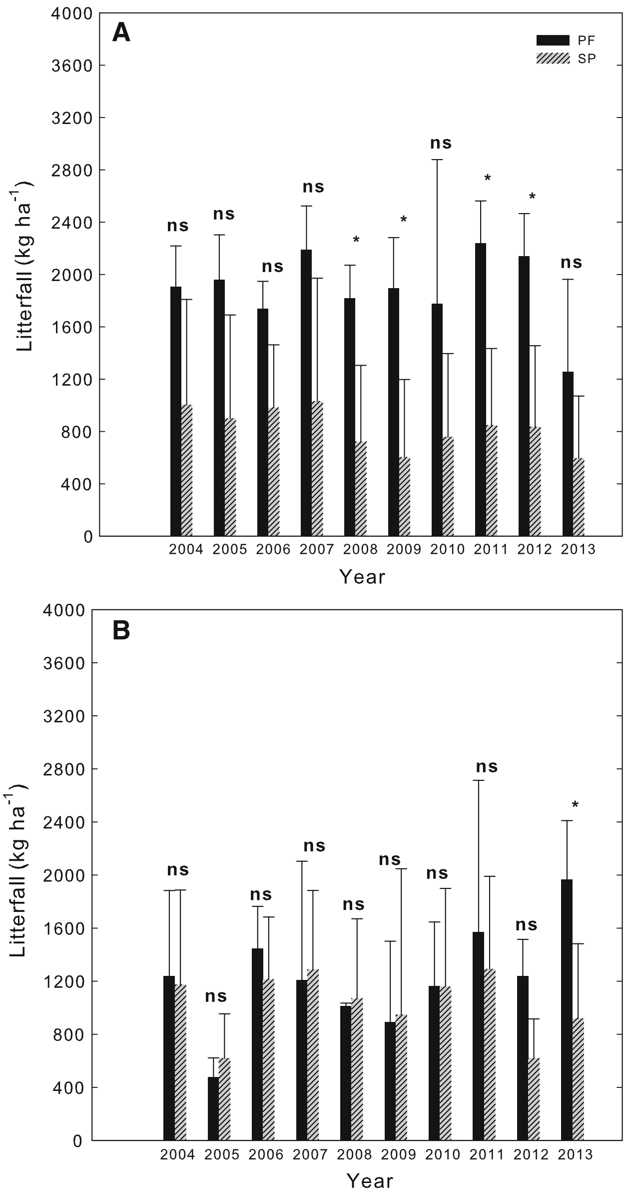

Fig. 3 Total litterfall measured in *N. antarctica* primary forest (PF) and under silvopastoral use (SP) stands growing in site class IV (**a**) and site class V (**b**) during 10 years. *Bars* represent the standard deviation of the mean. *$p < 0.05$; *ns* not significant

shrublands of northwestern Patagonia. These comparative results are consistent with the differences that we obtained among site classes. In the same way, these differences were to be expected considering that stands growing at better sites qualities have higher dasometric characteristics, as basal area and volume. Also, well known is that the forest site quality is a combination of physical and biological features of the site where the stand is growing (Skovsgaard and Vanklay 2008). In Tierra del Fuego, Barrera et al. (2000) measured greater amounts of litterfall in *N. pumilio* forests growing at 220 m asl compared to forests growing at 440 m asl in more restrictive environmental conditions. In ñire forests of Southern Patagonia, Gargaglione et al. (2010) reported that a stand growing in worse site quality (SCV) presented lower values of total biomass (above and belowground components) compared to stands growing in better sites (SCIII and SCIV). Also, these authors reported that the stand in SCV partitioned significantly more biomass to belowground components than better sites. This fact can be attributed to worse site quality stand is more limited by soil resources. In the same direction, the worst site qualities of ñire forests in Southern Patagonia are adjacent to the Patagonian steppe with lesser rainfall and higher windy environments (Bahamonde et al. 2009).

Despite no differences were found among years, due to high variability of the data, it should be noted the importance of analyzing 10-year temporal series. For example, there are no significant differences among site classes (data not shown) in five of the studied years, and if we not included a long-term analysis, we can lose these differences as was previously mentioned.

On the other hand, regardless the annual differences in the percentages of leaves, small branches and miscellaneous, it is notable the higher proportion that represents the leaves, which has been previously reported in others studies: Caldentey et al. (2001) published that 70 % of the litterfall were leaves in a *N. pumilio* forest in Chilean Patagonia and Mansilla (2012) informed more than 80 % of leaves in litterfall of *N. pumilio* in Tierra del Fuego (Argentina). This information is important for the knowledge of nutrient cycling of these systems, especially considering the different decomposition rates for each component of the ñire litterfall (Frangi et al. 1997; Bahamonde et al. 2012b).

The nutrients return did not show significant differences among SC despite the differences in the litterfall amounts. This can be explained by different reasons depending on each nutrient. Firstly, the high variability of the data could dilute the numerical differences between SCIII and SCV (mainly in N and Ca). Also, in some nutrients and components, its concentrations were higher in SCV than the better site qualities (e.g., concentrations of N, P and K in small branches and miscellaneous), which may partially compensate the higher amount of litterfall obtained in the better site quality classes. Compared to nutrients return in *N. antarctica* forest in a better site quality (14 m of height dominant trees) (Frangi et al. 2004), the values obtained in this work were lower in N, P and K, and similar in Ca and S.

Litterfall and nutrients return in primary and under silvopastoral use forests growing in different site classes

Although the main factor analyses showed significant differences in litterfall between forest uses, the interactions

Table 7 Percentages of different components of litterfall measured in *N. antarctica* primary forest (PF) and under silvopastoral use (SP) stands growing in SCIV during 10 years

Year	Leaves (%)		Small branches (%)		Miscellaneous material (%)	
	PF	SP	PF	SP	PF	SP
2004	80.5 (4.8)a	69.5 (11.3)a	10.5 (2.4)a	10.8 (2.5)a	8.8 (3.3)a	19.5 (9.5)a
2005	72.5 (7.5)b	83.3 (4.5)a	8.0 (0.8)a	3.3 (1.3)a	19.5 (8.1)a	13.5 (3.7)a
2006	74.8 (4.3)a	77.5 (3.4)a	8.3 (1.5)a	6.3 (0.5)a	17.0 (3.4)a	16.0 (3.2)a
2007	74.0 (4.2)a	82.3 (4.6)a	9.8 (2.2)a	8.0 (3.6)a	16.5 (2.4)a	10.0 (1.4)a
2008	70.5 (5.8)b	80.5 (3.1)a	12.0 (2.2)a	7.3 (5.1)a	17.5 (4.8)a	12.0 (4.1)a
2009	69.8 (4.6)a	81.5 (6.8)a	15.3 (3.3)a	6.8 (3.3)a	15.0 (3.5)a	12.0 (3.9)a
2010	70.5 (14.1)a	83.0 (2.7)a	13.5 (6.0)a	5.0 (1.8)b	16.0 (8.2)a	12.0 (2.6)a
2011	62.3 (4.3)a	74.8 (5.6)a	18.0 (3.7)a	10.0 (5.9)a	19.5 (4.4)a	15.3 (1.7)a
2012	60.5 (6.8)a	64.0 (2.9)a	14.5 (3.4)a	8.8 (5.1)a	25.3 (5.6)a	27.0 (6.3)a
2013	68.5 (17.3)a	81.8 (2.2)a	14.0 (6.8)a	6.0 (2.6)a	17.5 (10.5)a	12.8 (3.1)a

Numbers in parentheses are the standard deviation of the mean

Among PF and SP for a same year and component, means followed by the same letter do not differ significantly ($p > 0.05$)

Table 8 Percentages of different components of litterfall measured in *N. antarctica* primary forest (PF) and under silvopastoral use (SP) stands growing in SCV during 10 years

Year	Leaves (%)		Small branches (%)		Miscellaneous material (%)	
	PF	SP	PF	SP	PF	SP
2004	74.7 (15.6)a	77.0 (11.3)a	12.0 (9.2)a	15.0 (10.6)a	12.3 (7.1)a	14.0 (8.5)a
2005	16.3 (6.7)a	15.5 (0.7)a	24.0 (11.0)a	11.0 (4.6)b	61.3 (15.3)a	71.5 (0.7)a
2006	77.0 (7.9)a	67.0 (5.7)a	13.0 (5.2)a	9.3 (7.0)a	12.0 (1.7)b	20.0 (1.4)a
2007	68.3 (17.0)a	73.5 (2.1)a	16.7 (10.0)a	13.0 (3.6)a	9.3 (9.3)a	12.5 (0.7)a
2008	66.0 (6.2)a	60.0 (2.8)a	18.3 (6.5)a	11.3 (8.0)a	14.3 (3.1)b	24.5 (7.8)a
2009	72.7 (13.4)a	74.5 (13.4)a	18.3 (8.9)a	10.7 (8.1)a	10.0 (4.6)a	12.5 (3.5)a
2010	71.0 (13.1)a	48.5 (0.7)b	9.7 (4.6)b	21.3 (6.7)a	22.7 (11.0)a	33.0 (5.7)a
2011	61.0 (18.5)a	43.5 (9.2)a	22.3 (11.0)a	18.3 (3.8)a	16.3 (9.8)b	41.5 (6.4)a
2012	59.3 (9.3)a	36.5 (6.4)b	13.7 (4.9)a	16.0 (3.0)a	27.0 (4.6)b	47.0 (2.89a
2013	54.7 (13.9)a	43.5 (6.4)a	19.7 (8.4)a	30.7 (11.9)a	20.7 (2.9)a	19.5 (3.5)a

Numbers in parentheses are the standard deviation of the mean

Among PF and SP for a same year and component, means followed by the same letter do not differ significantly ($p > 0.05$)

Table 9 Repeated-measures ANOVA for nutrients return from litterfall estimated for two site classes, two uses (primary forest and silvopastoral use) and 10 years in *N. antarctica* forests

Source	*df*	N *F* (p)	P *F* (p)	K *F* (p)	Ca *F* (p)	S *F* (p)	Mg *F* (p)
Between subject effects							
Site class (SC)	1	0.73 (0.412)	0.081 (0.782)	2.48 (0.150)	6.39 (0.032)	11.63 (0.007)	2.81 (0.128)
Use (U)	1	4.32 (0.064)	11.75 (0.006)	3.87 (0.081)	8.96 (0.015)	16.91 (0.002)	6.23 (0.034)
Within subject effects							
Year (Y)	9	0.04 (0.849)	2.83 (0.006)	2.42 (0.017)	2.24 (0.122)	1.64 (0.216)	2.49 (0.015)
Interactions							
SC × U	1	4.89 (0.051)	2.72 (0.130)	5.77 (0.040)	4.18 (0.071)	10.21 (0.001)	1.75 (0.219)
SC × Y	9	6.12 (0.033)	2.27 (0.025)	3.20 (0.002)	2.46 (0.100)	2.33 (0.117)	2.29 (0.024)
U × Y	9	7.61 (0.020)	0.50 (0.869)	1.26 (0.272)	0.88 (0.445)	0.30 (0.762)	0.70 (0.706)
SC × U × Y	9	3.24 (0.102)	1.01 (0.437)	1.29 (0.257)	0.72 (0.694)	0.66 (0.542)	0.78 (0.639)

between factors were also significant; therefore, a more detailed analysis was needed. According to the multiple comparisons, the differences between uses depended on SC and year, as was mentioned in the results. Only in SCIV (during some years and the 10-year average), the better dasometric structure of the primary forest stand (crown cover, density and basal area) produced more litterfall than silvopastoral stand, as was expected. Similarly, Caldentey et al. (2001) reported a major contribution of litterfall in a primary forest of *N. pumilio* compared to a harvested stand,

Table 10 Nutrients return from litterfall estimated in *N. antarctica* primary forest (PF) and under silvopastoral use (SP) stands growing at SCIV during 10 years

Year	N (kg ha^{-1})		P (kg ha^{-1})		K (kg ha^{-1})		Ca (kg ha^{-1})		Mg (kg ha^{-1})		S (kg ha^{-1})	
	BP	SP	BP	SP	BP	SP	BP	SP	BP	SP	BP	SP
2004	14.8 (2.6)a	8.4 (6.4)a	2.6 (0.4)a	1.2 (1.0)a	5.9 (1.0)a	3.0 (2.3)b	22.3 (3.4)a	10.8 (8.3)b	4.1 (0.6)a	2.1 (1.8)a	2.0 (0.3)a	0.7 (0.5)b
2005	15.9 (2.9)a	7.5 (6.5)b	2.6 (0.5)a	1.1 (0.9)b	6.2 (1.1)a	2.7 (2.3)b	22.5 (4.2)a	9.3 (8.1)b	4.0 (0.7)a	1.9 (1.7)a	1.9 (0.3)a	0.6 (0.5)b
2006	14.0 (1.8)a	8.2 (3.9)b	2.3 (0.3)a	1.2 (0.6)b	5.5 (0.6)a	2.9 (1.4)b	20.3 (2.6)a	10.3 (4.8)b	3.6 (0.5)a	2.1 (1.1)a	1.7 (0.2)a	0.7 (0.3)b
2007	17.6 (2.7)a	8.5 (7.8)b	2.9 (0.4)a	1.2 (1.1)b	6.9 (1.0)a	3.1 (2.7)b	25.8 (3.9)a	11.0 (9.9)b	4.6 (0.7)a	2.2 (1.9)a	2.2 (0.3)a	0.7 (0.6)b
2008	14.7 (1.9)a	5.9 (4.7)b	2.4 (0.4)a	0.9 (0.7)b	5.6 (0.8)a	2.1 (1.7)b	21.0 (2.9)a	7.3 (6.1)b	3.7 (0.6)a	1.5 (1.3)b	1.7 (0.3)a	0.5 (0.4)b
2009	15.2 (3.3)a	5.0 (4.9)b	2.4 (0.5)a	0.7 (0.7)b	5.9 (1.2)a	1.8 (1.7)b	22.3 (4.7)a	6.0 (6.2)b	3.9 (0.8)a	1.3 (1.3)b	1.8 (0.4)a	0.4 (0.4)b
2010	14.1 (8.4)a	6.2 (5.2)a	2.4 (1.6)a	0.9 (0.8)a	5.5 (3.4)a	2.2 (1.9)a	21.0 (12.8)a	8.0 (6.2)a	3.7 (2.5)a	1.6 (1.4)a	1.8 (1.2)a	0.5 (0.5)b
2011	18.3 (2.8)a	7.1 (4.9)b	2.8 (0.4)a	1.0 (0.6)b	6.9 (1.0)a	2.5 (1.7)b	26.8 (3.9)a	9.3 (6.5)b	4.4 (0.6)a	1.7 (1.2)b	2.1 (0.3)a	0.6 (0.4)b
2012	17.8 (2.5)a	7.2 (5.2)b	2.6 (0.5)a	0.9 (0.6)b	6.7 (1.0)a	2.5 (1.8)b	25.3 (3.6)a	8.5 (6.8)b	4.1 (0.7)a	1.6 (1.2)b	2.0 (0.3)a	0.6 (0.4)b
2013	10.0 (5.5)a	4.9 (3.9)a	1.6 (1.0)a	0.7 (0.6)a	3.9 (2.2)a	1.7 (1.4)a	14.8 (8.2)a	6.3 (4.8)a	2.6 (1.6)a	1.2 (1.0)a	1.2 (0.7)a	0.4 (0.4)b

Numbers in parentheses are the standard deviation of the mean

Among PF and SP for a same year and nutrient, means followed by the same letter do not differ significantly ($p > 0.05$)

Table 11 Nutrients return from litterfall estimated in *N. antarctica* primary forest (PF) and under silvopastoral use (SP) stands growing at SCV during 10 years

Year	N (kg ha^{-1})		P (kg ha^{-1})		K (kg ha^{-1})		Ca (kg ha^{-1})		Mg (kg ha^{-1})		S (kg ha^{-1})	
	BP	SP	BP	SP	BP	SP	BP	SP	BP	SP	BP	SP
2004	10.8 (5.3)a	11.5 (5.0)a	2.2 (1.1)a	2.0 (1.0)a	3.1 (1.5)a	3.9 (2.5)a	10.3 (5.7)a	11.5 (7.8)a	2.4 (1.4)a	1.8 (1.8)a	0.7 (0.4)a	0.9 (0.6)a
2005	5.9 (2.3)a	6.9 (3.7)a	0.6 (0.2)a	0.7 (0.4)a	1.9 (0.7)a	2.1 (1.6)a	2.7 (1.2)a	3.0 (2.8)a	0.5 (0.2)a	0.4 (0.4)a	0.3 (0.1)a	0.4 (0.4)a
2006	11.4 (2.5)a	10.6 (4.2)a	2.3 (0.5)a	1.7 (0.6)a	3.3 (0.7)a	3.9 (2.1)a	12.3 (2.5)a	10.0 (5.7)a	2.7 (0.6)a	1.5 (1.4)a	0.8 (0.2)a	0.8 (0.4)a
2007	9.7 (5.4)a	10.9 (5.0)a	1.9 (1.2)a	1.7 (0.8)a	2.8 (1.5)a	3.7 (2.5)a	10.7 (8.1)a	10.0 (7.1)a	2.4 (2.0)a	1.5 (1.5)a	0.7 (0.6)a	0.8 (0.6)a
2008	7.9 (0.8)a	9.3 (5.1)a	1.4 (0.1)a	1.4 (0.8)a	2.4 (0.3)a	3.4 (2.7)a	8.0 (0.1)a	8.0 (7.1)a	1.8 (0.1)a	1.2 (1.4)a	0.5 (0.0)a	0.7 (0.6)a
2009	6.9 (3.5)a	8.1 (9.8)a	1.4 (0.8)a	1.2 (1.5)a	2.0 (1.0)a	0.9 (0.8)a	16.2 (8.1)a	7.5 (5.7)a	1.8 (1.3)a	0.4 (0.4)a	0.5 (0.4)a	0.2 (0.1)a
2010	9.2 (2.8)a	10.7 (6.7)a	1.7 (0.6)a	1.5 (0.9)a	2.7 (0.8)a	4.2 (3.3)a	9.3 (4.0)a	9.5 (7.8)a	2.1 (1.0)a	1.4 (1.4)a	0.7 (0.3)a	0.9 (0.6)a
2011	12.5 (6.1)a	12.7 (7.1)a	2.2 (1.4)a	1.6 (0.8)a	3.8 (1.7)a	3.2 (1.8)a	13.0 (10.4)a	8.5 (6.4)a	2.8 (2.5)a	1.7 (0.8)a	0.9 (0.6)a	0.6 (0.3)a
2012	10.1 (1.8)a	6.1 (2.9)a	1.7 (0.5)a	0.8 (0.4)a	3.0 (0.4)a	2.6 (0.9)a	9.3 (2.3)a	3.0 (1.4)a	2.1 (0.6)a	0.8 (0.4)a	0.7 (0.2)a	0.5 (0.1)a
2013	15.9 (2.6)a	8.3 (5.1)a	2.6 (0.6)a	1.0 (0.7)b	4.9 (0.7)a	3.1 (2.6)a	15.3 (4.0)a	7.5 (6.4)a	3.3 (1.0)a	1.6 (1.0)a	1.1 (0.3)a	0.6 (0.5)a

Numbers in parentheses are the standard deviation of the mean

Among PF and SP for a same year and nutrient, means followed by the same letter do not differ significantly ($p > 0.05$)

Table 12 Coefficients of determination (R^2) and significance (*p* value) of regressions between dasometric parameters (as independent variables) and litterfall and nutrients returns (as dependent variables) in five *N. antarctica* stands under different uses and growing in three different site classes

	Total litterfall	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})	Ca (kg ha^{-1})	S (kg ha^{-1})	Mg (kg ha^{-1})
BA	0.61 (<0.001)	0.70 (<0.001)	0.38 (<0.001)	0.67 (<0.001)	0.76 (<0.001)	0.64 (<0.001)	0.68 (<0.001)
Total volume	0.45 (<0.001)	0.58 (<0.001)	0.23 (<0.001)	0.47 (<0.001)	0.61 (<0.001)	0.46 (<0.001)	0.56 (<0.001)
Density	0.56 (<0.001)	0.58 (<0.001)	0.50 (<0.001)	0.52 (<0.001)	0.69 (<0.001)	0.53 (<0.001)	0.68 (<0.001)
DBH	0.14 (0.026)	0.26 (0.001)	0.07 (0.202)	0.13 (0.040)	0.18 (0.010)	0.07 (0.070)	0.11 (0.073)
% of dominant trees	0.32 (<0.001)	0.28 (<0.001)	0.27 (0.001)	0.33 (<0.001)	0.51 (<0.001)	0.45 (<0.001)	0.58 (<0.001)

The regressions were of the type: $y = ax^2 + bx + c$

BA basal area, *DBH* diameter at breast height

in Magallanes (Chile). Different it was the pattern in SCV, where the major crown cover, density and basal area in the primary forest were not expressed as more litterfall compared to the silvopastoral stand (except 1 of the ten evaluated years). This seemingly contradictory result could be explained by the proportion of crown classes in the stands (e.g., percentages of dominant and codominant trees). In the silvopastoral stand, the dominant and codominant trees represent more than 80 % while in the primary forest represent 49 %. Related to this, Peri et al. (2008) informed that in *N. antarctica* stands of different ages, the dominant and codominant trees contributed between 70 and 80 % of the total biomass of leaves, and similar percentages of the total biomass of small branches. This is consistent considering that the dominant and codominant trees presented advantages to acquire resources (mainly light) compared to the intermediate and suppressed trees. Similarly, Mansilla (2012) reported different responses in litterfall to the harvesting practices in *N. pumilio* forests of Tierra del Fuego, e.g., litterfall was significantly higher in primary forest compared to partially harvested forests (50 % basal area) after 1–10 years, but there was not differences in litterfall production (between primary and harvested stands) when the stand was harvested 50 years ago. In the 50 years of partially harvested stand, the crown cover was the same as in primary forest, but with the 30 % of trees, which suggests a higher proportion of dominant and codominant trees.

By and large, the use of the forests did not affect the proportions of each component in both SC, and the values were concordant with the reported in *N. pumilio* forests (Caldentey et al. 2001; Mansilla 2012). At more detailed level, there were some differences between uses and years in proportion of leaves and small branches in both SC, but without a definite pattern, which we attribute to the intrinsic variability of the forest system. The proportion of miscellaneous material was mildly higher than small branches inversely with those informed in *N. pumilio* by Mansilla (2012). In SCV, the higher proportion of miscellaneous in silvopastoral use stand some years should be due to a combination of higher amount of seeds (Bahamonde et al. 2011) and/or heavier seeds (Bahamonde et al. 2013a) compared to primary forests. Also, the wind effect could be an important factor in the contribution of miscellaneous to the litterfall, and there are antecedents indicating stronger winds in SCV (Bahamonde et al. 2009), which is accentuated when the structure of the forest is more open (Promis et al. 2010).

The incidence of the use of the forest on nutrients return was markedly different for each site class. While in SCIV there was a strong tendency to bigger nutrients return in the primary forest, in SCV, there were not differences between uses following the same pattern as the litterfall. Nevertheless, the range of values that we obtained was lower compared to those reported by Frangi et al. (2004) in ñire forests of Tierra del Fuego for all the nutrients (except S which was not evaluated in the cited report), but similar to those informed in *N. pumilio* by Caldentey et al. (2001). In our study, the different patterns showed by the different site classes were related to the litterfall and nutrients concentrations. Namely, in SCIV, the higher litterfall in primary forest during some years was accompanied by higher concentration of nutrients in leaves (only N was similar between uses), while in SCV, the litterfall was similar between uses and also the concentrations of nutrients were similar or higher in the silvopastoral stand.

The results suggest that the thinning practices for silvopastoral use in ñire forests could have different responses in the litterfall and nutrients return along the years depending on site class and the remaining structure after thinning. According that, the losses of litterfall caused by the removal of trees could be decreased (at less partially) leaving higher proportions of dominant and codominant trees keeping the wished crown cover. However, as we evaluated only one thinned stand for each site class, the conclusions are strictly valid only for the evaluated sites. Nevertheless, for a better understanding of the nutrients return in these systems, other aspects must be considered.

Related to this, Bahamonde et al. (2012b) informed an increase in the organic matter decomposition of leaves of ñire with increasing canopy opening, being replicated the pattern in two site classes, which could compensate the nutrients return into the soil in the short term. This is consistent with the reported by Bahamonde et al. (2013b) where the net nitrogen mineralization of soil did not change at different crown covers in the same two stands of ñire.

Influence of dasometric parameters on litterfall and nutrients return

The strong correlation between the basal area of the stands and its litterfall and nutrients return, regardless of the site class or use, is not surprising and has been suggested or documented in other studies. The data reported by Mansilla (2012) suggest that crown cover would be one of the key factors influencing the amount of litterfall, especially during the first year after thinning in stands of *N. pumilio*. Soler (2012) reported more production of seeds of *N. antarctica* in Tierra del Fuego in different types of stands (primary, secondary and silvopastoral forests) being this positively correlated to the basal area. This is coherent considering that within the basal area underlie other variables as DBH and density and that BA has been reported in some situations in ñire forests as correlated to the crown cover (Peri 2009) and therefore with the litterfall.

Conclusions

This study provides information about the role of the forest structure in its nutrient cycling. The results suggest that site quality where the ñire stand is growing has an incidence in litterfall and nutrients return. Thinning practices for silvopastoral use of these forests should consider the remaining structure as a key factor in nutrients return to the soil for long-term sustainability. Thus, the retention of a high proportion of dominant and codominant trees in the stand could reduce the loss of nutrients by the extraction.

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