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RESEARCH

CO_2 AND N_2O EMISSIONS FROM AN ANDISOL IN CHILE UNDER A NO-TILL SYSTEM USING NON-FIXED CLOSED CHAMBERS

Cristina Muñoz[1], Leandro Paulino[1], Jenniffer Vera[1], and Erick Zagal[1*]

ABSTRACT

Chile has different types of soil and climate conditions that favor a wide range of agricultural activities that can generate potential atmospheric contamination like greenhouse gases (GHG). Nevertheless, the contribution of agricultural soils to atmospheric emissions has yet to be measured in Chile. The aim of this study was to assess seasonal variability of CO_2 and N_2O effluxes *in situ* from a volcanic ash-derived soil under different agronomic management practices. Gas samples were obtained from headspaces of non-fixed closed chambers in an annual crop rotation under a no-till system in an Andisol in southern Chile (36° S). Two N-sources (NH_4^+ and NO_3^-) and ammonium fertilization plus two lime doses (0.5 and 1 Mg ha^{-1}) were considered for soil treatments Effluxes of CO_2 and N_2O were determined periodically for 1 yr, and soil variables, such as temperature, water, and mineral N content, were recorded. Results showed that CO_2 effluxes respond to a seasonal pattern. No effect was evidenced when considering crop management practices with a maximum of 53.2 ± 8.5 kg CO_2-C ha^{-1} d^{-1} in the wet fall period and a minimum of 9.7 ± 2.1 kg CO_2-C ha^{-1} d^{-1} for summer, fall dry period, and winter. N_2O efflux was highly variable throughout the year and showed no influence of treatments or season variability with a mean of 0.95 kg N_2O-N ha^{-1} yr^{-1}. Soil mineral N variations are not related to GHG effluxes as a single variable. Results indicate that an Andisol under a no-till system in southern Chile has a low N_2O emission potential, and higher CO_2 emissions are mainly produced in wet seasons (wet fall and/or spring).

Key words: Greenhouse gases, agriculture, nitrogen, global change, air pollution.

Agricultural soil may be a potential source or sink of greenhouse gases (GHG), mainly carbon dioxide (CO_2) and nitrous oxide (N_2O), which contribute to global warming and climate change. Patterns of GHG emissions from Chilean soils and related processes are of great interest for different agricultural scenarios, and tend to place Chile in global agreements on mitigation policies. Volcanic ash-derived soils of pristine ecosystems of southern Chile still reflect efficient nutrient cycling, which is only comparable to the pre-industrial period explained through biogeochemical patterns of nutrient retention (Huygens *et al*., 2008). However, ecosystem disturbances, such as agriculture, disrupt soil retention patterns, and favor nutrient loss that produces GHG emissions (Van Cleemput and Boeckx, 2005). Agricultural activities are increasing in southern Chile and intensive soil use could increase GHG emissions. Research on gas fluxes at the soil surface is strongly recommended to improve knowledge about GHG mitigation and develop future proposals for sustainable agricultural systems.

A Chilean GHG inventory for agricultural activities has been made with empirical information from the International Panel for Climate Change (IPCC) based on Tier 1 methodology (Novoa *et al*., 2000; Geng, 2003; DICTUC, 2004; González, 2009). In the last report, it was estimated that the agricultural sector produces GHG emissions of 13.3 Gg CO_2 equivalent (CO_2e) yr^{-1} for 2003, an increase since 1984 (10.1 Gg CO_2e yr^{-1}), as well as a global increase of about 32% where methane (CH_4) and N_2O are the main gases produced by agricultural systems. Although inventories constitute important baseline data, it is necessary to quantify GHG emissions from different agro-ecosystems due to the variability of geographic location, soil, climate, productive levels, and management practices, which will decrease the level of uncertainty (Tier 2) (IPCC, 2007).

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[1] Universidad de Concepción, Facultad de Agronomía, P.O. Box 537, Chillán, Chile. *Corresponding author (ezagal@udec.cl).
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The methodological approach regarding chambers as a tool to estimate GHG effluxes from soils (Hutchinson and Livingston, 2002; Hedley *et al.*, 2006) has been widely used in agricultural soils, and has contributed to the current knowledge of the magnitude and spatial-seasonal variability of GHG emission rates (Livingston *et al.*, 2006). Studying GHG emissions from agricultural soils with *in situ* gas sampling techniques and their quantification through gas chromatography has increased available information with results comparable to those obtained from outer latitudes (IAEA, 1992; Van Cleemput and Boeckx, 2002). The advantage of chamber techniques is related to their low cost and acceptable accuracy when properly designed (IAEA, 1992; Van Cleemput and Boeckx, 2002), and measurement error, associated to spatial variability, is decreased by increasing the number of experimental replicates (IAEA, 1992). An adequate application of the chamber techniques for soil gas sampling and measuring GHG emissions must follow the recommendations explained in Rochette and Eriksen-Hamel (2008). This technique has allowed quantifying N_2O emissions from different agricultural systems (Beauchamp, 1997), such as those receiving N-fertilizer under several croplands (Abbasi and Adams, 2000), making possible the relationship of GHG emissions with environmental variables (Ponce-Mendoza *et al.*, 2006), and establishing the relationship of CO_2 emissions with soil biological, physical, and chemical processes (Smith *et al.*, 2003; Ruser *et al.*, 2006).

Mineral N fertilizers raise N availability (N-NH_4^+ and -NO_3^-) to soil microorganisms promoting nitrification and denitrification processes that depend on soil chemical and physical patterns to generate N_2O as a final product (Jones *et al.*, 2007). A clay soil under pasture treated differentially with N-NH_4^+ and -NO_3^- fertilizers converted less than 3% of the N-NH_4^+ fertilizer to N_2O (0.4-7 kg N ha^{-1} from 250 kg N-$(NH_4)_2HPO_4$), while N-NO_3^- converted more than 20% (5-22 kg N ha^{-1} from 100 kg N-KNO_3 ha^{-1}).

The GHG emissions should also respect a seasonal pattern in agricultural soils. Water and NO_3^- content have been investigated as the main cause of increasing N_2O fluxes on account of the wet season's favorable conditions (remaining rain events and absence of vegetation in spring) that raised the denitrification process (Groffman *et al.*, 1993). A similar pattern was observed in a cereal crop in an Andisol where higher CO_2 and N_2O emissions during spring were related to soil variables, such as temperature and moisture (Chu *et al.*, 2007). The GHG emissions have been estimated *in situ* from several cropping systems in outer latitudes with respect to Chile where environmental variables, such as soil temperature and water content, provided some correlation patterns of soil-surface gas emissions (Ponce-Mendoza *et al.*, 2006; Saggar *et al.*, 2007; Ussiri and Lal, 2009). In order to carry out a similar study in Chile for the first time, our aim was to assess a 1-yr seasonal variability of CO_2 and N_2O effluxes in field conditions of volcanic ash-derived soil under different agronomic management practices.

MATERIALS AND METHODS

The study was located in a long-term (15 yr) crop rotation field experiment (*Triticum* aestivum L.-*Avena sativa* L.) under a no-till system in Chile (36° S, 72° W). This is common soil use and management practice by farmers of the Andes foothills in southern Chile. Soil is volcanic ash-derived classified as Typic Haploxerands (CIREN, 1999). A complete randomized design (n = 3) was established to assess the effect of annual inputs of N amendments and lime: nitrate-N fertilization (T1); ammonium-N fertilization (T2); ammonium-N plus 0.5 Mg lime ($CaCO_3$) ha^{-1} (T3); and ammonium-N plus 1 Mg lime ha^{-1} (T4) (chemical and physical soil characteristics shown in Table 1). Long-term doses of fertilizer in this field experiment were 150 kg N ha^{-1}, 150 kg P_2O_5 ha^{-1} (as triple superphosphate in T1 and ammonium monophosphate in other treatments), as well as 120 kg K_2O ha^{-1} (as potassium chloride). Gases and soil were sampled in the field over 1 yr (from January 2008 to January 2009) with a total of 15 sampling bases, which allowed obtaining enough data for a seasonal

Table 1. Chemical and physical characteristics of the soil under study with different treatments (0-5 cm), n = 3.

Treatments	pH (H_2O)	Organic C[1]	C/N ratio	P Olsen[2]	Ca exchange[3]	CICE	Al saturation[4]	Bulk density[5]
		%		mg kg^{-1}	—— cmol kg^{-1} ——		%	g cm^{-3}
T1	6.02	9.10	10.10	36.7	5.12	10.50	0.37	0.73
T2	4.40	8.84	12.71	49.4	0.87	2.40	16.79	0.75
T3	6.11	9.31	12.20	32.5	14.45	16.67	0.14	0.75
T4	6.59	9.59	12.11	24.9	21.02	23.70	0.18	0.74

T1: nitrate-N fertilization, T2: ammonium-N fertilization, T3: ammonium-N plus 0.5 Mg lime ha^{-1}, T4: ammonium-N plus 1 Mg lime ha^{-1}.
Analysis: [1]dry combustion, [2]extracted with sodium bicarbonate solution at 0.5 M and pH 8.5, [3]extracted with ammonium acetate 1 M at pH 7, [4]extracted with potassium chloride solution at 1 M, and [5]cylinder method.

emission pattern. The climate of the study area is humid Mediterranean with precipitation over 1400 mm yr^{-1}; the rainy season is concentrated between March and August with about 69 to 79% of total annual precipitation. Fall had a non-homogenous precipitation pattern and was divided as dry-fall season with 68.1 mm of accumulated precipitation from 22 March to 6 May 2008 and wet-fall season with 328.2 mm of accumulated precipitation from 7 to 23 May 2008. Potential evapotranspiration between December and March is greater than 350 mm and water deficit is about 3 to 4 mo. Mean temperature is between 12.5 and 13.9 °C with 5 to 6 mo free of freezing events (Del Pozo and Del Canto, 1999). Daily precipitation and temperature data were reported from the Universidad de Concepción weather station about 40 km W from the experiment.

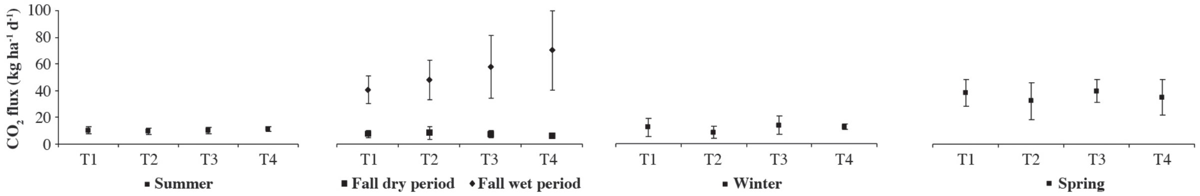
Stainless steel chambers built on a non-fixed closed passive system (as described by Hutchinson and Mosier, 1981) with 16 cm inner diameter and 20 cm height (4.021 L) were set on the soil surface (inserted 5 cm), gas samples were collected every 15 min (0, 15, 30, and 45 min), and initial time (0 min) was considered as the time when the chamber was inserted into the soil. Gas sampling was done from the chamber headspace as previously recommended (IAEA, 1992; Hutchinson and Livingston, 2002) and samples were obtained with a pre-evacuated 12 mL Exetainer® (Labco, High Wycombe, UK). Concentrations of CO_2 and N_2O gases were estimated simultaneously with a flame ionized detector (FID) and methanizer for CO_2 analysis, whereas N_2O analysis employed an electronic capture detector (ECD) (Van Cleemput and Boeckx, 2002; Hedley *et al*., 2006) on a gas chromatograph (Model Clarus 600, Perkin Elmer, Waltham, Massachusetts, USA). Gas samples of 1000 μL were injected into the gas chromatograph running at 100 °C in the injector, 40 °C in the oven (isothermal), 390 °C for FID, and 350 °C for ECD. Two analytical columns were employed: a Carboxen-filled 1004 80/100 (2 m, OD = 1/16 in) for CO_2 analysis and a Porapak-filled Q 80/100 (4 m, OD = 1/8 in, Waters, Milford, Massachusetts, USA) for N_2O analysis. CO_2 gas was converted into CH_4 and detected by FID at 7 min, and N_2O concentration was detected by ECD at 8 min. Chromatographic running time was 11 min per sample. Nitrogen (99.99% purity) was used as a carrier gas and a makeup gas of 5% methane in argon for N_2O analysis, while N_2 was used as carrier; hydrogen (99.99% purity) and synthetic air (99.99% purity) were used to generate combustion for CO_2 analysis. A special standard mixing of CO_2 and N_2O was employed for the calibration curve that covered the range of concentrations of the analyzed gas samples, which was checked for accuracy every 15 running samples. Work pressure was maintained constant at 40 psi. The GHG effluxes were estimated for each sampling date along a linear function of gas concentration to time of field sampling (0, 15, 30, and 45 min) and reported as kg CO_2 ha^{-1} d^{-1} and g N_2O ha^{-1} d^{-1}. Different soil variables, such as temperature, water-free pore space (WFPS), and amount of NH_4^+- and NO_3^--N were considered in order to establish correlations with GHG effluxes. A digital portable thermometer (Traceable, Control Co., Friendswood, Texas, USA) was used to measure both soil (at 5 cm depth) and air (on soil surface) temperatures (ºC). Gravimetric soil moisture was estimated with a TDR (Time Domain Reflectometry) dielectric HH1 probe (Delta-T Device, Cambridge, UK); water content was integrated as WFPS by considering soil bulk density by standard cylinder procedure and soil particle density by the liquid pycnometry method prior to strong oxidation of soil samples with warm hydrogen peroxide. NH_4^+- and NO_3^--N concentrations (mg N kg^{-1} soil) were determined by colorimetric analysis with an FIA Star analyzer (Foss Tecator AB, Höganäs, Sweden).

Statistical analysis

A completely randomized design with four treatments and three field replicates for each treatment was evaluated. Statistical analysis was performed by the modified Shapiro-Wilks test for normality. One-way ANOVA verified the effect of field treatments and seasons separately, and post-hoc Tukey tests ($p \leq 0.05$) were analyzed to identify significant effects ($p \leq 0.05$) for each experimental unit. Goodness-of-fit was verified through Pearson R^2 coefficient of determination between CO_2 and N_2O effluxes, while non-parametric Spearman R correlation assessed the relationship between gas fluxes and soil mineral N content.

RESULTS

The CO_2 effluxes in an Andisol under a no-till system for the different treatments of N fertilizer and lime showed two patterns (Figure 1) during the fall, a dry period with mean emissions of 7.3 ± 1.2 kg CO_2-C ha^{-1} d^{-1} and a wet period after the beginning of rainfall with values of 53.2 ± 8.5 kg CO_2-C ha^{-1} d^{-1}. Statistical analysis was carried out by separating both patterns and obtaining statistical differences between them (Figure 2); however, no statistical differences were observed between treatments ($p \leq 0.05$) in each season (Figure 1). The highest CO_2 effluxes detected in the wet fall period decreased in spring (34.7 ± 2.5 kg CO_2-C ha^{-1} d^{-1}), while the lowest CO_2values were observed during summer, dry fall, and winter with a mean of 9.7 ± 2.1 kg CO_2-C ha^{-1} d^{-1} for the whole period with no statistical differences ($p \leq 0.05$) between them. The N_2O effluxes neither showed effects from treatments between seasons (Figure 3) nor among treatments in each season (Figure 4). Considering the



T1: nitrate-N fertilization; T2: ammonium-N fertilization; T3: ammonium-N plus 0.5 Mg lime ($CaCO_3$) ha^{-1};
and T4: ammonium-N plus 1 Mg lime ha^{-1}.

Figure 1. Variations of CO_2 flux (kg ha^{-1} d^{-1}) among treatments for each season in volcanic ash-derived soil under different agronomic management practices. Mean ± standard deviation. There were no statistical differences among treatments in each season (Tukey test, $p \leq 0.05$).

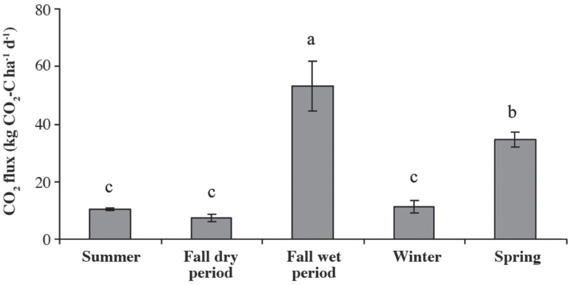


Figure 2. Mean CO_2 emission (kg ha^{-1} d^{-1}) for all treatments in each season in volcanic ash-derived soil under a no-till system in Chile. Mean ± standard deviation. Different letters indicate a statistical difference between seasons (Tukey test, $p \leq 0.05$).

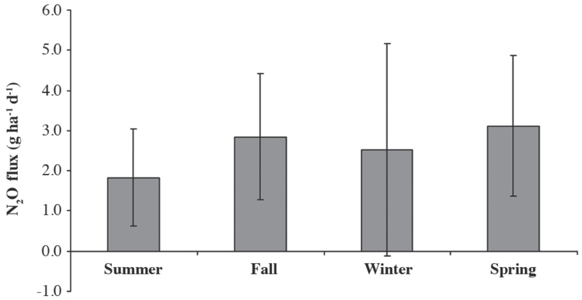


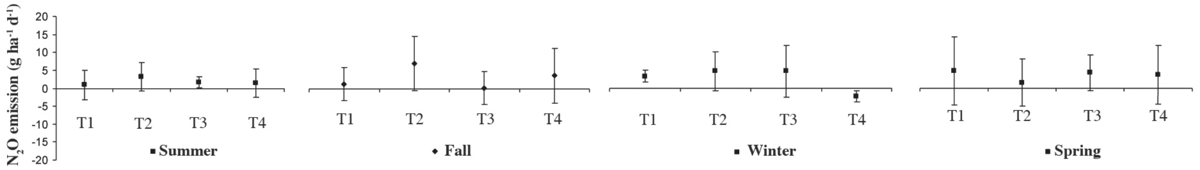
Figure 3. Mean N_2O flux (g ha^{-1} d^{-1}) for all treatments in each season in volcanic ash-derived soil under a no-till system in Chile. Mean ± standard deviation. There were no statistical differences between seasons (Tukey test, $p \leq 0.05$).

latter results there was no discrimination between the wet or dry fall periods. The N_2O efflux mean for each season and treatments was 2.6 ± 0.6 g N_2O-N ha^{-1} d^{-1} (Figure 3). No significant correlation ($p \leq 0.05$) was found between CO_2 and N_2O effluxes for treatments and seasons, and Pearson's coefficient was 0.12 in general (Table 2) between both gas effluxes. In addition, no significant correlation was determined between N mineral (N-NO_3^- and -NH_4^+) content in the soil with N_2O effluxes. Only CO_2 efflux was correlated with water content (expressed as WFPS) and NH_4^+ content with correlation values of 0.37 and 0.19 ($p \leq 0.05$), respectively.

Table 2. Pearson's coefficient between gas fluxes with different soil parameters.

Parameters	Pearson's coefficient
CO_2 flux/N_2O flux	0.12
CO_2 flux/NO_3^- content	0.12
CO_2 flux/NH_4^+ content	0.19*
CO_2 flux/WFPS	0.37*
N_2O flux/NO_3 content	0.09
N_2O flux/NH_4^+ content	0.10
N_2O flux/WFPS	-0.13

*Indicate P value ≤ 0.05. WFPS: water-free pore space.



T1: nitrate-N fertilization; T2: ammonium-N fertilization; T3: ammonium-N plus 0.5 Mg lime ($CaCO_3$) ha^{-1};
and T4: ammonium-N plus 1 Mg lime ha^{-1}.

Figure 4. Variation of N_2O flux (g ha^{-1} d^{-1}) among treatments for each season in volcanic ash-derived soil under different agronomic management practices. There were no statistical differences among treatments in each season (Tukey test, $p \leq 0.05$).

DISCUSSION

The Andisol studied in this research showed different chemical compositions as a result of long-term fertilization based on two N-sources and ammonium plus lime applications (Table 1). Ammonium fertilization decreased soil pH, increased Al saturation (T2), and resulted in less microbial biomass and soil respiration (unpublished data). However, no differences were found for CO_2 and N_2O effluxes as a consequence of treatments that received nitrate fertilization (T1) and lime application (T3 and T4) (Figures 1 and 3). Lime on soil pH had an acidifying effect when applying only ammonium fertilizer (T2) and clearly decreased soil pH during the trial period to 4.4 (Table 1). However, when ammonium fertilizer was applied with lime, its acidifying effect was neutralized and soil pH increased to 6.1 (T3) and 6.4 (T4). Soil pH at the start of the experiment was 5.8. There was no significant effect of increasing soil pH on GHG emissions in the volcanic ash-derived soil under study since no statistical differences were found in CO_2 and N_2O emissions among treatments. Similarly, Mørkved *et al.* (2007) found that nitrification rates are not affected by soil pH (for treatments with soil pH ≥ 5) and reported no effects when lime was applied. Zaman and Nguyen (2010) have reported that pasture treated with two N sources with lime did not have any effect on N_2O emissions. However, other authors reported that applying lime improves soil properties and increases both nitrification rate and soil respiration (Fuentes *et al.*, 2006). Therefore, the effect of lime on soil microbial activity and GHG emissions is not completely clear because CO_2 chemical release could be produced from lime. West and McBride (2005) indicate that, depending on soil pH and N fertilizer source, lime could react with strong acid sources (e.g., HNO_3) to release CO_2. Biasi *et al.* (2008) point out that it is necessary to separate biotic and abiotic CO_2 release from lime-rich soils because similar biotic respiration rates in limed and unlimed peat soils were obtained with no effect on microbial activity when soil pH increased.

Seasonal variability seems to be the main effect on the CO_2 flux pattern. The highest fluxes were reported during the wet fall and spring periods, while management practices (fertilization and liming) did not affect them. Moreover, CO_2 fluxes related better to WFPS in the soil under study than other factors (N_2O fluxes and NO_3^- content). The effect of seasonal variability on CO_2 fluxes has been reported by Gregorich *et al.* (2006), Chu *et al.* (2007), and Carvalho *et al.* (2009) who found significant seasonal variations and reported increasing CO_2 fluxes during the wet season.

The results of the present study showed that N-fertilizer sources in volcanic ash-derived soil did not affect N_2O emissions ($p \leq 0.05$), and there a weak relationship between N_2O emissions and soil mineral N content. These results do not support previous conclusions regarding other soil types. For example, Dobbie and Smith (2003) found that the essential factor affecting N_2O fluxes from soils is NO_3^- concentration, and Mu *et al.* (2009) indicated that N_2O emissions are strongly related to soil mineral N, CO_2 emissions, and C/N ratio in agricultural soils. The weak correlation found in the present research can probably be explained by high soil organic C content and low C/N ratio in all treatments (8.8 to 9.6% organic C, Table 1). These factors can produce or maintain a conservative nitrification/denitrification rate throughout the year that prevents the effect of N input on N_2O emissions. Similarly, Gregorich *et al.* (2005) point out that the effect of N-fertilization on N_2O emissions is highly variable and reported that N_2O emission rates are spatially variable and log-normally distributed due to hotspots driven by the distribution of anaerobic microsites and C availability in different types of soils in Canada.

The IPCC (1996; 2001) proposes emission factors (EF) that could be used to calculate N_2O emissions on the basis of the amount of N-fertilizer used in a country or region. In Chile, we have little data to generate our own EF for a specific region and default EF is being used for GHG inventories. The last national inventory of Chile (González, 2009) adopted an EF of 0.0125 kg N_2O-N kg^{-1} N to generate N_2O emission estimates for chemical fertilizer applications. Our results show lower N_2O emissions than values obtained using the default factor proposed by the IPCC with a mean of 0.95 kg N_2O-N ha^{-1} yr^{-1}. This N_2O flux is close to results obtained in well-aerated soils by Rochette (2008) who studied different soils and cropping systems in Canada and reported an accumulated range of 0.1 to 1.3 kg N_2O-N ha^{-1} in soils with a good aeration level, increasing to 0.3 to 2.1 and 1 to 32.7 kg N_2O-N ha^{-1} in soils with medium and poor aeration levels, respectively. The effect of a higher increase in N_2O emissions under some no-till systems may be due to their impact on soil density, water content, oxygen level, gas diffusion, and aeration (Gregorich *et al.*, 2005). Special attention should also be given to Andisols in southern Chile. Huygens *et al.* (2008) proposed a novel vision of the N cycle in a pristine ecosystem to explain a very conservative pattern that indicates special properties of biotic and abiotic mechanisms in an Andisol of evergreen forests in the Andes mountain range. These conservative processes were previously indicated as happening in such an environment where there is very low mineral N exportation from forest ecosystems to draining streams (Perakis *et al.,* 2005). However, there are no findings of gaseous N losses from this kind of soil and environment. Our results are the first to show a possible capacity of

N_2O-N retention in agricultural soil use and management. Taking into account the particular patterns and processes of Chilean native Andisols, future experiments should demonstrate their potential N_2O sink capacity under appropriate management.

CONCLUSION

N_2O and CO_2 fluxes are not influenced by the N source applied and lime addition in our study of an Andisol under a no-till system in southern Chile. N_2O efflux was highly variable over a 1-yr period and did not show any influence of seasonal variability with a mean of 0.95 kg N_2O-N ha^{-1} yr^{-1}. However, CO_2 fluxes respond to seasonal patterns. Soil mineral N variations are not related to GHG fluxes as a single variable. Our results indicate that an Andisol under a no-till system in southern Chile has a low potential for N_2O emissions, whereas high CO_2 emissions are produced mainly during the seasons that provide wet soil conditions (wet fall and/or spring).

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RESUMEN

Emisiones de CO_2 y N_2O desde un Andisol de Chile bajo sistema de cero labranza usando cámaras cerradas no-fijas. Chile tiene diferentes tipos de suelo y condiciones climáticas que favorecen un amplio rango de actividades agrícolas, las cuales pueden generar contaminación atmosférica potencial como los gases de efecto invernadero (GHG). Sin embargo, mediciones de la contribución de los suelos agrícolas en las emisiones atmosféricas de estos gases no ha sido realizado todavía en Chile. Este trabajo tiene como objetivo determinar los flujos de emisiones *in situ* de CO_2 y N_2O desde un suelo derivado de cenizas volcánicas bajo diferentes prácticas de manejo agronómico determinando su variación estacional. Las muestras gaseosas fueron obtenidas desde el espacio aéreo de cámaras cerradas no-fijas en una rotación anual de cultivos bajo sistema de cero labranza en un Andisol del Sur de Chile (36° S). Dos fuentes de N (NH_4^+ y NO_3^-) y fertilización amoniacal más dos dosis de encalado (0.5 y 1 Mg ha^{-1}) fueron considerados como tratamientos. Los flujos de CO_2 y N_2O fueron determinados periódicamente en un período de 1 año y variables de suelo tales como temperatura, contenido de agua, y N mineral fueron registrados. Los resultados muestran que los flujos de CO_2 responden a patrones de estacionalidad. No fue evidenciado un efecto cuando fue considerada la práctica de manejo del cultivo, con un máximo de 53.2 ± 8.5 kg CO_2-C ha^{-1} d^{-1} en la estación húmeda de otoño, y un mínimo de 9.7 ± 2.1 kg CO_2-C ha^{-1} d^{-1} para verano, estación seca de otoño e invierno. El flujo de N_2O fue altamente variable en el año y no muestra influencia de tratamientos o estacionalidad, con un promedio de 2.6 ± 0.6 g N_2O-N ha^{-1} d^{-1}. Variaciones de N mineral del suelo no están relacionadas a los flujos de GHG como una variable sola. Los resultados indican que un Andisol bajo sistema de cero labranza en el Sur de Chile tiene un bajo potencial de emisiones de N_2O, y las mayores emisiones de CO_2 son producidas principalmente en estaciones húmedas (otoño húmedo y/o primavera).

Palabras clave: Gases de efecto invernadero, agricultura, nitrógeno, cambio global, polución del aire.

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