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Sheep faeces decomposition and nutrient release across an environmental gradient in Southern Patagonia

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Abstract. In Southern Patagonia, most of the land ranging from the mountains to the sea in contrasting environmental conditions is devoted to extensive sheep farming. Existing estimations indicate that in ecosystems under livestock use, around 85% of the nitrogen (N) returning to the soil is through animal feces and urine. However, there is a lack of information concerning the rate of nutrient return into the soil from animal feces in Southern Patagonia. In this study, we evaluated the rate of sheep faeces decomposition and nutrient (N, P, Ca and K) release in three different ecological areas of Southern Patagonia, representing a West to East environmental gradient. Samples of fresh sheep dung were collected in the field, processed in the laboratory and located in three ecological areas and subsequently collected periodically during 820 days. The remaining organic matter (OM) of decomposing faeces did not vary between the three ecological areas. At the end of the trial (820 days), the rate of OM decomposition averaged 63% of the initial amount. According to the linear regressions performed, the time to reach 100% OM decomposition fluctuated between 3.7 and 4.2 years. Nutrient dynamics followed a common general trend, since nutrients were released during the first stages of decomposition, and then, fluctuations between nutrient immobilisation and release were observed. The prevailing environmental conditions among the ecological areas evaluated did not seem to involve a measurable effect on sheep faeces decomposition and nutrient release. The results obtained in this work may be useful for quantifying the return of organic matter and nutrients from sheep faeces to the soil in Southern Patagonia.

[Keywords: livestock, Patagonian steppe, soil fertility, nutrients dynamics]

Resumen. Descomposición y liberación de nutrientes de heces de oveja en un gradiente ambiental en la Patagonia austral. La mayor parte de la tierra en la Patagonia austral está dedicada a la actividad ganadera ovina extensiva, desde la cordillera al mar, en condiciones ambientales contrastantes. Hay estimaciones que indican que en ecosistemas con uso ganadero, alrededor de 85% del nitrógeno (N) retorna al suelo como heces y orina (en mayor proporción por las heces). Sin embargo, no existen estudios de retorno de nutrientes por heces en Patagonia sur. En este trabajo evaluamos la tasa de descomposición de heces de oveja y su liberación de nutrientes (N, P, Ca y K) en tres áreas ecológicas que representan un gradiente ambiental de oeste a este en la Patagonia austral. Se colectaron muestras frescas de heces de oveja en el campo, se procesaron en laboratorio y se instalaron en tres áreas distintas. Luego fueron colectadas de manera periódica durante 820 días. La materia orgánica remanente (MO) de las heces en descomposición no varió entre las tres áreas ecológicas estudiadas. Al final del ensayo (820 días), la MO descompuesta en promedio fue 63% de la cantidad inicial. Las regresiones lineales muestran que el tiempo para alcanzar 100% de la descomposición de la MO fluctuó entre 3.7 y 4.2 años. La dinámica de nutrientes siguió una misma tendencia general ya que fue liberada en las primeras etapas del proceso y después se registraron fluctuaciones entre inmovilización y liberación de nutrientes. Los resultados obtenidos en este trabajo pueden ser útiles para cuantificar el retorno de materia orgánica y nutrientes desde las heces de oveja al suelo, en las condiciones ambientales de la Patagonia austral.

[Palabras clave: ganadería, estepa patagónica, fertilidad de suelo, dinámica de nutrientes]

Introduction

In general, organic matter decomposition in terrestrial ecosystems has a big incidence on global carbon cycles (Canadell et al. 2007). In particular, in grazing sheep areas, decomposition and nutrient release from faeces represent an important component of nutrient cycle. Grazing sheep excrete a large part of the nutrient elements they ingest (Shand and Coutts 2006).

In Southern Santa Cruz Province (51°00′ - 52°20′ S) (Argentinean Patagonia), extensive sheep farming occupies broad land extensions of approximately 3.5 million ha (Sturzenbaum 2012). This activity extends from the mountains to the sea in a gradient (W-E) of contrasting environmental conditions. Although livestock activities in the western limit are in some cases carried out in *Nothofagus antarctica* (ñire) forest under silvopastoral use (Peri et al. 2015), most of livestock production of the region occurs in

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the steppe dominated by grasses and shrubs (Oliva et al. 2001).

In many semi-arid ecosystems, as Patagonia, the soils have low availability of nutrients which on the other hand are strongly released in pulses (Austin et al. 2004). For this reason, special attention is needed to understand nutrient cycling in such ecosystems. The little specific information available concerning nutrient fluxes in Southern Patagonia has been reported mainly for forest ecosystems. Bahamonde et al. (2012a; 2013; 2015) studied the rate of litter decomposition, soil N mineralization and nutrient return by litterfall in *N. antarctica* forests under different management practices in Santa Cruz Province. The authors reported that canopy opening increased the rate of litter decomposition and soil N mineralization, but nutrient returns associated with litterfall did not change during a period of ten years.

However, studies related to nutrient fluxes including other ecosystems in Southern Patagonia are extremely scarce. Peri (2011) reported C storage in cold temperate ecosystems, indicating that 90% of total C accumulation in a thicket zone and grassland of the steppe was in the first 30 cm of soil. Peri et al. (2015) measured soil respiration in Southern Patagonia and recorded soil respiration rates 30% higher in moderately grazed grasslands than in heavily grazed grasslands. They also reported a decrease of soil respiration in the following order: silvopastoral system > native forest > grassland. However, there is no preliminary information on nutrient returns from animal feces in Southern Patagonia, but there are estimations indicating that in ecosystems under livestock use ~85% of the N returning to the soil is through feces and urine (Russelle 1992), being the higher proportion from the faeces (Smith and Frost 2000). Also, faeces decomposition is another component of C cycling, which implies an additional element of significance in the context of increasing atmospheric CO_2 (IPCC 2000). On the other hand, in recent years, the Holistic method of grazing (Savory 1983) has increased in Southern Patagonia. This procedure basically consists in grazing with high stocking rates for short periods and has been indicated as a good strategy to improve the circulation of nutrients (e.g., by faeces deposition) (Savory and Butterfield 1999).

It is widely recognized that soil moisture and temperature have a positive correlation with organic matter decomposition (Chapin et al. 2002; Prescott 2005). In this regard, well known is that in low net primary productivity regions, as Patagonia, environmental factors (especially temperature) may have a critical role in decomposition rates (Lambers et al. 2008). The effect of photodegradation (understood as degradation of organic matter by effect of solar radiation) has also been reported as positively correlated with litter decomposition in semi-arid environments such as Patagonia (Austin and Vivanco 2006). Recently, it has been shown that photodegradation increases microbial enzyme accessibility to plant litter carbohydrates (Austin et al. 2016). These authors suggested that photodegradation is hence quantitatively important in determining rates of mass loss. In concordance with these findings, Bahamonde et al. (2012a) reported higher values of litter decomposition at higher levels of radiation when compared to the decomposition rates at different crown cover levels in *N. antarctica* forests of Southern Patagonia. Although there are no data available concerning the spatial variation of solar radiation at a regional scale in Southern Patagonia, the existing information in general in Argentina points towards a north-south gradient (Grossi Gallegos 2005). However, in Southern Patagonia, the vegetation has a key role in altering the total amounts of radiation reaching the soil in an east-west bound. Bahamonde et al. (2012b) reported a decrease of ~40% in PAR (photosynthetically active radiation) inside a *N. antarctica* forest, compared to adjacent places without trees, in Southern Patagonia. Therefore, it is expectable that shrubs such as *Mulguraea tridens*, which reach approximately 0.8 m height (Billoni 2015), could reduce the solar radiation reaching the soil compared to the steppe vegetation without shrubs, in Southern Patagonia.

Given the lack of information, the objective of the present study was to evaluate the sheep faeces decomposition and nutrient release in three different ecological areas representing a west-east temperature gradient in Southern Patagonia. We reckoned that temperature should be the most influential parameter affecting the rate of faeces decomposition in the different environmental conditions examined, therefore we hypothesized that the decomposition rates should decrease in the following gradient: grass steppe > shrub matorral thicket > ñire forest under silvopastoral use.

Materials and Methods

Study sites

In a regional context, the climate in Southern Argentinean Patagonia shows a strong precipitation gradient from 150 mm/year in the east (near the cost of the Atlantic Ocean) to more than 1000 mm/year in the west at the Andes Mountains (Paruelo et al. 1998; Hijmans et al. 2005). However, in some particular situations (e.g., places with a strong maritime influence) this gradient may be modified.

Three study areas occurring in a vegetation and climate gradient were selected, which represented three different ecological areas under extensive sheep grazing in Santa Cruz province, Southern Patagonia, Argentina: a) silvopastoral systems, in *Nothofagus antarctica* forests (SP) located in the ecological area called "Complejo andino", with understory vegetation dominated by grasses and graminoids of the genus *Agrostis* spp., *Bromus* spp., *Carex* spp., *Dactilys* spp., *Deschampsia* spp. and *Festuca* spp. (Bahamonde et al. 2012b); b) thicket zone, in the ecological area "Matorral de mata negra" (MT), where the shrub *Mulguraea tridens* covers an important proportion of the surface (35%), reaching a height of 0.8 m, and it is associated mostly to grasses such as *Jarava chrysophylla*, *J. ibari*, *Bromus setifolius* and *Festuca pyrogea* (Peri et al. 2015), and c) grass steppe (GS), located in the "Estepa magallánica seca" area, being the dominant specie the grass *Jarava chrysophylla*, which is associated with *Poa spiciformis*, *Carex andina* and *Rytidopserma virescens*. Three representative points of measurement (study site) were selected at each ecological area, which are described in Table 1.

Table 1. Climatic parameters, location and carrying capacity of the study sites.

Tabla 1. Parámetros climáticos, ubicación y capacidad de carga de los sitios de estudio.

	MAP (mm/year)	MAT (°C)	Coordinates of the study sites	Carrying capacity ($sheep.ha^{-1}.year^{-1}$)
SP	390	4.9	51°13′21″ S - 72°15′34″ W	0.94
			51°19′05″ S - 72°10′47″ W	
			51°57′22″ S - 71°31′41″ W	
MT	155	6.5	50°57′36″ S - 70°27′56″ W	0.22
			51°01′53″ S - 70°27′52″ W	
			51°05′38″ S - 70°40′53″ W	
GS	235	7.1	51°29′53″ S - 69°19′35″ W	0.35
			51°17′50″ S - 69°14′57″ W	
			51°56′59″ S - 70°25′10″ W	

MAP: mean annual precipitation; MAT: mean annual temperature.

Carrying capacity was obtained from Bahamonde and Peri (2013) for SP area; Peri et al. (2015) for MT area; Oliva et al. (2012) for GS area.

Experimental design and decomposition and nutrient release measurements

A factorial experiment design with study area and time as main factors was carried out. The study area factor had three levels (SP, MT and GS) and the time factor had eight levels corresponding to dates of extraction (60, 160, 290, 380, 465, 660, 735 and 820 days). Samples of fresh sheep dung were collected from two provenances one week before to the installation in the field. A group of samples was taken from *Nothofagus antarctica* forest under silvopastoral use (51°13′23″ S - 72°15′39″ W) and a second group was sampled from a grass steppe (51°56′56″ S - 70°25′9″ W), being the last considered as representative of MT and GS areas, because it has been documented a high similarity in the diets of sheep in both places (Andrade et al. 2015).

The collected material was transported to the laboratory in an icebox and stored in a fridge. Samples of 30 g of fresh faeces were enclosed in 20x20 cm polyethylene gauze bags (5 mm mesh). Sub-samples were oven dried for 48 h at 60 °C to calculate the moisture content. Also, samples of faeces 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 semi-micro Kjeldahl. Concentrations of P, K and Ca were determined with a plasma emission spectrometer (Shimadzu ICPS-1000 III, Japan). In November 2012, in each study site (3 per each ecological area) eight bags with fresh faeces were placed in a plot (1 plot per study site) of 1 m^2, protecting the bags of any disturbance that could cause the wild or domestic fauna. In the SP sites were placed faeces collected in SP, while in MT and GS sites were placed faeces from GS. The bags were placed horizontally on the soil surface and fixed with pegs. One bag per study site of each ecological area was taken 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. Material from each sample was taken to obtain organic matter proportion determining by loss on ignition (4 h, 500 °C), thus also inorganic contaminants (mainly soil particles) were excluded. Samples taken at each time were analysed for macro nutrients (N, P, K and Ca). The absolute amount of organic matter and each nutrient were calculated by multiplying the concentration by its corresponding remaining dry mass. The nutrient mass data obtained in each extraction date were expressed as a percentage of the initial values of ash-free basis.

Environmental measurements

To characterize soil properties, three composite samples of five soil cores were randomly taken (30 cm depth) at each study site. The following analyses were conducted: a) organic carbon (C), determined with spectrophotometry according to Kumies 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), and d) exchangeable potassium (K), determined using saturation with sodium acetate, washed with ethylic alcohol, displacement through pH 7 buffered ammonium acetate. The pH was determined by potentiometric measurements of a water saturated paste. The analysis of texture was carried out through the densimeter method of Bouyoucos and sieving the sand fractions.

Air and soil temperatures were measured continuously every 2 h with a datalogging system (HOBO H8 Family, Onset Computer Corporation, USA), using a sensor at each study site. Air temperature sensors were placed at 0.6 m height from ground level. Soil temperature was measured at 3 cm depth using soil thermometers (HOBO, Model TMC50-HA, USA). At each sampling date, the volumetric water content (0-20 cm) was measured in each study site using a soil moisture meter Time Domain Reflectometry proven precision equipment (TDR flag Eijkelkamp, Model FM-3-14.62, Santa Barbara, USA).

Data analysis

Exploratory testings were carried out to verify the compliance with the assumptions of normality, homoscedasticity and independence of data for each evaluated condition. While the Shapiro-Wilk test was performed to verify the normality of the data, the Levene test was used to verify homoscedasticity. Independence between repetitions was verified by visual analyses of residuals plots. Soil properties, air and soil temperature and soil volumetric moisture were analysed by analysis of variance (ANOVA) with ecological area as a factor. Similarly, the initial chemical composition of faeces was analysed with a *t* test comparing the two provenances. Decomposition of organic matter from faeces and the dynamics of nutrients over time were analysed by ANOVA for repeated measurements with the ecological area as an inter-subject factor and each sampling date as an intra-subject factor. Such analyses were implemented since the decomposition values are not independent over time. Tukey tests were performed to test differences among ecological areas when *F*-values were significant ($P<0.05$). To obtain more detailed information, multiple comparisons were made concerning inter-subject effects (ecological area) for each sampling date. Linear and nonlinear regressions were made to find the best model explaining the relationship between time and organic matter concentration during the period of faeces decomposition. Similarly, the same type of analysis was made to model the nutrient dynamics over time. The time (years) that takes to decompose 100% of organic matter and release 100% of nutrients (T_{100}) was estimated according to the best model obtained in each case. This type of regressions was also performed to relate micro-climatic variables to OM decomposition rates.

Results

Characteristics of the soils and decomposing material

Despite the differences in absolutes values observed for some parameters, no significant differences were found between experimental sites concerning soil properties at the beginning of the trial (Table 2). Similarly, the chemical features measured for the faeces from two provenances (SP and GS) did not show significant differences (Table 3).

Micro-climatic variables

Monthly mean air temperature varied significantly ($P<0.001$) between dates and ecological areas, being the interaction between these factors also significant ($P<0.001$). Average air temperature over the entire study period showed a significant gradient between sites ($P<0.001$) MT>GS>SP with 7.7, 7.1 and 6.4 °C, respectively. When considering monthly values this trend was maintained during spring and summer, but disappeared during autumn and winter. Similarly, monthly maximum air temperatures changed thorough dates and ecological areas with a significant

Table 2. Soil properties (0-30 cm) of the study sites.

Tabla 2. Propiedades del suelo (0-30 cm) de los sitios de estudio.

	C (%)	N (%)	P (ppm)	K (meq/100 g)	C:N	pH	Texture
SP	3.2 (1.9)	0.3 (0.07)	29 (18)	0.9 (0.58)	9.4 (5.0)	5.5 (0.6)	Sandy loam
MT	1.5 (0.7)	0.4 (0.18)	11 (3)	0.3 (0.14)	4.7 (1.9)	6.3 (0.3)	Sandy
GS	1.1 (0.5)	0.1 (0.03)	29 (7)	0.3 (0.14)	7.4 (3.3)	6.1 (0.3)	Sandy
Signif.	ns	ns	ns	ns	ns	ns	

Numbers in parentheses are the standard deviation of the mean; ns=not significant.

Los números entre paréntesis son el desvío estándar de la media; ns=no significativo.

Table 3. Initial mean values of lignin, carbon and macronutrients concentration in dry faeces used in the studied sites.

Tabla 3. Concentraciones medias iniciales de lignina, carbono y macronutrientes en heces secas usadas en los sitios de estudio.

	C (%)	N (%)	P (%)	K (%)	Ca (%)	Lignin (%)	C:N	Lignin:N
SP	37.5 (0.2)	1.8 (0.1)	0.3 (0.04)	0.9 (0.2)	0.9 (0.2)	9.4 (1.1)	21.4 (0.4)	5.4 (0.6)
MT-GS	37.4 (0.6)	1.9 (0.3)	0.2 (0.03)	1.0 (0.2)	0.9 (0.2)	9.3 (0.8)	19.9 (2.6)	4.9 (0.3)
Signif.	ns	ns	ns	ns	ns	ns	ns	ns

Numbers in parentheses are the standard deviation of the mean; ns=not significant.

Los números entre paréntesis son el desvío estándar de la media; ns=no significativo.

Table 4. Decay model, coefficient of determination (statistical significance) and total time (in years) of decomposition of 100% (T_{100}) organic matter for faeces decomposing in the studied sites.

Tabla 4. Modelo de descomposición, coeficiente de determinación (significancia estadística) y tiempo total (en años) de descomposición del 100% (T_{100}) de la materia orgánica de heces descomponiéndose en los sitios de estudio.

Ecological area	Decay model[f]	R^2 (P)	T_{100}
SP	y=0.067x+11.003	0.88 (<0.001)	3.7a
MT	y=0.067x+8.522	0.96 (<0.001)	3.8a
GS	y=0.063x+9.473	0.89 (<0.001)	4.2a

[f] y=organic matter decomposition (%); x= time in days. Different letters in the column T_{100} indicate significant differences between ecological areas.

[f] y=descomposición de la materia orgánica (%); x= tiempo en días. Letras diferentes en la columna T_{100} indican diferencias significativas entre áreas ecológicas.

interaction (P<0.001), being 16.2, 13.1 and 12.2 °C in MT, GS and SP, respectively. Minimum air temperatures varied significantly between date and ecological areas (P<0.001), but the interaction was not significant (P=0.52). The total period average was significantly lower in MT with 0.5 °C, but not differences were found between SP and GS with values of 1.8 and 2.0 °C, respectively. Mean soil temperatures were significantly higher in MT (with a total period average of 8.9 °C) than SP and GS (6.9 and 7.1 °C, respectively). Monthly trends were similar to the air temperature with higher values in MT during spring and summer months. Maximum soil temperatures during the study period averaged 13.7, 12.0 and 10.9 °C in MT, SG and SP, respectively, being significantly different between the MT ant the other two ecological areas. At a monthly level, significant differences were found only in a few months. Volumetric soil moisture did not vary significantly between ecological areas during the first five periods evaluated, however during the last three periods volumetric soil moisture contents were higher in SP that in the other two areas. All data of microclimatic variables is available in the appendix 1.

Decomposition of organic matter in faeces

The remaining OM of decomposing faeces did not vary between ecological sites either at the end of the evaluation period or any specific date (P>0.05) (Figure 1A). At the end of the trial (820 days) the remaining OM averaged 37% of the initial amount. Also, when each period was analysed, OM decomposition did not show significant differences (P>0.05) between ecological areas (Figure 1B). However, the decomposition of faeces varied between periods (P<0.001), being the first period of evaluation the highest, with a mean value of 10% of organic matter decomposition 1/30 days, and the periods January-April 2013 and September-December 2013 the lowest, with negative values (Figure 1B). Linear regression models were the best adjusted models in the three ecological areas (Table 4), fluctuating between 3.7 and 4.2 years the time to decomposing the 100% of OM, with no differences among ecological areas. No one of the environmental variables had a significant (P>0.05, data not shown) effect on organic matter decomposition at any ecological area.

Nutrient release in decomposing sheep faeces

During the first 60 days of decomposition there was a significant (P<0.05) release of N

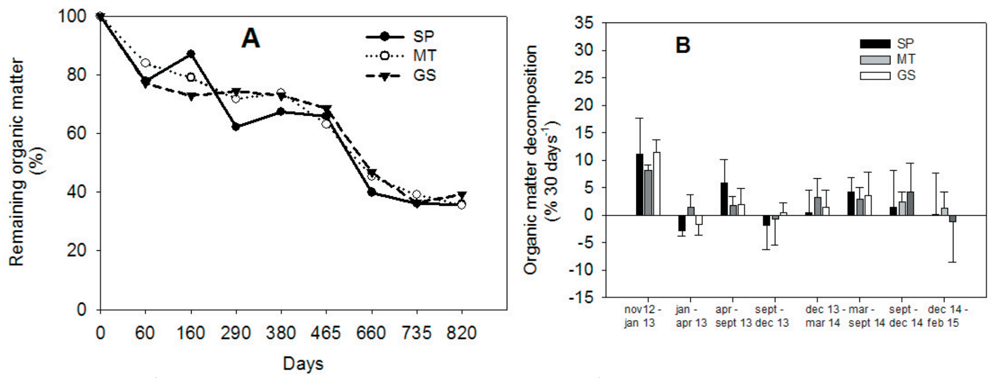

Figure 1. Variation of remaining organic matter (as a percentage of the initial weight) over time (start November 2012) (A) and organic matter decomposition by period (B) of sheep faeces decomposing at three ecological areas in Southern Patagonia.

Figura 1. Variación de la materia orgánica remanente (como porcentaje del peso inicial) a través del tiempo (comienzo en noviembre de 2012) (A) y tasa de descomposición de la materia orgánica por período (B) de heces de oveja descomponiéndose en tres áreas ecológicas en Patagonia austral.

in the three ecological areas with an average of 38% released in relation to original amount. Then, there was a period of immobilization until the 380 days and since that moment a progressive release until the end of the evaluated period, averaging 49.2% of release (Figure 2). There were no significant differences (P>0.05) between ecological areas during any period. A similar trend occurred with P release, where there were fluctuations among release and immobilisation during the first five periods and a sustained release in the last periods averaging a final release of 53.8% (Figure 2). Potassium was continuously released from the beginning until 290 days, reaching an average release of 84%. Then the

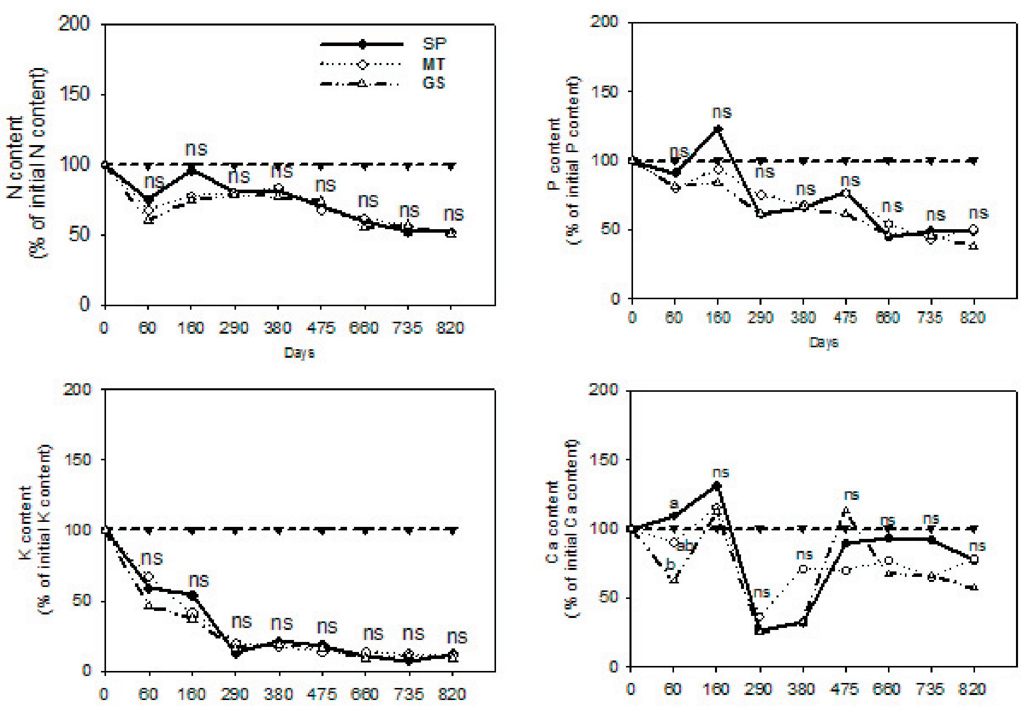

Figure 2. Change over time (beginning November 2012) of nitrogen (N), phosphorus (P), potassium (K) and calcium (Ca) content as percentage of initial content in sheep faeces incubated at three different ecological areas in Southern Patagonia. Different letters in a same date indicate significative differences (P<0.05) between ecological areas. ns=not significant. The dotted line corresponds to the reference value (100%).

Figura 2. Cambio a través del tiempo (comienzo en noviembre de 2012) del contenido de nitrógeno (N), fósforo (P), potasio (K) y calcio (Ca) como porcentaje del contenido inicial, en heces de oveja incubadas en tres áreas ecológicas en Patagonia austral. Letras diferentes en una misma fecha indican diferencias significativas (P<0.05) entre áreas ecológicas. ns=no significativo. La línea punteada corresponde al valor de referencia (100%).

Table 5. Release model, coefficient of determination (statistical significance) and total time (in years) of release of 100% (T_{100}) N, P, K and Ca for sheep faeces decomposing in the studied sites.
Tabla 5. Modelo de liberación, coeficiente de determinación (significancia estadística) y tiempo total (en años) de liberación del 100% (T100) de N, P, K y Ca de heces de oveja descomponiéndose en los sitios de estudio.

	N			P			K			Ca		
Ecological area	Release model[f]	R^2 (*P*)	T_{100}	Release model[f]	R^2 (*P*)	T_{100}	Release model[f]	R^2 (*P*)	T_{100}	Release model[f]	R^2 (*P*)	T_{100}
SP	y=0.049x+6.868	0.75 (=0.005)	5.2a	y=0.076x-4.199	0.63 (=0.018)	3.8a	y=0.062x+48.033	0.70 (=0.01)	2.3a	ns	-	-
MT	y=0.032x+17.285	0.56 (=0.033)	7.0a	y=0.055x+7.305	0.80 (=0.003)	4.6a	y=0.059x+49.314	0.67 (=0.013)	2.4a	ns	-	-
GS	ns	-	-	y=0.057x+13.975	0.93 (<0.001)	4.2a	y=0.044x+59.876	0.78 (=0.003)	2.5a	ns	-	-

y=nutrient releasing (%); x=time in days. Different letters in the column T_{100} indicate differences between ecological areas. ns: not significant model was found for a nutrient in a specific ecological area.

y=liberación de nutrientes (%); x=tiempo en días. Letras diferentes en la columna T_{100} indican diferencias significativas entre áreas ecológicas. ns=no se encontró modelo significativo para un nutriente en un área ecológica específica.

K in decomposing faeces kept stable until the end of the evaluation period (Figure 2). Calcium dynamics were different between ecological areas during the first 60 days, Ca being released in the GS area and immobilised in the other two ecological areas. After this period, there were fluctuations between periods, releasing the maximal amount of Ca at the 290 days, averaging 71%, with no differences between ecological areas (Figure 2).

The best models explaining nutrient release rates were linear regressions with different levels of significance and coefficient of determination depending on each nutrient and ecological area (Table 5). The time to release 100% of the nutrient (T_{100}) varied according to each mineral element. However, no differences were found between ecological areas for a particular nutrient. There was a gradient in T_{100}, being 6.1, 4.2 and 2.4 years for N, P and K, respectively, while for Ca no significant model explaining its release could be found for any ecological area (Table 5).

DISCUSSION

Characteristics decomposing material

Our study is one of the first reports about the chemical composition of sheep faeces in Patagonia. The N concentrations measured in this study were higher than other sheep faeces reported worldwide (Maff 1976, cited in Smith and Frost 2000), but similar to the reported for cow faeces in the "Flooding Pampas" of Argentina (Semmartin 2006). Lignin concentrations in faeces evaluated in our study were lower than those reported by Kyvsgaard et al. (2000), with a mean value of 20% of lignin in the faeces of sheep fed with hay. Also, Semmartin (2000) found higher Lignin:N ratios (9.2) compared with those estimated in our study. C:N values were in the range of those reported for sheep faeces (Kyvsgaard et al. 2000). Nevertheless, these comparisons may only serve as reference, because the chemical composition of faeces is related to the chemical composition of the food consumed by sheep (Kyvsgaard et al. 2000).

The lack of differences in the chemical composition among faeces provenances from different ecological areas may be explained due to similarity in sheep diet. This has been supported by the results of Ormaechea and Peri (2015) who reported that the diet of sheep in forest and steppe paddocks in Southern Patagonia showed a similarity of around 70%. The relevance of the initial chemical composition of materials on their rate of decomposition and mineral release is broadly recognised (Swift et al. 1979; Seneviratne 2000). Therefore, given the lack of chemical composition differences among the two faeces provenances analysed, we could compare the potential effect of environmental variables on decay rates and discard any significant effect of the composition of the materials.

Micro-climatic variables

The annual average air temperature measured in the three ecological areas was in the range of the reported as historical average for each studied area (Hijmans et al. 2005). The higher mean and maximum values and lower minimal temperatures in the MT area compared with SP and GS areas would be due to a more continental location. In the particular case of SP, there are antecedents reporting the effect of the *Nothofagus antarctica* forest in the region (Bahamonde et al. 2009) where the thermal amplitude decreased (i.e., lower maximum temperatures and higher minimum temperatures) compared with open areas. This is explained because in summer, the radiation in open areas is higher, but in winter the interception of radiation by the tree canopy generates a layer of warm temperature that compensate open areas (Gómez Sanz 2004). Similarly, the location of sites in the GS area close to the sea and a lake would imply a cushioning effect produced by the high specific heat of water. The expectations were that volumetric soil moisture in the SP area were higher than others sites, but this only occurred during last three periods, being the resting first five periods lower than previously reported in the same forests (Bahamonde et al. 2012a,b) and similar to values measured in MT and GS areas. Volumetric soil moisture values found for GS and MT areas were similar to the reported by Ferrante (2011) and Billoni (2015).

Decomposition of organic matter in faeces

Contrary to our hypothesis, the different environmental conditions (mainly temperature) among ecological areas did not affect sheep faeces decomposition. We can speculate that differences in environmental variables among areas were compensated (e.g., higher soil moisture in the area located in the forest and higher temperature in areas located in the steppe), which resulted in no major differences in decomposition between areas. Similarly, other authors reported at a regional scale, that the chemical composition of litter may be a stronger driver of decomposition rather than differences in environmental factors (Aerts 1997).

There is scarce information about sheep faeces decomposition rates in Patagonia. The decomposition values obtained in this study during the first year of decay are similar to those reported by Semmartin (2006) where the cow faeces kept 60% of the initial material. This could be unexpected if we consider that the experiment of Semmartin (2006) was carried out under controlled conditions with temperatures between 20 and 25 °C, and soil permanently humid. However, the more limiting environmental conditions in our study could be offset by the minor value of lignin concentration of faeces. It is widely recognised that for different materials, lignin concentrations are inversely related to decomposition rates (Berg 2000).

When comparing our results with the decomposition rates of other materials in Southern Patagonia, faeces decomposition was slightly higher than *Nothofagus antarctica* leaves and grasses decomposing in these forests under silvopastoral use (Bahamonde et al. 2012a) for a similar evaluation period (480 days). Furthermore, sheep faeces decomposed more than three times the value of grasses and six times the decomposition of *Mulguraea tridens* shrub in a thicket zone located near to our MT ecological area (Billoni 2015). The highest decomposition rate measured during the first 60 days is coherent with previous studies which associated these results with the leaching of soluble components and fast degradation of the more labile parts of the decomposing material (Swift et al. 1979; Berg et al. 1996). This has also been observed in Southern Patagonia for others materials (Bahamonde et al. 2012a). The lower monthly decomposition rates in others periods are attributable to environmental limitations, mainly temperature and soil moisture, and/or the interaction between these factors. Similarly, the counterintuitive increase of organic matter decomposing in a subsequent period, as we found at 160 days in SP area, may be attributed to immobilization, which could be caused by the death of microorganisms, and has been reported in others decomposing materials such as *Nothofagus* litters in Chile (Decker and Boerner 2006) and *Eucalyptus* in Uruguay (Hernández et al. 2009).

Although the best models explaining faeces decomposition over time were linear regressions, this kind of models may underestimate the decomposition at early stages and overestimate it latter stages (Wieder and Lang 1982). Nonetheless, the obtained equations are useful for estimating OM losses for a total period. Thus, the estimated times to reach a 100% decomposition of faeces in the three ecological areas were considerably lower than for other materials in Southern Patagonia. For example, Bahamonde et al. (2012a) estimated that 99% of tree leaves and grasses decomposition in *Nothofagus antarctica* forests took between 11.8 and 27.1 years. Billoni (2015) reported that grasses and litterfall of the shrub *Mulguraea tridens* would need between 45 and 149 years to decompose 99% of OM.

Nutrient release in decomposing sheep faeces

The release and/or immobilisation of N from decomposing material has been linked to its initial N concentration and environmental conditions (Prescott 2005). Patterns found in our study, with mineralization at the beginning and subsequent fluctuations in release and immobilisation, have been reported for different environmental conditions and materials (Decker and Boerner 2006;

Bahamonde et al. 2012a; Billoni 2015). Similar to OM decomposition, the greater values in the first 60 days may be due to the leaching and release of N associated with more labile structures, and the initial N concentration of the material (Aber and Melillo 1980; Yavitt and Fahey 1986; Seneviratne 2000). The further immobilisation of N probably was influenced by environmental conditions (low temperatures and/or low soil moisture) limiting microorganism activity (Swift et al. 1979).

The P release rates found in this work were similar to the results of Bahamonde et al. (2012a) for *N. antarctica* leaves and Billoni (2015) for grasses and shrubs, and of decomposing cow faeces (Semmartin 2006). According to several authors (Vogt et al. 1986; Berg and Laskowski et al. 1995) the P release dynamics of decaying material is closely related to the N:P ratio, where values lower than 15 stimulate P release, as it is the case in our study.

The continuous release of K in the first 290 days in the decaying sheep faeces found in this study is in agreement with several investigations carried out with different materials and environmental conditions (Laskowski et al. 1995; Osono and Takeda 2004). A different pattern was reported by Bahamonde et al. (2012a) where K in decomposing *N. antarctica* leaves was always immobilised in a period of 420 days and grasses showed fluctuations of mineralization and immobilisation similar to those reported by Billoni (2015), both in Southern Patagonia. This different pattern between our study and the mentioned investigations may be due the initial K concentrations of materials, being the values measured by Bahamonde et al. (2012a) and Billoni (2015) significantly lower than faeces concentrations, which may limit microbial activity and result in K immobilisation (Swift et al. 1979; Berg 1986).

It is difficult to explain the differences between ecological areas concerning Ca dynamics during the first 60 days, because the initial Ca concentrations of the faeces were not different. A possible explanation could be the different requirements of Ca by microorganisms in the soil. Swift et al. (1979) suggested that there are microorganisms with high Ca requirements, specially growing in acid soils, which may be the case in the SP ecological area. As we did not evaluate Ca concentration in soils, this may be only a plausible speculation. The subsequent trend of Ca concentration in all areas was similar to OM decomposition, which has been reported for different situations (Laskowski et al. 1995; Barrera et al. 2004). This may occur because Ca is strongly associated with structural tissues of the residues.

Considering that the digestibility of the consumed forage by sheep may vary between 50 and 64% in the SP area (Peri and Bahamonde 2012), and between 47 and 61% in the two other ecological areas investigated (Andrade et al. 2015), the return of OM and nutrients from sheep faeces decomposition in these areas average 45% of the consumed forage, which would be a very important contribution to the fertility of these soils. There is information about the nutrients return from litterfall in silvopastoral systems in the SP area (Bahamonde et al. 2015), being the time to decompose that litter fluctuates between 17 and 27 years (Bahamonde et al. 2012a). Similarly, the information gathered by Billoni (2015) indicates that the return of 99% OM from litter contribution may vary between 45 and 149 years. Similarly, quantification of soil N mineralization in these areas related to low amounts of $kg.ha^{-1}.year^{-1}$ (Bahamonde et al. 2013; Billoni 2015). This highlight the information obtained in this study because the time to decompose OM and release nutrients from sheep faeces decomposition is much lower and became a source of nutrients more rapidly available for plants in these ecological areas. Additionally, this quantification of sheep faeces decomposition can be useful for evaluating the impact of different grazing methods (as continuous or rotational) (Briske et al. 2008) on the circulation of nutrients, as suggested for Holistic method (Savory and Butterfield 1999).

Conclusions

Environmental differences between the three ecological areas evaluated did not produce measurable effects on sheep faeces decomposition rates. Similarly, the pattern of nutrient release from decaying sheep faeces was independent of the ecological area. Nevertheless, in light of the existing information on plant litter decomposition and on the results of this study, it seems that the nutrients in the plants consumed as forage by sheep would return to the soil (via faeces) faster than through litter decomposition. The results obtained in this investigation may be useful to quantify the return of OM and nutrients from sheep faeces in Southern Patagonia, but future studies will be required for characterising such processes with more detail.

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References

Aber, J. D., and J. M. Melillo. 1980. Litter decomposition: measuring relative contribution of organic matter and nitrogen to forest soils. Can J Bot **58**:416-421. doi:10.1139/b80-046

Aerts, R. 1997. Climate, leaf litter chemistry and leaf litter decomposition in terrestrial ecosystems: a triangular relationship. Oikos **79**(3):439-449.

Andrade, M., D. Suárez, P. L. Peri, P. Borrelli, S. Ormaechea, D. Ferrante, E. Rivera, and M. V. Sturzenbaum. 2015. Desarrollo de un modelo de asignación variable de carga animal en Patagonia Sur. Ediciones INTA. ISBN 978-987-521-592-4. Pp. 62.

Austin, A. T., and L. Vivanco. 2006. Plant litter decomposition in a semi-arid ecosystem controlled by photodegradation. Nature **442**:555-558. doi:10.1038/nature05038

Austin, A., L. Yahdjian, J. M. Stark, J. Belnap, A. Porporato, I. C. Burke, U. Norton, D. A, Ravetta, and S. M. Schaeffer. 2004. Water pulses and biogeochemical cycles in arid and semiarid ecosystems. Oecologia **141**:1-15. doi: 10.1007/s00442-004-1519-1

Austin, A. T., M. S. Méndez, and C. L. Ballaré. 2016. Photodegradation alleviates the lignin bottleneck for carbon turnover in terrestrial ecosystems. Proceedings of the National Academy of Sciences **113**:4392-4397.

Bahamonde, H. A., P. L. Peri, G. Martínez Pastur, and V. Lencinas. 2009. Variaciones microclimáticas en bosques primarios y bajo uso silvopastoril de *Nothofagus antarctica* en dos Clases de Sitio en Patagonia Sur. Pp. 289-296 *in*: Proceedings of the 1st National Congress of Silvopastoral Systems, Misiones, Argentina, 14-16 May 2009.

Bahamonde, H. A., P. L. Peri, R. Álvarez, A. Barneix, A. Moretto, and G. Martínez Pastur. 2012a. Litter decomposition and nutrients dynamics in *Nothofagus antarctica* forests under silvopastoral use in Southern Patagonia. Agrofor Syst **84**:345-360. doi: 10.1007/s10457-012-9479-7

Bahamonde, H. A., P. L. Peri, R. Álvarez, and A. Barneix. 2012b. Producción y calidad de gramíneas en un gradiente de calidades de sitio y coberturas en bosques de *Nothofagus antarctica* (G. Forster) Oerst. en Patagonia. Ecol Austral **22**:62-73.

Bahamonde, H. A., and P. L. Peri. 2013. Receptividad ganadera en bosques de *Nothofagus antarctica* (ñire) bajo uso silvopastoril en Patagonia Sur basado en los requerimientos energéticos de los animales. Actas Cuarto Congreso Forestal argentino y latinoamericano, Iguazú, Misiones, Argentina. ISSN 1669 6786. Pp. 10.

Bahamonde, H. A., P. L. Peri, R. Álvarez, A. Barneix, A. Moretto, and G. Martínez Pastur. 2013. Silvopastoral use of *Nothofagus antarctica* in Southern Patagonian forests, influence over net nitrogen soil mineralization. Agrofor Syst **87**:259-271. doi: 10.1007/s10457-012-9541-5

Bahamonde, H. A., P. L. Peri, G. Martínez Pastur, and L. Monelos. 2015. Litterfall and nutrients return in *Nothofagus antarctica* forests growing in a site quality gradient with different management uses in Southern Patagonia. Eur J. Forest Res **134**(1):113-124. doi: 10.1007/s10342-014-0837-z.

Barrera, M. D., J. L. Frangi, J. J. Ferrando, and J. F. Goya. 2004. Descomposición del mantillo y liberación foliar neta de nutrientes de *Austrocedrus chilensis* (D. Don) Pic. Serm. et Bizzarri en El Bolsón, Río Negro. Ecol Austral **14**:99-112.

Berg B. 1986. Nutrient release from litter and humus in coniferous forest soils - a mini review. Scand J Forest Res **1**: 359-369.

Berg, B. 2000. Initial rates and limit values for decomposition of Scots pine and Norway spruce needle litter: a synthesis for N-fertilized forest stands. Can J For Res **30**:122-135. doi: 10.1139/x99-194

Berg, B., G. Ekbohm, M. B. Johansson, C. McClaugherty, F. Rutigliano, and A. Virzo de Santo. 1996. Maximum decomposition limits of forest litter types: a synthesis. Can J Bot **74**:659-672. doi:10.1139/b96-084

Billoni, S. 2015. Evaluación de un sistema de manejo de arbustales de mata negra (*Mulguraea tridens*) de Patagonia Sur. Master thesis presented in the Universidad Nacional de la Patagonia Austral, Argentina. Pp. 123.

Briske, D. D., J. D. Derener, J. R. Brown, S. D. Fuhlendorf, W. R. Teague, K. M. Havstad, R. L. Gillen, A. J. Ash, and W. D. Willms. 2008. Rotational grazing on rangelands: Reconciliation of perception and experimental evidence. Rangeland Ecol Management **61**:3-17. doi: 10.2111/06-159R.1

Canadell, J. G., C. Le Quere, M. R. Raupach, C. B. Field, E. T. Buitenhuis, P. Ciais, et al. 2007. Contributions to accelerating atmospheric CO_2 growth from economic activity, carbon intensity, and efficiency of natural sinks. Proc Natl Acad Sci USA **104**:18866-18870.

Chapin, F. S., P. A. Matson, and H. A. Mooney. 2002. Principles of terrestrial ecosystem ecology. Springer-Verlag, New York, USA.

Decker, K. L., and R. E. J. Boerner. 2006. Mass loss and nutrient release from decomposing evergreen and deciduodus *Nothofagus* litters from Chilean Andes. Austral Ecol **31**:1005-1015. doi:10.1111/j.1442-9993.2006.01670.x

Ferrante, D. 2011. Distribución del agua en el suelo y su relación con la estructura radical y producción de biomasa de tres tipos funcionales, en un pastizal de la Estepa Magallánica seca, Santa Cruz. Master thesis, Universidad de Buenos Aires, Argentina. Pp. 119.

Gómez Sanz, V. 2004. Cubiertas forestales y respuesta microclimática. Investigación Agraria: Sistemas y Recursos Forestales. http://www.inia.es/gcontrec/pub/084-100-(04)-Cubiertas 1162210233484.pdf.

Grossi Gallegos, H. 2005. Distribución espacial de la radiación fotosintéticamente activa en Argentina. Meteorológica **29**:27-36.

Hernández, J., A. del Pino, L. Salvo, and G. Arrarte. 2009. Nutrient export and harvest residue decomposition patterns of a *Eucalyptus dunnii* Maiden plantation in temperate climate of Uruguay. For Ecol Manage **258**:92-99.

Hijmans, R. J., S. E. Cameron, and J. L. Parra. 2005. Very high resolution interpolated climate surfaces for global land areas. Int J Climatol **25**:1965-1978.

Houba, V. J. G., J. J. Van Der Lee, I. Novozamsky, and I. Walinga. 1988. Soil analysis procedures. In: Soil and plant analysis, 1st edn. Wageningen Agricultural University, Department of Soil Science and Plant Nutrition, Wageningen. Pp 1-56

Intergovernmental Panel on Climate Change (IPCC). 2000. Land use, land-use change and forestry - special report. R. T. Watson, I. R. Noble, B. Bolin, N. H. Ravindranath, D. J. Verardo, and D. J. Dokken (eds.). IPCC, Meteorological Office. Bracknell, United Kingdom. Pp. 377.

Kyvsgaard, P., P. Sorensen, E. Moller, and J. Magid. 2000. Nitrogen mineralization from sheep faeces can be predicted from the apparent digestibility of the feed. Nutr Cycl Agroecosys **57**:207-214. doi: 10.1023/A:1009874500769

Lambers, H., F. S. Chapin III, and T. L. Pons. 2008. Role in Ecosystems and global processes. Pp. 545-569 *in*: Plant Physiological Ecology. Springer, New York.

Laskowski, R., M. Niklinska, and M. Maryanski. 1995. The dynamics of chemical elements in forest litter. Ecology **76**: 1393-1406.

Oliva, G., L. González, P. Rial, and E. Livraghi. 2001. El ambiente en la Patagonia Austral. Cap. 2. Pp. 19-82 *in:* P. Borrelli and G. Oliva (eds.). Ganadería Ovina Sustentable en la Patagonia Austral. INTA Reg. Pat. Sur.

Oliva, G., D. Ferrante, S. Puig, and M. Williams. 2012. Sustainable sheep management using continuous grazing and variable stocking rates in Patagonia: a case study. The rangeland journal **34**:285-295.

Ormaechea, S., and P. L. Peri. 2015. Landscape heterogeneity influences on sheep habits under extensive grazing management in Southern Patagonia. Livestock Research for Rural Development **27**(6). http://lrrd.cipav.org.co/lrrd27/6/orma27105.html.

Osono, T., and H. Takeda. 2004. Potassium, calcium and magnesium dynamics during litter decomposition in a cool temperate forest. J For Res **9**:23-31.

Paruelo, J. M., A. Beltrán, E. Jobbágy, O. E. Sala, and R. A. Golluscio. 1998. El clima de la Patagonia: patrones generales y controles sobre los procesos bióticos. Ecol Austral **8**:85-101.

Peri, P. L. 2011. Carbon storage in cold temperate ecosystems in Southern Patagonia, Argentina. Pp. 213-226 *in*: Islam Atazadeh (ed.). Biomass and remoting sensing of biomass. ISBN 978-953-307-490-0, In Tech, Croatia.

Peri, P. L., and H. A. Bahamonde. 2012. Digestibilidad de gramíneas creciendo en bosques de ñire (*Nothofagus antarctica*) bajo uso silvopastoril. Pp. 264-269 *in:* Proceedings 2nd National Congress of Silvopastoral Systems, Santiago del Estero, Argentina. 7-9 May 2012.

Peri, P. L., H. Bahamonde, and R. Christiansen. 2015. Soil respiration in Patagonian semiarid grasslands under contrasting environmental and use conditions. J Arid Environ **119**:1-8. doi: 10.1016/j.jaridenv.2015.03.008

Prescott, C. E. 2005. Decomposition and mineralization of nutrients from Litter and Humus. Pp. 15-41 *in*: H. BassiriRad (ed.). Nutrient Acquisition by Plants. An Ecological Perspective.

Russelle MP. 1992. Nitrogen cycling in pasture and range. J Prod Agric, **5:** 13-23.

Savory, A. 1983. The Savory grazing method or holistic resource management. Rangelands **5**:155-159.

Savory, A., and J. Butterfield. 1999. Holistic management: a new framework for decision making. 2nd edition. Island Press, Covelo, California. ISBN 1-55963-487-1. Pp. 617.

Semmartin, M. 2006. Dinámica de la descomposición y la mineralización neta del nitrógeno y del fósforo de heces de vacunos en pastoreo sobre un pastizal templado. Revista Argentina de Producción Animal **26**:193-202.

Seneviratne, G. 2000. Litter quality and nitrogen release in tropical agriculture: a synthesis. Biol Fert Soils **31**:384-391.

Shand, S. A., and G. Coutts. 2006. The effects of sheep faeces on soil solution composition. Plant Soil **285**:135-148.

Smith, K. A., and J. P. Frost. 2000. Nitrogen excretion by farm livestock with respect to land spreading requirements end controlling nitrogen losses to ground and surface waters. Part 1: cattle and sheep. Bioresource Technol **71**:173-181.

Sparks, D. L. 1996. Methods of Soil Analysis. Part 3. Chemical Methods and Processes. Am. Soc. Agron. Inc., Madison, Wisconsin, USA.

Sturzenbaum, M. V. 2012. Los productores ganaderos ovino-extensivos y la adopción tecnológica en el sureste de la provincia de Santa Cruz. Specialization Thesis, Universidad de Buenos Aires. Pp. 83.

Swift, M. J., O. W. Heal, and J. M. Anderson. 1979. Decomposition in Terrestrial Ecosystems. Blackwell Scientific Publications, Oxford. Pp. 372.

Theander, O., P. Aman, E. Westerlund, R. Andersson, and D. Pettersson. 1995. Total dietary fiber determined as neutral sugar residues, uronic acid residues and klason lignin (the Uppsala Method): collaborative study. J Assoc Off Anal Chem **78**:1030-1044.

Vogt, K. A., C. C. Grier, and D. J. Vogt. 1986. Production, turnover, and nutrient dynamics of above- and belowground detritus of world forests. Adv Ecol Res **15**:303-377.

Wieder, R. K., and G. E. Lang. 1982. A critique of the analytical methods used in examining decomposition data obtained from litter bags. Ecology **63**:1636-1642.

Yavitt, J. B., and T. J. Fahey. 1986. Litter decay and leaching from the forest floor in *Pinus contorta* (lodgepole pine) ecosystems. J Ecol **74**:525-545.