Soil nitrogen contribution to grasslands yield in southern Chile its implications for nitrogen use efficiency nitrogen use efficiency

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Abstract

In pasture systems of southern Chile, nitrogen (N) fertilization is mostly carried out without considering soil N supply, while seasonal N plant uptake is partially accounted for. These aspects are fundamental to correctly decide N fertilization. The aim of this work was to determine soil N contribution to grasslands yield in southern Chile and its implication for N use efficiency. Three treatments were distributed in a completely randomized block design with four replicates. A negative control treatment without N application and a positive control without N deficiency (450 kg N ha⁻¹) were considered. An optimized treatment was also used, so that the total amount of mineral N applied as fertilizer was only that necessary to account for the arithmetic difference among plant uptake and N soil supply, resulting in the application of 171 kg N ha⁻¹ only. Soil mineralization was high (241-934 kg N ha⁻¹) and strongly affected by soil available N (VIP > 0.8). The 450 kg N ha⁻¹ treatment produced 1,726 kg DM more than the 171 kg N ha⁻¹ treatment. Nevertheless, this increase was associated to the application of an extra 279 kg N ha⁻¹, so that the extra yield was produced at a 6 kg DM kg⁻¹ N efficiency. This value was one third of that showed by the optimized treatment, which was 1.8 times more efficient in the use of N than the 450 kg N ha⁻¹ treatment, on average. Results suggest that it is possible to adjust pasture's N fertilization considering soil N contribution via mineralization, and that this improves resources efficiency while maintaining pasture productivity.

Keywords: Soil available nitrogen, fertilization, mineralization, soil budget

1. Introduction

The Lagos Region of southern Chile has suitable climatic conditions and soil types for cattle production. Thus, this region concentrates 56% of the national cattle herd, 80% of Chile's dairy farmers and 67% of the land dedicated to dairy production used nationally (Anrique, 1999). This production is based on direct grazing of naturalized and improved pastures, resulting in the production of 81% of the country's milk and 62% of the meat (INE, 2013). Pastures in this area are located mainly on volcanic soils (Goic and Rojas, 2004), which are characterized by low nutrient availability, high phosphorus (P) fixation capacity, a pH-dependent cation exchange capacity (Escudey *et al.*, 2001; Matus *et al.*, 2008), and high organic matter (OM) concentration, which is usually dominated by humic acids (Huygens *et al.*, 2010).

The use of nitrogen (N) fertilizers in the area has increased over the last 10 years (Alfaro and Salazar, 2005), being this element usually the main cost of fertilizer application. This has resulted in greater yields and stocking rates being used in direct grazing (Alfaro *et al.*, 2008). Moreover, available data suggest that further intensification of grasslands is still possible (Oenema *et al.*, 2014).

Nitrogen is a nutrient that strongly regulates pasture production, but it can also contribute to environmental degradation through nitrate (NO_3^-) leaching, ammonia (NH_3) volatilization, and nitrous oxide (N_2O) emission (Bolan *et al.*, 2004; Saggar *et al.*, 2009; Martínez-Lagos *et al.*, 2014; Núñez *et al.*, 2010). The main contribution of N to plant uptake in volcanic soils of southern Chile comes from organic matter mineralization. In many cases, this income represents more than 60% of total N received by the pasture, although this contribution is rarely considered when estimating nitrogen fertilizer requirements (Alfaro *et al.*, 2009). This contribution can be related to the high soil OM

concentration, which results in high total N content in the soil. Most of the N contribution via mineralization is not necessarily synchronized to the varying requirements of plant growth. Thus pastures, frequently receive N applications of up to $300 \text{ kg N ha}^{-1} \text{ yr}^{-1}$, risking losses to the wider environment (Alfaro *et al.*, 2006). Several approaches have been recommended to mitigate the economic and environmental impacts of N losses (Saggar *et al.*, 2009; Luo *et al.*, 2010), but little work has done to utilize soil N contribution to improve N fertilization decision.

The aim of this work was to estimate the contribution of soil nitrogen to the overall N balance in pasture systems of southern Chile to optimize N fertilization in pastures.

2. Materials and Methods

2.1. Experimental site

A field experiment was established at INIA Remehue ($40^\circ 35' \text{ S}$, $73^\circ 12' \text{ W}$) to determine soil N contribution and soil N budgets in a permanent pasture, between January 2012 and March 2013. The soil in the area has been classified as an Andisol of the Osorno Serie according to CIREN (2005). In modern systems the soil is ranked as a Silándic Andosol (IUSS, 2007) and typical medium mesic Hapludand (Salazar *et al.*, 2005; Soil Survey Staff, 2010). The experimental site was a permanent pasture with *Lolium perenne* L., *Holcus lanatus* L., and *Dactylis glomerata* L. as predominant species. Based on the initial soil analysis (Table 1), all plots received $150 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1}$ (triple superphosphate, 46% P_2O_5), $150 \text{ kg K}_2\text{O ha}^{-1}$ (potassium chloride, 62% KCl), 20 kg Mg ha^{-1} (magnesium oxide, 85% MgO), and 20 kg S ha^{-1} (gypsum, 18% CaSO_4) in December

2011, as basal nutrient application. An application of Picloram and Dichlorophenoxyacetic (Tordon 24% SL Dow AgroSciences, and DM-6 67% SL Dow AgroSciences) had been previously done, in order to eliminate weeds.

Table 1. Initial soil physico-chemical characterization at the experimental site. 0-10 cm depth, 28th/12/2011. (n=4; $\pm$ standard error of the mean)

Parameter	Results
Classification ¹	Typic Hapludands
Series	Osorno
Texture	Loamy
Bulk density, g cm ⁻³	0.7 $\pm$ 0.01
pH H ₂ O (soil:water, 1:2.5)	6.0 $\pm$ 0.00
pH CaCl ₂ (soil:CaCl ₂ , 1:2.5)	5.3 $\pm$ 0.00
Organic matter, g kg ⁻¹	215 $\pm$ 17
Available N, mg kg ⁻¹	23.5 $\pm$ 2.20
Olsen P, mg kg ⁻¹	41.7 $\pm$ 1.90
Available S, mg kg ⁻¹	7.2 $\pm$ 0.70
Exchangeable Ca, cmol ₍₊₎ kg ⁻¹	12.2 $\pm$ 0.90
Exchangeable Mg, cmol ₍₊₎ kg ⁻¹	2.6 $\pm$ 0.20
Exchangeable K, cmol ₍₊₎ kg ⁻¹	0.6 $\pm$ 0.00
Exchangeable Na, cmol ₍₊₎ kg ⁻¹	0.2 $\pm$ 0.00
Exchangeable Al, cmol ₍₊₎ kg ⁻¹	0.1 $\pm$ 0.10
Al saturation, % ²	0.5 $\pm$ 0.10

¹According to CIREN (2005), ²Al saturation: proportion of available Al in relation to total cation concentrations (Ca+Mg+K+Na+Al)

2.2. Treatments

Three treatments were distributed in a completely randomized block design (DCBA) with four replicates, considering a negative control treatment without N application (0 kg N ha⁻¹) and a positive control treatment without N deficiency (450 kg N ha⁻¹). In this

treatment, N was applied at equal rates every 15 days (15 kg N ha⁻¹; NaNO₃, 16% N) to ensure a constant N supply of readily available N for plant uptake. Sodium nitrate was used as a source of fertilizer, to avoid N losses by volatilization, because when urea is applied to soil ammonium soil, NH₃ volatilization can be the main pathway of N loss in grasslands in southern Chile Salazar *et al.*, 2012a.

An optimized treatment was also used considering soil N contribution by mineralization, so that the total amount of mineral N applied was that necessary to reduce the arithmetic difference among plant uptake and N soil supply (see ahead), for a specific period. The total amount of N applied in this treatment was 171 kg N ha⁻¹.

2.3. Measurements

2.3.1. Climatic data

Daily rainfall and air temperature during the experimental period were recorded with an automatic weather station (CR10X-1M Model, Campbell Scientific Inc., Logan, Utah, USA), placed within 1 km distance of the experimental site.

Soil temperature (0-10 cm) was recorded manually each 15 days in the plots. Weekly composed rainfall samples were analyzed to determine the N contribution by wet deposition (NH₄⁺-N and NO₃⁻-N).

Samples were analyzed by ionic chromatography according to Standard Methods (2005), and total deposition was calculated as the result of cumulative rainfall for a sampling period and N concentration in the respective composed samples. For this, an equivalent of 1 mm rainfall to 1 L m⁻² was used to transform rainfall data (mm) to a water input per unit of area (L ha⁻¹).

2.3.2. Soil

2.3.2.1. Initial characterization

At the start of the experiment, soil samples (0–10 cm depth) were collected, air-dried, sieved through a 2 mm sieve, and stored in plastic containers until analysis. These samples were analyzed for soil texture ($n=4$) and bulk density ($n=8$), according to Rowell (1997). Chemical characteristics ($n=4$) were determined by the methods outlined in Sadzawka *et al.* (2006). Briefly, soil pH was measured potentiometrically in water and CaCl_2 by soil suspensions at a 1:2.5 soil: solution ratio. Organic matter was estimated by wet digestion through a modified Walkley-Black method. Exchangeable cations (Ca, Mg, K, and Na) and exchangeable Al were extracted with 1 M NH_4Ac at pH 7.0 and 1 M KCl, respectively, and analyzed by atomic absorption spectrophotometry (AAS). Phosphate and sulfate were extracted with 0.5 M NaHCO_3 at pH 8.5 and 1 M $\text{Ca}(\text{H}_2\text{PO}_4)_2$ and analyzed by the Murphy and Riley method and turbidimetry (Tabatabai, 1982), respectively.

2.3.2.2. Temporal variations in soil N

Soil available N (0–10 cm) was determined in four soil samples taken randomly following a zig zag distribution in each plot, every 15 days before N addition, and immediately analyzed for $\text{NH}_4^+\text{-N}$ and $\text{NO}_3^-\text{-N}$ according to Sadzawka *et al.* (2006). Gravimetric soil moisture was also determined by drying a fresh soil sample (50g) at 105 °C for 24 h, in agreement with Sadzawka *et al.* (2006). The field N mineralization during the experimental period was measured by the soil core aerobic incubation technique with acetylene (C_2H_2) inhibition (Hatch *et al.*, 1990; 1991; Lober and Rydeer, 1993). Briefly, four cylindrical soil cores (2.6 cm diameter x 10cm deep) were taken randomly from each

plot employing a steel corer every two weeks. These cores were placed in a glass jar (1000 mL) maintaining the soil structure. The jars were sealed with a metal lid, which has a rubber septum fixed in the center. Each jar was labeled and buried in the soil, exposing only the upper surface of the lid, which allows incubating the samples at the same climatic conditions than the surrounding soil.

Using a hypodermic syringe, 20mL of air was withdrawn from the headspace of each jar. This air was discarded and later 20mL of C_2H_2 was injected providing a 2% v/v concentration, so that NH_4^+ was the only available N form possible in the jar.

At each sampling time, the fresh and the incubated soil were taken to the laboratory, where NH_4^+ and NO_3^- concentrations and soil moisture were determined, as described previously. Nitrate values were not taken into consideration in the current study according to Hatch *et al.* (1990; 1991). Ammonium was determinate by a 2 M KCl extraction. The mix was shaken for 1 h at 180 rpm, and the suspension was filtered using a Whatmann N°1 filter paper. Soil extracts were kept at <4°C until analysis by sulfuric acid titration according to Sadzawka *et al.* (2006).

Mineralization for any incubation period was calculated as the difference between the N-NH_4^+ concentration in the soil at the start and the end of the incubation time ($\text{mg NH}_4^+\text{-N kg}^{-1}$ dry soil). Negative rates of N mineralization were assumed as net immobilization or assimilation periods according to Hatch *et al.* (1998).

The total mineralization ($\text{kg NH}_4^+\text{-N ha}^{-1}$) was estimated as the cumulative amount of mineralization/immobilization values during the experimental period.

2.3.3. Pasture

2.3.3.1. Yield

The pasture was mown with a lawn mower every 15 days, except when height was less than 8 cm, and clippings were collected and weighed fresh. A subsample was then taken for dry matter (DM) determination at 60 °C for 48 h (Sadzawka *et al.*, 2007), so that yield was calculated as kg DM ha⁻¹.

2.3.3.2. N concentration

The previous grass dry samples were then grinded (1 mm) (Thomas Wiley mill, model 4; Arthur H. Thomas Co., Philadelphia, PA) and analyzed for N concentration (%) by near-infrared spectroscopy (NIRS), according to Lobos *et al.* (2013).

2.3.3.3. Plant uptake

Using the DM yield and the N concentration in plants, the total N plant uptake was calculated for the respective period (kg N ha⁻¹). This represented the total plant demand.

2.3.4. N gap

Mineral nitrogen was applied to reduce the gap between plant demand and soil N supply in the optimized treatment only when the differential was greater than 10 kg N ha⁻¹. This criterion was chosen considering the potential cost of application at the farm level.

2.3.4.1. Nitrogen soil budgets

Nitrogen applied as fertilizer, N deposition in rainfall, N generated by biological fixation (NBF), and N mineralization were considered as N inputs. The legumes

N contribution was estimated according to Ledgard *et al.* (2001). Nitrogen leaching, N denitrification and total N plant uptake were considered as N outputs. Leaching and denitrification values used were those of Salazar *et al.* (2012b) and Cardenas *et al.* (2013) respectively, for experiments carried out under similar conditions of that of the present experiment (Table 3).

2.3.4.2. Nitrogen used efficiency (NUE)

The efficiency of nitrogen use for the experimental period was calculated for the 171 y 450 kg N ha⁻¹ treatments, according to the following equation 1:

$$NUE = \frac{(N \text{ uptake treatment} - N \text{ uptake control})}{N \text{ applied}} \times 100$$

2.3.5. Statistical analysis

All data were statistically analyzed by ANOVA with the SPSS software version 15.0. Comparison of means was done by Tukey-HSD test at a 95% confidence level. In order to explain variations in soil available and mineralized N a partial least squares analysis was conducted with JMP®11.0.0. Most relevant variables regarding responses of interest were defined as those with a variable importance for projection value (VIP) greater than 0.8 (Wold, 1994).

3. Results and Discussion

3.1. Climatic data

Total rainfall during the experimental period was 1,161 mm, while the mean air temperature was 11.7 °C, both similar to the total 36 years average for this area (1,260 mm and 12 °C, respectively). However, when considering the seasonal distribution, it can be seen that rainfall during the summer months (December and February)

was three times higher than that of a normal year, while during winter this was 0.7 times lower than the average value (Figure 1a). In relation to temperature, the experimental period was similar to the 36 years

average, with only 1° C difference during the summer and winter months (Figure 1b). The mean soil temperature was 13.3°C.

Figure 1. Climatic parameters at the experimental site during the experimental period (02nd/01/12 to 11th/03/13), in comparison to the 36 years average for the site, a) monthly rainfall (mm), and b) air temperature (°C) .

3.2. Soil

3.2.1. Initial characterization

The experimental site had good soil fertility conditions for pasture production. It had a high OM content (215 g kg⁻¹) and a moderately acid reaction (Table 1). Soil P status was high but sulphur concentration was low, which is common in most Andisols of this area (Alfaro *et al.*, 2006; Vistoso *et al.*, 2012). This deficiency was corrected with the basal nutrients application carried out.

3.2.2 . Available N

Total available N was high in all treatments and greater in the 171 kg N ha⁻¹ treatment amounting 1,417 ± 6.1, 1,108 ± 77.1 and 1,017 ± 18.0 kg N ha⁻¹ for the 171 kg N ha⁻¹, control and 450 kg N ha⁻¹ treatments, respectively ($p \leq 0.05$). The high values measured

could be related to the N mineralization registered, as this organic fraction can be transformed to available N (Whitehead, 2000).

The greatest soil available N contribution in the control treatment was registered in mid-April (120 ± 16.9 kg N ha⁻¹), and the lower contribution was measured in September (0.7 ± 0.68 kg N ha⁻¹). The 450 kg N ha⁻¹ treatment had a lower N contribution, compared to that of the control and optimized treatments, so that excessive N addition did not increase the soil available N in this treatment. The maximum soil N contribution for this treatment was also registered in April (107 ± 30.3 kg N ha⁻¹), and the minimum contribution was observed in 4 out of 32 of the dates studied. The optimized treatment (171 kg N ha⁻¹) presented N contributions 1.3-3.5 times higher than the control treatment and 2-40 times higher than the 450 N ha⁻¹ treatment in February, August and December. The minimum contribution was measured in June 2012 (0 ± 0.0 kg N ha⁻¹; Figure 2).

Figure 2. Dynamic of soil available N (kg N ha^{-1}) for each treatment, during January 2012 to March 2013.

According to the partial least squares regression analysis, soil available N was highly influenced by a combination of adequate soil temperature and rainfall conditions ($\text{VIP}=1.41$ and 0.97 , respectively), which could explain the higher values registered in autumn and spring 2012, followed by December 2012 and February 2013. Data suggest that excessive rainfall would result in a lower soil N contribution even under conditions of adequate temperature (i.e. January 2012; Figure 1a).

Our data also suggest that N fertilization should be restrained at these times of the year, in opposition to the traditional N management carried out by Chilean farmers, as soil provides available N in amounts that could maintain an adequate grassland yield. If, N fertilizer is applied at these times, potential environmental or animal health issues could arise.

Low N available data measured in winter months may be related to immobilization by the microbial biomass and roots (Pérez *et al.*, 1998), as denitrification has been shown to be low in fertilized grassland soils of the same characteristics to that of the present study (Cardenas *et al.*, 2013).

3.2.3. N mineralization

The greater soil N mineralization was measured in the 450 kg N ha^{-1} (934 ± 48.7 , 643 ± 135.5 and 241 ± 20.4 for the 450 kg N ha^{-1} , 171 kg N ha^{-1} and control treatments, respectively; $p \leq 0.05$). These values are within the ranges reported by Alfaro *et al.* (2009) and Martínez-Lagos *et al.* (2015), in experiments carried out in the same soil series with different N fertilization treatments.

The mineralization values were high and could be related to the high organic matter content of the soil ($> 17\%$), in agreement with Cardenas *et al.* (2013). The partial least squares analysis indicated that the most relevant variable for N mineralization was the concentration of soil available N ($\text{VIP}=1.76$), so that N fertilization could favor this process. This priming effect has been previously described by Mora *et al.* (2007). This statistical analysis also showed that rainfall and soil temperature do not have a significant impact on soil N mineralization ($\text{VIP}=0.49$ and 0.52 for rainfall and temperature, respectively), so that the impact of soil available N masks the impact of environmental variables as for soil N mineralization.

These variables seem to have only a short term (15 days) effect on soil available N (VIP=0.96 and 1.41 for rainfall and temperature, respectively).

3.3. Pasture demand

3.3.1. Yield

Nitrogen application increased DM yield and resulted in 58% more DM yield in the +N treatments in relation to the control with no N addition ($p \leq 0.05$; Table 2). Thus, yields in the 450 and 171 kg N ha⁻¹ treatments were higher than those of the control treatment by 71 and 45% respectively ($11,299 \pm 373.3$ kg DM ha⁻¹, $9,573 \pm 299.0$ kg DM ha⁻¹, and $6,605 \pm 284.8$ kg DM ha⁻¹, for the 450, 171 and control treatments, respectively), the control results are similar to those found by Salazar *et al.* 2012b, who determined a N uptake between 175-188 kg N ha⁻¹ yr⁻¹. This indicates that the pasture responded to N addition in agreement with previous data from Teuber *et al.* (1988) and Mora *et al.* (2007). The 450 kg N ha⁻¹ treatment produced 1,726 kg DM more than the 171 kg N ha⁻¹ treatment. Nevertheless, this increase in yield was associated to the application of 279 kg N ha⁻¹, if compared to the 171 kg N ha⁻¹ treatment, so that the extra yield was produced at a 6 kg DM kg⁻¹ N efficiency, which is one third of that showed by the optimized treatment over the experimental period (17 kg DM kg⁻¹ N).

3.3.2. N concentration

The application of N increased pasture N concentration by 10%, on average ($p \leq 0.05$), although there was no significance difference in N concentration among +N treatments ($p \geq 0.05$, Table 2). Average pasture N concentration in the control treatment was $3.7 \pm 0.08\%$ (Table 2). All N concentrations found in this experiment were within the range for N-fertilized

pastures of this area (Anrique *et al.*, 2008), so that although no N fertilizer was applied, soil natural N contribution resulted in an adequate N concentration in pastures for animal production.

3.3.3. Plant uptake

The highest N uptake was obtained in the pasture receiving N in excess ($p \leq 0.05$; Table 2). This would be related to the differential in DM yield obtained in this treatment.

3.4. N gap

Mineral N application was only required in the spring-summer of 2012 (24th/09, 22nd/10, 19th/11, 17th/12 and 31st/12), with amounts that ranged from 23 up to 67 kg N ha⁻¹ per dressing, this was a 38% of the total N applied in the 450 kg N ha⁻¹ treatment for the year, and 44% of the amount applied in the same period in that treatment. Thus, although this was a time of high soil N contribution, and probably due to the high pasture growing rates at this time, the soil supply was not sufficient to cover the total plant uptake.

3.4.1. Nitrogen budget

Organic matter mineralization was the main N input for all treatments (80-97% of the total input for N; $p \leq 0.05$), greater than the contribution of N fertilizer, which occupied the second place. The contribution of biological fixation and rainfall was low (17% and 3% of total N inputs, respectively), with contributions 44% and 2 times higher than the values reported by Alfaro *et al.* (2009) for the area with similar techniques and conditions. This was probably associated to differences in management and climate conditions, although relative contribution to N inputs does not vary significantly among years (Alfaro *et al.*, 2009).

In the previous study, pasture was managed under rotational grazing while in the present experiment a cutting regime was used. Grazing could have resulted in lower legumes presence in the pasture due to uneven harvesting. Also, in the prior experiment, the evaluations carried out considered a 12 months period, while in the

present study the experimental period was 14 months. The main output for all treatments was plant uptake, which represented between 90-95% of the total N outputs, in agreement with Alfaro *et al.* (2009) and Martínez-Lagos *et al.* (2014). Nitrogen losses by leaching and denitrification were low as they were taken from previous studies.

Table 2. Yield, N concentration and N plant uptake per treatment during the study period. (n=4, $\pm$ standard error of the mean).

Treatment	Yield (kg DM ha ⁻¹)	N concentration (%)	N plant uptake (kg ha ⁻¹)
Control	6,605 $\pm$ 284.8 ^c	3.7 $\pm$ 0.08 ^b	248 $\pm$ 13.9 ^c
450 kg N ha ⁻¹	11,299 $\pm$ 373.3 ^a	4.1 $\pm$ 0.08 ^a	459 $\pm$ 21.8 ^a
171 kg N ha ⁻¹	9,573 $\pm$ 299.0 ^b	4.0 $\pm$ 0.02 ^a	390 $\pm$ 12.3 ^b

Different letters in columns indicate significant differences between treatments ($p \leq 0.05$).

Table 3. Soil N budgets estimated for the treatments in the experimental period (02nd/01/2012 to 11th/03/2013). (n=2 for soil samples, n=4 for plant samples; $\pm$ standard error of the mean).

Components evaluated		Treatments (kg ha ⁻¹)		
		0 N	450 N	171 N
Inputs	Fertilization	0	450	171
	N mineralization	241 $\pm$ 20.4 ^b	934 $\pm$ 48.7 ^a	643 $\pm$ 135.4 ^{ab}
	N Biological Fixation (NBF)	50 $\pm$ 12.5	17 $\pm$ 2.1	20 $\pm$ 7.8
	N in rainfall	10	10	10
Total inputs		301 $\pm$ 32.9	961 $\pm$ 50.8	673 $\pm$ 143.3
Outputs	Plant uptake	248 $\pm$ 13.9	459 $\pm$ 21.8	390 $\pm$ 12.3
	Leaching*	13	53	38
	Denitrification*	0	0.27	0.10
	Total outputs	261 $\pm$ 13.9	512 $\pm$ 21.8	428 $\pm$ 12.3
Inputs-Outputs		40 $\pm$ 19.0	449 $\pm$ 29.0	245 $\pm$ 131.0
Outputs/Inputs (%)		87	53	64
NUE (%)		-	47 $\pm$ 4.5 ^b	84 $\pm$ 3.8 ^a

Different letters in columns indicate significant differences between treatments ($p \leq 0.05$). *from Salazar *et al.* (2010) and Cardenas, *et al.* (2012), respectively.

3.4.2. NUE

The optimized treatment was 1.8 times more efficient in the use of N than the 450 kg N ha⁻¹ treatment (Table 3). According to the N soil budgets, control plots had less available N in comparison with the +N treatments. The positive values suggest an accumulation of N in the soil, which could be used by plants or the biomass communities, or loss to the wider environment by leaching or gaseous emissions (Martínez-Lagos *et al.*, 2014; Salazar *et al.*, 2012a).

The NUE values were similar to those reported by Alfaro *et al.* (2009), who reported a 66% average. Our results suggest that it is possible to maintain permanent pasture yield using only 38% of the total dose used in the treatment without N restriction. This also contributes to high levels of soil N natural supply, as our results showed that this decreases with increasing N fertilization, optimizing utilization and potentially reducing environmental risks.

This study showed that in an organic grassland soil of adequate soil fertility level, it is necessary to add N fertilizer only during periods of high plant demand and not at the fixed traditionally periods used by farmers, such as early fall (March), and early spring (end of August). This will contribute to increase fertilizer use efficiency from around 40% at present (Alfaro *et al.*, 2009) to over 80% at the soil-plant interface. Moreover, according to the experimental conditions the optimized control treatment was more efficient in the used and utilization of N than the 450 kg N ha⁻¹ treatment with sodium nitrate (Table 3). Although this study was only carried out for one year on a site with no significant soil fertility restrictions, the data show that it is possible to increase the efficiency of the N applied as fertilizer by quantifying soil N contribution and the actual pasture demand on short time scales. This can bring benefits such as i) improving the resources efficiency while maintaining pasture produc-

tivity, ii) increasing the profitability of livestock systems based on grazing, and iii) reducing the potential environmental risks in pasture systems of southern Chile.

4. Conclusions

The main N input in all treatments was the N mineralization (80-97% of the total N input), the main output was plant N uptake (90-95% of the total outputs for N). The contribution of rainfall and biological fixation to the total N inputs to the systems was small (<17%). The optimized treatment proved to be 1.8 times more efficient in the use of N than the 450 kg N ha⁻¹ treatment. The present results suggest that it is possible to adjust pasture's N fertilization considering soil N contribution via mineralization, and that this improves resources efficiency while maintaining pasture productivity.

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