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Emission of nitrous oxide in flooded rice cultivation in tropical area of Brazil

Abstract – The objective of this work was to evaluate the effects of nitrogen fertilizers on the N dynamics and grain yield in flooded rice (*Oryza sativa*) cultivation in Brazilian tropical wetland. The experiment was carried out in a randomized complete block design with six treatments, as follows: common and protected urea; topdressing application of N doses (30, 70, and 150 kg ha^{-1}); and one control treatment, without N fertilization. Emissions of N_2O-N, global warming potential (pGWP), emission factors (EF) for mineral fertilizers, grain yield, emission intensity, nitrate, ammonium, pH, and potential redox were quantified. Gas sampling was carried out in two crop seasons of rice cultivation and in one off-season. During the flooded period of the two crop seasons, N_2O fluxes did not exceed 862.41 μg m^{-2} h^{-1} N_2O-N; in the off-season, the fluxes varied from -52.95 to 274.34 μg m^{-2} h^{-1} N_2O-N. Consistent emission peaks were observed in soil draining before harvest, when the highest rate of both N sources was used, and also in the control treatment in the off-season. Protected urea does not reduce N_2O emissions or EF. Nitrogen increases the grain yield. Protected urea does not have any effect on the pGWP. The concentrations of NO_3^- and NH_4^+ in the soil are not related to N_2O fluxes.

Index terms: *Oryza sativa*, climate change, emission factor, greenhouse gases, nitrogen use efficiency.

Emissão de óxido nitroso em cultivo de arroz inundado em área tropical do Brasil

Resumo – O objetivo deste trabalho foi avaliar os efeitos dos fertilizantes nitrogenados na dinâmica do N e na produtividade de arroz (*Oryza sativa*) inundado em áreas úmidas tropicais Brasileiras. O experimento foi realizado em delineamento de blocos ao acaso, com seis tratamentos: ureia comum e protegida; doses de N (30, 70 e 150 kg ha^{-1}) em cobertura; e controle, sem fertilização com N. Foram quantificados emissões de N-N_2O, potencial de aquecimento global (pGWP), fatores de emissão (EF) para fertilizantes minerais, rendimento de grãos, intensidade de emissão, nitrato, amônio, pH e potencial redox. As amostragens foram realizadas em duas safras e na entressafra do arroz. Durante o período de inundação das duas safras, os fluxos de N-N_2O não excederam 862,41μg m^{2} h^{1}; no período de entressafra, os fluxos variaram de -52,95 a 274,34 μg m^{-2} h^{-1} N-N_2O. Observaram-se picos de emissão consistentes na drenagem do solo, antes da colheita, quando a dose mais alta de ambas as fontes de N foi utilizada, e também no controle na entressafra. A ureia protegida não reduz as emissões de N_2O ou EF. O nitrogênio aumenta o rendimento de grãos. A ureia protegida não afeta o pGWP. As concentrações de NO_3^- e NH_4^+ no solo não estão relacionadas aos fluxos de N_2O.

Termos para indexação: *Oryza sativa*, mudanças climáticas, fator de emissão, gases de efeito estufa, eficiência de uso de nitrogênio.

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Introduction

Brazil is the ninth largest rice (*Oryza sativa* L.) producer in the world (FAO, 2020). More than 80% of the Brazilian production comes from wetland areas, whose basic cultivation system is irrigated by flood. In 2019, rice grain production in tropical lowlands was approximately 9% of the national production, and 10% of the total was produced in flooded systems (Conab, 2020). Because of the modern cultivars, it is possible to have high-quality grain outside Southern Brazil, which contributes to economic and social development, enhancing human life quality in the Cerrado, and collaborates for national food security. However, this demands the increasing use of nitrogen mineral fertilizer in the rice production system that directly influences the emission rates of N_2O, with direct and indirect effects on the emissions of this greenhouse gas (GHG).

High N rates generally promote higher N_2O emissions; however, these emissions may vary according to the climate (dry or moisture air condition), soil type and management, N (source and rates), cultivars, and dry-moisture soil cycles (Linquist et al., 2012; 3ª Comunicação..., 2016). Nitrous oxide (N_2O) is an important greenhouse gas whose global warming potential is 265 times greater than CO_2 (Smith et al., 2014).

Studies carried out in production areas of flooded rice in the world have verified significant N_2O emissions in those humid areas, both before flooding and after drainage, especially because of nitrogen fertilizer applications (Linquist et al., 2012; Adviento-Borbe et al., 2015; Zschornack et al., 2016). The use of protected nitrogen fertilizers (protected urea) can be a way to reduce N losses compared with conventional urea (Grohs et al., 2011). There are reports on a positive effect of using protected urea on the N_2O emissions decrease (Xia et al., 2017; Li et al., 2018). However, there is no consensus on the real advantages of using coated nitrogen fertilizers (Fageria & Carvalho, 2014). Nevertheless, in the Brazilian tropical lowlands, where the chemical reactions can be intensified because of high temperatures of the air, data on emissions and emission factors are still incipient for greenhouse gases, such as N_2O, for the use of N fertilizers in flooded rice.

Therefore, studies covering effects of N fertilizer application on N_2O emission and emission intensity, in tropical flooded rice systems, are essential to develop strategies for increasing the N use efficiency from mineral fertilizers, decreasing N_2O losses to the atmosphere, besides being a tool for public policies for agriculture in Brazil.

The objective of this work was to evaluate the effects of sources and doses of N fertilizers on the N dynamics and grain yield of flooded rice cultivation in Brazil.

Materials and Methods

The study is part of the experiments developed under the international partnership project “NUCLEUS: a virtual joint center to deliver enhanced NUE via an integrated soil-plant system approach for the United Kingdom and Brazil”. It was carried out under field conditions, in the 2014/2015 rice crop season, in the 2015 off-season, and in the 2015/2016 crop season, in the experimental station of Palmital Farm, belonging to Embrapa Arroz e Feijão, in the municipality of Goianira, in the state of Goiás, Brazil (16°26'45"S, 49°23'31"W, at 729 m altitude). According to the Köppen-Geiger’s classification, the climate is Aw, with 1,485 mm annual mean precipitation and 71% annual mean relative humidity.

The soil is classified as Gleissolo Háplico Ta eutrófico neofluvissólico, according Brazilian Soil Classification System (Santos et al., 2018), i.e., Gleysol, according FAO (IUSS Working Group WRB, 2015), with medium texture, and it has been cultivated with flooded rice for approximately 36 years. Soil chemical characteristics in the 2014/2015 crop season were: pH (H_2O) 5.6; 2.8 $cmol_c$ dm^{-3} Ca; 0.8 $cmol_c$ dm^{-3} Mg; 0.2 $cmol_c$ dm^{-3} Al; 0.2 $cmol_c$ dm^{-3} K; 123.6 mg dm^{-3} P; 7.4 mg dm^{-3} Cu; 5.9 mg dm^{-3} Zn; 364.2 mg dm^{-3} Fe; 24 mg dm^{-3} Mn; 1.8% total C; and, 0.2% total N. Soil chemical characteristics in the 2015/2016 crop season were: pH (H_2O) 5.2; 2.0 $cmol_c$ dm^{-3} Ca; 0.6 $cmol_c$ dm^{-3} Mg; 0.7 $cmol_c$ dm^{-3} Al; 0.15 $cmol_c$ dm^{-3} K; 43.2 mg dm^{-3} P; 2.3 mg dm^{-3} Cu; 3.9 mg dm^{-3} Zn; 324.2 mg dm^{-3} Fe; 41 mg dm^{-3} Mn; 2.3% total C; and, 0.2% total N. The soil texture was: 239 g kg^{-1} clay; 242 g kg^{-1} silt; and 519 g kg^{-1} sand.

The experiment was carried out in a randomized complete block design with six treatments, in a 2 x 3 + 1 arrangement, with two nitrogen sources, three N doses, one control, and three replicates. The treatments were: N fertilizer source [common urea (CU) and protected urea (PU, urea coated with 0.15% Cu plus 0.4% B)]; doses of N topdressing for each urea type (30, 70, 150 kg ha^{-1}); and a control (without N application).

Rice 'BRS Catiana' was sown in the 2014/2015 and 2015/2016 crop seasons, in twenty-one experimental plots of 5.5×3.3 m, with 17 cm between rows, using 85 seed per linear meter of row. At the sowing in the 2014/2015 crop season, 6.5 kg ha^{-1} N (in the form of urea), 40 kg ha^{-1} P_2O_5, and 60 kg ha^{-1} K_2O were used. In the 2015/2016 crop season, the fertilization was performed with 20 kg ha^{-1} N (urea), 40 kg ha^{-1} P_2O_5, and 50 kg ha^{-1} K_2O. The doses of P and K were calculated according to the soil chemical analysis. The recommended fertilizer dose for rice cultivars ranges from 90 and 120 kg ha^{-1} N (Fageria et al., 2003).

Nitrogen was applied twice, by topdressing, in the rice phenological stages V3-V4 (beginning of the tillering, 23 days after sowing) and in V7-V8 (effective tillering, 45 days after sowing), respectively. The topdressing N need was determined with chlorophyll meter SPAD-502 (Minolta, 1989) in rice leaves, to monitor the N status in rice. When the N sufficiency index (NSI), calculated according Santos et al. (2019), was less than or equal to 90%, 30 kg ha^{-1} N was applied as the first topdressing, except for the control treatment, and the remaining N was applied as the second topdressing to complete the doses, for each source. The area was flooded three days after the first topdressing, with a constant water depth of approximately 10 cm, until near the rice harvest. The N_2O emissions were quantified using the closed static chamber method (Hutchinson & Mosier, 1981). NH_4^+ and NO_3 were extracted according Tedesco et al. (1995) and analyzed with the colorimetric method by flow injection analysis (FIA), according to Greenberg (1984), in soil and soil solution. Soil solution pH and potential redox (Eh) were obtained using the electrode method (Donagema, 2011).

Gas sampling started one day after sowing. It was performed twice a week in the no flooded period, and once a week during the flooded period. After each N fertilization, the sampling was carried out daily for a period of seven days, while, in the off-season, samplings were biweekly. For the air sampling, in the 2014/2015 crop season, there was one chamber for each plot, in a rectangular shape metal basis (40×60×15 cm), partially inserted into the ground (5 cm). During the growth of rice plants, an extender was inserted between the basis and the top of the chamber. In the 2015/2016 crop season, the static chambers used had a circular shape made of plastic (20 cm height and 17.5 cm radius), partially inserted into the ground (10 cm), with a plastic lid. In both chamber shapes there were a hole in the lid for sampling gases using a manual pump. A 38 cm high extender was used, according to growing plants. The chambers were positioned to achieve as many rows as possible. Air samplings were performed in the morning, between 9:00 and 11:00 h, according to Jantalia et al. (2008), at the pre-established time intervals of 0, 15, and 30 min after closing the chambers. Water was added to the top of the basis and extenders (junctions) to guarantee no gas escaping. Before and after each air sampling, the temperatures of the inner chamber, soil, and air were monitored with a digital thermometer.

The concentrations of N_2O were determined using a gas chromatographer GC 2014 “Greenhouse” (Shimadzu Co., Tokyo, Japan). The rate of gas increase over time was calculated considering the linear adjustment model (ΔC/Δt), for the increases of gas that presented linear adjustment. When the increases of gas did not show linear adjustment, the Hutchinson & Mosier model (Venterea et al., 2012) was used, which is described by the equation

$$F = (C1 - C0)2/[t1 \times (2 \times C1 - C2 - C0)] \times \ln[(C1 - C0)/(C2 - C1)],$$

in which: F is the flux (μL L^{-1} h^{-1} gas); C0, C1, and C2 are the gas concentrations (ppb - N_2O) in the measuring chamber, at times 0, 1, and 2, respectively; and t1 is the interval between sampling times (h).

After these criteria, N_2O flux was converted from volumetric unit (μL m^{-2} h^{-1}) to mass unit (μg m^{-2} h^{-1}) using the ideal gas law: PV = nRT, in which: P is the pressure (atm); V is the volume (L); n is the number of moles of gas (μmol); R is the constant of the ideal gas; and T is the temperature (K). Only fluxes with coefficients of determination (R^2) greater than 0.8

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were considered, otherwise, data were considered as missing.

Total N_2O emission was calculated from the integration of the daily N_2O fluxes throughout the evaluation period. The emission factor (EF) from the N fertilizer application was calculated as the proportion of N_2O-N emitted in the evaluation period related to the total synthetic N applied, according to the following equation (Carvalho et al., 2018):

$$EF_{N2O} (\%) = [(N_2O\text{-}N_{treatment} - N_2O\text{-}N_{control})/\text{N applied in the treatment}] \times 100,$$

in which: EF_{N2O} is the nitrous oxide emission factor; N_2O-$N_{treatment}$ is the N emitted from the soil as nitrous oxide from N fertilization (kg ha^{-1}); N_2O-$N_{control}$ is the N emitted from the soil as nitrous oxide without N fertilization (kg ha^{-1}).

The partial global warming potential (pGWP) was calculated by converting N_2O emissions to CO_2 equivalent (kg ha^{-1} $CO_{2eq.}$), according to the expression pGWP = (N_2O × 265), in which: N_2O corresponds to the accumulated N_2O emissions during the crop seasons (kg ha^{-1}); and the GWP values for N_2O consider an atmospheric residence time of 100 years (Forster et al., 2007). In no flooded period, together with air sampling, soil samples were collected at 0–10 cm soil depth to determine the gravimetric moisture, nitrate (NO_3^-), and ammonium (NH_4^+) in the soil. When the area was flooded, the soil solution was collected using commercial soil solution extractors, which are pipes of 60 cm high with a pore cap of 5 cm length at one end, inserted 15 cm into the ground to allow of the capture of soil solution at 10 to 15 cm soil depth, to determine soil pH and redox potential (Eh), in addition to NO_3^- and NH_4^+ levels.

To determine grain yield, four lines of 2.5 m were harvested and weighted, to obtain data (kg ha^{-1}). Emission intensity was calculated as being accumulated N_2O-N emission split rice grain yield, as follows: I = N/yield, in which: I is the emission intensity (N_2O-N g kg^{-1} grain); N = N_2O emitted (g ha^{-1}); and yield is expressed in kilogram per hectare.

Descriptive analyses were used to explore the daily N_2O emissions and the soil variables. Accumulated N_2O emissions were evaluated from the sources of variation of the experiment. Correlation and regression analyses were performed to verify N_2O flux dependence on the nitrate, ammonium, Eh, and pH levels. Statistical analyzes were performed using the R program (R Core Team, 2017).

Results and Discussion

The N_2O-N emission peaks were observed after rice sowing in all treatments (Figure 1), and may be resulted from the application of N fertilizer at this stage, which may have improved N releasing to soil. In the flooded period of the 2014/2015 and 2015/2016 crop seasons, N_2O fluxes did not exceed 862.41 μg m^{-2} h^{-1} N_2O-N, and there were no statistical differences between sources or rates. However, consistent emission peaks were observed when the highest N rate was used for both sources, in draining soil before harvest. The main pathway of nitrous oxide emission from the rice-soil system depends on the soil water status, that is, when the soil is flooded, the emission is predominantly through the rice plants, while in the absence of floodwater, N_2O is emitted mainly through the soil surface, by soil microorganisms, (Yan et al., 2000; Timilsina et al., 2020). According to Ponnamperuma (1972), in anaerobic conditions, there is a high consumption of electrons due to the soil reduction process, which reduces the availability of nitrate and, consequently, N_2O. In addition, the water depth would act as a physical barrier, limiting the diffusion of N_2O from the soil to the atmosphere. In the present study, an increase of N_2O emissions from the soil was observed in the soil drainage process, which confirms that this process created ideal conditions for nitrification and denitrification, occurring in microsites of inner soil aggregates (Adviento-Borbe et al., 2015), enhancing emissions of N_2O-N from the soil.

At the beginning of the off-season period, N_2O-N emission peaks were observed in the treatment PU 70 (274.34 μg m^{-2} h^{-1} N_2O-N), which may be resulted from late emissions when protected urea was used (Figure 1 C). Subsequently, the N_2O-N peaks remained relatively low, close to zero, and constant until the beginning of the 2015/2016 crop season, especially because of the rain absence in this period of the year (from May to October), which is a very common condition in Brazilian Cerrado. Emissions during the off-season varied from -52.95 to 274.34 μg m^{-2} h^{-1} N_2O-N.

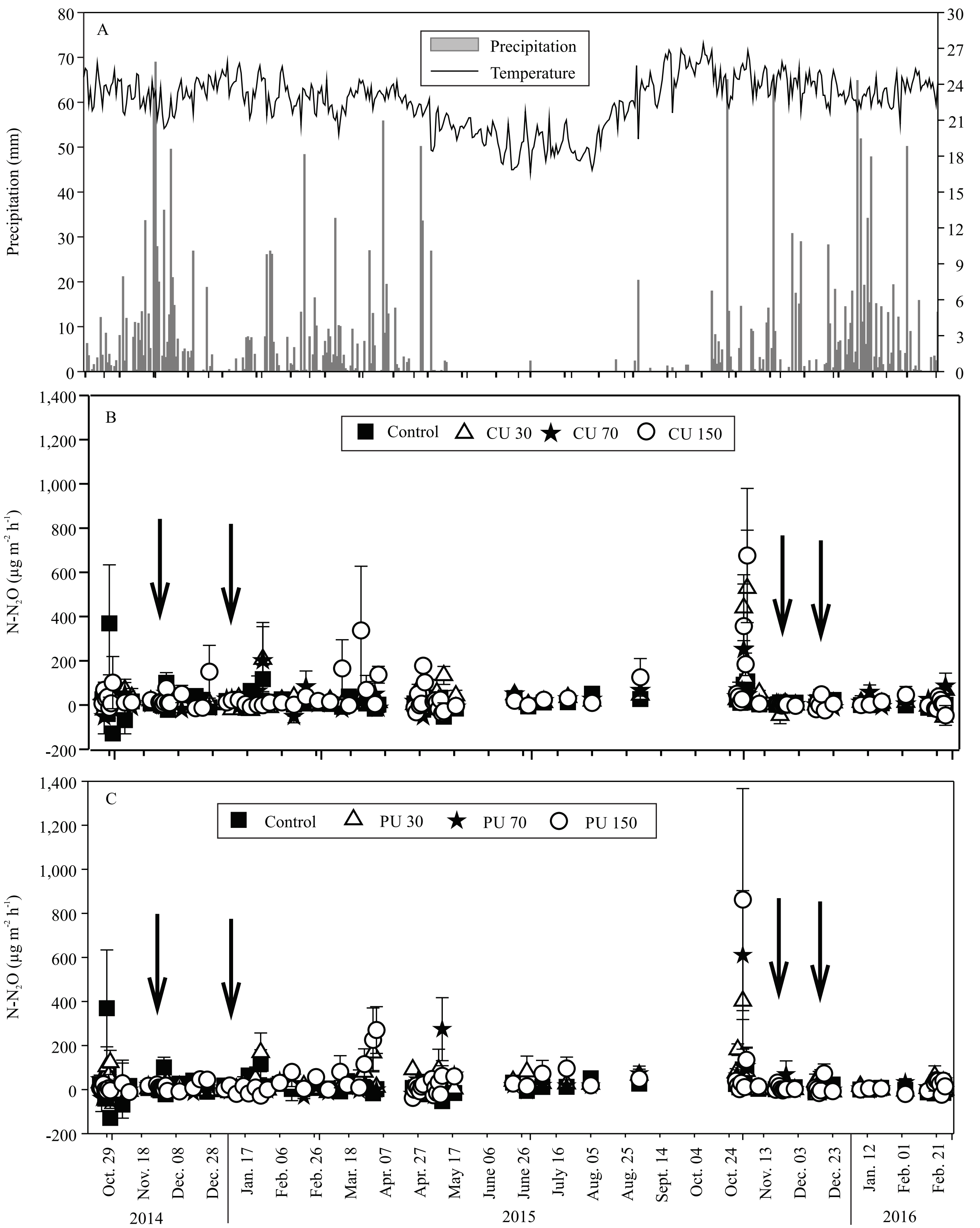

Figure 1. Monthly air temperature and precipitation (A), and N_2O-N flux from the application of common urea (CU) (B) and protected urea (PU) (C), at the doses of 30, 70, and 150 kg ha^{-1} N to flooded rice (*Oryza sativa*) cultivation in tropical wetland. The arrows represent the application dates of nitrogen fertilizer (November 26, 2014, January 04, 2015, November 17, 2015, and December 12, 2015)**.**

However, no significant differences were observed in the N_2O-N emissions related to N rates, which corroborate the results described by Pittelkow et al. (2013), when studying GHG in flooded rice cultivation in response to the addition of N.

In the 2015/2016 crop season, peaks ranged from -54.28 to 862.41 μg m^{-2} h^{-1} N_2O-N, and the highest peaks were recorded in the treatments PU 150 (862.41 μg m^{-2} h^{-1} N_2O-N), CU 150 (675.85 μg m^{-2} h^{-1} N_2O-N), PU 70 (610.54 μg m^{-2} h^{-1} N_2O-N), and CU 30 (528.25 μg m^{-2} h^{-1} N_2O-N). All peaks described in both crop seasons were observed during the period when the soil was not flooded, but humid after rain occurrences, which enhances N_2O emissions similarly to that of the drainage preharvest condition (Zou et al., 2007). The values of the highest fluxes observed in the 2015/2016 crop season – just after sowing (on October 24, 2015) and before flooding (on December 03, 2015) – could be related to the sowing fertilization with mineral N (Figure 1) associated to the occurrence of precipitations in the period, especially that with 65 mm on October 31, 2016. Precipitations can affect the extent of anaerobic sites in the soil due to the increase of soil moisture and water-filled pore space (WFPS), which influences the N_2O-N emission rates both by the nitrification process, when the WFPS volume is <60%, and the denitrification process, when the WFPS volume is >80% (Signor & Cerri, 2013).

In the experimental plots, a decrease of nitrate contents was observed after flooding and, at the same time, an increase of ammonium soil contents, irrespectively of N rates or sources (Figure 2). Initial losses of NO_3^-, soon after flooding, result from the absorption by plants, leaching in soil profile, ammonia volatilization and, mainly, from the denitrification of gaseous N_2O and N_2 (Camargo et al., 1999). Despite the use of different N sources, no statistical differences were observed between both sources for releasing nitrate or ammonium, during the flooded period, and soil NO_3^- availability also remained close to zero, as expected due denitrification process, while a greater amount of NH_4^+ was observed just after the first topdressing, which corroborates the observations by Pittelkow et al. (2013) in flooded rice. The main reason for these results is the kind of inhibitor associated with urea, which when used in soils with low organic matter content (~2% total C) could impact negatively the denitrification process.

Grain yield presented a quadratic response with the increase of N rates in the range 0–150 kg ha^{-1}. By the regression equation, the maximum grain yield was estimated at the dose of 129 kg ha^{-1} N, and the maximum economic dose, which reaches 90% of the maximum yield, was approximately 64 kg ha^{-1} N (Figure 3). This dose is below that found by Fageria et al. (2003), who have obtained approximately 90 kg ha^{-1} N as the average economic dose of three years of experimentation with flooded rice, in a Gleissolo Háplico soil, in the conditions of tropical wetland. These results are very important not just for environment, by reducing N inputs into rice fields, but, specially from stakeholders' point of view, because this could promote a positive impact, by reducing production costs and increasing farmer profits, and contribute to sustainability of tropical flooded rice production system.

The N_2O emission factor (EF) of fertilizers showed no statistical differences between common and protected urea, and the values ranged from 0.39 to 1.08% (Table 1). However, the values found in the present work were higher than those found by Akiyama et al. (2005), who did a meta-analysis using 113 measurements from 17 sites from China, and concluded that the N_2O EF in rice cultivation irrigated by continuous flooding is on average 0.22±0.24% of the applied N. The findings for EF of the present work are also higher than the standard value (0.3%) considered by the IPCC (Eggleston et al., 2006) for flooded rice systems. Several studies have indicated that this factor can be quite variable depending on the type of soil, environment, and soil and crop management (Linquist et al., 2012; Smith et al., 2014; 3ª Comunicação..., 2016).

The pGWP of the N_2O showed no significant differences among treatments (Table 2). The pGWP relates GHG emissions to grain yields. Through the pGWP is possible to know how much each kilogram of produced grain emitted GHG in CO_2 equivalent. In management systems that are difficult to reduce N_2O emissions, increasing crop yield is an alternative to reduce the emission intensity (pGWP / grain yields). However, in the present study, the evaluated treatments had no influence on pGWP, and the sources did not

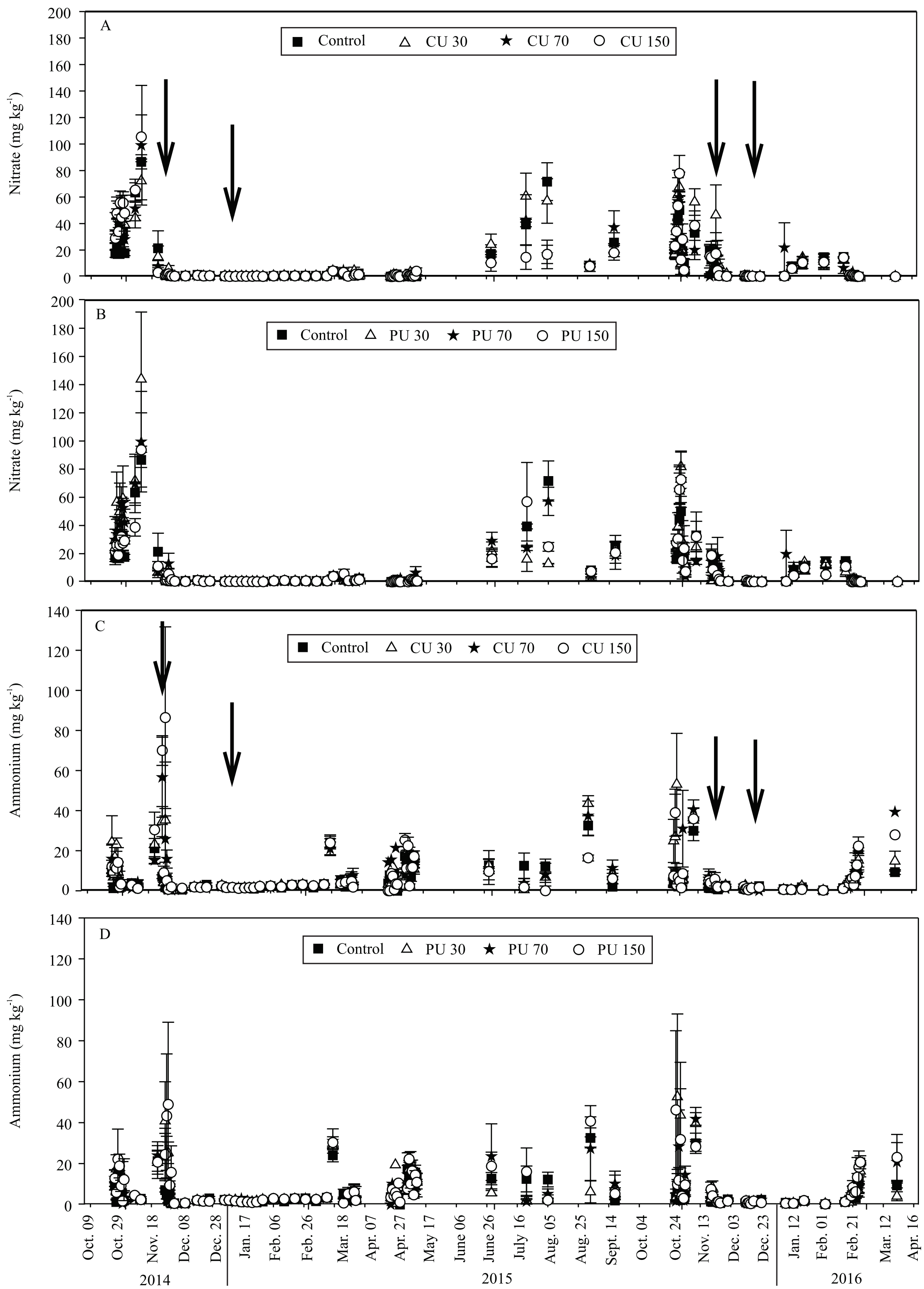

Figure 2. Variation of nitrate content (A and B) and ammonium content (C and D) in soil and soil solution, during flooded rice (*Oryza sativa*) cultivation in tropical wetland. Treatments: common urea (CU) and protected urea (PU) at the doses of 30, 70, and 150 kg ha^{-1} N. The arrows represent the application dates of nitrogen fertilizer (November 26, 2014, January 04, 2015, November 17, 2015, and December 12, 2015).

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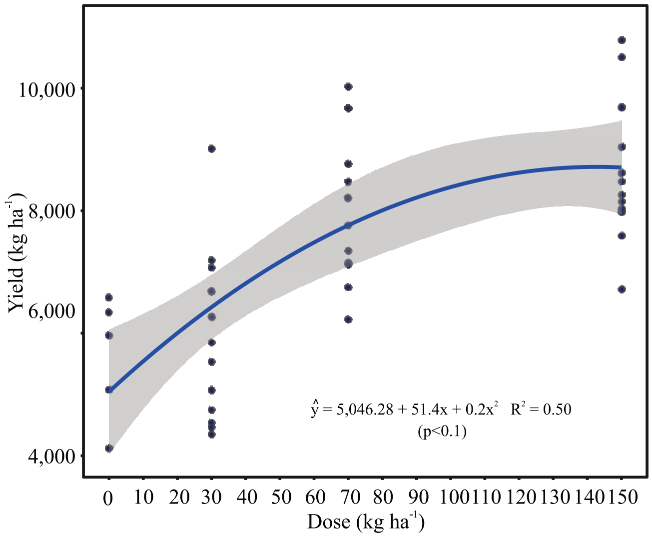

Figure 3. Effect of the doses of mineral nitrogen fertilizer on the yield of tropical flooded rice 'BRS Catiana' (*Oryza sativa*) in a Gleissolo Háplico (Gleysol).

Table 1. Nitrogen emission factor in flooded rice (*Oryza sativa*) cultivation in tropical wetland from fertilization with common urea (CU) and protected urea (PU), in two crop seasons and one off-season[(1)].

Treatment	Emission factor (%)			
	2014/2015	Off-season	2015/2016	General
Common urea	0.56^{ns}	0.76^{ns}	1.00^{ns}	0.78^{ns}
Protected urea	0.43^{ns}	1.08^{ns}	0.39^{ns}	0.63^{ns}

[(1)]Means followed by equal letters do not differ, by the Tukey's test, at 5% probability. General, mean of the three periods, two crop seasons and off-season.

Table 2. Partial global warming potential (pGWP), grain yield of rice, and greenhouse gas (GHG) emission intensity in a tropical wetland cultivated with the flooded rice 'BRS Catiana' (*Oryza sativa*), in 2014/2015 and 2015/2016 crop seasons.

Treatment	pGWP (kg ha^{-1} CO_{2eq})	Grain yield (kg ha^{-1})	Emission intensity (kg of CO_{2eq} kg^{-1} grains)
		2014/2015 Crop season	
T0	129^{ns}	5264	0.025
CU 30	202^{ns}	5367	0.038
CU 70	160^{ns}	7498	0.021
CU 150	447^{ns}	7487	0.060
PU 30	240^{ns}	6154	0.039
PU 70	66^{ns}	7288	0.009
PU 150	298^{ns}	8091	0.037
		2015/2016 Crop season	
T0	66^{ns}	6156	0.011
CU 30	270^{ns}	5235	0.052
CU 70	114^{ns}	8219	0.014
CU 150	291^{ns}	8929	0.033
PU 30	119^{ns}	6853	0.017
PU 70	157^{ns}	9388	0.017
PU 150	132^{ns}	10110	0.013

T0, control; CU, common urea at the doses 30, 70, and 150 kg ha^{-1}; PU, protected urea (PU) at the doses 30, 70, and 150 kg ha^{-1}.

influence the grain yield of flood-irrigated rice 'BRS Catiana'.

The results of the research show the importance of studies to understand the behavior of GHG in tropical wetland areas. They show that emissions can be affected by climatic conditions, such as precipitation, by the management of N fertilization, and by other factors.

Conclusions

1. Protected urea coated with 0.15% Cu plus 0.4% B does not reduce N_2O emissions and the emission factor, when compared to common urea in irrigated flooded rice (*Oryza sativa*).

2. Protected urea coated with 0.15% Cu plus 0.4% B does not have any effect on the partial global warming potential (pGWP).

3. The concentrations of NO_3^- and NH_4^+ in the soil or solution are not related to N_2O fluxes.

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