Nitrous oxide emissions from a tropical Oxisol under monocultures and an integrated system in the Southern Amazon – Brazil

Alexandre Ferreira do Nascimento[(1)]* (iD), **Renato de Aragão Ribeiro Rodrigues**[(2)] (iD), **Julia Graziela da Silveira**[(3)] (iD), **Jacqueline Jesus Nogueira da Silva**[(4)] (iD), **Vagner de Carvalho Daniel** [(5)] (iD) **and Eduardo Reckers Segatto**[(6)] (iD)

[(1)] Empresa Brasileira de Pesquisa Agropecuária, Embrapa Agrossilvipastoril, Sinop, Mato Grosso, Brasil.
[(2)] Empresa Brasileira de Pesquisa Agropecuária, Embrapa Solos, Rio de Janeiro, Rio de Janeiro, Brasil.
[(3)] Universidade Federal de Viçosa, Departamento de Engenharia Florestal, Viçosa, Minas Gerais, Brasil.
[(4)] Universidade Federal Fluminense, Instituto de Química, Departamento de Geoquímica, Niterói, Rio de Janeiro, Brasil.
[(5)] Universidade Federal de Mato Grosso, Departamento de Agronomia, Sinop, Mato Grosso, Brasil.
[(6)] Universidade Federal de Mato Grosso, Departamento de Engenharia Agrícola e Ambiental, Sinop, Mato Grosso, Brasil.

ABSTRACT: Although agriculture and livestock systems represent important sources of N_2O from the soil, they may also aid in emissions mitigation, mainly when integrated systems are taken into account, such as crop-livestock-forest, for food production. This work assessed the soil N_2O emissions from a tropical Oxisol under row-crop, livestock, forest monocultures, and an integrated crop-livestock-forest system in the Southern Amazon - Brazil. Soil N_2O emissions were measured using static chambers from November 2014 to October 2016 in four soil use systems [row-crop, livestock, forest, and integrated crop-livestock-forest (CLF)], and in a reference area under native forest fragment. For the whole period, the average of soil N_2O fluxes was 16.9, 12.2, and 15.4 µg N_2O-N m^{-2} h^{-1}, to row-crop, livestock, and CLF systems, respectively, all with a similar average among them. The lowest fluxes were observed in the forest system and native forest fragment, with average fluxes of 4.0 and 6.3 µg N_2O-N m^{-2} h^{-1}, respectively, both lower than the agricultural systems. The largest soil N_2O fluxes were observed throughout the rainy seasons in the row-crop, livestock, and CLF, mostly after N-fertilizer application to the soil surface or in the planted row. As a consequence, the cumulative emissions were greater in row-crop, livestock, and CLF systems, which in the averages of two cycles emitted respectively 1.40, 1.15, and 1.27 kg N_2O-N ha^{-1} yr^{-1}, all different of the forest system and native forest fragment (0.33 and 0.52 kg N_2O-N ha^{-1} yr^{-1}, respectively). Nitrogen fertilization and soil moisture influenced soil N_2O emissions of all systems assessed in the Southern Amazon. The N_2O emissions took place after both factors were met, corroborating the hole-in-the-pipe model. Even with more soil use intensification, once in the same area there were three cultures in succession during a year and perennial trees, CLF did not lead to greater N_2O emissions from the soil than row-crop and livestock. Thus, CLF represents a good option for N_2O mitigation for the edaphic and climatic conditions of the Southern Amazon.

Keywords: global warming, mitigation, greenhouse effect gases, Oxisols, agricultural soils, forest soils.

INTRODUCTION

Nitrous oxide (N_2O) is a powerful gas that alters the radioactive balance of the atmosphere and the ozone chemistry of the stratosphere (Salmon et al., 2016). Although N_2O appears in trace concentrations, it contributes more than 6 % of the global radioactive force, with a global warming potential of 298 times greater than carbon dioxide (CO_2) (IPCC, 2013).

According to IPCC (2013), the concentration of N_2O in the atmosphere increased by 20 % compared to the pre-Industrial Era. Agricultural systems to supply the food demand have been pointed out as the main cause for this increase, responsible for 80 % of anthropic emissions of N_2O (IPCC, 2013). In Brazil, N_2O emissions mainly come from agricultural activities and the livestock sectors (~84 % in 2010), mainly from livestock on pastures (Brasil, 2016). Direct emissions from agricultural soils account for about 50 % (~30 % if only livestock is considered), and indirect emissions for 30 %, followed by emissions from animal waste (less than 3 %), and burning of agricultural waste (less than 1 %) (Brasil, 2016).

Although the agricultural and livestock sectors are important sources of N_2O, their production systems can also act as sinks by adopting practices and techniques that aim to reduce/avoid emissions or removing C from the atmosphere (Smith et al., 2007). Mitigation practices include: good agricultural practices for fertilization, irrigation, livestock, and waste management; adoption of the no-tillage system and agro-forest systems; and recovery of degraded areas (Smith et al., 2007, 2014).

Some of the agricultural practices and techniques have greater potential to reduce or avoid N_2O and methane (CH_4) emissions, and others to remove CO_2 from the atmosphere and storing C in the soil or in the biomass trees. A no-tillage system and the inclusion of trees in the animal or vegetable production system (integrated systems) can provide for C removal (Smith et al., 2014; Cardinael et al., 2017), thus acting as a C sink. Good agricultural practices for fertilization, irrigation, livestock, and waste management, among others, focus on reducing or avoiding greenhouse gas emissions (Cerri et al., 2007; Smith et al., 2014; Sanz-Cobena et al., 2017).

Evaluating soil N_2O emissions with the adoption of alternative production practices can contribute to identify the best soil use and management strategies that align food and fiber production and emissions mitigation (Cerri et al., 2007; Smith et al., 2014). This information is even more important to the Southern Amazon, a region of agriculture and livestock expansion that has one of the largest cultivated areas in Brazil with pasture and row-crop systems, where integrated systems would likely adapt well to the region because it has more precipitation than some areas located in the Cerrado (Alvares et al., 2013). It allows that the corn cultivated after soybean be intercropped with grasses and, after corn harvesting, the pasture is formed and can be used to cattle grazing, what becomes feasible to have three cultures during a year in the same area (Ceccon, 2013).

As integrated systems intensify the soil use, they can lead to changes in edaphic properties that favor and increase the direct emissions of N_2O (Butterbach-Bahl et al., 2013; Smith et al., 2014; Cardoso et al., 2016). Thus, it is likely that the intensification of the soil use and management in integrated systems contributes more to soil N_2O emissions than the monocultures. To test this hypothesis, this study assessed the N_2O emissions from a tropical Oxisol under monocultures (row-crop, livestock, and forest) and an integrated crop-livestock-forest system (CLF) in the Southern Amazon – Brazil. Results will support the identification of which food production systems contribute more to N_2O mitigation under the edaphoclimatic conditions of the Amazon.

MATERIALS AND METHODS

Field experiment

The study was conducted at the experimental farm of Embrapa Agrossilvipastoril, Sinop, state of Mato Grosso – Brazil. For this study, N_2O emissions from November

2014 to October 2016 were measured from an Oxisol under four treatments: row-crop, livestock, forest with eucalyptus, and an intergraded crop-livestock-forest (CLF) system. Row-crop and forest treatments were established in 1-ha plots, and the livestock and CLF in 2-ha plots, all with three replicates distributed in randomized block design. As a reference, a native forest fragment was also assessed in a continuous area around 1 km far away from the experimental area, where the three chambers (replicates) were randomized distributed. The soil of all these treatments, including the native forest, is a *Latossolo Vermelho Amarelo Distrófico típico* according to Brazilian Soil Taxonomy (Santos et al., 2018), equivalent to a Hapludox following the US Soil Taxonomy (Soil Survey Staff, 2014), with clay textures (around 500 g kg^{-1} of clay content), in a flat relief. The climate is Aw according to Köppen system, which is characterized by dry (May to September) and wet season (October to April) (Alvares et al., 2013).

The forest system was established in November 2011 composed on eucalyptus (*Eucalyptus urograndhis* clone H13) with a density of 952 trees ha^{-1}. Before eucalyptus transplanting, 350 kg ha^{-1} of simple superphosphate were distributed in the planting groove. Nitrogen and K$_2$O were applied on soil surface 30 days after eucalyptus transplanting at a rate of 20 kg ha^{-1}. From November 2014 to September 2016, the managed forest did not receive cultural or soil management. In September 2016, trees with low potential for wood production and/or firewood were trimmed.

Row-crop system was established in November 2011, when soybean (*Glycine max* L.) was sowed with zero tillage and followed by corn (*Zea mays*) intercropped with Marandu grass (*Brachiaria brizantha* cv. Marandu) for the formation of soil cover until the new crop cycle. In September 2015, the row-crop system received 1,000 kg ha^{-1} of dolomitic limestone applied on the soil surface. In the two crop cycles, soybean sowing occurred in October, with seeding rate to reach 10 plants m^{-1} and 0.45 m of row space. In 2014/2015, 80 kg ha^{-1} of P$_2$O$_5$ and 80 kg ha^{-1} of K$_2$O, and in 2015/2016, 8 kg ha^{-1} of N, 80 kg ha^{-1} of P$_2$O$_5$, and 80 kg ha^{-1} of K$_2$O, all applied in the planted row. After soybean harvest, in February of each year, corn was sown using a seeding rate to have 3 plants m^{-1} and row space of 0.45 m intercropped with Marandu grass. Fertilization in the corn row consisted of 36 kg ha^{-1} of N, 90 kg ha^{-1} of P$_2$O$_5$, and 48 kg ha^{-1} of K$_2$O in 2014/2015, and 42 kg ha^{-1} of N, 105 kg ha^{-1} of P$_2$O$_5$, and 56 kg ha^{-1} of K$_2$O in 2015/2016. The corn intercropped with Marandu grass received fertilization of 135 kg ha^{-1} of N and 67 kg ha^{-1} of N on the soil surface in the 2014/2015 and 2015/2016 cycles, respectively, between the plant growth stages 4 and 6 (V4-V6). Corn harvest occurred in June of each cycle; however, Marandu grass remained in the area without grazing to provide soil cover for the next rotation cycle. The whole fertilizations were based on soil fertility status and crop requirements.

The livestock pasture was established in November 2011 using Marandu grass. In September 2015, the pasture received 1,500 kg ha^{-1} of dolomitic limestone applied on the soil surface. In November 2015, 200 kg ha^{-1} of simple superphosphate, 50 kg ha^{-1} of N, and 50 kg ha^{-1} of K$_2$O were applied on pasture. In March 2016, 40 kg ha^{-1} of N and 40 kg ha^{-1} of K$_2$O also were applied on soil surface cover. The pasture was grazed with beef cattle (*Bos taurus indicus*) from July 2015 using the continuous grazing with a variable stocking rate according to the availability of forage to maintain a canopy height of 0.30 m.

The integrated system, CLF, received the same soil management described to the monocultures. After the corn harvesting, what took place in July of both assessed cycle, CLF system was maintained under cattle grazing for two months (August and September), using the same pasture management, including fertilization, as described to livestock. Hence, we highlight that CLF had two months more soil use than row-crop, which was not grazed. More details of the assessed systems can be found in Magalhães et al. (2019).

The forest fragment is composed of native species classified as Seasonal Semideciduous Forest (Borges et al., 2014). This native forest fragment is located at the same landscape position of the treatments, approximately 1 km far away from the treatments. Considered as a reference state of the original ecosystem of the region, in the fragment there are indications of selective logging and fire occurrence.

Soil N₂O fluxes

Soil N_2O fluxes were evaluated using rectangular static chambers. The base was made of metal and the top of polyethylene. The chamber size was 0.60 × 0.40 × 0.09 m in length, width, and height, respectively. In the center of the top of the chamber a three-way faucet was connected for gas sampling in a 20-cm^3 syringe and a tube for internal ventilation was installed on the side of the chamber (Parkin and Venterea, 2010). Gas samples were collected weekly in the morning between 8 and 11 am, with four samples collected during 60 min at 20 min intervals, thus obtaining samples at 0, 20, 40, and 60 min (Parkin and Venterea, 2010). At the time of gas collection, the internal temperature of the chamber was also measured using a digital thermometer. Following Parkin and Venterea (2010) and Rochette et al. (2015), for each plot, two chambers were installed with the base driven 8 cm into the ground and the chamber top deployed in each event of gas samplings.

Samples in syringes were transferred to 20-cm^3 vials, after being sealed with gray butyl septa and subjected to vacuum, and were used to determine N_2O concentrations in a gas chromatograph, equipped with an automatic injector and electron capture detector (ECD). The chromatograph system consisted of Hayesep 80/100 mesh (1/8" × 2.1 mm) serial columns, T, D, and N of 1, 2, and 1.5 m in length, respectively, maintained at 75 °C during the whole analysis. Ultrapure N was used as carrier gas at a flow of 25 mL min^{-1} and the injector pressure was maintained at 300 kPa. The injection volume was 1 mL and the total analysis time was 5 min. The analytical curve was obtained by determining three known concentrations of N_2O standards (383, 808, and 2,027 nmol mol^{-1}).

From the analytical results, a linear equation was determined from the relationship between N_2O concentrations over the chamber measurement (0, 20, 40, and 60 min). Equation parameters were used to calculate N_2O fluxes from the soil to the atmosphere following the equation proposed by Hutchinson and Livingston (1993): Flux (µg N_2O-N m^{-2} h^{-1}) = (dC/dt) × V/A × (m/Vm); in which: dC/dt = change in gas concentrations within the chamber based on time; V = chamber volume (L); A = chamber area (m^2); m = molecular weight of the gas (g mol^{-1}); Vm = molar volume of the gas (m^3 mol^{-1}) corrected for the air temperature (K) of the headspace chamber.

The fluxes obtained were considered as representative of the average daily fluxes (Rochette et al., 2015). So, the flux results were used to estimate cumulative emissions of the gas during the evaluation period, which were calculated using the trapezoid-integration method (Rochette et al., 2015) between weekly measurements. Cumulative emissions were calculated for the dry season of the region (May to September), and for the wet season (October to April), for each cycle (2014/2015 and 2015/2016) and the average of the whole period (2014/2016).

To characterize the main climatic variables, average daily air and soil temperatures and the pluvial precipitation (Figure 1a) were obtained from an automatic station located approximately 1 km from the treatments and native forest fragment. Water-filled soil pore space (WFPS) was calculated according to Van der Weerden et al. (2012) for soil samples collected monthly during the whole experimental period at a depth of 0.00-0.10 m (Figure 1b).
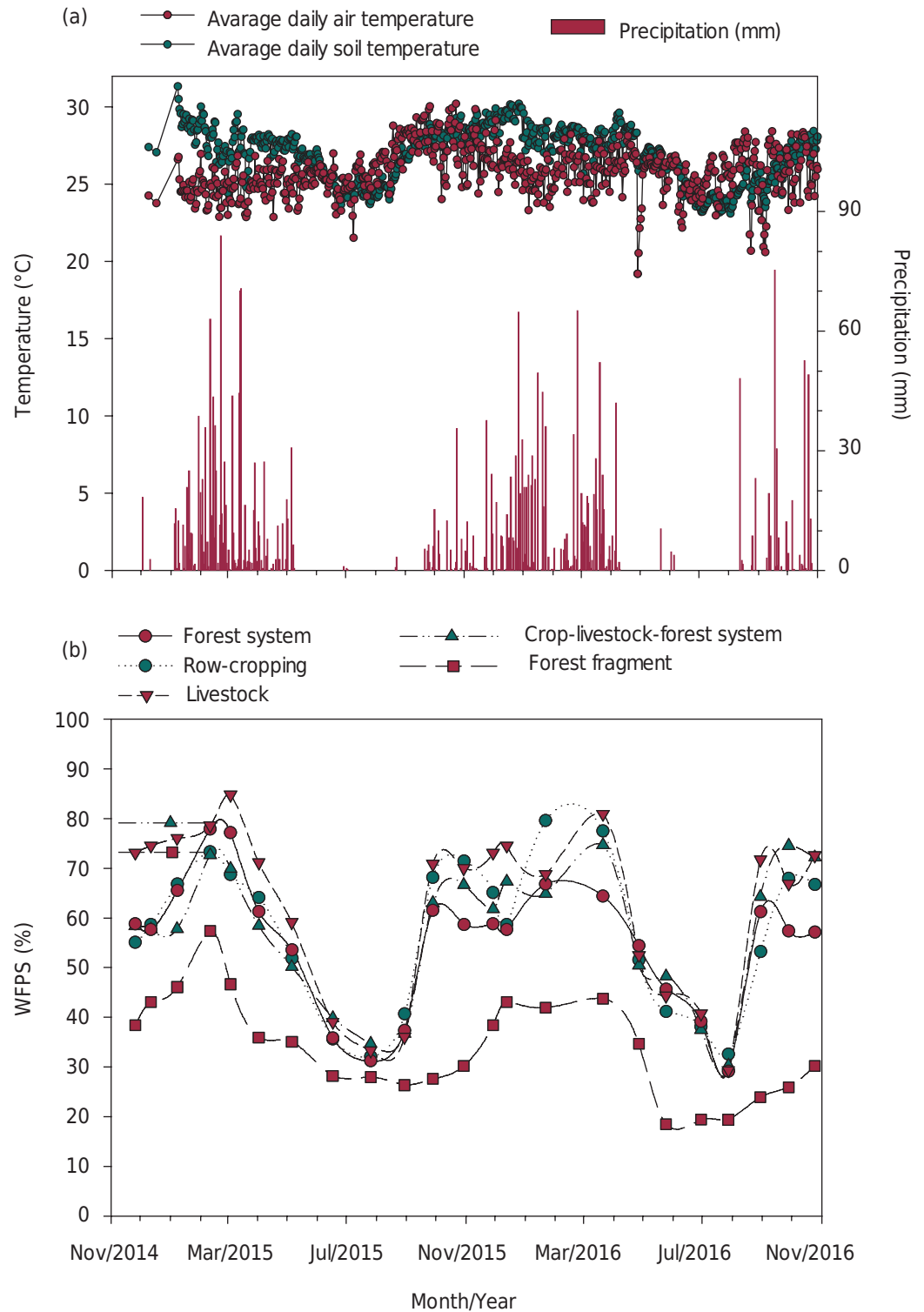
Figure 1. Average daily air and soil temperature and pluvial precipitation (a) and water-filled soil pore space (WFPS) (b) from November 2014 to October 2016.

Statistical analysis

The cumulative N$_2$O emissions were subjected to variance analysis and, if significant, the Tukey's range test at 5 % of probability was applied. The daily data obtained from weekly samplings over the two years of evaluation of emissions of N$_2$O did not follow a normal distribution, even after data transformation, what led to use the standard error (SE) of the mean to compare daily fluxes from the treatments (Alfaro et al., 2015).

RESULTS

The largest N_2O flux peaks from the Oxisol during the two annual cycles were observed in the wet seasons, mainly in the row-crop, livestock, and CLF systems, which received fertilization during these periods (Figure 2). In the dry seasons, mainly from July to September, WFPS was low due to low or nonexistent rainfall (Figures 1a and 1b) and, the soil N_2O fluxes were low for all agricultural systems, with values close to zero.

Row-crop and CLF system fluxes were similar during wet seasons. After soybean and corn sowing and after fertilization applied on the soil surface in corn crop, the largest N_2O flux peaks (Figures 2b and 2c) were observed in the row-crop and CLF system. It should also be highlighted that in the two cycles at the end of the single soybean crop cycles and in the CLF system, N_2O flux peaks of up to 100 µg N_2O-N m^{-2} h^{-1} were measured.

Because the livestock system did not receive surface-applied N fertilization and had undergone grazing only three months in the 2014/2015 cycle, N_2O fluxes were low throughout the whole evaluated period, with results similar to the forest system and forest fragment (Figure 2b). However, in the 2015/2016 cycle, when two N fertilization was performed and the grass was grazed during the whole cycle, the largest N_2O flux peaks occurred, with a flux up to 350 µg N_2O-N m^{-2} h^{-1}, the largest flux measured in both cropping cycles (Figure 2b). At times after N fertilization, soil N_2O fluxes from the livestock system were similar to those observed in forest system and native forest fragment, with fluxes predominantly below 50 µg N_2O-N m^{-2} h^{-1}. The average values were below 10 µg N_2O-N m^{-2} h^{-1}.

Taking into account the two cycles, row-crop, livestock, and CLF systems had similar average fluxes (Figure 2a), with values of 16.9 (SE=3.0), 12.2 (SE=2.5), and 15.4 (SE=2.4) µg N_2O-N m^{-2} h^{-1}, respectively. These agricultural systems presented higher fluxes than forest system and native forest fragment (Figures 2b, 2c, and 2d) that presented average fluxes of 4.0 (SE=1.3) and 6.3 (SE=2.4) µg N_2O-N m^{-2} h^{-1}, respectively.

The largest cumulative N_2O emissions, an average of the two cycles (2014/2016), occurred from the row-crop, livestock, and CLF systems, with values of 1.40, 1.15, and 1.27 kg N_2O-N ha^{-1}, respectively. In contrast, the lowest N_2O emissions occurred in the forest fragment and forest system, with values of 0.33 and 0.52 kg N_2O-N ha^{-1}, respectively (Figure 3c). The average of emissions during the dry seasons (2014/2016 cycle) showed that the CLF and row-crop systems had the greatest N_2O emissions during this evaluation period. During the wet season across the two rotation cycles, the row-crop, livestock, and CLF systems had similar N_2O emissions but were three or four times greater than the forest system. At the end of the two rotation cycles (2014/2016 cycle), the average of cumulative N_2O emissions was greatest from soil used with row-crop, livestock, and CLF systems, which did not differ from each other, and were lowest emissions from forest system and forest fragment. The differences of N_2O emissions from agricultural systems and forest systems were of two or four times greater. Cumulative emissions from the livestock system in the 2015/2016 cycle were more than twice the emissions during the cycle before, 2014/2015, with values 1.54 and of 0.77 kg N_2O-N ha^{-1}, respectively (Figures 3a and 3b). In the average of both cycles, the cumulative emission of N_2O in the livestock was similar to row-crop and CLF systems. The forest fragment emitted the same amount of N_2O as the livestock in dry periods, including the average of dry periods of 2014/2015 and 2015/2016 cycles, and also during the wet season of the 2014/2015 cycle, a period when the livestock did not receive N fertilizer.

The great N_2O emissions during the dry season of the 2015/2016 cycle came from the forest fragment, row-crop, and CLF systems, with values of 0.22, 0.19, and 0.24 kg N_2O-N ha^{-1}, which did not differ from each other (Figure 3b). Row-crop and CLF systems had similar cumulative emissions throughout the cycles, during both seasons, including the average of both cycles, with the highest values of cumulative emissions (Figure 3c). Row-crop
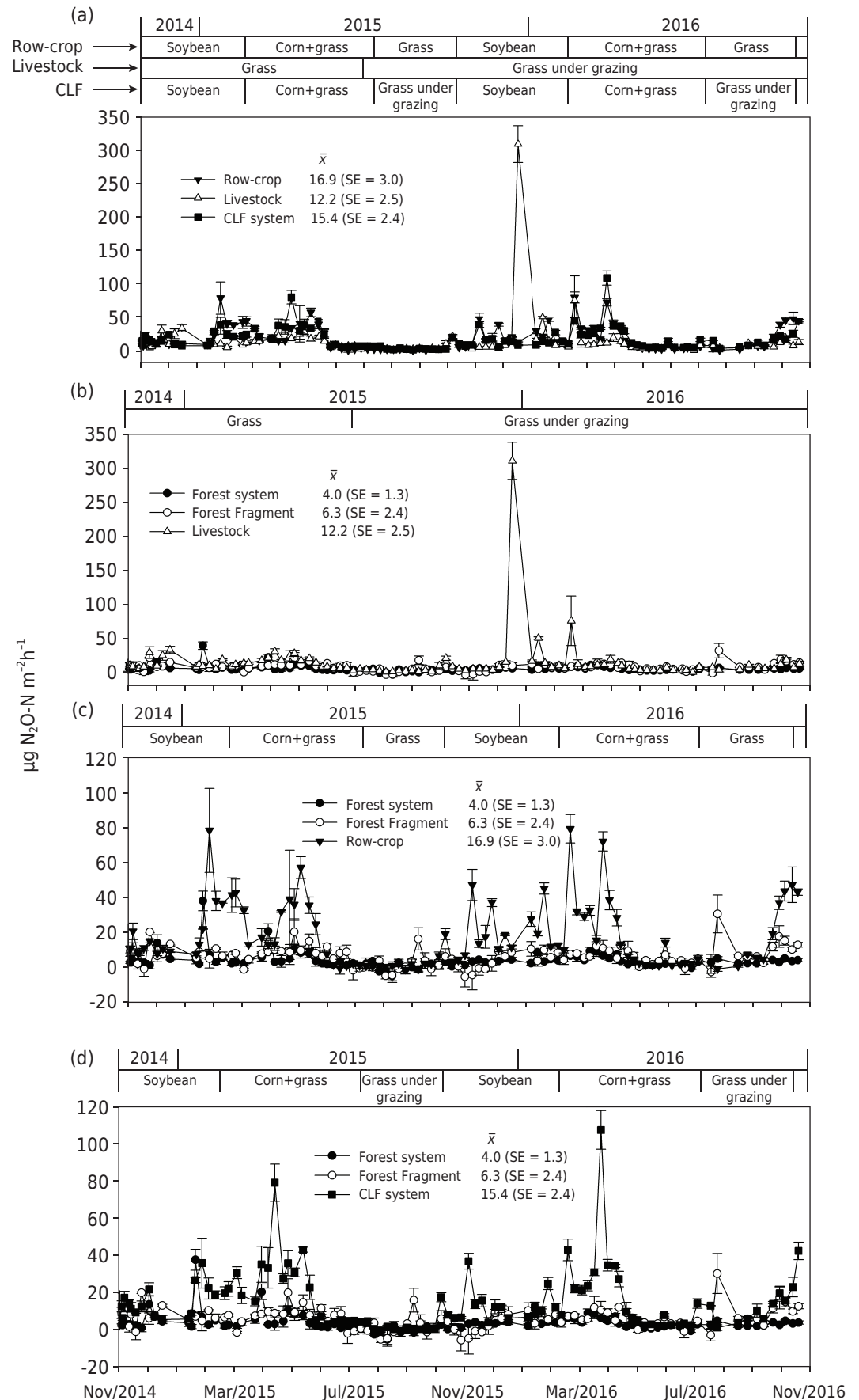
Figure 2. Nitrous oxide (µg N$_2$O-N m^{-2} h^{-1}) flux dynamics from row-cropping, livestock, CLF systems, and comparisons with the cultivation of eucalyptus and forest fragment during the two cycles (from November 2014 to October 2016). Above each subfigure are shown the temporal soil use for all systems: livestock (b), row-crop (c), and CLF (d). Vertical bars refer to standard error (SE) of the average (n = 3). The black arrows pointing down indicate the application of nitrogen fertilizer in the system.
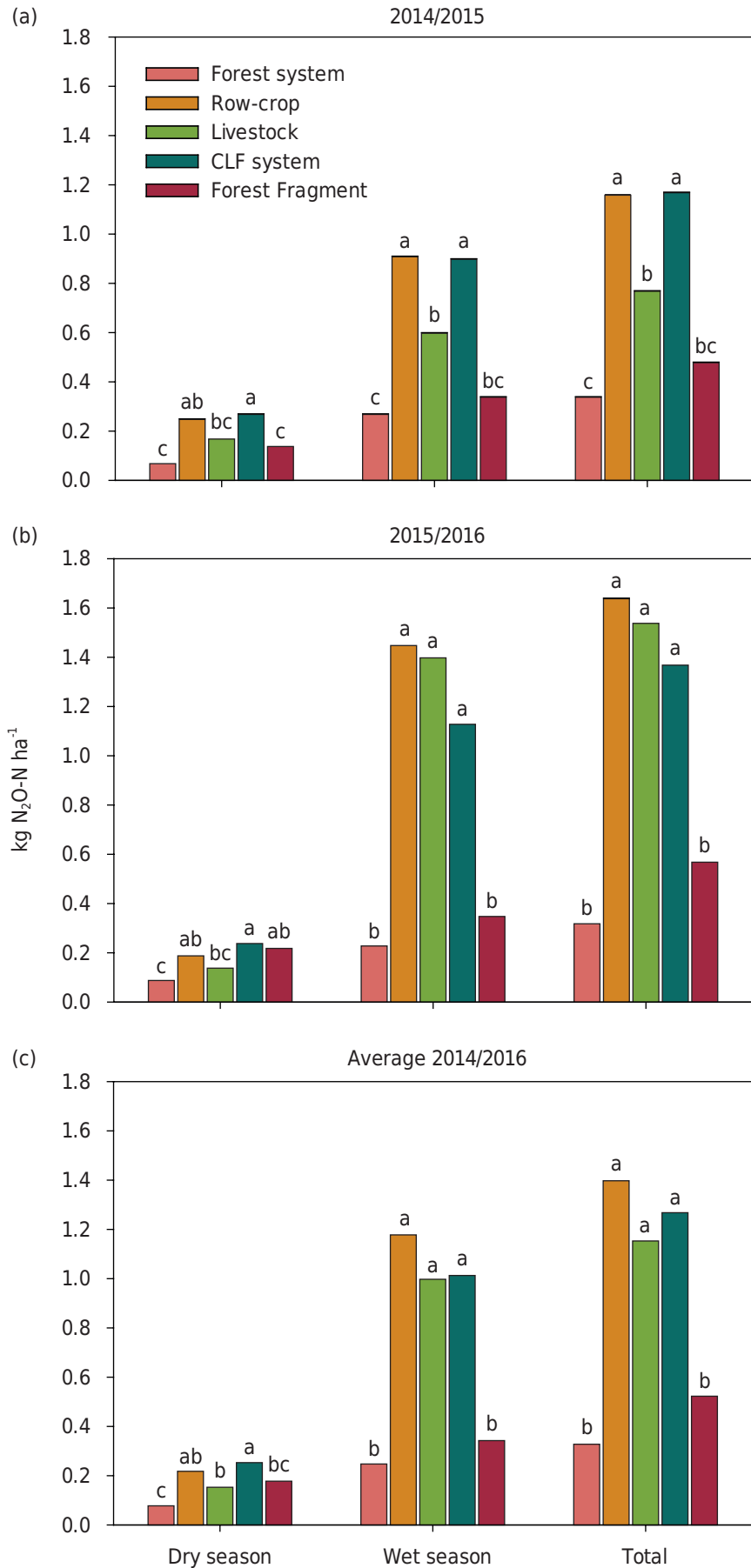
Figure 3. Cumulative emissions from soil under forest, agricultural systems, and a forest fragment in dry and wet seasons during 2014/2015 and 2015/2016 cycles, and the average both cycles - 2014/2016. Averages followed by the same letters in the column of each cycle do not differ by Tukey's test at 5 % probability.

emitted 1.16 kg N_2O-N ha^{-1} during 2014/2015 and 1.64 kg N_2O-N ha^{-1} in 2015/2016 cycle. In the first cycle, around 78 % came from the wet season and, in the second cycle, 88 % came from the season with more precipitation. Cumulative emissions in 2014/2015 and 2015/2016 were 1.17 and 1.37 kg N_2O-N ha^{-1}, respectively, from the soil cultivated with CLF system. Such as in the row-crop, in the CLF system, the wet season was responsible for 77 and 82 % of the emission in the first and second cycles, respectively.

DISCUSSION

Cumulative soil N_2O emissions measured in this study for row-crop, with an average value of 1.40 kg N_2O-N ha^{-1}, support the results observed by Nogueira et al. (2016) and are higher than the average of 0.80 kg N_2O-N ha^{-1} reported by Meurer et al. (2016) to cropland soils in Brazil. All the agricultural systems assessed for the present study showed accumulated emission below those related to croplands in Canada, Europe, and in the United States, with values of 2.27, 2.47, and 3.37 kg N_2O-N ha^{-1}, respectively (Roelandt et al., 2005). Likewise, our results are also below 2.42 and 4.26 kg N_2O-N ha^{-1} measured in conventional tillage and integrated cropping systems, respectively, to subtropical conditions of Brazil (Piva et al., 2012, 2014).

Meurer et al. (2016) reported about 17 studies that measured soil N_2O emissions in the Amazon biome, all in agricultural or natural systems with soil management unlike those assessed for the present work. Nogueira et al. (2016) assessed the same treatments on similar soil management in 2013/2014 and reported emissions of about 0.3 and 0.4 kg N_2O-N ha^{-1} from the livestock and CLF systems, lower than those measured by the present study. The emissions contrast between Nogueira et al. (2016) and the data presented here may be related to the greater N supply in the systems in the 2014/2016 cycle compared to the 2013/2014 cycle, once in 2014/2016 were applied more N on soil surface and the livestock and CLF systems were grazed more time in 2015, receiving cattle excretions, which can have increased the N availability, leading consequently to a higher N_2O emission (Piva et al., 2014). Aside from the addition of animal wastes, animal trampling can increased the bulk density and the micropore:macropore ratio, what changed the aeration in the topsoil (Pietola et al., 2005), which favors, in high moisture, denitrification, indicated as the main soil process of N_2O production (Butterbach-Bahl et al., 2013).

The greater fluxes and, consequently, greater cumulative emissions in the wet season of the cycles may be related to the greater activity of microorganisms responsible for nitrification and, mainly, denitrification processes, enhanced when WFPS is more than 70 % (Van der Weerden, 2012; Butterbach-Bahl et al., 2013; Corrêa et al., 2016). When WFPS was below 50 %, which in the evaluated soils was predominant from May/June to September/October, N_2O fluxes were low or negative, further highlighting the role of soil moisture related to N_2O emissions. Once the soils under native forest in the Amazon have high values of macroporosity (Zenero et al., 2016), what allows a free drainage that triggered WFPS majority below 50 % throughout the assessment time (Figure 1b). Even so, in the soil under native forest fragment was observed higher N_2O fluxes than from forest system, which may be a result of the heterotrophic nitrification since forest fragment has features to trigger the process (Zhang et al., 2015).

In addition to soil moisture, the assessments of the two rotation cycles in the systems showed that N fertilization applied to the soil surface or in the row also represented an important source of N_2O emission from soil within two weeks after the application, corroborating results reported in others edaphoclimatic conditions (Baggs et al., 2003; Zanatta et al., 2010; Piva et al., 2014). Fertilization increases the availability of inorganic N in soil (NO_3^- and NH_4^+), favoring nitrification and denitrification processes (Butterbach-Bahl et al., 2013). Beyond N fertilization, at the end of the soybean cycle seems to be an important period of increases of N availability in the soils, as shown here, corroborating Yang and Cai (2005) and Nogueira et al. (2016), which observed peaks of N_2O fluxes in the

same plant stage. In this period, the senescent leaves of soybean fall on soil surface, and roots and nodules cease their activities (Yang and Cai, 2005), increasing the amount of organic matter content of low C:N ratio and allowing that sunlight heats the soil surface, once the soybean plants decrease the sunlight interception due to the leaves losses. Hence, the peaks of N$_2$O fluxes at the end of the soybean cycle may have been triggered by the priming effects, once input of soybean organic matter added the soil temperature, can have altered the activity and amount of soil microbial biomass (Kuzyakov et al., 2000), and increased the N mineralization related to the decomposition of plant residues, roots, and nodules of the soybean (Yang and Cai, 2005; Nogueira et al., 2016).

Hence, greater emissions in the row-crop, livestock, and CLF systems during the wet season are supported by the hole-in-the-pipe model proposed by Firestone and Davidson (1989), which established that in the first level of emissions control ("pipe") is the N availability, provided by fertilizations in the systems, and in the second level ("hole") is, mainly, the soil moisture, which was higher in the wet season (Figure 1b). The evidence for this statement is because even with high WFPS, there were no N$_2$O fluxes unless after N fertilization or after the input of soybean organic matter at the end of the plant cycle (Figure 2). For instance, forest system (eucalyptus), even with WFPS similar to row-crop, livestock, and CLF had no peaks of N$_2$O fluxes, such as those systems that received input of N fertilization.

Even though CLF system has been conducted with a more intensive soil use and management, from which greater emissions would be expected (Crosson et al., 2011; Cardoso et al., 2016), CLF emitted the same amount as row-crop and livestock systems for the two rotation cycles, and less than agricultural soil of other countries (Roelandt et al., 2005). In addition, the CLF system had the potential of increasing the soil carbon content by 8 % in three years after its establishment, while it was 4 % in livestock and negative in the row-crop system (Conceição et al., 2017). Magalhães et al. (2019) observed that the same CLF system has a potential of producing around 8 m^3 ha^{-1} yr^{-1} of eucalyptus wood, which could remove about 2 Mg ha^{-1} yr^{-1} of C, taking into account that eucalyptus has wood density of 500 kg m^{-3} (Gonçalez et al., 2014) and C content of 500 kg per Mg of wood (Razakamanarivo et al., 2011). Thus, besides CLF to have similar soil N$_2$O emissions compared to other agricultural systems, it has a great potential to C sequestration, removing C from the atmosphere and storing it in the soil and the biomass.

However, since it is a more intensive system in the use and soil management, CLF system potentially has more productivity, on average, than monoculture systems (Balbino et al., 2012). More food or energy productivity contributes to avoiding the opening of new areas and aid to reduce the emission intensity, decreasing the emission:product ratio, which is also a mitigation pathway (Smith et al., 2007). Considering the complexity of CLF systems, it is necessary to continue evaluations to quantify the emissions throughout the whole cycle of the CLF system for edaphoclimatic conditions of the Amazon, to confirm the mitigation potential provided by the integrated system.

The results presented here are singular because there were no works that measured and addressed soil N$_2$O emissions from Amazon biome throughout two years, neither measuring similar agricultural systems (Meurer et al., 2016). The data become even more important because the geographical region is considered of agricultural expansion, where sustainable alternatives have to be identified to improve greenhouse gas mitigation and to show that Brazilian agriculture has alternatives to combine yield and environmental responsibility, fulfilling international agreements signed on climate change.

CONCLUSIONS

Row-crop, livestock, and CLF systems managed on Oxisol of the Southern Amazon emitted more N$_2$O than forest system and forest fragment.

Nitrogen fertilization and soil water content influenced soil N_2O emissions of all systems assessed in the Southern Amazon. The N_2O emissions just took place after both factors were met, corroborating the hole-in-the-pipe model.

Soil use and management intensification in CLF system did not lead to more N_2O emission than row-crop and livestock, in which the soil use is less intensive.

To confirm the mitigation potential provided by the integrated system and considering its complexity, it is imperative to quantify the N_2O emissions throughout the whole cycle of the CLF system.

ACKNOWLEDGMENTS

AUTHOR CONTRIBUTION

Conceptualization: iD Alexandre Ferreira do Nascimento (lead) and iD Renato de Aragão Ribeiro Rodrigues (lead).

Investigation: iD Alexandre Ferreira do Nascimento (lead), iD Renato de Aragão Ribeiro Rodrigues (lead), iD Julia Graziela da Silveira (equal), iD Jacqueline Jesus Nogueira da Silva (equal), iD Vagner de Carvalho Daniel (equal), and iD Eduardo Reckers Segatto (equal).

Formal analysis: iD Alexandre Ferreira do Nascimento (lead), iD Renato de Aragão Ribeiro Rodrigues (lead), iD Vagner de Carvalho Daniel (supporting), and iD Eduardo Reckers Segatto (supporting).

Whitting – original draft: iD Alexandre Ferreira do Nascimento (lead) and iD Renato de Aragão Ribeiro Rodrigues (lead).

Whitting – review & editing: iD Julia Graziela da Silveira (supporting), iD Jacqueline Jesus Nogueira da Silva (supporting), iD Vagner de Carvalho Daniel (supporting), and iD Eduardo Reckers Segatto (supporting).

Software: iD Alexandre Ferreira do Nascimento (lead).

Supervision: iD Alexandre Ferreira do Nascimento (lead) and iD Renato de Aragão Ribeiro Rodrigues (lead).

REFERENCES

Alfaro MA, Giltrap D, Topp CFE, Klein CAM. How to report your experimental data. In: Klein CAM, Harvey MJ, editors. Nitrous oxide chamber methodology guidelines - Version 1.1 New Zealand: Global Research Alliance; 2015. p. 122-30.

Alvares CA, Stape JL, Sentelhas PC, De Moraes Gonçalves JL, Sparovek G. Köppen's climate classification map for Brazil. Meteorol Z. 2013;22:711-28. https://doi.org/10.1127/0941-2948/2013/0507

Baggs EM, Stevenson M, Pihlatie M, Regar A, Cook H, Cadisch G. Nitrous oxide emissions following application of residues and fertilizer under zero and conventional tillage. Plant Soil. 2003;254:361-70. https://doi.org/10.1023/A:1025593121839

Balbino LC, Cordeiro LAM, Oliveira P, Kluthcouski J, Galerani PR, Vilela L. Agricultura sustentável por meio da integração Lavoura-Pecuária-Floresta (ILPF). Piracicaba: IPNI; 2012. (Informações agronômicas, 138).

Borges HBN, Silveira EA, Vendramin LN. Flora arbórea de Mato Grosso: tipologias vegetais e suas espécies. Cuiabá: Entrelinhas; 2014 [cited 2019 November]. Available from: https://www.inputbrasil.org/wp-content/uploads/2017/11/Flora_Arborea_de_Mato_Grosso.pdf.

Brasil. Third national communication of Brazil to the United Nations framework convention on climate change. Brasília, DF: Ministry of Science, Technology and Innovation; 2016 [cited 2018 July]. Available from: https://unfccc.int/resource/docs/natc/branc3es.pdf.

Butterbach-Bahl K, Baggs EM, Dannenmann M, Kiese R, Zechmeister-Boltenstern S. Nitrous oxide emissions from soils: how well do we understand the processes and their controls? Philos T R Soc B. 2013;368:20130122. https://doi.org/10.1098/rstb.2013.0122

Cardinael R, Chevallier T, Cambou A, Béral C, Barthès BG, Dupraz C, Durand C, Kouakoua E, Chenu C. Increased soil organic carbon stocks under agroforestry: a survey of six different sites in France. Agr Ecosyst Environ. 2017;236:243-55. https://doi.org/10.1016/j.agee.2016.12.011

Cardoso AS, Berndt A, Leytem A, Alves BJR, Carvalho INO, Soares LHB, Boddey RM. Impact of the intensification of beef production in Brazil on greenhouse gas emissions and land use. Agr Syst. 2016;143:86-96. https://doi.org/10.1016/j.agsy.2015.12.007

Ceccon G. Consórcio milho-braquiária. Brasília, DF: Embrapa; 2013 [cited 2019 November]. Available from: https://ainfo.cnptia.embrapa.br/digital/bitstream/item/106254/1/LV-CONSORCIOMB.pdf.

Cerri CEP, Sparovek G, Bernoux M, Easterling WE, Melillo JM, Cerri CC. Tropical agriculture and global warming: Impacts and mitigation options. Sci Agri. 2007;64:83-99. https://doi.org/10.1590/S0103-90162007000100013

Conceição MCG, Matos ES, Bidone ED, Rodrigues RAR, Cordeiro RC. Changes in soil carbon stocks under integrated crop-livestock-forest system in the Brazilian Amazon region. Agr Sci. 2017;8:904-13. https://doi.org/10.4236/as.2017.89066

Corrêa RS, Madari BE, Carvalho GD, Costa AR, Pereira ACC, Medeiros JC. Fluxos de óxido nitroso e suas relações com atributos físicos e químicos do solo. Pesq Agropec Bras. 2016;51:1148-55. https://doi.org/10.1590/s0100-204x2016000900014

Crosson P, Shallo L, O`Brien D, Lanigan GJ, Foley PA, Boland TM, Kenny DA. A review of the whole farm systems models of greenhouse gas emissions from beef and dairy cattle production systems. Anim Feed Sci Tech. 2011;166-167:29-45. https://doi.org/10.1016/j.anifeedsci.2011.04.001

Firestone MK, Davidson EA. Microbial basis of NO and N_2O production and consumption in soils. In: Andrae MO, Schimel DS, editors. Exchange of trace gases between terrestrial ecosystems and the atmosphere. New York: John Wiley; 1989. p. 7-21.

Gonçalez JC, Santos GL, Silva Junior FG, Martins IS, Costa JA. Relações entre dimensões de fibras e de densidade da madeira ao longo do tronco de Eucalyptus urograndis. Sci For. 2014;42:81-9.

Hutchinson GL, Livingston GP. Use of chamber systems to measure trace gas fluxes. In: Harper LA, editor. Agricultural ecosystem effects on trace gases and global climate change. Madison: ASA, CSSA, SSSA; 1993. p. 63-78.

Intergovernmental Panel on Climate Change - IPCC. Climate Change 2013: the physical science basis - Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change. New York: Cambridge University Press; 2013.

Kuzyakov Y, Friedel J, Stahr K. Review of mechanisms and quantification of priming effects. Soil Biol Biochem. 2000;32:1485-98. https://doi.org/10.1016/s0038-0717(00)00084-5

Magalhães CAS, Pedreira BC, Tonini H, Farias Neto AL. Crop, livestock and forestry performance assessment under different production systems in the north of Mato Grosso, Brazil. Agroforest Syst. 2019;93:2085. https://doi.org/10.1007/s10457-018-0311-x

Meurer KHE, Franko U, Stange CF, Rosa JD, Madari BE, Jungkunst HF. Direct nitrous oxide (N_2O) fluxes from soils under different land use in Brazil - a critical review. Environ Res Lett. 2016;11:023001. https://doi.org/10.1088/1748-9326/11/2/023001

Nogueira AKS, Rodrigues RAR, Silva JJN, Botin AA, Silveira JG, Mombach MA, Armacolo NM, Romeiro SO. Fluxos de óxido nitroso em sistema de integração lavoura-pecuária-floresta. Pesq Agropec Bras. 2016;51:1156-62. https://doi.org/10.1590/s0100-204x2016000900015

Parkin TB, Venterea RT. Chamber-based trace gas flux measurements. In: Follet RF, editor. Sampling protocols. Washington: USDA-ARS; 2010. p. 3.1-3.39.

Pietola L, Horn R, Yli-Halla M. Effects of trampling by cattle on the hydraulic and mechanical properties of soil. Soil Till Res. 2005;82:99-108. https://doi.org/10.1016/j.still.2004.08.004

Piva JT, Dieckow J, Bayer C, Zanatta JA, Moraes A, Pauletti V, Pergher M. No-till reduces global warming potential in a subtropical Ferralsol. Plant Soil. 2012;361:359-73. https://doi.org/10.1007/s11104-012-1244-1

Piva JT, Dieckow J, Bayer C, Zanatta JA, Moraes A, Tomazi M, Pauletti V, Barth G, Piccolo MC. Soil gaseous N₂O and CH₄ emissions and carbon pool due to integrated crop-livestock in a subtropical Ferralsol. Agr Ecosyst Environ. 2014;190:87-93. https://doi.org/10.1016/j.agee.2013.09.008

Razakamanarivo RH, Grinand C, Razafindrakoto MA, Bernoux M, Albrecht A. Mapping organic carbon stocks in eucalyptus plantations of the central highlands of Madagascar: a multiple regression approach. Geoderma. 2011;162:335-46. https://doi.org/10.1016/j.geoderma.2011.03.006

Rochette P, Chadwick DR, Klein CAM, Cameron K. Deployment protocol. In: Klein CAM, Harvey MJ, editors. Nitrous oxide chamber methodology guidelines. New Zealand: Global Research Alliance; 2015. p. 34-55.

Roelandt C, van Wesemael B, Rounsevell M. Estimating annual N₂O emissions from agricultural soils in temperate climates. Glob Change Biol. 2005;11:1701-11. https://doi.org/10.1111/j.1365-2486.2005.01025.x

Salmon SR, Lange KM, Lane JR. Structure and abundance of nitrous oxide complexes in Earth's atmosphere. J Phys Chem A. 2016;120:2096-105. https://doi.org/10.1021/acs.jpca.5b11853

Santos HG, Jacomine PKT, Anjos LHC, Oliveira VA, Lumbreras JF, Coelho MR, Almeida JA, Araujo Filho JC, Oliveira JB, Cunha TJF. Sistema brasileiro de classificação de solos. 5. ed rev ampl. Brasília, DF: Embrapa; 2018.

Sanz-Cobena A, Lassaletta L, Aguilera E, del Prado A, Garnier J, Billen G, Iglesias A, Sánchez B, Guardia G, Abalos D, Plaza-Bonilla D, Puigdueta I, Moral R, Galán E, Arriaga H, Merino P, Infante-Amate J, Meijide A, Pardo G, Alvaro-Fuentes J, Gilsanz C, Báez D, Doltra J, González-Ubierna S, Cayuela ML, Menendez S, Diaz-Pines E, Le-Noe J, Quemada M, Estellés F, Calvet S, van Grinsven H, Westhoek H, Sanz MJ, Sánchez-Jimeno B, Vallejo A, Smith P. Strategies for GHG mitigation in Mediterranean agriculture: a review. Agr Ecosyst Environ. 2017;238:5-24. https://doi.org/10.1016/j.agee.2016.09.038

Smith P, Bustamante M, Ahammad H, Clark H, Dong H, Elsiddig EA, Haberl H, Harper R, House J, Jafari M, Masera O, Mbow C, Ravindranath NH, Rice CW, Robledo Abad C, Romanovskaya A, Sperling F, Tubiello F. Agriculture, forestry and other land use (AFOLU). In: Intergovernmental Panel on Climate Change - IPCC. Climate Change 2014: mitigation of climate change - Contribution of working group III to the fifth assessment report of the intergovernmental panel on climate change. New York: Cambridge University Press; 2014.

Smith P, Martino D, Cai Z, Gwary D, Janzen H, Kumar P, Mccarl B, Ogle S, O'Mara F, Rice C, Scholes B, Sirotenko O, Howden M, Mcallister T, Pan G, Romanenkov V, Schneider U, Towprayoon S, Wattenbach M, Smith J. Greenhouse gas mitigation in agriculture. Philos T R Soc B. 2007;363:789-813. https://doi.org/10.1098/rstb.2007.2184

Soil Survey Staff. Keys to soil taxonomy. 12th ed. Washington, DC: USDA-Natural Resources Conservation Service; 2014.

Van der Weerden TJ, Kelliher FM, Klein CAM. Influence of pore size distribution and soil water content on nitrous oxide emissions. Soil Res. 2012;50:125-35. https://doi.org/10.1071/SR11112

Yang L, Cai Z. The effect of growing soybean (Glicine max. L.) on N₂O emission from soil. Soil Biol Biochem. 2005;37:1205-9. https://doi.org/10.1016/j.soilbio.2004.08.027

Zanatta JA, Bayer C, Vieira FCB, Gomes J, Tomazi M. Nitrous oxide and methane fluxes in South Brazilian Gleysol as affected by nitrogen fertilizers. Rev Bras Cienc Solo. 2010;34:1653-65. https://doi.org/10.1590/S0100-06832010000500018

Zenero MDO, Silva LFS, Castilho SCP, Vidal A, Grimaldi M, Cooper M. characterization and classification of soils under forest and pasture in an agroextractivist project in eastern Amazonia. Rev Bras Cienc Solo. 2016;40:e0160165. https://doi.org/10.1590/18069657rbcs20160165

Zhang J, Müller C, Cai Z. Heterotrophic nitrification of organic N and its contribution to nitrous oxide emissions in soils. Soil Biol Biochem. 2015;84:199-209. https://doi.org/10.1016/j.soilbio.2015.02.028