

EFFECT OF NITROGEN INHIBITORS ON NITROUS OXIDE EMISSIONS AND PASTURE GROWTH AFTER AN AUTUMN APPLICATION IN VOLCANIC SOIL

Erika Vistoso^{1*}, Marta Alfaro¹, Surinder Sagar², and Francisco Salazar¹

A range of technologies is available to reduce greenhouse gas emissions from agricultural systems. Among these, applying N transformation inhibitors is promising in reducing nitrous oxide (N₂O) emissions in both arable and pastoral soils. A randomized complete block design with six replicates was used to quantify the effect of urease (UI) and nitrification (NI) inhibitors on N₂O emissions and pasture production from permanent pasture in an Andisol after autumn-applied urea. The N₂O emissions were measured periodically for 8 wk with PVC stationary chambers. Mineral N, DM yield, N concentration, and N uptake were analyzed. Our results show that adding fertilizer (40 kg N ha⁻¹) significantly increased N₂O emissions by 281% over the control treatment ($P < 0.05$) and adding N inhibitors to fertilizer N resulted in a 10%-29% reduction in emissions. Both inhibitors initially reduced nitrate-N production in the Andisol (Osorno series) either by slowing urea hydrolysis or the nitrification process. Increases in pasture yield (8%-13%), N concentration (7%-9%), and N uptake (46%-56%) were measured by adding N inhibitors with urea. Emission factors, measured under field conditions in Chile after autumn-applied urea and N inhibitors (applied alone or combined), were very low (0.052%-0.114%) compared with values reported in the literature and the Intergovernmental Panel on Climate Change (IPCC) default value (1%). Using these technologies could contribute to Chile's nationally established goal of a 20% reduction in greenhouse gas emissions by 2020.

Key words: Andisol, emission factor, urease inhibitor, nitrification inhibitor, urea.

Livestock production (dairy and beef) in southern Chile is based on direct grazing of permanent pastures that are mainly on volcanic soils (Goic and Rojas, 2004); it has been intensified in the last decade with an increasing stocking rate. This has resulted in an increased use of N fertilizer and a greater accumulation of organic residues, e.g., dairy slurry (Alfaro and Salazar, 2008). Urea is the main N inorganic fertilizer in these livestock production systems. Thus, Chilean agricultural soils receive an annual application of 0.42 million Mg urea, which is estimated will reach 0.48 million Mg by 2020 (ODEPA, 2010).

Nitrogen is a nutrient that strongly regulates pasture production, but it can also contribute to environmental degradation through nitrate (NO₃⁻) leaching, ammonia (NH₃) volatilization, and nitrous oxide (N₂O) emission (Bolan *et al.*, 2004; Sagar *et al.*, 2009; Martínez-Lagos *et al.*, 2010; Núñez *et al.*, 2010). Nitrous oxide is a potent

greenhouse gas (GHG) with a global warming potential 310 times greater than CO₂ and contributes to ozone layer depletion (Crutzen, 1981). In many agriculturally-based countries, including Chile, New Zealand, Ireland, and Uruguay, N₂O emissions and other GHGs are increasing (UNFCCC, 2011). Greenhouse gas emissions from the agricultural sector in Chile have increased by 33% between 1984 and 2003 (González *et al.*, 2009).

Several approaches have been recommended to mitigate the economic and environmental impacts of N losses (Sagar *et al.*, 2009; Luo *et al.*, 2010). One of these is the use of urease and nitrification inhibitors (Di and Cameron, 2002; 2005). Numerous studies in the last decade have evaluated the use of these inhibitors to reduce N gaseous and leaching losses and increase N-use efficiency in cropping and pastoral soils of the USA, Europe, and New Zealand (Di and Cameron, 2005; 2006; Subbarao *et al.*, 2006; Sagar *et al.*, 2009; Luo *et al.*, 2010). However, no published information is available about the effect of N inhibitors on N loss (N₂O-N emission) mitigation in Chilean pastoral soils and little information has been published about the seasonal variability of CO₂ and N₂O emission fluxes from volcanic ash soil under different agricultural uses and management (Muñoz *et al.*, 2010; 2011) in southern-central Chile.

¹Instituto de Investigaciones Agropecuarias INIA, Casilla 24-O, Osorno, Chile. *Corresponding author (evistoso@inia.cl).

²Landcare Research, Private Bag 11052, Manawatu Mail Centre, Palmerston North 4442, New Zealand.

Received: 4 October 2011.

Accepted: 12 December 2011.

We hypothesize that using N cycle inhibitors will be effective in reducing N₂O emissions in a grassland Andisol in southern Chile. Thus, the aim of this research study was to quantify the effect of urease and nitrification inhibitors on N₂O emissions and pasture yield in an Andisol after autumn-applied urea.

MATERIALS AND METHODS

Experimental site

The experiment was carried out at the Instituto de Investigaciones Agropecuarias (INIA), Centro Remehue (40°35' S, 73°12' W). The soil at the experimental site is an Andisol (Osorno series) managed under permanent pasture (*Lolium perenne* L., *Holcus lanatus* L., and *Dactylis glomerata* L.) with good drainage and a 60-120 cm depth (CIREN, 2003).

Prior to starting the experiment, legumes and soil worms were eliminated to control the N input as N biological fixation (Picloram, a.i. 0.25 L ha⁻¹) and as part of pest management, respectively. Black caterpillars (*Dalaca palens* B.) and white worms (*Phytoloema herrmanni* Germ.) were eliminated early in autumn with the entomopathogenic fungus (*Beauveria bassiana* Vuill. Qu-B931 strain and *Metarhizium anisopliae* Metschn. Qu M270 strain, respectively, with doses of 10¹² spores ha⁻¹.

Climatic data. Daily rainfall and temperature during the experimental period, were recorded with an automatic weather station (CR10X-1M Model, Campbell Scientific Inc., Logan, Utah, USA) placed within 3 km of the experimental site.

Treatments and experimental design

A randomized complete block design with six replicates tested the effectiveness of the urease inhibitor (UI) and nitrification inhibitor (NI) treatments: Control, Urea, Urea+UI, Urea+NI, and Urea+UI+NI. Nitrogen as urea (46% N) was applied at the rate of 40 kg N ha⁻¹. Each treatment was applied to a 2 m² (1 m × 2 m) area plot with a 0.5 m buffer zone around each plot. Urease inhibitor and NI were added manually at the rate of 0.25 g N-(n-butyl) thiophosphoric triamide kg⁻¹ N (NBPT, Agrotain International, USA) and 10 kg dicyandiamide ha⁻¹ (DCD, Alfa Aesar, USA), respectively.

All plots received 65 kg P ha⁻¹ (triple superphosphate, 20% P), 125 kg K ha⁻¹ (potassium chloride, 52% K), 24 kg Mg ha⁻¹ (magnesium oxide, 51% Mg), and 40 kg S ha⁻¹ (gypsum, 18% S) as basal nutrients.

Gas sample collection and analysis

Gaseous emissions of N₂O were measured periodically for 8 wk by the closed static chamber techniques described by Saggart *et al.* (2004). Briefly the N₂O gas was accumulated in an air-tight static chamber (25 cm diameter and 20 cm

depth) placed in each plot, and gas samples were collected daily in vials (22 mL capacity). The static chambers were closed once a day with a hermetic PVC lid; samples were taken at 0, 30, and 60 min for three alternate days during the first week, twice per week between the 2nd and 5th weeks, and then once a week for 3 more weeks.

The N₂O concentration in the gas samples was determined with a Gas Chromatograph (Perkin Elmer® Precisely, Clarus 600 Model, Shelton, USA) fitted with an ⁶³Ni electron capture detector (ECD) and a Carboxen™ 1010 PLOT column (30 m × 0.32 mm ID, Sigma-Aldrich Co. LLC., St. Louis, USA). The oven, injector, and detector temperatures were operated at 80, 260, and 360 °C, respectively. The carrier gas was helium with a flow of 4 mL min⁻¹. The limit detection for the methodology is 0.1478 and 0.1401 for 1 and 5 mg L⁻¹, respectively. The N₂O fluxes were calculated with the equations described in Saggart *et al.* (2004).

Estimation of emission factor

The proportion of N emitted as N₂O-N (EF) was estimated for each treatment with Equation [1]:

$$\text{Emission factor (EF)} = [(A - B)/C]/100 \quad [1]$$

where A is N₂O-N emitted in the treated plot, B is N₂O-N emitted by the control treatment, and C is the amount of applied N, considering that it constitutes the N inhibitor.

Soil and plant analysis

At the start of the experiment, six representative soil samples (0-10 cm depth) were collected, air-dried, and sieved through a 2 mm sieve and stored in plastic containers for analysis. These samples were analyzed for soil texture and chemical characteristics by the methods outlined in Sadzawka *et al.* (2006). Briefly soil pH was measured potentiometrically in water and CaCl₂ 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 base cations (Ca, Mg, K, and Na) and exchangeable Al were extracted with 1 M NH₄Ac 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 NaHCO₃ at pH 8.5 and 1 M Ca(H₂PO₄)₂ and analyzed by the Murphy and Riley method and turbidimetry (Tabatabai, 1982), respectively.

In addition, during the experimental period (28 April to 22 June 2011), a composite soil sample (0-10 cm depth) was collected every week from each plot and immediately analyzed for NH₄⁺-N and NO₃⁻-N in accordance with the method described by Sadzawka *et al.* (2006). Soil moisture in a subsample of this soil (n = 2) was measured for weight loss after drying the sample at 105 °C for 24 h (Rowell, 1997).

The pasture was mown with a lawn mower when it was 20 cm high and clippings were collected and weighed fresh. A subsample was then taken to determine DM content at 60 °C for 48 h (Sadzawka *et al.*, 2007),

and then DM production was calculated as kg DM ha⁻¹. Herbage samples were analyzed for total N by the Kjeldahl digestion method in accordance with the method described by Sadzawka *et al.* (2007).

Statistical analysis

All data were statistically analyzed (ANOVA) with the Genstat version 12.0 (Genstat, 2003) to determine statistical significance. Comparison of means was done by a Least Significant Difference Test (LSD) at a 95% confidence level.

RESULTS AND DISCUSSION

Soil

The experimental site had good soil fertility for pasture and animal production. It had high OM (230 g kg⁻¹) and a moderately acid reaction (Table 1). Soil P status was high but S concentration was low, which is common in most Andisols of this area (Alfaro *et al.*, 2006).

Rainfall, temperature, and soil moisture

During the measurement period, rainfall was lower (167 and 144 mm for the mean and experimental period, respectively) than the 34-yr mean for this site (Figure 1); mean air temperature (8.4 °C) was similar to the 34-yr average (8.8 °C), and soil moisture varied between 68% and 93%.

Pasture production

Yield. Applying N increased DM yield, which indicates that this soil responds to N input ($P < 0.05$) according to Teuber *et al.* (1988), and resulted in 45%-50% more DM yield than the control treatment (Table 2). Dry matter yield with added urea was higher (1252 ± 246.17 kg DM ha⁻¹) than the control treatment (910 ± 151.22 kg DM ha⁻¹) by 37%. Our lower response to urea is consistent with autumn-applied N when the DM response to added N is lower than spring applications (Teuber *et al.*, 1988).

Table 1. Initial soil characteristic (0-10 cm, n = 3, ± standard error of the mean). Date: 29 April 2011.

Parameter	Results
Classification ¹	Typic Hapludands
Series	Osorno
Texture	Loamy
pH H ₂ O (soil:water, 1:2.5)	6.1 ± 0.03
pH CaCl ₂ (soil:CaCl ₂ , 1:2.5)	5.3 ± 0.04
Organic matter, g kg ⁻¹	230 ± 0.76
Available N, mg kg ⁻¹	45 ± 2.44
Olsen P, mg kg ⁻¹	45 ± 3.22
Available S, mg kg ⁻¹	7 ± 0.82
Exchangeable Ca, cmol ₍₊₎ kg ⁻¹	11.6 ± 0.32
Exchangeable Mg, cmol ₍₊₎ kg ⁻¹	3.0 ± 0.08
Exchangeable K, cmol ₍₊₎ kg ⁻¹	0.6 ± 0.05
Exchangeable Na, cmol ₍₊₎ kg ⁻¹	0.2 ± 0.02
Exchangeable Al, cmol ₍₊₎ kg ⁻¹	0.1 ± 0.01
Al Saturation, % ²	0.5 ± 0.08
Bulk density, g cm ⁻³	0.68 ± 0.01

¹According to CIREN (2003).

²Al Saturation: proportion of available Al in relation to total cation content (Ca + Mg + K + Na + Al).

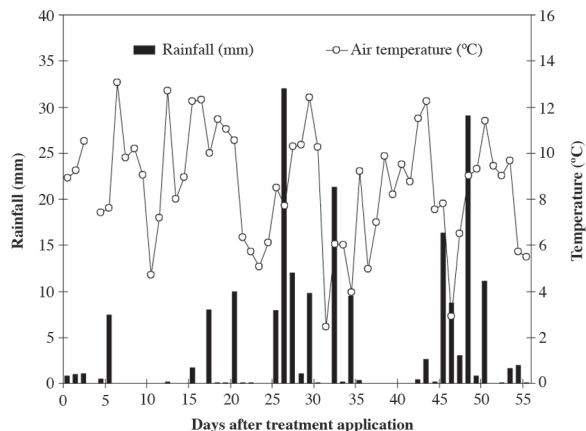


Figure 1. Daily rainfall and air temperature during the experimental period (29 April to 22 July 2011).

Higher DM yield responses have also been reported (128% increase) in pastoral systems by adding increasing N rates (Mora *et al.*, 2007).

Adding N inhibitors to urea individually (urea+UI and urea+NI) or combined (urea+UI+NI) produced a marginally higher DM yield (1325 ± 142.48 to 1363 ± 132.81 kg ha⁻¹) than urea alone ($P > 0.05$, Table 2) in accordance with the results of Di and Cameron (2006) and Luo *et al.* (2007).

The observed DM yield trend between these treatments suggested that N conserved with inhibitors was used by the pasture plants to enhance their productivity as shown by the N uptake and N use efficiency data (Table 2). The lack of difference between treatments could be related to the high spatial variability in pasture growth commonly found in permanent pastures. We only had six replicated plots (1 m × 1 m) to measure pasture yield. Considering pasture DM variability measured during this autumn growth (compared with other seasons of the year) a larger number of replicates would be required to test the statistical significance of differences in DM yield, N content, and N uptake obtained in this study. The highest autumn DM yield during the 16-wk study period was obtained in the urea+UI+NI treatment.

Nitrogen concentration. Pasture N concentration was lower in the control treatment (3.5 ± 0.18%, Table 2) than

Table 2. Yield, N concentration, N plant uptake, N use efficiency, and N emission factor per treatment after autumn-applied N to a permanent pasture (n = 6, ± standard error of the mean).

Treatment	Yield	N	N	N	N
		concentration	plant uptake	use efficiency	emission factor
	kg ha ⁻¹	%	kg ha ⁻¹	—	%
Control	910 ± 151.22	3.5 ± 0.18	32.6 ± 6.10	-	-
Urea	1252 ± 246.17	3.8 ± 0.09	47.7 ± 9.51	38 ± 0.24	0.114
Urea+UI	1325 ± 142.48	3.7 ± 0.13	49.7 ± 6.07	43 ± 0.15	0.098
Urea+NI	1335 ± 185.07	3.7 ± 0.10	49.5 ± 6.67	42 ± 0.17	0.076
Urea+UI+NI	1363 ± 132.81	3.8 ± 0.10	50.9 ± 4.42	46 ± 0.11	0.052
	ns	ns	ns	-	-

UI: urease inhibitor; NI: nitrification inhibitor; ns: non significant.

in the treatments receiving only urea and urea with N inhibitors (applied alone or combined with urea). There was no difference in N concentration in plots from urea and urea with N inhibitor treatments ($P > 0.05$, Table 2). Thus, applying N alone or with N inhibitors increased pasture N concentration by 7%-9% and improved their protein level. The pasture N/protein contents obtained during autumn-applied N are within the adequate range recommended for animal nutrition and also within the range generally found in this region's N-fertilized pastures (Whitehead, 2000; Anrique *et al.*, 2008).

Nitrogen uptake. Pasture N uptake increased significantly when N was applied compared to the control treatment, but no differences were observed among N treatments ($P > 0.05$, Table 2). The highest N uptake was obtained in the pasture receiving urea+UI+NI. Overall, the N-fertilized pasture treatment removed an extra 18 kg N ha⁻¹, which resulted in an increase of 38%-46% in N use efficiency (Table 2). All treatments receiving N met the potential dairy cow protein requirements for a 30 L milk d⁻¹ production (NRC, 2001).

Soil N transformations

The NH₄⁺-N and NO₃⁻-N concentrations on day 1 fluctuated between 39.7 ± 2.28 to 73.2 ± 0.81 mg kg⁻¹ dry soil and 6.5 ± 0.65 to 11.1 ± 0.33 mg kg⁻¹ dry soil, respectively (Figure 3).

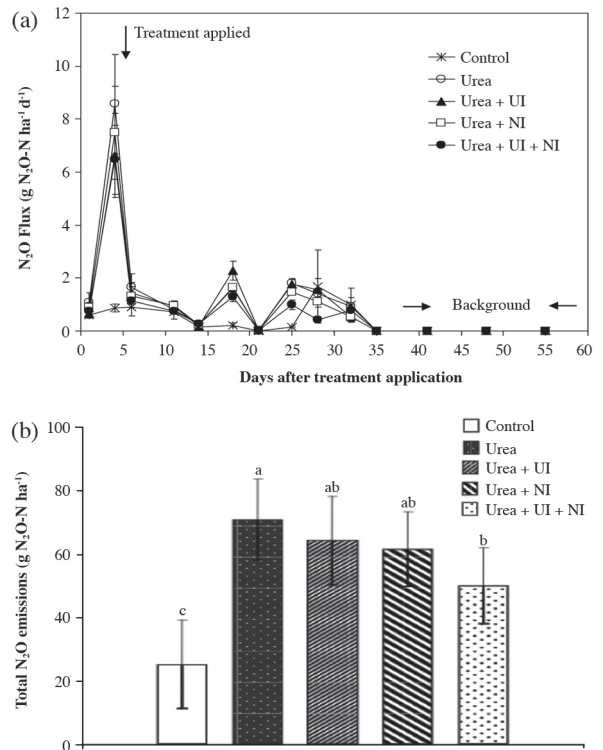
Applying urea initially increased NH₄⁺-N concentrations (58.9 ± 3.74 mg kg⁻¹ dry soil), urea+UI (67.7 ± 1.95 mg kg⁻¹ dry soil), and urea+NI (73.2 ± 0.81 mg kg⁻¹ dry soil) with a subsequent decline (Figure 3a). The NH₄⁺-N concentrations at the end of the experimental period were 24.3 ± 0.00, 23.3 ± 1.01, 12.5 ± 1.01, 27.7 ± 2.36, and 21.6 ± 0.34 mg kg⁻¹ dry soil in the control, only urea, urea+UI, urea+NI, and urea+UI+NI treatments, respectively.

The NO₃⁻-N concentration was low in all the treatments before starting the experiment and increased 27 d after the treatment was applied (Figure 3b), thus corroborating previous studies by Cartes *et al.* (2009) and Vistoro and Alfaro (2010) regarding the effect of applying N on N mineralization. This has implications for the N dynamics in this soil.

Adding urea+UI+NI was more effective in inhibiting the transformation of the nitrification process in the Osorno soil (Figure 3).

Nitrous oxide emissions

The N₂O-N fluxes were low and, on average, varied between 0.001 ± 0.0001 and 8.567 ± 1.8795 g N₂O-N ha⁻¹ d⁻¹ with three emission peaks in all treatments during the measurement period (Figure 2a). The first high peak was observed 4 d after urea was applied (8.6 ± 1.88 g N₂O-N ha⁻¹ d⁻¹) and emissions were seven- and ten fold greater than in the control treatment. The second peak



Different letters indicate a statistical difference between treatments (LSD test, $P < 0.05$).

Figure 2. Fluxes (a) and total emissions (b) of nitrous oxide after applying only urea and with urease (UI) and nitrification (NI) inhibitors after autumn-applied N to permanent pasture ($n = 6$, ± standard error of the mean).

occurred in all treatments, except the control, 18 d after treatments were applied and was the highest in the urea+UI treatment (2.2 ± 0.35 g N₂O-N ha⁻¹ d⁻¹) followed by the urea and urea+NI treatments (1.7 ± 0.16 and 1.6 ± 0.05 g N₂O-N ha⁻¹ d⁻¹, respectively). The third peak occurred in the urea+UI (1.9 ± 0.21 g N₂O-N ha⁻¹ d⁻¹), urea (1.8 ± 0.15 g N₂O-N ha⁻¹ d⁻¹), urea+NI (1.5 ± 0.09 g N₂O-N ha⁻¹ d⁻¹), and urea+UI+NI (0.1 ± 0.18 g N₂O-N ha⁻¹ d⁻¹) treatments 25 d after they were applied. These N₂O emissions continued to decrease in all the treatments up to base levels 35 d after treatments were applied. Higher N₂O-N emission peaks were associated with rainfall events and increasing temperatures during the measurement period (Figure 1) because they were related to restricted aeration and high water content in the soil, according to Saggarr *et al.* (2007) and Luo *et al.* (2008).

Total N₂O-N emissions were low in the control treatment and high in the urea treatment. Emissions decreased when inhibitors were applied ($P < 0.05$; Figure 2b) from 70.8 ± 12.82 g N₂O-N ha⁻¹ with only urea to 64.2 ± 12.82, 61.5 ± 11.71 and 50.0 ± 12.00 g N₂O-N ha⁻¹ with urea+UI, urea+NI, and urea+UI+NI treatments, resulting in 9%, 13%, and 29% N₂O emission reduction, respectively.

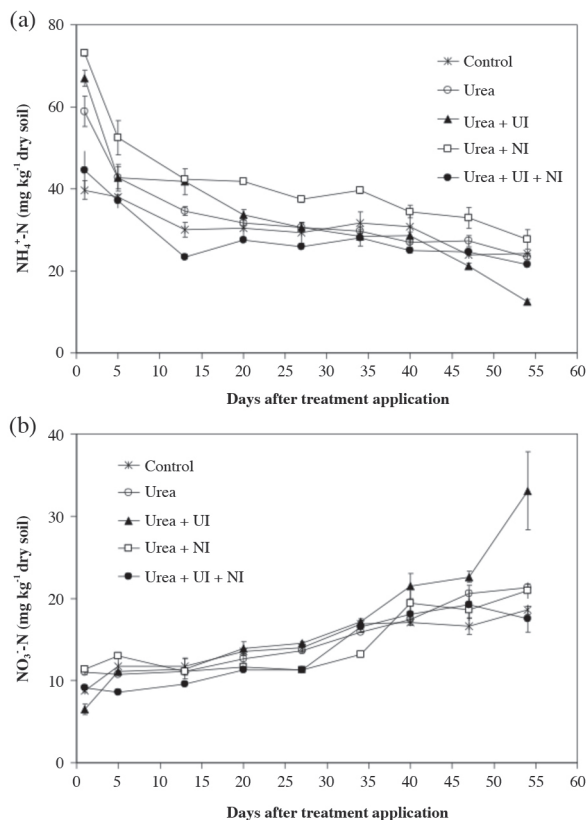


Figure 3. Distribution of $\text{NH}_4^+\text{-N}$ (a) and $\text{NO}_3^-\text{-N}$ (b) concentration after applying only urea and with urease (UI) and nitrification (NI) inhibitors after autumn-applied N to permanent pasture ($n = 3$, \pm standard error of the mean).

Urease inhibitor was less effective in inhibiting urease hydrolysis since $\text{NH}_4^+\text{-N}$ concentrations were higher ($67.0 \pm 1.95 \text{ mg kg}^{-1}$ dry soil) in that treatment than in the treatment with only urea ($58.9 \pm 3.74 \text{ mg kg}^{-1}$ dry soil) on the first day; however, this behavior was reversed over time in accordance with previous studies by Subbarao *et al.* (2006) and Zaman *et al.* (2007). This difference can be attributed to the experimental site spatial variability and temporary soil sampling variability.

The DCD nitrification inhibitor showed better efficacy at reducing N_2O emissions because of its nitrification inhibition (Amberger, 1989) and prolonged residence time of ammoniacal-N in the soil, thus resulting in reduced N_2O emissions (Di and Cameron, 2002; 2003). Therefore, UI plus NI combined with urea significantly reduced N_2O emissions from added urea ($P < 0.05$, Figure 2a). Emissions decreased to base levels ($0.31 \pm 0.002 \text{ mg kg}$, $n = 34$) after day 35 despite an increase in soil $\text{NO}_3^-\text{-N}$ at that time; this could be related to the low potential denitrification in this soil type (Dixon *et al.*, 2011), which contrasted with studies by Luo *et al.* (1999), Bolan *et al.* (2004), and Sagar *et al.* (2004; 2009) for N_2O emissions in New Zealand's dairy-grazed permanent pastures.

The total amounts of N_2O emitted from N fertilizer

ranged from 0.052%-0.114% of total N added through urea and nitrification inhibitors. The emission factor (EF) from the autumn-applied N fertilizer was 0.1%, which is ten fold lower than the 1.0% default value recommended by the IPCC (2001) and currently used to estimate N_2O emissions from applied N fertilizer in Chilean soils (González *et al.*, 2009).

The results of this study indicate that N_2O emissions and autumn-applied EF are low in Chilean grassland Andisols and emissions could be additionally reduced by applying N inhibitors. However, further research is required to fully understand the long-term variability and effects of using these products in Chilean grassland soils. These mitigation technologies can reduce N_2O emissions and are an alternative in developing strategies for Chile to achieve the 20% GHG emission reduction target in 2020.

CONCLUSIONS

Applying urea fertilizer (40 kg N ha^{-1}) in autumn to volcanic soil (Andisol, Osorno series) resulted in N loss as N_2O -N emissions of only 0.114%. Emissions were significantly reduced (up to 29%) by applying N inhibitors (UI and/or NI) with the fertilizer. Applying N plus N inhibitors (alone or combined) decreased soil $\text{NH}_4^+\text{-N}$ concentrations and increased soil $\text{NO}_3^-\text{-N}$ concentrations. The urea+UI+NI treatment was more effective in inhibiting the nitrification process in the Osorno series soil. These inhibitors also increased DM yield (8%-13%), N concentration (7%-9%), and N uptake (46%-56%) ($P > 0.05$) resulting in an increased N use efficiency of 38%-46%. This is the first field study carried out in Chile that reports nitrous oxide emission factors (EF) from N fertilizer and emission reductions from N inhibitors (applied alone or combined) in a grassland soil. An EF value of 0.114 obtained for fertilizer is almost one-tenth of the current default IPCC value used in the Chilean GHG inventory. In addition, EF could be reduced to 0.052 by adding N inhibitors.

ACKNOWLEDGEMENTS

We thank the Comisión Nacional de Investigación Científica y Tecnológica (CONICYT), PDA-08 and MEC-CONICYT N° 80100011 projects, and the Instituto de Investigaciones Agropecuarias (INIA) for supporting this research. We also thank Hugo Flores, Biometric Specialist, INIA (Centro La Platina) for his statistical advice and to Luis Ramírez, Sara Hube, Josué Martínez-Lagos, and Ana Rosas for their help in the field and laboratory.

Efecto de inhibidores de nitrógeno en las emisiones de óxido nitroso y crecimiento de la pradera después de la aplicación otoñal en un suelo volcánico. Una gama de tecnologías están disponibles para reducir las emisiones

de gases de efecto invernadero desde sistemas agrícolas. Entre éstas, la aplicación de inhibidores de transformación del N es considerada prometedora para reducir emisiones de óxido nitroso (N₂O) en suelos de cultivo y praderas. Un diseño de bloques completos al azar con seis repeticiones se utilizó para cuantificar el efecto de inhibidores de ureasa (UI) y nitrificación (NI) sobre emisiones de N₂O y producción de pradera permanente sobre un Andisol después de la aplicación otoñal de urea. Las emisiones de N₂O se midieron periódicamente durante 8 semanas en cámara estacionaria de PVC. Se analizaron N mineral, rendimiento de MS, concentración de N, y absorción de N. Los resultados muestran que la aplicación de fertilizante (40 kg N ha⁻¹) aumentó significativamente las emisiones de N₂O en 281% sobre el tratamiento control (P < 0,05) y generó 10-29% de reducción de emisiones. Ambos inhibidores redujeron la producción de N-nitrato en el Andisol serie Osorno por detener la hidrólisis de urea o el proceso de nitrificación. Se midieron aumentos en producción (8-13%), concentración N (7-9%) y absorción N (46-56%) con la adición de inhibidores del N con urea sobre el tratamiento control. Los factores de emisión medidos bajo condiciones de campo en Chile por la aplicación otoñal de urea e inhibidores del N (aplicados solos o combinados) fueron muy bajos (0,052-0,114%) en comparación con los valores reportados en literatura y valores por defecto del Panel Intergubernamental para el Cambio Climático (IPCC) (1%). El uso de estas tecnologías puede contribuir al objetivo establecido a nivel nacional de reducir las emisiones de gases de efecto invernadero en un 20% para el año 2020.

Palabras clave: Andisol, factor de emisión, inhibidor de la ureasa, inhibidor de la nitrificación, urea.

LITERATURE CITED

- Alfaro, M., R. Bernier, and S. Iraira. 2006. Sulphur effect on yield and quality of wheat and pasture on Andisols. *Agricultura Técnica* 66:283-294.
- Alfaro, M., and F. Salazar. 2008. Livestock production and diffuse pollution in a volcanic soil. *Journal of Soil Science and Plant Nutrition* 8(2):1-8.
- Amberger, A. 1989. Research on dicyandiamide as a nitrification inhibitor and future outlook. *Communications in Soil Science and Plant Analysis* 20:1933-1955.
- Anrique, R., R. Fuschlocher, S. Iraira, y R. Saldaña. 2008. Composición de alimentos para el ganado bovino. 87 p. Consorcio Lechero, Universidad Austral de Chile UACH, Instituto de Investigaciones Agropecuarias INIA, Centro Regional de Investigación Remehue INIA Remehue, Fundación para la Innovación Agraria FIA. Imprenta América, Valdivia, Chile.
- Bolan, N.S., S. Saggar, J.F. Luo, R. Bhandral, and J. Singh. 2004. Gaseous emissions of nitrogen from grazed pastures: Processes, measurements and modelling, environmental implications and mitigation. *Advances in Agronomy* 84:37-120.
- Cartes, P., A. Jara, R. Demanet, and M.L. Mora. 2009. Urease activity and nitrogen mineralization as affected by time, temperature and urea input rate in Andisol. *Journal of Soil Science and Plant Nutrition* 9:69-82.
- CIREN. 2003. Descripción de suelos, materiales y símbolos. Estudio Agrológico X Región. Vol. II. 225 p. Centro de Información de Recursos Naturales (CIREN), Santiago, Chile.
- Crutzen, P.J. 1981. Atmospheric chemical processes of the oxides of nitrogen including nitrous oxide. p. 17-44. *In* Delwiche, C.C. (ed.) Denitrification, nitrification and atmospheric nitrous oxide. John Wiley, New York, USA.
- Di, H.J., and K.C. Cameron. 2002. The use of a nitrification inhibitor, dicyandiamide (DCD), to decrease nitrate leaching and nitrous oxide emissions in a simulated grazed and irrigated grassland. *Soil Use and Management* 18:395-403.
- Di, H.J., and K.C. Cameron. 2003. Mitigation of nitrous oxide emissions in spray irrigated grazed grassland by treating the soil with dicyandiamide, a nitrification inhibitor. *Soil Use and Management* 19:284-290.
- Di, H.J., and K.C. Cameron. 2005. Reducing environmental impacts of agriculture by using a fine particle suspension nitrification inhibitor to decrease nitrate leaching from grazed pastures. *Agriculture Ecosystems & Environment* 109:202-212.
- Di, H.J., and K.C. Cameron. 2006. Nitrous oxide emissions from two dairy pasture soils as affected by different rates of a fine particle suspension nitrification inhibitor, dicyandiamide. *Biology and Fertility of Soils* 42:472-480.
- Dixon, E.R., L. Cardenas, M. Alfaro, F. Salazar, and D.J. Hatch. 2011. High rates of nitrogen cycling in volcanic soils from Chilean grasslands. *Rapid Communications in Mass Spectrometry* 25:1-6.
- Genstat. 2003. *Genstat for Windows*. Version 12.0. 336 p. 7th ed. Lawes Agricultural Trust, Rothamsted, UK.
- Goic, L., y C. Rojas. 2004. Sistemas de crianza, de recría y engorda en la zona sur. p. 107-120. *In* Rojas, C., M. Doussoulin, y A. Olivares (eds.) Manual de producción de bovinos de carne para la VIII, IX y X regiones. Fundación para la Innovación Agraria FIA-Instituto de Investigaciones Agropecuarias INIA, Santiago, Chile.
- González, S., F. Salazar, A. Neuenschander, P. Arata, R. Tessedá, C. Salas, y J. Searle. 2009. Resultados del sector 4: Agricultura. p. 181-209. *In* González, S. (ed.) Inventarios anuales de gases de efecto invernadero de Chile. Serie Temporal 1984/2003 para Sectores No-Energía. Boletín INIA N° 185. Instituto de Investigaciones Agropecuarias INIA, Santiago, Chile.
- Luo, J., C.A.M. de Klein, S.F. Ledgard, and S. Saggar. 2010. Management options to reduce nitrous oxide from intensively grazed pasture: a review. *Agriculture, Ecosystems & Environment* 136: 282-291.
- Luo, J., S.F. Ledgard, and S.B. Lindsey. 2007. Nitrous oxide emissions from application of urea on New Zealand pasture. *New Zealand Journal of Agricultural Research* 50:1-11.
- Luo, J., S.B. Lindsey, and S.F. Ledgard. 2008. Nitrous emissions from animal urine application on a New Zealand pasture. *Biology and Fertility of Soils* 44:463-470.
- Luo, J., R.W. Tillman, and P.R. Ball. 1999. Factors regulating denitrification in a soil under pasture during two contrasting seasons. *Soil Biology & Biochemistry* 31:913-927.
- IPCC. 2001. Tercer Informe de Evaluación. Cambio Climático 2001. La base científica. Resumen para responsables de políticas y resumen técnico. Informe del grupo de trabajo I del Grupo Intergubernamental de Expertos sobre el Cambio Climático. Intergovernmental Panel on Climate Change (IPCC), Geneva, Switzerland. Available at <http://www.ipcc.ch/pub/un/ipccwg1s.pdf> (accessed September 2011).
- Martínez-Lagos, J., F. Salazar, M. Alfaro, and T. Misselbrook. 2010. Inventory of ammonia emissions from livestock production in Los Lagos and Los Ríos Regions, Chile. *Chilean Journal of Agricultural Research* 70:95-103.
- Mora, M.L., P. Cartes, P. Núñez, F. Salazar, and R. Demanet. 2007. Movement of NO₃⁻-N and NH₄⁺-N in an Andisol and its influence on ryegrass production in a short term study. *Journal of Soil Science and Plant Nutrition* 7:46-63.
- Muñoz, C., L. Paulino, C. Monreal, and E. Zagal. 2010. Greenhouse gas (CO₂ and N₂O) emissions from soils: A review. *Chilean Journal of Agricultural Research* 70:485-497.
- Muñoz, C., L. Paulino, J. Vera, and E. Zagal. 2011. CO₂ and N₂O emissions from an Andisol in Chile under a no-till system using non-fixed closed chambers. *Chilean Journal of Agricultural Research* 71:275-282.
- NRC. 2001. Nutrient requirement of dairy cattle. Subcommittee on dairy cattle nutrition. 382 p. 7th revised ed. National Research Council (NRC), National Academy Press, Washington, USA.
- Núñez, P., R. Demanet, T. Misselbrook, M. Alfaro, and M.L. Mora. 2010. Nitrogen losses under different cattle grazing frequencies and intensities in a volcanic soil of Southern Chile. *Chilean Journal of Agricultural Research* 70:237-250.

- ODEPA. 2010. Estudio de diagnóstico de mercado y estudio de la cadena de comercialización de fertilizantes en Chile. Oficina de Estudios y Políticas Agrarias (ODEPA), Santiago, Chile. Available at <http://www.odepa.cl> (accessed September 2011).
- Rowell, D.L. 1997. Soil science: Methods & applications. p. 79-108. Addison Wesley Longman Limited, Essex, UK.
- Sadzawka, A., M.A. Carrasco, R. Demanet, H. Flores, R. Grez, M.L. Mora, y A. Neaman. 2007. Métodos de análisis de tejidos vegetales. 2ª ed. Serie Actas N° 40. 139 p. Instituto de Investigaciones Agropecuarias INIA, Santiago, Chile. Available at <http://www.inia.cl/medios/biblioteca/serieactas/NR34664.pdf> (accessed July 2011).
- Sadzawka, A., M.A. Carrasco, R. Grez, M.L. Mora, H. Flores, y A. Reaman. 2006. Métodos de análisis recomendados para los suelos chilenos. Revisión 2006. Serie Actas N° 34. 164 p. Instituto de Investigaciones Agropecuarias INIA, Santiago, Chile. Available at <http://www.inia.cl/medios/biblioteca/serieactas/NR33998.pdf> (accessed July 2011).
- Saggar, S., R.M. Andrew, K.R. Tate, C.B. Hedley, N.J. Rodda, and J.A. Townsend. 2004. Modelling nitrous oxide emissions from dairy-grazed pastures. *Nutrient Cycling in Agroecosystems* 68:243-255.
- Saggar, S., C.B. Hedley, D.L. Giltrap, and S.M. Lambie. 2007. Measured and modeled estimates of nitrous oxide emission and methane consumption from sheep-grazed pasture. *Agriculture, Ecosystems & Environment* 122:357-362.
- Saggar, S., J. Luo, D.L. Giltrap, and M. Maddena. 2009. Nitrous oxide emissions from temperature grasslands: Processes, measurements, modeling and mitigation. 66 p. *In* Sheldon, A.I., and E.P. Barnhart (eds.) Nitrous oxide emissions research progress. Nova Science Publishers, New York, USA.
- Subbarao, G.V., O. Ito, K.L. Sahrawat, W.L. Berry, K. Nakahara, T. Ishikawa, *et al.* 2006. Scope and strategies for regulation of nitrification in agricultural systems-challenges and opportunities. *Critical Reviews in Plant Sciences* 25:303-335.
- Tabatabai, M.A. 1982. Sulfur. p. 501-538. *In* Page, A.L., R.H. Miller, and D.R. Keent (eds.) *Methods of soil analysis. Part 2. Microbiological and chemical properties.* 2nd ed. Soil Science Society of America Book Series N° 5, Madison, Wisconsin, USA.
- Teuber, N., L. Rosso, y C. Winkler. 1988. Niveles y frecuencias de aplicación de nitrógeno en ballica anual Cabalan. *Agricultura Técnica* 48:370-374.
- UNFCCC. 2011. GHG emission profiles for Annex I Parties and major groups. United Nations Framework Convention on Climate Change (UNFCCC), Bonn, Germany. Available at http://unfccc.int/ghg_data/ghg_data_unfccc/ghg_profiles/items/4625.php (accessed September 2011).
- Vistoso, E., y M. Alfaro. 2010. Estimación del nitrógeno potencialmente mineralizable en un Andisol con diferente fertilización. p. 51-52. *In* Hepp C., y A. Sotomayor (eds.) Libro Resúmenes del XXXV Congreso Anual de la Sociedad Chilena de Producción Animal (SOCHIPA), Coyhaique 2010. SOCHIPA, Santiago, Chile.
- Whitehead, D.C. 2000. Nutrient elements in grassland. 369 p. *Soil-Plant-Animal Relationships.* CABI Publishing, University Press, Cambridge, UK.
- Zaman, M., M.L. Nguyen, J.D. Blennerhassett, and B.F. Quin. 2007. Reducing NH₃, N₂O and NO₃⁻, NO₃⁻-N losses from a pasture soil with urease or nitrification inhibitors and elemental S-amended nitrogenous fertilizers. *Biology and Fertility of Soil* 693-705.