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Emissions of Nitrous Oxide and Methane in a Subtropical Ferralsol Subjected to Nitrogen Fertilization and Sheep Grazing in Integrated Crop-Livestock System

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ABSTRACT: Brazilian agriculture contributes significantly to nitrous oxide (N_2O) and methane (CH_4) emissions, so the understanding of such emissions at the field is crucial for mitigation strategies. This study quantified the impact of N application and sheep grazing on the N_2O and CH_4 emissions from a subtropical Ferralsol under an integrated crop-livestock (ICL) management system. In a long-term experiment in southern Brazil, gaseous fluxes were measured during a year-long cycle of ryegrass (*Lolium multiflorum*) plus oats (*Avena sativa*) winter pasture and a summer crop of common beans (*Phaseolus vulgaris*). Three rates of urea-nitrogen (0, 75, and 150 kg ha^{-1}) were applied to the winter-pasture, which was subjected to two sheep grazing levels (continuously grazed, and ungrazed). The experiment had a complete randomized block design with three replicates. Soil N_2O and CH_4 fluxes were measured with closed static-chambers (0.20 m high × 0.25 m in diameter). Nitrous oxide emission peaks occurred 28 days after N application and increased with N application rate. Accordingly, the cumulative N_2O emissions averaged across grazed and ungrazed treatments increased from 0.45 kg ha^{-1} in the control soil to 1.78 and 2.10 kg ha^{-1} after application of 75 and 150 kg ha^{-1}, respectively. The N_2O emission factors were 1.7 and 1.1 % when the N rates were 75 and 150 kg ha^{-1}, respectively. The cumulative average N_2O emission for all N rates was 2.09 kg ha^{-1} in ungrazed pasture, but it was reduced by 62 % with grazing to 0.80 kg ha^{-1}, perhaps because of a possible denitrification of N_2O to N_2 associated with soil compaction from trampling. Overall, fertilizer-N is an important source of N_2O from soil under ICL based on sheep grazing, with emission factors consistent with the IPCC's default of 1 % (0.3-3.0 %). Grazing reduced the emission of soil N_2O, but the underlying cause of that reduction needs to be better understood.

Keywords: nitrate, ammonium, water filled pore space, sheep.

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INTRODUCTION

Agriculture and land use change are some of the most important sources of greenhouse gases, accounting for about one-fourth of the global gaseous emissions (IPCC, 2014). In Brazil, this source accounts for the more significant fraction of about two-thirds of the overall emissions, and more remarkably for 92 % of nitrous oxide (N_2O) and 78 % of methane (CH_4) emissions (MCTI, 2014; Azevedo, 2016). Therefore, it is worth seeking strategies to mitigate emissions related to agriculture and land use change.

In farming systems, nitrogen fertilization is an important source of N_2O produced by nitrification and denitrification processes (Butterbach-Bahl et al., 2013). The IPCC, in its guidelines for national inventories (IPCC, 2006), considers a N_2O emission factor of 1 % for nitrogenous fertilizers (i.e., 1 % of the applied nitrogen being released as N_2O), although higher (1.6 %) (Soares et al., 2016) or lower (0.2 %) (Martins et al., 2015) values have been reported in the literature. This variation in the N_2O emission factor could be related to local aspects such as temperature, precipitation, and soil type (Bell et al., 2015), or rates of nitrogen fertilizer application. This justifies the need for regional studies that result in region-specific information. According to McSwiney and Robertson (2005) and Ma et al. (2010), N_2O emissions can increase exponentially (and not linearly) with application rates of nitrogen fertilizer, resulting in an increase in the N_2O emission factor.

With respect to CH_4, agricultural soils are generally sinks for this gas, because aeration allows microorganisms to oxidize CH_4 into CO_2 via methanotrophy, a process mediated by the methane monooxygenase enzyme (Le Mer and Roger, 2001; Bayer et al., 2016). However, nitrogen fertilizer application that results in ammonium could reduce the capacity of soil to consume CH_4, because ammonium competes with CH_4 for the same active site of the monooxygenase enzyme, and thus may decrease the methanotrophy rate (Bédard and Knowles, 1989).

Information on the effects of integrated crop-livestock (ICL) systems on greenhouse gas emissions from soil is still scarce and is even scarcer for sheep-based ICL systems. Some studies on ICL systems suggest that grazing may intensify soil N_2O emissions because of animal trampling and the formation of anaerobic microsites in soil (Carvalho et al., 2014; Piva et al., 2014). Yet, others have found that it may positively affect the stock of soil carbon and thus mitigate CO_2 emissions (Carvalho et al., 2010; Salton et al., 2011). However, Sato et al. (2017) reported a reduction of N_2O emissions in a Cerrado soil under an ICL system relative to a continuous cropland system. With respect to soil CH_4 emission in ICL areas, research results point to an increase in soil consumption rates, the magnitude of which is possibly controlled by inorganic nitrogen content in soil and soil moisture (Piva et al., 2014).

Thus, the hypothesis of work is that sheep grazing decreases the soil N_2O emission, maybe due to complete denitrification of N_2O into N_2. The objective of this study was to quantify the impact of nitrogen fertilization on winter pasture and of sheep grazing on N_2O and CH_4 emissions in a soil under an ICL system in the Brazilian subtropics.

MATERIALS AND METHODS

Experimental site

A field experiment was carried out at CEDETEG/UNICENTRO (Universidade Estadual do Centro-Oeste), Guarapuava-Paraná, Brazil (25° 33’ S, 51° 29’ W; altitude of 1,095 m). The climate was subtropical humid (Cfb, Köppen Classification System), with an annual precipitation of 1,806 mm, and an average monthly temperature ranging between 12.3 °C (July) and 20.2 °C (January) (INMET, 2009). The soil was classified as *Latossolo Bruno* (Santos et al., 2013), which is equivalent to a Ferralsol (IUSS Working Group

WRB, 2015); and contained 624 g kg^{-1} of clay, 306 g kg^{-1} of silt, and 70 g kg^{-1} of sand in the upper 0.00-0.20 m.

Before the experiment, the area was used for growing silage corn in the summer and was fallow in the winter. The experiment was established in June 2006 and was based on an integrated crop-livestock (ICL) system that included a pasture of ryegrass (*Lolium multiflorum* Lam.) plus oats (*Avena sativa* L.) in winter, and cash cropping of corn (*Zea mays* L.) or common beans (*Phaseolus vulgaris* L.) in the summer. In the winter pasture, three rates of urea-nitrogen (0, 75, and 150 kg ha^{-1}) were applied in the main plots, and two sheep grazing levels (continuous grazing, and ungrazed) were set up in the subplots, which were arranged in a complete randomized block experimental design with split plots and three replicates. In grazed plots, the stocking rate of 'Ile de France' sheep was varied to maintain the pasture with a mean height of 0.14 m. The grazed plot had an average area of 2,050 m^2 (~40 × 50 m) and the ungrazed plot had on average area of 102 m^2 (~10 × 10 m, as an exclusion area adjacent to the grazed plot).

The present study was conducted during one annual cycle, which included the pasture phase in winter 2010 and one cropping of common beans in the summer of 2010/11. Ryegrass and oats were sown on May 28, 2010 in rows spaced 0.17 m, and 60 kg ha^{-1} P_2O_5 fertilizer was applied with triple superphosphate at sowing and 60 kg ha^{-1} K_2O was applied as potassium chloride as a top dressing. The nitrogen was applied on June 21 as top dressing at the tillering stage of ryegrass and oats. Grazing started on July 05 and lasted until November 12 (131 days), when the pasture was desiccated with glyphosate herbicide (2.5 L ha^{-1}). The common beans (FT 'Soberano' cultivar) were sown on December 08 in rows spaced at 0.50 m and 100 kg ha^{-1} P_2O_5 as triple superphosphate and 90 kg ha^{-1} K_2O as potassium chloride fertilizer were applied during planting, without the application of nitrogen. Common beans were harvested on April 02, 2011.

Nitrous oxide and methane emissions from soil

Soil N_2O and CH_4 fluxes were measured in 13 air-sampling sessions, over ~10 months from June 14, 2010 to April 04, 2011 at intervals of 2 to 76 days, being the shortest intervals after nitrogen application. Air samples were collected by the closed static-chamber method, consisting of a PVC cylinder (0.20 m high × 0.25 m in diameter) closed at the top and deployed during air sampling on a metal collar. The collars were inserted 0.05 m into the soil soon after sowing the ryegrass and oats, but they were removed and replaced soon after the sowing of common beans. Two collars were inserted as duplicates in the central part of each subplot, being approximately 20 m distant from one another in the grazed treatment, or 5 m apart in the ungrazed treatment. When nitrogen rates were applied in the whole plot, an area of 1.5 × 1.5 m for each metal collar was covered with a plastic sheet and nitrogen rates were specifically applied for that area and for the area delimited by the metal collar. Each air-sampling session was carried out from 9:00 to 11:00 h, a period when fluxes of N_2O and CH_4 are representative of the mean daily fluxes (Jantalia et al., 2008). Air samples were collected with a 20-mL polypropylene syringe at 0, 15, and 30 min after the chamber closure, and they were analyzed within 36 h by gas chromatography in a Shimadzu GC 2014 chromatograph (Federal University of Rio Grande do Sul) for the determination of N_2O and CH_4. Samples were kept refrigerated between sampling to analysis.

The fluxes of each gas were estimated from the angular coefficient of the linear model adjusted to describe the increase of the gas concentration in the chamber headspace during the 30 min deployment (Gomes et al., 2009). The volume and the temperature of the chamber headspace and the area delimited by the metal collar were also considered. The cumulative annual emissions of N_2O and CH_4 were calculated by integrating fluxes over time (area under the curve). The emission factor (EF) of N_2O, which consisted of a fraction of applied N that was emitted as N_2O, was calculated according to equation 1:

$$\text{EF} - \text{N}_2\text{O (\%)} = \left[\frac{\text{kg N} - \text{N}_2\text{O (treatment)} - \text{kg N} - \text{N}_2\text{O (control)}}{\text{rate (kg of N applied)}}\right] \times 100 \qquad \text{Eq. 1}$$

Soil and meteorological properties, and statistical analysis

Chemical properties of the 0.00-0.10 m soil layer were evaluated two months before the beginning of the air-sampling campaign and are presented in table 1. By this time, soil bulk densities of the 0.00-0.05 m layer were also evaluated by using the core method (Blake and Hartge, 1986). Subsequently, during each air-sampling session, three soil samples from the 0.00-0.05 m layer were collected from each plot with a core auger. The three samples were collected within a 0.4-m radius from the metal collars and composited. The soil moisture (at 105 °C) was determined in part of the composite sample and, together with information on soil bulk density, was used to calculate the water filled pore space (WFPS). Another part of the composite sample was used for the determination of ammonium and nitrate contents by the semi-micro-Kjeldahl method (Mulvaney, 1996).

Daily data for precipitation and air temperature from June 01, 2010 to April 30, 2011 were obtained in an automatic meteorological station adjacent to the experiment.

Data were tested for and fulfilled the assumptions of normality and homogeneity of variance, according to the Kolmogorov-Smirnov and Bartlett ($p<0.05$) tests, respectively. Then, the data were submitted to analysis of variance (ANOVA), and means were compared using Tukey's test ($p<0.05$).

RESULTS AND DISCUSSION

Nitrous oxide emission

A peak of N_2O emission occurred 28 days after nitrogen application and was more intense in the ungrazed pasture, while fluxes were very low for the remainder of the evaluation period, close to the background level (Figure 1). The 28-d interval between nitrogen application and the N_2O emission peak was relatively long when compared to the 3-5-days intervals verified in other studies of nitrogen fertilizer application conducted in the region (Zanatta et al., 2010; Piva et al., 2014). It could be possible that the N_2O peak delay was associated to the absence of rain for 20 days following the application of urea (Figure 2) and to the resulting reduction of the WFPS during the same period (Figure 3a).

Table 1. Chemical properties of the top 0.10 m of a Ferralsol under integrated crop-livestock system (ryegrass plus oats as winter pasture, and corn or common beans cropping in summer) subjected to three nitrogen rates to pasture (0, 75, and 150 kg ha^{-1}) and to two sheep grazing levels (grazed and ungrazed) for four years. Guarapuava-Paraná, Brazil, April 2010

Grazing	pH($CaCl_2$)	OM	P	K^+	Ca^{2+}	Mg^{2+}	Al^{3+}	H+Al	CEC	Base saturation	Al saturation
		g kg^{-1}	mg kg^{-1}	cmol$_c$ dm^{-3}						%	
					0 kg ha^{-1}						
Grazed	4.6	55.9	8.0	0.53	3.6	2.4	0.0	4.4	11.0	58.6	1.1
Ungrazed	4.8	50.1	9.6	0.29	3.3	2.5	0.0	4.6	10.7	57.0	0.0
					75 kg ha^{-1}						
Grazed	4.5	53.7	6.1	0.48	3.6	2.4	0.2	4.8	11.4	57.7	3.1
Ungrazed	4.9	53.7	5.9	0.29	4.0	2.4	0.0	5.0	11.7	57.5	1.5
					150 kg ha^{-1}						
Grazed	4.8	51.0	6.8	0.44	3.5	2.4	0.1	4.9	11.3	56.5	2.0
Ungrazed	4.6	52.8	6.8	0.31	3.2	2.1	0.0	5.4	11.1	51.2	1.5

pH measured in solution $CaCl_2$ at 1:2.5 ratio; OM determined by the Walkley Black method; P and K were extracted with Mehlich-1; Ca, Mg, and Al were extracted with KCl 1 mol L^{-1}.

However, urea application was followed by a rapid and substantial increase in the soil ammonium content, which peaked 1-5 days after application (Figure 3b). That indicates that hydrolysis and ammonification of urea occurred normally. The following increment in nitrate content (Figure 3c) indicates that nitrification also occurred normally during this period. The highest nitrate contents that occurred at 28 days after urea application (Figure 3c) coincided with the highest levels of WFPS (Figure 3a), which were certainly caused by the cumulative 100-mm rainfall of the previous week (July 13-19, Figure 2). Thus, these high nitrate and WFPS conditions certainly led the N_2O emission peak to occur at that same time of 28 days after application (July 19, Figure 1). Given the low aeration and possibly low redox potential conditions of the wet soil, it was likely that denitrification was the main process involved in N_2O production (Davidson et al., 2000; Schils et al., 2008).

The increase of the N application rate had an effect on the N_2O emission peak. In the ungrazed treatment, the emission peak varied from 57 µg m^{-2} h^{-1} in the soil without N

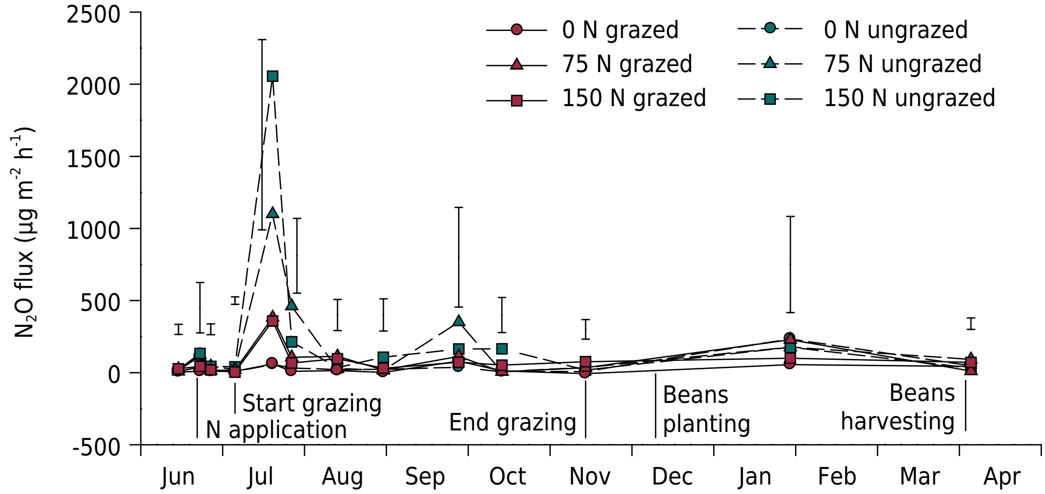


Figure 1. Nitrous oxide fluxes of a Ferralsol under integrated crop-livestock system (ryegrass plus oats as winter pasture, and a common beans crop in summer), with the winter pasture subjected to three nitrogen rates (0, 75, and 150 kg ha^{-1}) and two sheep grazing levels (grazed and ungrazed). Vertical bars denote the significant difference according to Tukey's test (p<0.05). Guarapuava-Paraná, Brazil, Jun/14/2010 to Apr/04/2011.

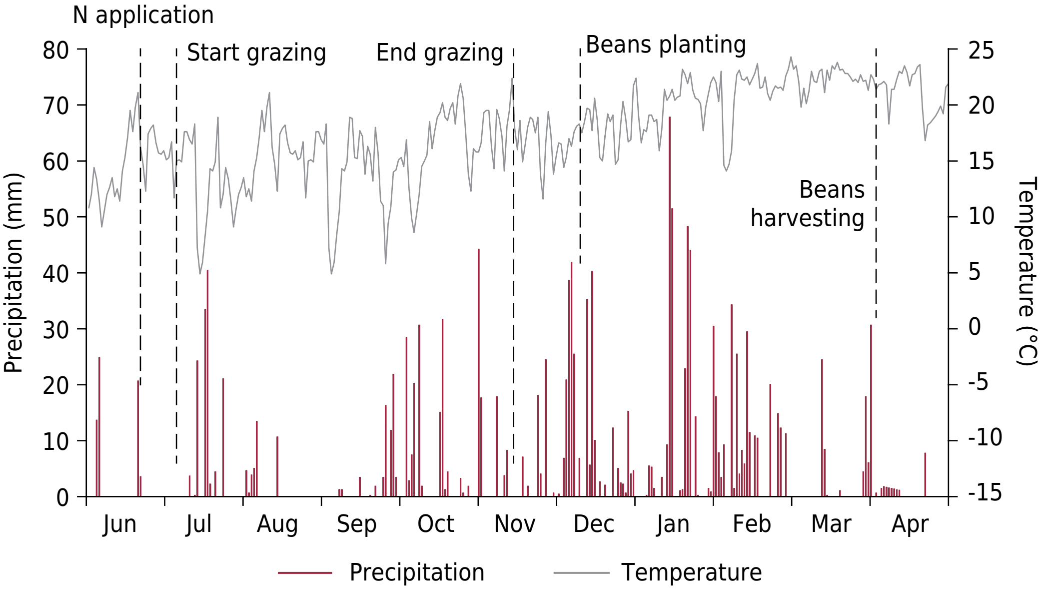
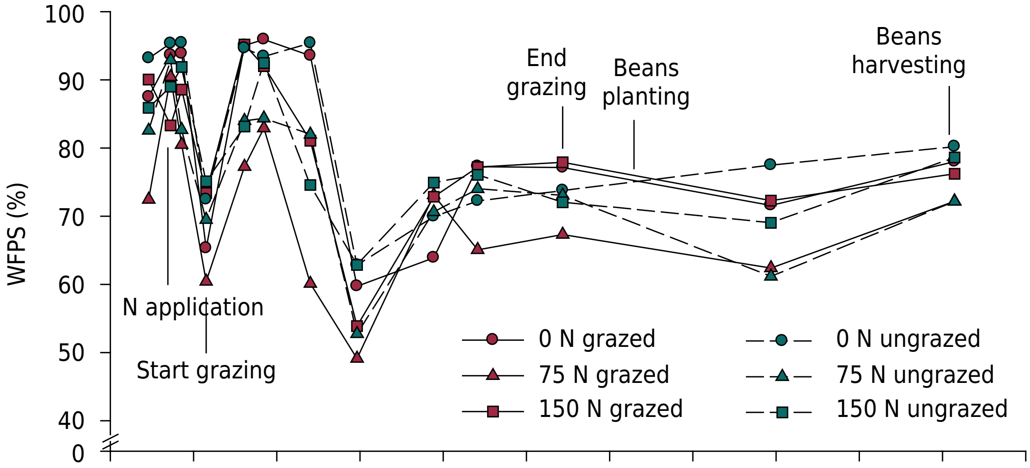
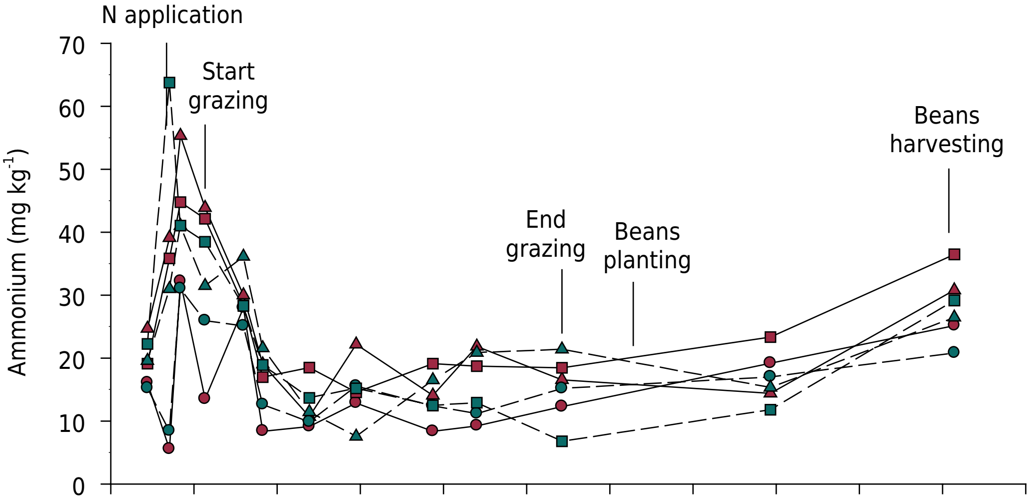


Figure 2. Daily precipitation and daily mean air temperature from June 2010 to April 2011. Guarapuava-Paraná, Brazil.

(a) WFPS



(b) Ammonium



(c) Nitrate

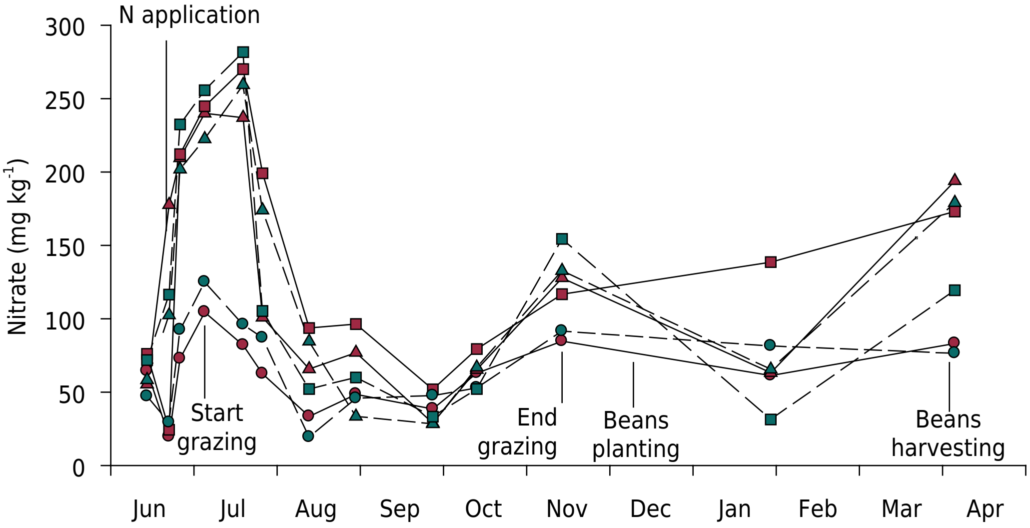


Figure 3. Water filled pore space (WFPS) (a) as well as ammonium (b) and nitrate (c) contents in the 0.00-0.05 m layer of a Ferralsol under integrated crop-livestock system (ryegrass plus oats as winter pasture, and a common beans crop in summer), with the winter pasture subjected to three nitrogen rates (0, 75, and 150 kg ha^{-1}) and two sheep grazing levels (grazed and ungrazed). Guarapuava-Paraná, Brazil, Jun/14/2010 to Apr/04/2011.

application (control) to 1,099 and 2,055 μg m^{-2} h^{-1} at 75 and 150 kg ha^{-1}, respectively (Figure 1). The N_2O emissions data in the control area were in agreement with another work in the south of Brazil, which evaluated N_2O emissions in an ICL system with sheep, where values ranged from 4 to 53 μg m^{-2} h^{-1} (Tomazi et al., 2015). Under continuous grazing, N_2O emission peaks also occurred after urea application, but at a much lower intensity, and they were similar for the N rates of 75 and 150 kg ha^{-1} (~350 μg m^{-2} h^{-1}, Figure 1). In another work with grazing carried out in the Brazilian Cerrado that evaluated the ICL and ICLF systems, the highest flux occurred after the application of N in the systems, and it was associated with the rainy season, with values ranging from approximately 50 to 150 μg m^{-2} h^{-1}. Carvalho et al. (2017) presenting the same trend observed in our study, but with lower N_2O emissions values, because the tested N application rates were lower than that used in our study.

For the overall cumulative N_2O emission, there was no significant interaction between N rate and grazing level; the cumulative emission averaged across grazed and ungrazed pastures increased significantly from 0.45 kg ha^{-1} in the soil without urea application to 1.78 and 2.10 kg ha^{-1} with application rates of 75 and 150 kg ha^{-1}, respectively (Figure 4a).

The cumulative emission of N_2O did not show significant difference between N 75 and 150 kg ha^{-1} rates, with emissions of 1.78 and 2.10 kg ha^{-1}, respectively (Figure 4a). Accordingly, the N_2O emission factor decreased from 1.7 to 1.1 % when nitrogen rate increased from 75 to 150 kg ha^{-1}. One explanation for that result could have been an exponential increase in ammonia loss by volatilization with increasing nitrogen rate (Jiang et al., 2017). In a temperate New Zealand pasture, the ammonia loss increased from 13 to 33 % of the applied nitrogen when the application rate increased from 30 to 200 kg ha^{-1}, respectively (Black et al., 1985). A proportionally higher loss of ammonia at 150 kg ha^{-1} would also be consistent with soil nitrate contents at this rate not increasing relative to the application of 75 kg ha^{-1} (Figure 3c). In a study with sugarcane in the Brazilian Cerrado, Signor et al. (2013) also observed stabilization or even decrease in nitrous oxide emissions with increases in urea-N rates. However, different from what was found in the present study, most of the literature results, especially from temperate

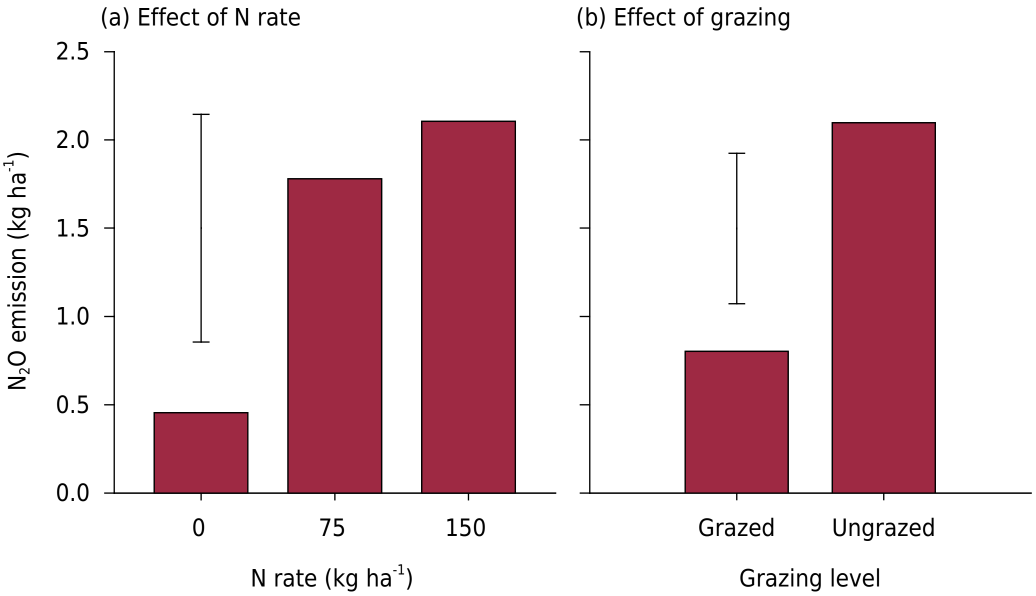


Figure 4. Cumulative emission of nitrous oxide for ~10 months (Jun/14/2010 to Apr/04/2011) in a Ferralsol under integrated crop-livestock system (ryegrass plus oats as winter pasture, and a common beans crop in summer), with the winter pasture subjected to three nitrogen rates (0, 75, and 150 kg ha^{-1}) and two sheep grazing levels (grazed and ungrazed). Vertical bars denote the significant difference according to Tukey's test (p<0.05). As the interaction between nitrogen rate and grazing level was not significant, such factors are presented separately. Guarapuava-Paraná, Brazil.

regions, show an exponential increase of N_2O emission with nitrogen fertilizer rate, with the explanation that, with higher rates, the N use efficiency by plants decreases, and thus more N is available for denitrification (McSwiney and Robertson, 2005; Ma et al., 2010). In view of these different results for N_2O emission with nitrogen rate increments, new studies on this matter should be conducted under subtropical pasture conditions.

The N_2O emission factors of 1.7 and 1.1 % obtained in this study are consistent with the 1 % default value recommended by the IPCC for synthetic N fertilizers, especially considering its range of uncertainty from 0.3 to 3.0 % (IPCC, 2006). Therefore, our results do not indicate any need to revise the default value. However, higher emission factors, in the range of 2 to 7 %, have been reported for North American conditions (McSwiney and Robertson, 2005), as well as a 2 % value having been reported by Zhang et al. (2016) for China. On the other hand, emission factors of 0.39-0.75 % (Gomes et al., 2009) and 0.45-1.05 % (Jantalia et al., 2008) obtained in the Brazilian subtropics suggest that the default 1 % is overestimating N_2O emissions by fertilizers in this region. This is in agreement with other studies in different regions of the world (Schils et al., 2008; Misselbrook et al., 2014; van der Weerden et al., 2016). It seems, therefore, that the emission factor results with nitrogen fertilizer application differ considerably between studies, and more efforts are needed to consolidate regional emission factors.

With respect to grazing, it considerably reduced the N_2O emission peak observed at 28 days after urea application (Figure 1), so that the cumulative N_2O emission averaged across the three N rates, decreased by 62 %, from 2.09 kg ha^{-1} in the ungrazed system to 0.80 kg ha^{-1} in the grazed treatment (Figure 4b). Nogueira et al. (2016) also observed reductions in the accumulated emissions of N_2O from the cropping areas to the integrated systems, from 1.4 kg ha^{-1} to 0.36 kg ha^{-1}, respectively.

Two explanations are possible that are not mutually exclusive for the reduction of N_2O emissions with grazing. The first would be the complete denitrification of N_2O into N_2, caused by a possibly extreme anoxic condition on the top centimeters of soil due to sheep trampling in continuous grazing associated with high soil moisture during the emission peak (100 mm rainfall in the week before the peak of July 19, Figure 2). Studies have shown that the reduction of soil gas diffusivity associated with compaction caused by animal trampling can considerably reduce the N_2O:N_2 ratio due to complete denitrification into N_2 (Harrison-Kirk et al., 2015; Balaine et al., 2016). Although N_2 emission is environmentally benign, agronomically it can be a considerable loss of N. The second explanation could be a greater competition of the pasture plants with the denitrifying microorganisms for the inorganic nitrogen of the soil (Sato et al., 2017). In this case, the grazing regrowth would be stimulating this competition by increasing the net primary production and the N demand by plants, leaving less N available to denitrification than in the grazed system.

Methane emission

In general, there was an influx (negative flux) of CH_4 into the soil most of the time (Figure 5), indicating the consumption of this gas by methanotrophy, a very common process in unsaturated soils, where the oxidizing condition allows methanotrophs to oxidize CH_4 into CO_2 (Le Mer and Roger, 2001). However, there was a tendency of two CH_4 emission peaks to occur during the evaluation period. The first peak was five days after N application (Figure 5), and it coincided with the highest levels of soil ammonium (Figure 3b). It is known that ammonium competes with CH_4 for the active site of methane monooxygenase (Bédard and Knowles, 1989; Hütsch, 1998), making it likely that high ammonium levels reduced the capacity of the enzyme to oxidize CH_4, and thus allowed the release of this gas into the atmosphere. This reduction of CH_4 consumption with N fertilization is in agreement with the results of Zanatta et al. (2010), who found CH_4 emission peaks 4–6 days after N fertilizer application. The second peak was on September 26, and coincided with rains that occurred after a dry period of ~40 days (Figure 2) and increased the WFPS from ~55 to ~70 % (Figure 3a). The cause of this peak is unclear, but it could be associated with a possible pulse of methanogenesis in this return of rains. In general, the range of fluxes of 62 to -45 µg m^{-2} h^{-1} obtained in this study was consistent with the range of 62-40 µg m^{-2} h^{-1} reported by Bayer et al. (2012) in subtropical soil.

Overall, there was a net consumption of CH_4 into the soil for the three N rates and the two grazing levels (Figure 6), confirming the potential of this soil to act as atmospheric CH_4 sink. However, no significant difference occurred for the consumption of CH_4 between the three N rates (Figure 6a), although the N application promoted an emission peak (Figure 5), and the rate of 150 kg ha^{-1} tended to reduce the consumption of 0.66 kg ha^{-1} in the control soil to 0.26 kg ha^{-1} (Figure 6a). This insignificant effect of the treatments

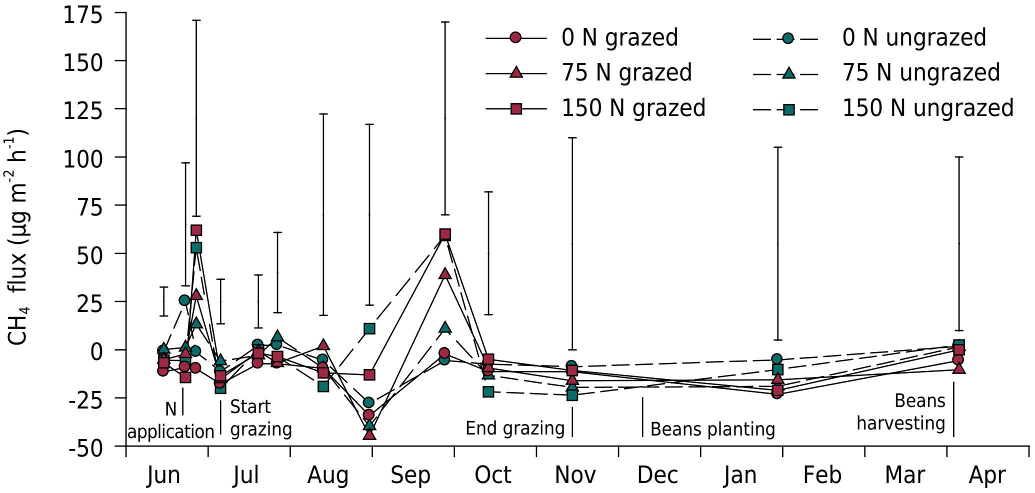


Figure 5. Methane fluxes of a Ferralsol under an integrated crop-livestock system (ryegrass plus oats as winter pasture, and common beans cropping in summer), with the winter pasture subjected to three nitrogen rates (0, 75, and 150 kg ha^{-1}) and two sheep grazing levels (grazed and ungrazed). Vertical bars denote the significant difference according to Tukey's test ($p<0.05$). Guarapuava-Paraná, Brazil, Jun/14/2010 to Apr/04/2011.

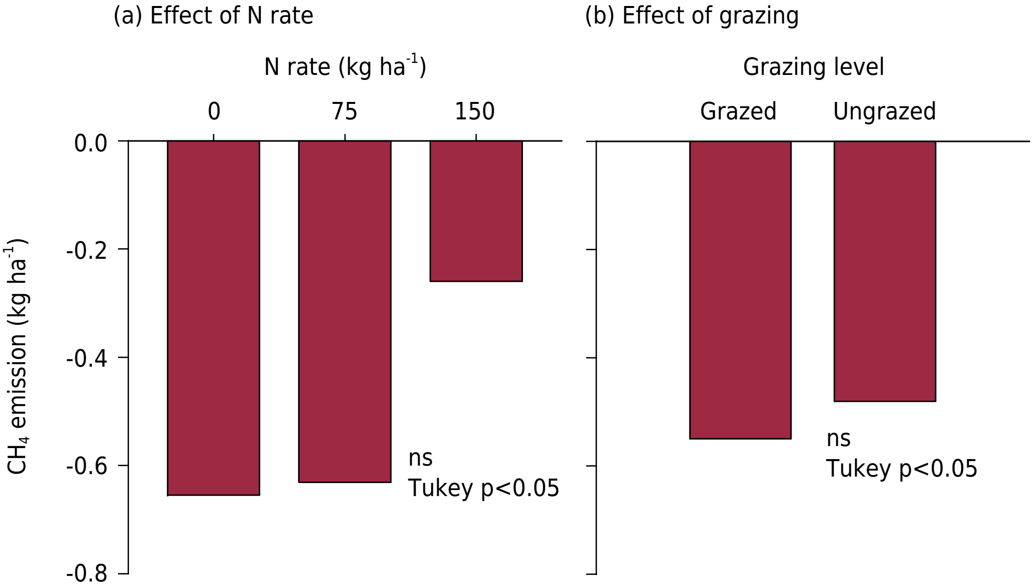


Figure 6. Cumulative emission of methane for ~10 months (Jun/14/2010 to Apr/04/2011) in a Ferralsol under integrated crop-livestock system (ryegrass plus oats as winter pasture, and common beans cropping in summer), with the winter pasture subjected to three nitrogen rates (0, 75, and 150 kg ha^{-1}) and two sheep grazing levels (grazed and ungrazed). As the interaction between nitrogen rate and grazing level was not significant (ns), such factors are presented separately. Guarapuava-Paraná, Brazil.

could be associated with the coefficients of variation (~60 %) obtained for the fluxes and cumulative emissions of CH_4.

There was also no significant difference for the CH_4 consumption between grazed and ungrazed treatments, with the consumption at ~0.50 kg ha^{-1} for both grazing levels (Figure 6b). However, other studies have reported a net efflux of CH_4 in pasture areas compared to cropland soils (Siqueira-Neto et al., 2011; Shi et al., 2017), possibly due to increased soil bulk density and the lower aeration porosity associated to animal trampling.

CONCLUSIONS

The emission factors in this study were consistent with the default of 1 % established by the IPCC and its uncertainty range of 0.3-3.0 %, being 1.7 and 1.1 % for 75 and 150 kg ha^{-1}, respectively. In addition, the application of nitrogen promotes a pulse in the soil CH_4 flux, possibly due to the inhibitory effect of the fertilizer-derived ammonium on methanotrophy. However, due to the CH_4 influxes most of the time, the overall result is that the soil acts as a CH_4 sink, regardless of the nitrogen rate.

In the present study, sheep grazing decreased the soil N_2O emission, perhaps due to the complete denitrification of N_2O into N_2 caused possibly by extreme anoxia in the first centimeters of soil associated with trampling and high soil moisture at the peak of emission (rainy period). Alternately, it could be because the grazing regrowth stimulated nitrogen uptake by the pasture and diminished its denitrification availability. Grazing had no influence on the consumption of CH_4 by the soil.

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