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Litter decomposition and nutrients dynamics in *Nothofagus antarctica* forests under silvopastoral use in Southern Patagonia

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Abstract The role of environmental variables on litter decomposition and its nutrient release in *Nothofagus antarctica* forest in Patagonia is poorly understood. Moreover, in these forests under silvopastoral use there are few antecedents. Litter decomposition and nutrient release of grasses and tree leaves were evaluated under different crown cover and two site quality stands during 480 days. Organic matter decomposition varied with crown cover for both types of litter, achieving mean values of 23 and 34% for maximal and minimal crown cover, respectively. Total transmitted radiation was the main environmental factor explaining 61 and 49% of the variation of grass and tree leaves decay rates, respectively. N, P, and Ca were mineralized during first 60 days in decomposing tree leaves and then immobilized without differences between crown cover. The K was immobilized during the evaluated period. In decomposing grass leaves the results varied according to site quality and time. There was a tendency of nutrient mineralization at the first 120 days and then immobilization. The removal of trees for silvopastoral use of *N. antarctica* may increase litter decomposition by changing the microclimate, but nutrients release or immobilization was mainly affected for their concentration in decomposing material.

Keywords Litter decomposition · *Nothofagus* · Mineralization-immobilization · Silvopastoral system · Patagonia

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Introduction

Litter decomposition and its subsequent nutrient release is a fundamental process in nutrient cycles (Chapin et al. 2002). Nutrient release-immobilization in decomposing organic matter is affected by micro-environmental factors (e.g., temperature, air humidity and soil moisture) as well as litter quality (i.e., chemical composition) and organism and arthropod presence (Swift et al. 1979). Beside this, different forest uses may alter nutrient flows, and therefore their productivity in the long term. In Patagonia, ñire (*Nothofagus antarctica* (G. Forster) Oerst.) forests have been used mainly as silvopastoral systems where thinning increases understorey forage production by increasing available photosynthetic active radiation (PAR). There is evidence that canopy opening modifies micro environmental factors such as air temperature (Chen et al. 1999), soil temperature, soil moisture (Schroth and Sinclair 2003), soil properties (Hobbie and Gough 2004) and these changes consequently modify the litter decomposition process.

A few studies have been conducted in *Nothofagus* forest analyzing litter weight losses over time: woody debris decomposition (Frangi et al. 1997), litter decomposition in *N. pumilio* forests with different structures (Caldentey et al. 2001) and in an altitudinal gradients (Frangi et al. 2005), and *N. obliqua*, *N. pumilio* and *N. dombeyi* leaves decomposition and nutrient release in the Chilean Andes (Decker and Boerner 2006). However, there are no reports of leaf decomposition of tree and understorey species and nutrient release in *N. antarctica* forests under silvopastoral use.

Peri et al. (2008a) reported that the litter fall in these silvopastoral systems decreased by 30–50% compared with primary forest. Litter quality is also modified by changing the proportion of tree leaves and understorey plant species that are incorporated into the forest soil. This lower biomass with contrasting chemical composition such as carbon, nitrogen and lignin may modify the rates of litter decomposition at the stand level (Swift et al. 1979). Therefore, for a complete understanding of forest ecosystem functioning, it is necessary to know the dynamics of both the decomposition and nutrient release of tree leaves and understorey plant species. In this context we aim to answer the following questions: (i) does the silvicultural management of *N. antarctica* forest, through thinning practices, affect decomposition rates of grass and tree leaves? (ii) is this effect equal in forests having different site qualities? to answer these questions, the aims of this study were to (1) quantify the effects of different crown cover on the decomposition of grass and tree leaves in two stands growing in sites of different qualities; and (2) determine mineralization-immobilization nutrient dynamics in tree and grass leaves.

Materials and methods

Study sites

The study was conducted in pure *N. antarctica* forests under silvopastoral use in two site quality stands in the southwestern of the Santa Cruz province (Argentina): (i) site class IV (SCIV) (51°13′23″S–72°15′39″W) where the mean dominant height (H) of mature trees reached 8.0 m and (ii) site class V (SCV) (51°19′05″S–72°10′47″W) where H reached 4.7 m. (Lencinas et al. 2002). In each site, an adjacent area was selected without trees representing a transition zone between forest and steppe.

The regional climate is cold temperate humid with a mean annual temperatures between 5.5 and 8.0°C, and precipitation (rain and snow) ranging between 400 and 800 mm year^{-1} (Soto 2004).

The soils classified as Mollisols-haploxerolls according to USDA classification had 0.8 m of depth. The slopes were 8 and 5% for SCIV and SCV, respectively.

To characterize soil properties, composite samples of five soil cores were taken (30 cm depth) at random under the tree crown projection (0.5 m from main trunk), between tree crowns (mean distances between trees of 8.2 m), and the adjacent area without trees in all the studied stands. The following analyses were conducted: (a) organic carbon (C) determined with spectrophotometry according to Kurmies after wet oxidation in acid medium (Houba et al. 1988); (b) total nitrogen content (N) determined by semi-micro Kjeldhal method (Sparks 1996); (c) available phosphorus content (P) using the Truog method (Sparks 1996); (d) cation exchange capacity (CEC) determined using saturation with sodium acetate, washed with ethylic alcohol, displacement through pH 7 buffered ammonium acetate, and sodium determination using an inductively-coupled plasma atomic emission spectrometer (ICPS Shimadzu 1000III, Japan). The pH was obtained by potentiometric measurement in water-saturated paste. The determination of texture was carried out through the densimeter method of Bouyoucos and sieving the sand fractions. Soil properties are given in Table 1.

Stands were characterized with three circular plots of 500 m^2. 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 identify the grasses species in each site, vegetation census were conducted in the forest stands and in the adjacent area without trees using a phytosociological method (Braun-Blanquet 1950). The main grass species found in the forest were: *Agrostis flavidula*, *Bromus setifolius*, *Deschampsia flexuosa*, *Festuca pallescens*, *Phleum commutatum*, *Poa pratensis*, and *Rytidosperma virescens*. In the adjacent area the main grass species were: *Agrostis flavidula*, *Festuca gracilima* and *Festuca pallescens*.

Environmental measurements

Solar radiation intensities (direct and diffuse) reaching the forest soil were estimated in two contrasting crown cover situations (under and between crowns) in each study site. For this, hemispherical photos of forest canopy were taken at 1 m high from ground level in two phenological moments: maximum leaf expansion (February) and winter when mast tree leaf fall occurred (July). Photos were taken in each position of crown cover by using a fisheye lens (Sigma, Japan) of 8 mm mounted on a 35 mm digital camera (Nikon D70, Japan) levelled with a tripod to ensure the horizontal position. Each photo was taken oriented with reference to magnetic north and in cloudy sky conditions, early morning or during the evening after sunset. Photos were analysed using the software Gap Light Analyser v.2.0 (Robison and McCarthy 1999) obtaining the following parameters: crown cover (CC) as the forest canopy percentage in the photo and photosynthetically active radiation (PAR) at the understorey level as the total direct and diffuse radiation transmitted through the canopy. The software was supplemented with the following variables: (a) a projection of distortion provided by the manufacturer of the lens; (b) a sky division grid consisted of 20 azimuths and 4 regions of zenith; (c) a constant of 1,367 W m^2 for solar radiation that reaches the earth and a clear sky transmission coefficient of 0.6; (d) a cloudiness index, spectral fraction and a relationship between direct and global radiation derived from radiation data series (years 2004–2005) of the Universidad de Magallanes (Punta Arenas, Chile) (Santana et al. 2006) and the VAG-Ushuaia (Global Atmospheric Watch Station).

Air and soil temperatures, and air relative humidity were measured continuously every 2 h with a datalogging system (HOBO H8 Family, Onset Computer Corporation, USA), using a sensor at each crown cover (under and between crowns) and the adjacent area without trees in both studied site quality stands. Sensors of air temperature and air relative humidity were placed at 1 m height from ground level. Soil temperature was measured at 3 cm depth using soil thermometers (HOBO, Model TMC50-HA, USA).

Table 1 Soil properties (0–30 cm) of *Nothofagus antarctica* study sites

Crown cover	C (%)	N (%)	C/N	P Truog (ppm)	Ca ($cmol_c\ kg^{-1}$)	K ($cmol_c\ kg^{-1}$)	pH	Sbd ($gr\ cm^{-3}$)	Texture
Site class IV									
Under crown	4.4	0.32	13.7	8	11.6	0.5	4.9	0.61	Sandy loam
Between crowns	3.5	0.28	12.5	31	5.8	1.3	4.9	0.84	Sandy loam
Without trees	6.8	0.84	8.1	6.8	31.7	0.4	5.6	0.48	Sandy loam
Site class V									
Under crown	4.7	0.40	11.8	67	32.6	2.7	5.5	0.75	Loam
Between crowns	4.5	0.43	10.5	32	3.3	1.0	5.5	0.68	Loam
Without trees	6.8	0.67	10.1	8	24.6	1.0	5.3	0.75	Loam

Sbd Soil bulk density

Periodically measurements of gravimetric soil moisture were obtained from the first 30 cm ($n = 5$) in each study situation. Then, volumetric soil moisture was calculated using soil bulk density and the gravimetric measurements.

Experimental design and biological measurements

A factorial experiment design with level of radiation and time as main factors was carried out at each study site. For decomposition and nutrient release of *N. antarctica* senescent leaves two radiation levels (under and between tree crowns) and three levels of radiation for grass (under and between tree crowns, and adjacent area without trees) were used. For both cases, the time factor had six levels corresponding to dates of extraction (60, 120, 180, 330, 420 and 480 days). Senescent leaves of *N. antarctica* and main grasses species of understorey were collected between March and May. At the same moment senescent leaves of main grass species were collected in the adjacent areas without trees. The collected material was taken to the laboratory and air dried at room temperature to constant weight. Samples of 5 g of each material were enclosed in 10 × 10 cm polyethylene gauze bags (2 mm mesh). Sub-samples of 3 g were oven dried for 48 h at 60°C to calculate the moisture content. Also, samples of *N. antarctica* and grass leaves were analysed for determination of initial lignin, C, N, P, K and Ca concentration. Lignin was determined using Klason method in sulphuric acid in Ancom system (Theander et al. 1995). C was determined by dry combustion method with an elemental analyser (Leco, model CR-1, USA) and N was determined by semimicro Kjeldahl. Concentrations of P, K and Ca were determined with a plasma emission spectrometer (Shimadzu ICPS-1000 III, Japan).

In October 2005, in each study site six bags with *N. antarctica* senescent leaves and senescent grass leaves were placed in five plots of 1.8 m^2 (replicates) under tree crowns and five plots between crowns. In the adjacent areas without trees five plots (replicates) were set up with six bags containing senescent grass leaves. The bags were placed horizontally on the soil surface and fixed with pegs. Five bags (one per plot) of each material and radiation levels (crown cover) were taken from both sites at each date. In the laboratory, the material was removed from the bags, cleaned by removing external material, and weighed after drying at 60°C for 48 h. Corrections for inorganic contaminants (mainly soil particles) were made after determining loss-on ignition of all samples (4 h, 500°C). Samples taken at each time were analysed for macro nutrients (N, P, K and Ca). Carbon was analysed only once at the start and the end of the experiment. The absolute amount of each nutrient was calculated by multiplying the concentration by its corresponding remaining mass. The nutrient mass data obtained in each extraction date were expressed as a percentage of the initial values of ash-free basis.

Data analysis

Dasometric characteristics of each study stand were analysed by analysis of variance (ANOVA). Total transmitted radiation data were analysed by ANOVA with crown cover as a factor. Decomposition of organic matter from senescent *N. antarctica* leaves and grasses were analysed with ANOVA for repeated measurements with crown cover as an inter-subject factor and each sampling date as an intra-subject factor. This analysis was done because the decomposition values are not independent of time. This type of analysis has been shown to be appropriate for these cases (Gurevitch and Chester 1986). Decomposition of *N. antarctica* senescent leaves and grass were analysed separately for each site. Tukey tests were performed to test differences among crown cover when *F*-values were significant ($P < 0.05$). To avoid misinterpretations due to significant interaction between factors (Willems and Raffaelle 2001) multiple comparisons were made concerning to intra-subject effects, (radiation levels) for each sampling date.

Similarly ANOVA was conducted for repeated measurements over time for each studied nutrient. To calculate the decomposition constant (k) for the evaluation period, a simple exponential decay model was used (1) described by Olson (1963). The corresponding decay constants k for each crown cover in the study stands was calculated using (Eq. 2).

$$X1/X0 = e^{-kt} \tag{1}$$

$$k = \frac{-\ln(X1/X0)}{t} \tag{2}$$

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.

Subsequently, the obtained decay constants *k* were compared between crown covers by ANOVA using the Tukey test ($P < 0.05$) for mean separation. These tests were conducted separately for each site class and material (*N. antarctica* and grass senescent leaves). Linear regression analysis between environmental variables and *k* was carried out to determine which variable would have more influence on litter decomposition. The time (years) that takes to decompose 99% of organic matter (t_{99}) was estimated according to *k* values obtained (Eq. 2).

Results

Dasometric characteristics and micro-climate variation

The total height (dominant trees), number of trees and basal area were higher in SCIV ($P < 0.05$) than in SCV (Table 2). In both stands, light transmissivity and total photosynthetically active radiation reaching the forest floor increased ($P < 0.05$) in places where crown cover decreased (Table 3).

Both air and soil temperatures showed maximum values during summer and minimum in winter (Figs. 1, 2). Air temperature did not differ between different crown cover in any of the two evaluated site quality stands. In contrast, soil temperatures were higher in open sites in spring and summer during the first season in SCIV, but not in SCV. Volumetric soil moisture was higher in more open sites of the silvopastoral stands during spring and summer in SCIV (Fig. 1), while in SCV no differences were found between crown cover (Fig. 2). Relative air humidity was lower in the adjacent open areas.

Characteristics of the decomposing material

The initial concentrations of lignin and nutrients evaluated for senescent *N. antarctica* leaves showed that P, Ca, C/N and Lignin/N ratios was higher ($P < 0.05$) in SCIV compared with SCV (Table 4). Initial values of Ca concentration and Lignin/N ratio for grass leaves were lower ($P < 0.05$) in SCIV than SCV, while the C/P and N/P ratios were higher.

On the other hand, there were no significant differences ($P > 0.05$) in final values of carbon and macro nutrients content of tree leaves between radiation levels and for grass leaves in SCV (Table 5). For grass leaves in SCIV, the final value of *k* was lower ($P < 0.05$) under crown, the Ca was lower ($P < 0.05$)

Table 2 Mean dasometric characteristics of studied *N. antarctica* stands

Site class	Height (m)	Density (trees ha^{-1})	DBH (m)	Basal area (m^2 ha^{-1})	Crown classes (%)			
					D	C	I	S
IV	8.0a	418a	28.3a	47.0a	37a	25b	19a	19a
V	4.7b	357b	25.7a	19.8b	43a	38a	14a	5b

Note: Among Site Class, means followed by the same letter do not differ significantly ($P > 0.05$)

DBH diameter at breast height

D dominant trees, *C* codominant trees, *I* intermediate trees, *S* suppressed trees

Table 3 Light transmissivity (%) and mean annual PAR (mols m^{-2} day^{-1}) of studied *N. antarctica* stands under different crown cover

	Crown cover (SCIV)			Crown cover (SCV)		
	Under crown	Between crowns	Without trees	Under crown	Between crowns	Without trees
Light transmissivity (%)	30c	49b	100a	32c	64b	100a
Direct radiation	2.7c	4.1b	5.6a	2.8c	4.6b	5.5a
Diffuse radiation	9.1c	14.5b	20.4a	9.1c	15.9b	20.4a
Total radiation	11.8c	18.6b	26.0a	11.9c	20.5b	25.9a

Note: Among Crown cover, means followed by the same letter do not differ significantly ($P > 0.05$). Analyses were performed separately for each Site Class (SC)

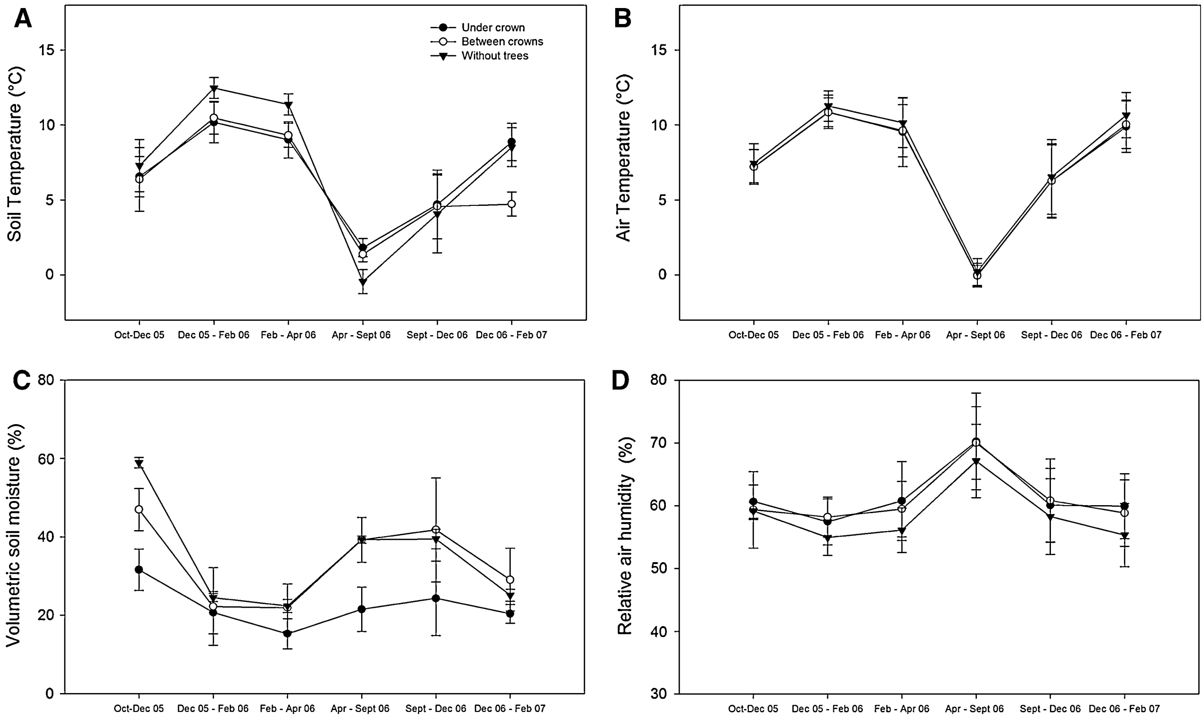

Fig. 1 Mean soil (**A**) and air (**B**) temperature, volumetric soil moisture (**C**), and air relative humidity (**D**) of each evaluated period for three radiation levels in *N. antarctica* forest grown at site class IV. *Bars* indicate the standard deviation of the mean

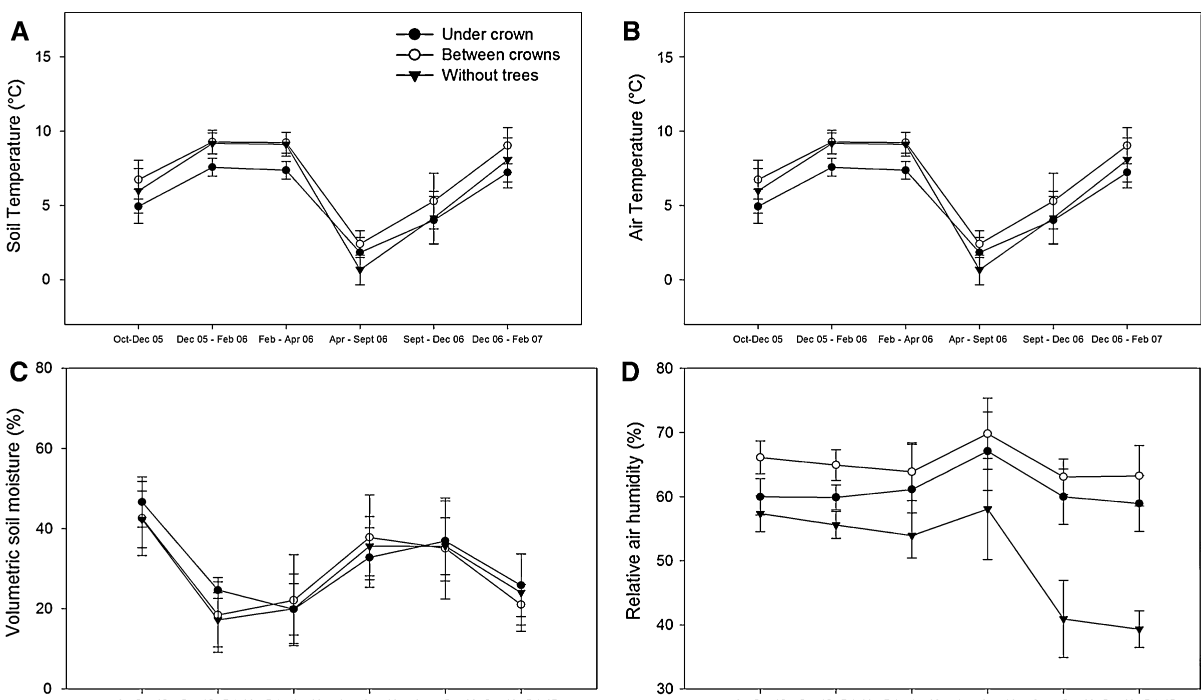

Fig. 2 Mean soil (**A**) and air (**B**) temperature, volumetric soil moisture (**C**), and air relative humidity (**D**) of each evaluated period for three radiation levels in *N. antarctica* forest grown at site class V. *Bars* indicate the standard deviation of the mean

Table 4 Initial mean values of lignin, carbon and macronutrients concentration in senescents *N. antarctica* and grasses leaves of the studied sites

	Lignin (%)	N (%)	P (%)	K (%)	Ca (%)	C/N	Lignin/N	C/P	N/P
N. antarctica leaves									
Site class IV	17.9 (1.7)	0.58 (0.17)	0.12 (0.02)	0.05 (0.02)	1.68 (0.40)	86 (2)	30.9 (1.5)	416 (124)	5.0 (1.5)
Site class V	16.0 (1.4)	0.72 (0.23)	0.07 (0.01)	0.08 (0.04)	1.12 (0.08)	70 (3)	22.2 (1.1)	723 (187)	9.8 (3.0)
Statistical significance	ns	ns	*	ns	*	**	**	ns	ns
Grasses leaves									
Site class IV	3.5 (0.5)	0.39 (0.09)	0.03 (0.01)	0.10 (0.02)	0.17 (0.02)	104 (20)	9.1 (0.5)	1353 (142)	13.8 (1.0)
Site class V	3.8 (0.3)	0.37 (0.08)	0.05 (0.01)	0.16 (0.09)	0.44 (0.04)	106 (16)	12.6 (0.7)	786 (228)	7.6 (1.1)
Statistical significance	ns	ns	ns	ns	**	ns	*	*	*

Number in parentheses are the Standard deviation of the mean

ns not significant

$*P < 0.05$; $**P < 0.01$

between crown and C/P ratio was lower ($P < 0.05$) in the adjacent area without trees (Table 5).

Organic matter decomposition

In both site class stands, the remaining organic matter of tree leaves varied significantly over time ($P < 0.001$) with a significant interaction ($P < 0.05$) between time and crown cover (Fig. 3). The decomposition rate of organic matter was higher during the first 60 days and the lowest values occurred between 180 and 330 days (period April–September). Decomposition differences were observed between levels of radiation from 120 days, being higher between crowns. In both stands, the decomposition of *N. antarctica* leaves reached 20 and 30% under and between crowns, respectively.

Similarly, remaining organic matter of grass leaves varied over time ($P < 0.001$), being the decomposition higher during the first 60 days and decreasing in the period April–September (from 180 to 330 days after the beginning of the experiment). There was also an interaction ($P < 0.05$) between time and radiation levels in both site class stands. After 60 days, there were significant differences ($P < 0.05$) in decomposition between radiation levels, being higher in the adjacent areas without trees at both sites (Fig. 4). At the end of the period (480 days), decomposition values in both stands were 27 and 38% under crown and without trees, respectively.

Decay constants of tree and grass leaves

Decay constants of *N. antarctica* leaves differed between levels of radiation in both site class stands (Table 6). Decay constants were higher ($P < 0.05$) at the highest levels of radiation (between crowns). The time to decompose 99% (t_{99}) organic matter at these rates (14.9 and 17.1 years in SCIV and SCV, respectively) varied significantly with radiation levels, being lower between crowns. Similarly, the decay constants of grass leaves were higher ($P < 0.05$) in situations without trees in both sites, and consequently with lower decomposition time (Table 7).

While almost all environmental variables had a significant ($P < 0.05$) effect on organic matter decomposition, total transmitted radiation was the main factor explaining 61 and 49% of decay rates variation for grass and tree leaves, respectively (Table 8).

Table 5 Final mean values of carbon and macronutrients concentration in senescent *N. antarctica* and grasses leaves, at the end of the evaluated period in the studied sites

	N (%)	P (%)	K (%)	Ca (%)	C/N	C/P	N/P
N. antarctica leaves							
Site class IV							
Under crown	0.78 (0.13)	0.05 (0.01)	0.22 (0.14)	1.23 (0.12)	57 (12)	951 (317)	16 (6)
Between crowns	0.82 (0.17)	0.06 (0.01)	0.27 (0.15)	1.37 (0.04)	63 (15)	815 (114)	13 (2)
Statistical significance	ns	ns	ns	ns	ns	ns	ns
Site class V							
Under crown	0.84 (0.07)	0.06 (0.01)	0.15 (0.07)	1.26 (0.16)	56 (5)	779 (116)	13 (2)
Between crowns	1.08 (0.34)	0.06 (0.01)	0.22 (0.07)	1.33 (0.18)	45 (14)	735 (182)	16 (6)
Statistical significance	ns	ns	ns	ns	ns	ns	ns
Grasses leaves							
Site class IV							
Under crown	0.39 (0.09)	0.05 (0.02)	0.15b (0.09)	0.25ab (0.04)	118 (30)	1053ab (387)	9 (3)
Between crowns	0.30 (0.10)	0.03 (0.01)	0.33a (0.05)	0.22b (0.08)	159 (53)	1822a (726)	12 (4)
Without trees	0.47 (0.17)	0.04 (0.01)	0.30a (0.09)	0.34a (0.03)	103 (65)	998b (207)	11 (5)
Statistical significance	ns	ns	**	*	ns	*	ns
Site class V							
Under crown	0.39 (0.19)	0.04 (0.02)	0.28 (0.07)	0.31 (0.10)	127 (55)	1269 (455)	10 (3)
Between crowns	0.56 (0.17)	0.04 (0.01)	0.23 (0.13)	0.33 (0.07)	80 (23)	1007 (189)	13 (3)
Without trees	0.48 (0.09)	0.04 (0.01)	0.24 (0.06)	0.27 (0.05)	87 (17)	1134 (331)	13 (3)
Statistical significance	ns	ns	ns	ns	ns	ns	ns

Number in parentheses are the Standard deviation of the mean

ns not significant

*$P < 0.05$; **$P < 0.01$

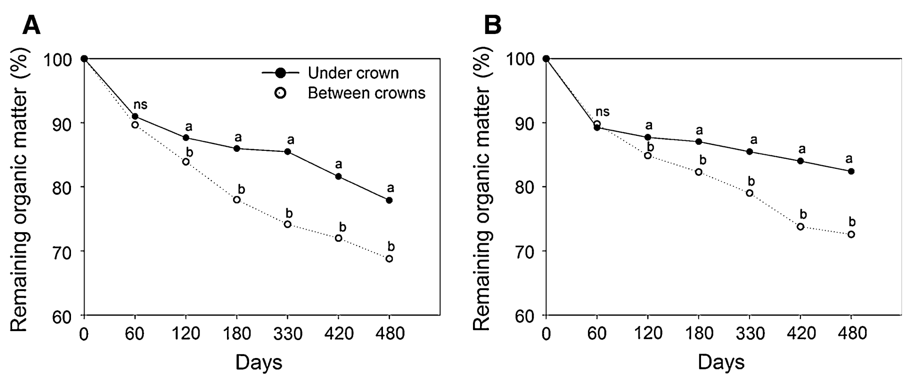

Fig. 3 Variation of remaining organic matter (as a percentage of the initial weight) over time (start October 2005) of tree leaves under two levels of radiation in N. antarctica forests growing at site class IV (**A**) and V (**B**). *Different letters* in a same date indicate significative differences ($P < 0.05$); *ns* not significant

There were no significant differences ($P > 0.05$) in decay constants (k) due to material quality (chemical composition) of *N. antarctica* and grass leaves over the evaluated period in both site class stands and under different radiation level.

Nutrient mineralization of *Nothofagus antarctica* leaves

During the first 60 days, there was a release of N from *N. antarctica* leaves at the two site class stands, and

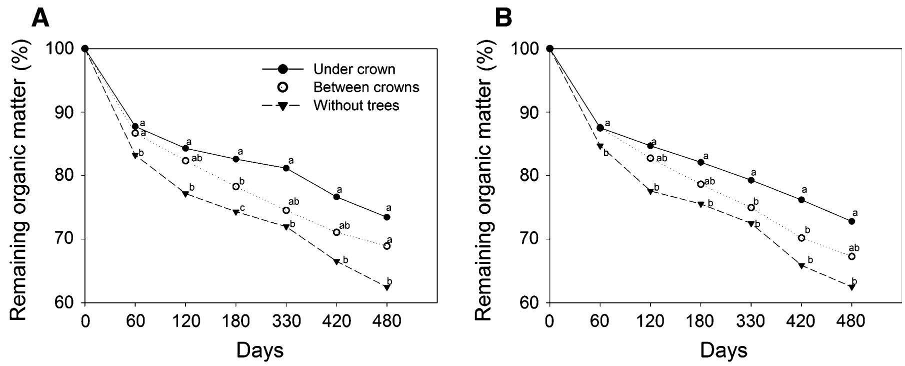

Fig. 4 Variation of remaining organic matter (as a percentage of the initial weight) over time (start October 2005) of grasses leaves under three levels of radiation in N. antarctica forests growing at site class IV (**A**) and V (**B**). *Different letters* in a same date indicate significative differences ($P < 0.05$); *ns* not significant

Table 6 Decay constants (k) and total time of decomposition of 99% (t_{99}) organic matter for *N. antarctica* tree leaves in the studied sites

Crown cover	Model†	Significance‡	R^2	$k^{\S}$ (year^{-1})	$t_{99}^{\S}$ (years)
SCIV					
Under crown	$X_1/X_0 = 92.0\ e^{-0.112\ t}$	**	0.88	0.20b	23.0a
Between crowns	$X_1/X_0 = 90.0\ e^{-0.21\ t}$	***	0.93	0.31a	14.9b
SCV					
Under crown	$X_1/X_0 = 89.4\ e^{-0.06\ t}$	**	0.89	0.17b	27.1a
Between crowns	$X_1/X_0 = 90.9\ e^{-0.17\ t}$	***	0.96	0.27a	17.1b

† Model, decay model according to Olson (1963)

R^2 coefficient of determination

‡ Significance, decay model significance, ** $P < 0.01$, *** $P < 0.001$

§ Among crown cover, means followed by the same letter do not differ significantly ($P > 0.05$). Analyses were performed separately for each Site Class (SC)

Table 7 Decay constants (k) and total time of decomposition of 99% (t_{99}) organic matter for grass leaves in the studied sites

Situation	Model†	Significance‡	R^2	$k^{\S}$ (year^{-1})	$t_{99}^{\S}$ (years)
SCIV					
Under crown	$X_1/X_0 = 89.1\ e^{-0.14\ t}$	***	0.94	0.26b	17.7a
Between crowns	$X_1/X_0 = 87.8\ e^{-0.19\ t}$	***	0.97	0.31b	14.9a
Without trees	$X_1/X_0 = 84.6\ e^{-0.22\ t}$	***	0.94	0.39a	11.8b
SCV					
Under crown	$X_1/X_0 = 89.2\ e^{-0.15\ t}$	***	0.98	0.25b	18.4a
Between crowns	$X_1/X_0 = 89.2\ e^{-0.21\ t}$	***	0.97	0.32ab	14.4ab
Without trees	$X_1/X_0 = 86.1\ e^{-0.24\ t}$	***	0.94	0.39a	11.8b

† Model, decay model according to Olson (1963)

R^2 coefficient of determination

‡ Significance, decay model significance, ** $P < 0.01$, *** $P < 0.001$

§ Among crown cover, means followed by the same letter do not differ significantly ($P > 0.05$). Analyses were performed separately for each Site Class (SC)

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* not significant

R^2 coefficient of determination

then there was immobilization without significant differences ($P > 0.05$) between radiation levels (Fig. 5), except in SCV at the end of evaluated period.

P was mineralized at the two radiation levels in the first 60 days with different magnitude depending on the stand site class. Then, there was a tendency of immobilization until the end of evaluation period with no differences ($P > 0.05$) between radiation levels.

In both site class stands the mineralization–immobilization process of Ca did not differ ($P > 0.05$) between radiation levels at any time. Ca mineralization occurred only between 120 and 180 days in SCV and mainly during the first 180 days in SC IV. K was immobilized in all situations with higher ($P < 0.05$) values between crowns.

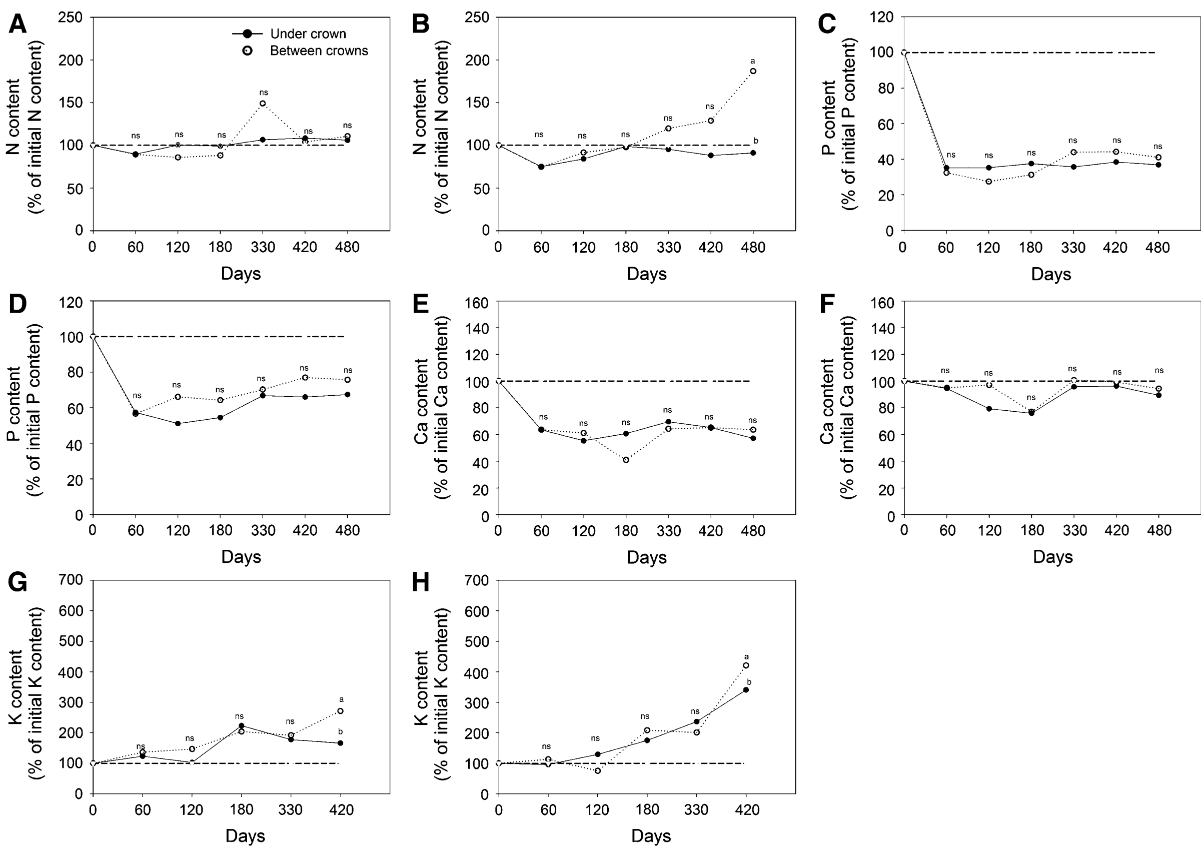

Fig. 5 Change over time (beginning October 2005) of nitrogen (N), phosphorus (P), calcium (Ca) and potassium (K) content as percentage of initial content in tree leaves incubated at two levels of radiation in *N. antarctica* forests growing at site class IV (**A**, **C**, **E** and **G**) and V (**B**, **D**, **F** and **H**). *Different lowercase letters* indicate significative differences ($P < 0.05$) between radiation levels for each site class; *ns* not significant. The *dotted line* corresponds to the reference value (100%)

Nutrient mineralization of grasses leaves

While in SCIV, there was mineralization of N from decomposing grass leaves during the first 60 days in all radiation levels, in SCV this occurred only under crown (Fig. 6).

P was mineralized with no differences ($P > 0.05$) between levels of radiation during the first 60 days in SCIV (Fig. 6). Then, there was a tendency to immobilization by increasing P content until the end of evaluation period with different magnitudes depending on radiation levels. In SCV, P was released during the first 60 days with higher values under crown ($P < 0.05$), following by immobilization.

Ca dynamics strongly depended on site class (Fig. 6). In SCIV there was immobilization of Ca throughout the experiment duration with different magnitudes according to radiation levels. In SCV, Ca was mineralized during the first 60 days with higher values under crown, and then immobilized until the end of the evaluation period.

K from grass leaves was mineralized during the first 60 days in SCIV and the first 120 days in SCV at all levels of radiation (Fig. 6). Since these dates, there was a fluctuation between immobilization and mineralization.

Discussion

Organic matter decomposition

In general most of the nutrients and lignin initial values of this study were in the range of those reported

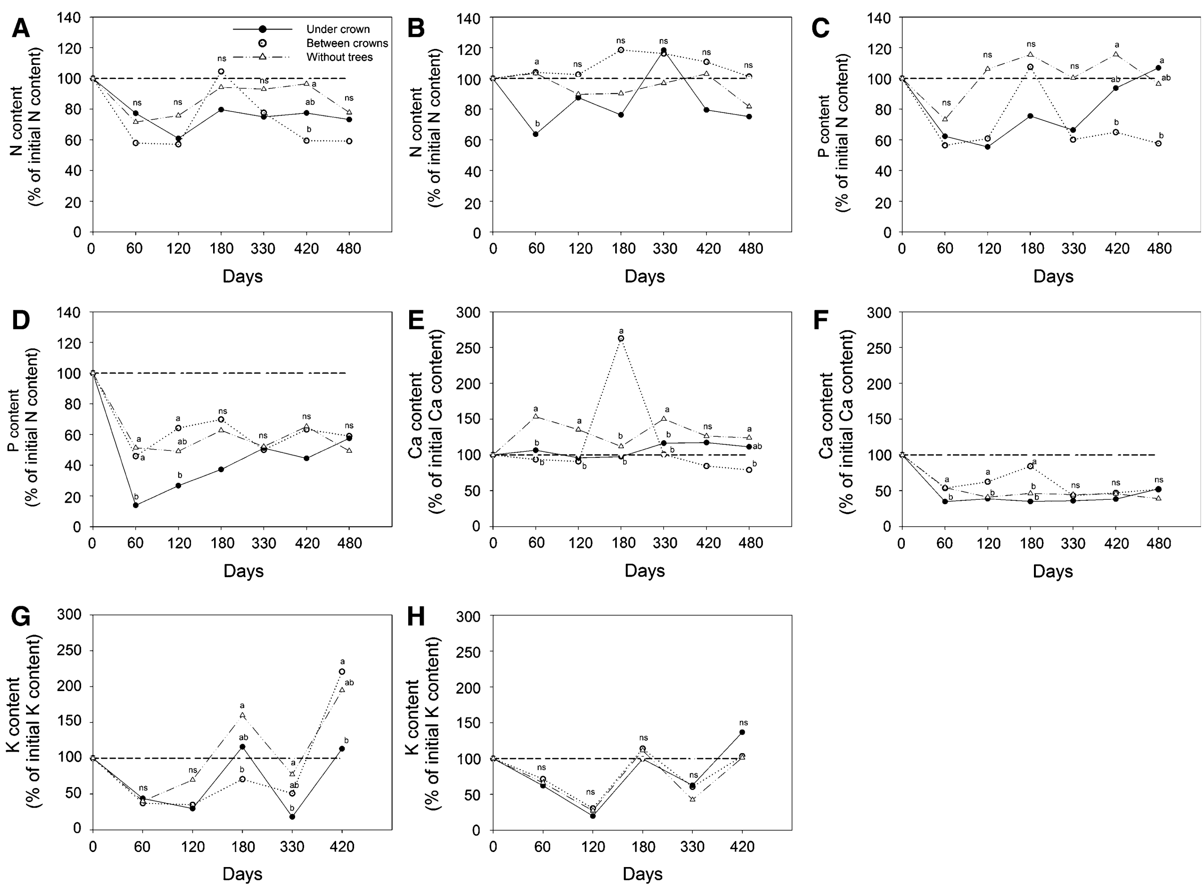

Fig. 6 Change over time (beginning October 2005) of nitrogen (N), phosphorus (P), calcium (Ca) and potassium (K) content as percentage of initial content in grasses leaves incubated at three levels of radiation in *N. antarctica* forests growing at site class IV (**A**, **C**, **E** and **G**) and V (**B**, **D**, **F** and **H**). *Different lowercase letters* indicate significative differences ($P < 0.05$) between radiation levels for each site class; *ns* not significant. The *dotted line* corresponds to the reference value (100%)

by other authors for *N. antarctica* (i.e., Mazzarino et al. 1998; Moretto et al. 2004), except the concentration of K which had lower values that would indicate a high resorption of this element before leaves fall (Diehl et al. 2003). Mazzarino et al. (1998) reported similar concentrations of lignin, C, N y P for grasses grown in the steppe of northern Patagonia.

There were no antecedents about grass leaf decomposition under silvopastoral systems in Patagonia. In this work, organic matter decomposition of *N. antarctica* and grass was affected by crown cover. Similarly, Caldentey et al. (2001) reported higher values of leaf litter decomposition (53% in 360 days) in a *N. pumilio* forest managed through shelterwood cuts (50% crown cover) compared to primary unmanaged forests (80–90% crown cover) in southern Chile. Similarly, Moretto et al. (2004) reported an increased decomposition of leaf litter in *N. pumilio* forests under silvicultural management compared with unmanaged forests in Tierra del Fuego (Argentina). However, Prescott et al. (2000) found that the decomposition of *Populus tremuloides* leaves between thinned and unmanaged forests did not show significant differences. The results found in the present study indicate that a canopy opening generated environmental conditions that increased *N. antarctica* and grass leaves decomposition. These modifications in the environmental conditions were reflected mainly in the increasing soil temperature in the most canopy open situations (between trees in the silvopastoral system and in the adjacent areas without trees) that promotes decomposition in cold weather areas (Swift et al. 1979; Yin et al. 1989). Highest level of solar radiation may have a direct action (i.e., photo degradation processes) or indirectly facilitating the action of micro organisms over litter decomposition (Austin and Vivanco 2006). Besides this, there are other factors that also affect organic matter decomposition such as soil moisture, which varied between seasons and radiation levels (i.e., soil moisture was higher in open sites). Low percentages of soil moisture can decrease the diffusion rate of substrates for decomposer organisms (Chapin et al. 2002). Yahdjian et al. (2006) reported a linear correlation between decomposition rates and soil water content. Also, rainfall and winds could cause losses of litter by leaching or physical fragmentation (Brandt et al. 2007). In general, wind speed (of great importance in Patagonia) is reduced in *Nothofagus* stands with higher crown cover levels (Bahamonde et al. 2009) and this could affected the organic matter decomposition found in the present work.

The highest percentage of *N. antarctica* and grass leaf decomposition occurred in the first stage of the process (60 days). This observation has been also documented in a wide range of environmental conditions and litter types (i.e., Moretto and Distel 2003; Brandt et al. 2007). This rapid disappearance is driven mainly by the leaching of soluble substances and a rapid degradation of the more labile components of the decomposing material (Berg et al. 1996) when environmental conditions do not restrict the micro organism activity. In our study, the microclimatic factors in the first 60 days (6°C mean soil temperature and 40% volumetric soil moisture) were within a range that microbial activity is not limited (Prescott 2005). The lowest decomposition rates found in the period autumn–winter may correspond to limitations of the process due to low soil temperatures.

The quality of decaying litter interacting with environment may affect decomposition rate of organic matter. Brandt et al. (2007) reported a higher percentage of litter decomposition in a high C/N ratio litter exposed to high ultraviolet radiation compared with litter exposed to a low radiation levels. This can be considered of importance in our study, since the initial values of C/N ratio were high (>70) and therefore N would be limiting the biological action on the decomposition (Swift et al. 1979). Furthermore k values obtained in the present work for *N. antarctica* leaves were in the range of those found for the same specie in Tierra del Fuego (Frangi et al. 2004), but lower than those reported for *N. pumilio* in Southern Chile (Caldentey et al. 2001), probably because of differences in the quality of the decomposing litter. Also, the decay constants for grass leaves were in the range of values reported previously for different species (i.e., Moretto and Distel 2003; Yahdjian et al. 2006). In our study, decay constants were affected mainly by lower crown cover resulting in higher levels of radiation.

Nutrient mineralization of *Nothofagus antarctica* leaves

In our work, the release of N from *N. antarctica* leaves was similar to those reported by Moretto et al. (2004) for *N. pumilio* leaves in primary forests and different regeneration systems in Tierra del Fuego, Argentina. Similarly, Decker and Boerner (2006) reported similar results in litter of other *Nothofagus* species in the Central Andes in Chile, despite the difference in environmental conditions and quality of the material. Differences in N mineralization can be attributed to litter quality of material (i.e., initial N concentration) or environmental factors (temperature, humidity, precipitations) (Prescott 2005) and their interactions. In our work, the N immobilization was driven mainly by the low initial N concentration of leaves that increase the C/N ratio and consequently limited the micro-organisms activity. The positive correlation between initial litter N content and mineralization in the initial stage of the process has been also reported for different types of decomposing material (i.e., Aber and Melillo 1980; Berg and Ekbohm 1983). Also, the immobilization of N was caused by low soil temperatures during winter that would slow microbial activities, in general, resulting in lower mineralization and or immobilization (Swift et al. 1979).

P was mineralized mainly in the first 60 days. In contrast, Decker and Boerner (2006) reported immobilization of P in leaves of three *Nothofagus* species in Chile during the first year. Similar to what occurred with N, the initial release of P (mineralization) in decaying material has been attributed to its initial concentration and the C/P ratio (Prescott 2005). In our study the initial C/P values of 416 and 723 for SCIV and SCV, respectively (Table 4), were in the suggested range for P release. For example, Rustad and Cronan (1988) indicated values of C/P between 350 and 450, and Edmonds (1980) found P mineralization even with values of 694. It has also been established that mineralization or immobilization of N and P are closely related to the litter N/P ratio (Prescott 2005). Several authors (i.e., Berg and Laskowski 1997) reported that initial N/P ratio of litter less than 15 facilitate the release of P. In the present study N/P ratios were below the initial critical of 15 which indicate that the N and P mineralization was not limited by this litter quality ratio.

The differential response between sites in Ca release was due mainly by the initial litter Ca concentration. The low initial litter Ca concentration in SCV limited the requirements of biological organisms (Laskowski et al. 1995) resulting in Ca immobilization. In contrast, the highest Ca concentration in SCIV would be enough to keep biological demand and release the excess, at least during the first 180 days of measurements. After this period, the trend of Ca immobilization in both site class stands contrasted with other studies, where Ca showed similar response to organic matter decomposition (i.e., Laskowski et al. 1995; Barrera et al. 2004). The temporal variation found in this study also contrasts with Osono and Takeda (2004) who reported a response in two phases with increasing Ca concentration (immobilization) up to the first 21 months, and then a decreased in Ca concentration (mineralization) during 3 years. Our results suggest that the evaluated period was not long enough to account for Ca decomposition of structural components due to low temperature environment.

In this work, K was immobilized in all evaluated situations. This contrasts with other authors who reported for different types of material and environmental conditions a K release from litter (i.e., Schlesinger and Hasey 1981; Laskowski et al. 1995; Barrera et al. 2004; Osono and Takeda 2004). In our study, the extremely low initial concentrations of K would limit the microbial activity (Swift et al. 1979) with its consequent immobilization. Low K concentration in senescent leaves could be explained because it is highly resorpted (Peri et al. 2008b) and easily washed by rainfall prior to leaf fall (Fisher and Binkley 2000). Also the significant increase in K over time could be due rainfall deposition (Goulding 1987).

In contrast with organic matter decomposition results, nutrient release from *N. antarctica* leaves was not affected by canopy opening.

Nutrient mineralization of grass leaves

The results of nutrient mineralization from senescent grass leaves are relevant in *N. antarctica* forest under silvopastoral use.

The mineralization of N in the early period (60 days) of the process would be associated with the washing of more labile components of decomposing material, which has been demonstrated for other grass species and different environmental conditions (Moretto and Distel 2003). The subsequent N immobilization after the rapid initial release could be explained for the extremely low concentrations that limit microbial activity (Aber and Melillo 1980). This is consistent with Aerts and De Caluwe (1997) who found negative correlations between N immobilization from decomposing grass and its initial N concentration. Similar to *N. antarctica* leaves, the relative increase of N in decomposing grass leaves could be caused by microclimatic environmental factors (i.e., soil and air temperature, and air humidity) that limit microbial activity and exogenous inputs N.

The rapid P release of labile components of decaying material found in this study was similar to results reported by Moretto and Distel (2003). The subsequent rise in P (immobilization) should be due to low initial P concentrations (especially in SCIV) which limited the micro-organisms activity (Qiu et al. 2008).

The differential response between site classes in Ca release, especially in the first 60 days was due to a higher initial Ca concentration of litter in SCV. As for *N. antarctica* leaves, in the evaluated period there was not a strong decomposition of structural components. Also, the soil acidity may determine that micro-organisms increased the demand for this nutrient with its consequent immobilization especially when the amounts of Ca in decomposing materials were limiting (Swift et al. 1979).

The rapid release of K in the early stages of decomposition (60 days) has been reported for other grass litter quality and environmental conditions (Osono and Takeda 2004), but lasting for longer period of time. This is because in most cases the initial litter concentration of K is high compared with the grass species evaluated in the present study.

There was no consistency between the rate of grass leaves decomposition and nutrient dynamics for the different tree crown cover (levels of radiation). This underscores that nutrient dynamic was determined primarily by the litter chemical composition and in less extent by its interaction with the environment.

The removal of trees through thinning practices for silvopastoral use of *N. antarctica* forest in Patagonia caused a decrease of 35–50% in the contribution of litter to soil forest (Peri et al. 2008a). However, this reduction of litter in managed forests is accompanied by an increased rate of decomposition that may result in a faster nutrient cycling and reduce accumulation of litter in the topsoil along with other fine and coarse detritus (Frangi et al. 1997). Furthermore, opening the canopy generates light conditions that favour the grass growth (Peri 2009) increasing competition with trees for nutrients, but incorporating grass organic litter to the forest floor. Considering that grasses have a favorable chemical composition compared with *N. antarctica* leaves (i.e., lower concentrations of lignin) may have an additive effect in the silvopastoral system by increasing the rate of decomposition of tree leaves. This is consistent with Perez Harguindeguy et al. (2008), who reported an increase in the decomposition rate in mixtures of different residues compared with individual low quality litter.

Conclusions

Litter decomposition rates were higher in the first 60 days in different radiation levels and site classes. After this first period, organic matter decomposition rates indicated that beyond the differences in litter quality (mainly lignin/nitrogen ratio), the environmental factors had a greater influence on the decomposition, being total radiation the most important variable driving decomposition.

The removal of trees through thinning practices for silvopastoral use of *N. antarctica* may improve the rate of litter decomposition, but decrease the litter production.

The mineralization–immobilization of the nutrients depended mainly on the chemical characteristics of litter (grass and tree leaves) and to a lesser extent on their interaction with environmental conditions.

These results provide information for long-term sustainability in the natural maintenance of nutrient cycles of forest ecosystems under management. There seems to be lacking a general conclusion relating all of the investigation to site quality.

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