Revista Brasileira de Ciência do Solo

Division - Soil Processes and Properties | Commission – Soil Biology

N_2O emissions from soils under different uses in the Brazilian Cerrado - A review

Thais Rodrigues de Sousa[1], **Maria Lucrecia Gerosa Ramos**[1]*, **Cícero Célio de Figueiredo**[1] **and Arminda Moreira de Carvalho**[2]

[1] Universidade de Brasília, Faculdade de Agronomia e Medicina Veterinária, *Campus* Darcy Ribeiro, Brasília, Distrito Federal, Brasil.

[2] Empresa Brasileira de Pesquisa Agropecuária, Embrapa Cerrados, Planaltina, Distrito Federal, Brasil.

ABSTRACT: The Cerrado (Brazilian savannah) is a biome of great socio-economic and environmental importance to Brazil. The rapid agricultural expansion in the Cerrado biome areas promoted biogeochemical cycles that affect nitrogen and carbon dynamics, leading to increased greenhouse gas (GHG) emissions. In Brazil, nitrous oxide (N_2O) is the main gas in agriculture, and agricultural practices increase emissions into the atmosphere. This review aimed to assess the influence of agriculture on N_2O emissions in the Cerrado region, based on existing data in the literature, and extract patterns of direct N_2O emissions in different agricultural systems in the Cerrado from existing data. A systematic review of data from 36 scientific publications in the Cerrado region with several crop systems revealed that N_2O emissions varied from 0.15 kg ha^{-1} in native cerrado to 4.84 kg ha^{-1} in conventional tillage. Agricultural systems, nitrogen fertilizer application, and crop residues influence N_2O emissions. One of the strategies to mitigate emissions is the sustainable intensification of farming systems. Cumulative N_2O emissions in the Cerrado range from 0.001 to 4.84 kg ha^{-1} in different land-use scenarios. Soil under the conventional tillage system (CT) had the highest emissions, with an overall average of 1.58 kg ha^{-1} of N_2O, compared to no-till system (NT) (0.82 kg ha^{-1}) and native Cerrado 0.15 kg ha^{-1}. Integrated crop-livestock (ICL) systems in the Cerrado had emissions with an overall average of 1.68 kg ha^{-1}, integrated crop-livestock-forest systems (ICLF) had 1.20 ha^{-1}, and eucalyptus plantations had 0.48 kg ha^{-1}.

Keywords: Brazilian savannah, agricultural systems, greenhouse gases, nitrogen dioxide.

*** Corresponding author:**
E-mail: lucreciaunb@gmail.com

Received: August 03, 2021

Approved: September 29, 2021

How to cite: Sousa TR, Ramos MLG, Figueiredo CC, Carvalho AM. N_2O emissions from soils under different uses in the Brazilian Cerrado - A review. Rev Bras Cienc Solo. 2021;45:e0210093.
https://doi.org/10.36783/18069657rbcs20210093

Editors: José Miguel Reichert and Etelvino Henrique Novotny.

INTRODUCTION

On a global scale, the main changes in the Earth's climate are due to global warming and are associated with a greater frequency of extreme weather phenomena (Galaz et al., 2018). Since the Industrial Revolution, there has been a significant increase in the planet's temperature, amplified by agricultural and industrial production, and consequently an increase in greenhouse gases (GHGs) (Ren et al., 2017). The warming of the Earth's surface occurs due to the reception of energy in short and long waves, GHGs absorb in wavelength and, the greater the concentration of these GHGs, the greater the effect of absorption of long-wave energy and emission to the surface, increasing global temperature (NOAA, 2020).

Average temperature of planet Earth is rising, and since the last century, global temperatures have risen more than 1 °C above their pre-industrial levels, affecting weather patterns (Shukla et al., 2019). Furthermore, the acceleration of economic growth has encouraged the exploitation of natural resources, particularly minerals and fossil fuels, in addition to increasing food production. The United Nations (NU) predicts that the world's population will exceed 9 billion by 2050, which poses the challenge of increasing agricultural production sustainably (WWAP, 2015).

Greenhouse effect was first described by the French mathematician Jean-Baptiste Joseph Fourier in 1824; he observed that the atmosphere warms the planet and compared it to the glass shell of a greenhouse, which absorbs solar radiation and retains thermal radiation. This is a natural phenomenon caused by certain greenhouse gases in the atmosphere, which causes infrared radiation to be retained, which is responsible for maintaining heat from the sun and keeping the planet warm (Fourier, 1827). However, the problem is not the greenhouse effect *per se*, but the excessive and rapid increase in GHG emissions, especially in the last 200 years with the acceleration of fossil fuel consumption, waste generation, deforestation and fire. If GHG emissions are not mitigated by 2100, the sea level will likely rise between 0.61 and 1.10 m (Shukla et al., 2019).

Climate change is one of the most relevant issues of recent decades. Despite the natural changes in the climate throughout history, environmental changes are increasingly considered due to human activities. In 2020, the concentration of carbon dioxide (CO_2) in the atmosphere reached 413 ppm (NOAA, 2020), and recent studies show that this concentration will exceed 427 ppm CO_2 by 2025 (De La Vega et al., 2020).

Global concern about climate change associated with anthropic activities and natural events necessitates expanding research in these areas. These changes related to greenhouse gas (GHG) emissions are increasing, as are advanced in research and debates on the topic (Almeida et al., 2015).

The leading cause of global warming is the amplification of the greenhouse effect, which has been enhanced mainly by agricultural and industrial activities (Seeg-Brasil, 2019). The increase in the concentration of greenhouse gases in the atmosphere, which include CO_2, CH_4 (methane) and N_2O (nitrous oxide), promotes climate changes, and these have been the primary gasses contributing to global warming due to the increase in infrared radiation in the atmosphere (Oertel et al., 2016; Ren et al., 2017).

Three GHGs most affected by agriculture are CO_2, CH_4, and N_2O, which are essential for the Earth's radioactive balance (Gardi et al., 2014). Agriculture plays a significant role in the variation of GHG concentrations and contributes 10-14 % of total global emissions, of which 50-60 % come from N_2O and CH_4. These gases (N_2O and CH_4) are directly linked to agricultural soils and their inputs (Shakoor et al., 2020). Nitrogen dioxide is one of the most critical greenhouse gasses and has a lower concentration in the atmosphere, as it has 265 times greater heating power than CO_2 (IPCC, 2014). Moreover, it remains in the atmosphere for more than 130 years (Myhre et al., 2013; Beuchle et al., 2015).

The main share of GHG emissions in Brazil is related to CO_2 due to the change in land use caused by the exploitation of agricultural activities, which will significantly increase the concentration of this gas by 2100 (Goldman et al., 2017). Among GHGs, N_2O is the most important for agricultural systems since 70 % of their global emissions come from nitrogen dynamics in the soil (Ussiri and Lal, 2013).

One of the most biodiverse savannas globally, the Brazilian Cerrado occupies 2 million km², about 24 % of the national territory, and is a biome of great importance for food production, agro-energy and its biodiversity (Bonanomi et al., 2019). In Brazil, 85.4 % of total N_2O emissions come from agriculture (Seeg-Brasil, 2020), of which 17 % are due to fertilizer use and crop residue management (Seeg-Brasil, 2019). In 2019, approximately 598.7 million tons of CO_2-eq were emitted from land-use change and cattle grazing, accounting for more than half of all GHG emissions (Seeg-Brasil, 2020).

Among the different factors affecting N_2O emissions in agricultural soils, the conversion of native Cerrado vegetation to agroecosystems favors the emission of N_2O to the atmosphere, under sugarcane cropping systems (Silva et al., 2017), integrated cropping-livestock production, no-till and conventional tillage (Martins et al., 2015; Carvalho et al., 2017; Sato et al., 2017). In addition, N_2O emissions are usually associated with soil moisture (Carvalho et al., 2013; Santos et al., 2016) and nitrogen fertilizer application (Carvalho et al., 2016; Silva et al., 2017).

The first studies published in Brazil on N_2O emissions were developed in the Amazon region by Davidson et al. (2001). They presented annual N_2O values ranging from 1.4 to 2.4 kg ha^{-1} yr^{-1}, while in the Cerrado areas, annual average flows were close to zero (0.4 kg ha^{-1} yr^{-1}). These low annual N_2O flows were attributed to the conditions of aeration and drainage of the Cerrado Oxisols, a predominant soil under natural vegetation that favors soil aggregation (Bronick and Lal, 2005). Among the factors favoring higher N_2O fluxes in the Brazilian Cerrado, soil moisture had the highest association with N_2O emissions, followed by mineral N in the soil (NO_3^- and NH_4^+) and sources of mineral nitrogen (Carvalho et al., 2021).

The N_2O emissions in field conditions have been performed systematically since 2001. Published papers in indexed journals generated from these studies changed the average direct emission factor of N_2O from Brazil, published in IPCC reports (Intergovernmental Panel on Climate Change), from 1 % (0.3-3 %) to 0.30 % (0.20-0.47 %). Specifically, concerning mineral fertilizers, organic and N mineralization of crop residues, the methodology for assessing N_2O emissions proposes that 1 % of the amount of N applied is lost in the form of N_2O (IPCC, 2006). This was a result of great relevance for Brazil before the United Nations Conference of the Parties on Climate Change, which until then had its emissions based on data collected in a temperate climate region that overestimated the emission factors calculated for Brazil. These results should subsidize the government in complying with international global climate change agreements, such as at COP26 (UN's 26th Conference of the Parties on Climate Change), to achieve the GHG emission reduction target. They can also contribute to formulating public policies on climate change mitigation and adaptation, where the Low Carbon Agriculture Programme represents a government policy in this area (Norse, 2012). Therefore, it is necessary to obtain more data on N_2O emissions in the Cerrado region and Brazil. One of the limitations for research on N_2O emissions is the need for more investments in infrastructure, training of new research groups in Brazil. In addition, several evaluations are required throughout the crop cycle and agricultural systems. The covariable evaluations for the interpretation of the data, such as soil moisture, doses and sources of nitrogen fertilizer applied, NH_4^+ and NO_3^- in the soil, can lead to high analysis costs. Despite this, it is essential to have more information on N_2O emissions in the different Brazilian biomes and agroecosystems. It is possible to have the whole panorama of emissions of this gas to feed the database generated in the country.

Considering the importance of agricultural expansion in the Cerrado and the adoption of agricultural systems with the potential to mitigate N_2O emissions from soil, the objective of this review was to assess the influence of agriculture on N_2O emissions in the Cerrado region. The review is based on existing data in the literature, and we aim to extract patterns of direct N_2O emissions in different agricultural systems.

MATERIALS AND METHODS

Systematic literature searches were conducted in four databases for articles published between 1988 and April 2021: Web of Science: Main Collection (Clarivate Analytics), ScienceDirect (Elsevier), Scopus (Elsevier), and Brazilian Agricultural Research (PAB) Journal (Scielo). Duplicate references were excluded at the end of the search in each database.

The following criteria were used to select the articles for the literature review: (a) greenhouse gases in agriculture; (b) N_2O fluxes in agricultural systems in the Brazilian Cerrado; (c) agricultural systems and N_2O; (d) climate change in the Brazilian Cerrado. Studies that did not contain this information were excluded. Articles under the global aspect that included information on the following topics were also used: (a) climate change; (b) factors affecting greenhouse gas emissions; and (c) soil organic matter.

When indexing the terms, the search in “title”, “abstracts”, and “keyword” was selected in the Web of Science and PAB databases. In the other databases (Science Direct and Scopus), the fields “title”, “abstracts”, and “keywords” also were adopted. The strategy used aimed to find a more extensive set of papers within the set criteria. Thus, it was possible to select articles written in English and Portuguese.

In the Web of Science database, to find the terms of interest, the following keywords were used in the first search: nitrous oxide AND soil AND organic matter. A total of 1.490 papers were detected. To refine this search and exclude documents that did not address the Brazilian Cerrado, a different set of terms was used: nitrous oxide AND soil AND organic matter AND Cerrado. Here the database returned seven results. When using the keywords: nitrous oxide AND soil AND Cerrado, specifying the titles, the database generated only one result. The arrangement used in the final indexing was: nitrous oxide AND soil AND Cerrado, in all search fields, which identified 27 published articles.

The search performed on Science Direct used the same keywords on Web of Science from 1995 to 2021, where 18.921 results were obtained. This search was refined with the following arrangement of terms: nitrous oxide AND soil AND Cerrado, which yielded 174 results. In review articles and articles, 126 articles were found. Another attempt at the arrangement: nitrous oxide AND soil AND Cerrado AND organic matter, yielded 130 results, but the data was not concentrated in the Brazilian Cerrado. The final index words used were: nitrous oxide AND soil AND Cerrado, search field “titles”, “abstracts” and “keywords”, which generated 26 published articles.

In the Scopus database, the words used in the initial search were: nitrous oxide AND soil AND Cerrado, which generated 789 results. The arrangement used in the final indexing was: nitrous oxide AND soil AND Cerrado, search field: “title”, “abstract” and “keyword”, which generated 23 published articles. In the PAB database, the terms used were: nitrous oxide AND soil AND Cerrado, all fields, which generated seven published articles. From these results, within the context, a selection step was necessary that considered the association of the generated papers, removed the duplicate documents and selected according to the research. After the selection, 36 different published articles were obtained (Figure 1).

Research with soil N_2O assessments in the Brazilian Cerrado intensified after 2006, with further studies from 2011 (Figure 2). The GHG emission factor until 2006 in Brazil was calculated with data from other countries. In 2010, Brazil made a voluntary commitment to reduce its GHG emissions (Brasil, 2012), which allowed for a more significant number of local studies in Brazil.

BRAZILIAN CERRADO

Cerrado is the second largest Brazilian biome, known for its phytophysiognomic diversity and for having a rich flora among the world's savannas (Bustamante et al., 2012), with about 200 million hectares, in the mid-west of Brazil (Silva and Bates, 2002). The conversion of native areas to agriculture exceeds 30 % in most regions and more than

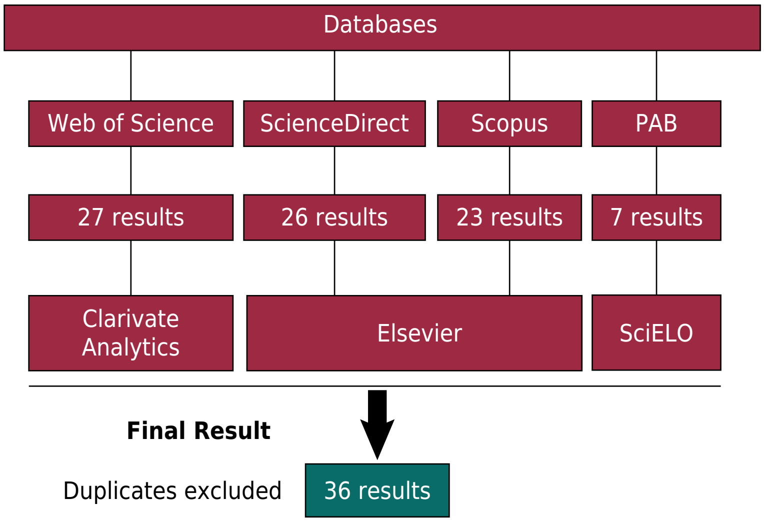

Figure 1. Schematic showing the procedures used to select the articles in the different databases (PAB – *Pesquisa Agropecuária Brasileira*).

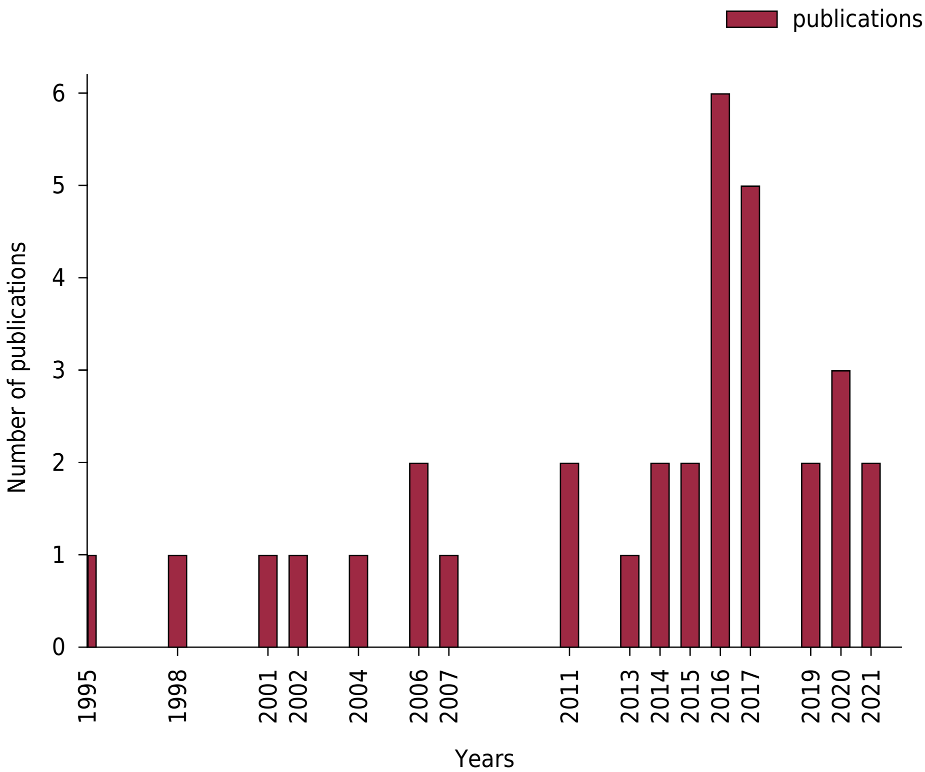

Figure 2. The number of articles published on N_2O emissions in the Brazilian Cerrado.

50 % in three regions, namely Central Highlands (50.2 %), Paraná-Guimarães (61.9 %) and Pará Basalts (71.5 %) (Sano et al., 2019).

Cerrado climate is considered seasonal, with rainfall events from October to March and drought from April to September. Temperatures are usually between 22 and 27 °C, and the average annual precipitation is about 1,500 mm (Silva et al., 2014). Due to intense changes in land use over the years, only 20 % of the Cerrado biome is still preserved without human intervention (Strassburg et al., 2017).

Brazil has become a significant exporter of agricultural commodities in recent decades thanks to the expansion and consolidation of agriculture in the Cerrado (Rada, 2013). It is expected that agriculture will continue to grow in the Cerrado. The change in land use (Soterroni et al., 2019) leads to environmental problems and likely regional climate changes (Beuchle et al., 2015). Besides impacting chemical, physical and biological properties of the soil (Carneiro et al., 2009; Ferreira et al., 2016), altering N_2O fluxes from the soil to the atmosphere.

Rapid agricultural expansion of the Cerrado has caused substantial changes in biogeochemical cycles (Cruvinel et al., 2011), especially in the dynamics of N and P (Bustamante et al., 2012) and increased greenhouse gas (GHG) emissions, mainly of N_2O, contributing to climate change (Strassburg et al., 2014).

Results of research in the Cerrado (Santos et al., 2016; Carvalho et al., 2017; Sato et al., 2017; Figueiredo et al., 2018; Sato et al., 2019) showed reductions in N_2O emissions, with the use of agricultural practices as crop rotation, including rotation between legumes and some grasses, such as *Brachiaria* spp, which promote lower dependence on external sources of N (Hungria et al., 2016).

Dynamics of nitrogen in soil

Most of the N_2O emitted by soil comes from two biological processes: Nitrification and Denitrification. In agricultural soils, denitrification and nitrification are the main microbial processes responsible for the production of N_2O, even if they are not the principal end product of these processes (Signor and Cerri, 2013). Nitrogen (N) in the biosphere is in the form of organic compounds synthesized by plants and microorganisms. For plant uptake, the organic forms of N are converted to ammonium (NH_4^+) and nitrate (NO_3^-) through the processes of ammonification and nitrification (Hirsch and Mauchline, 2015). The N available in the soil depends on the C/N and lignin/N ratio of the residues (Carvalho et al., 2012). A high ratio promotes the immobilization of N in the soil and residues with a low C/N ratio (between 10 and 20), causing the mineralization process.

In the conceptual model that incorporates several soil variables, the emission of N_2O and nitric oxide (NO) is regulated by the amount of fluid flowing through the "tube", which is similar to the oxidation rates of NH_4^+ by nitrifying bacteria and a reduction of NO_3^- by denitrifying bacteria, as well as by the amount of N circulating outside the "tube", such as NO and N_2O and determined by various soil properties (Davidson et al., 2000). The N_2O is formed by nitrification under aerobic conditions and denitrification under anaerobic conditions (Signor and Cerri, 2013). The NO_3^- is formed by the oxidation of NH_4^+ by the action of aerobic bacteria, while ammonification converts NH_4^+ by mineralization of organic matter (Thomson et al., 2012). The main soil and aquatic bacteria that oxidize NH_4^+ to nitrite are *Nitrosomonas* and *Nitrosospira*, while *Nitrobacter* is the primary bacteria genus that oxidizes nitrite to NO_3^- (Mosier et al., 2006).

Denitrification is the microbiological reduction of NO_3^- or nitrite to N-gas carried out by anaerobic and heterotrophic bacteria (Cameron et al., 2013; Signor and Cerri, 2013), with N_2O produced and released to the atmosphere during the processes (Baggs and Philippot, 2010). Pinto et al. (2002) hypothesized that low nitrification rates and low levels of NO_3^- in soil lead to lower fluxes of N_2O and that soils under native vegetation have efficient cycling and little N is lost through leaching and denitrification (Bustamante et al., 2006).

FACTORS INFLUENCING N_2O EMISSIONS IN SOIL

The N_2O emissions to the atmosphere are influenced by several factors, such as: soil moisture (Santos et al., 2016), N availability, pH (Carvalho et al., 2017), application of nitrogen fertilizers (Campanha et al., 2019), in addition to tillage practices that accelerate the oxidation process of organic matter and contribute to the increase in N_2O emissions (Santos et al., 2016).

Among the factors favoring higher N_2O fluxes in the Brazilian Cerrado, soil moisture had the highest association with emissions, followed by mineral N in the soil in the form of NO_3^- and NH_4^+ and sources of mineral nitrogen (Table 1). Of the eighteen studies conducted in the Cerrado, seventeen were related to water-filled pore space (WFPS), twelve to mineral N, two to N sources, and four to soil temperature.

Some soil and climate variables are essential to explain the N_2O flows of the soil and are very important for future modeling exercises. Therefore, there is a protocol for measuring N_2O flows from the soil in air sampling (Zanatta et al., 2014), and other data called covariables are also collected. Some variables are listed below, but the GHG modeling teams must confirm whether they are sufficient and at what frequency these evaluations will be required. The recommended meteorological variables are precipitation and average air temperature, both obtained from meteorological stations. The following analyses are suggested among the soil variables: mineral N (NH_4^+ and NO_3^-), soil humidity and temperature (Zanatta et al., 2014).

Availability of N, humidity and temperature

One of the main sources of N_2O emissions is applying N fertilizer in agricultural systems (Zanatta et al., 2014), and crops with high N demand have the potential to N_2O emissions. The N_2O fluxes are increased after the application of N fertilizers (Carvalho et al., 2017; Santos et al., 2016; Martins et al., 2015), and the combination of fertilizers with irrigation (Silva et al., 2017; Carvalho et al., 2021) is one of the indicators with the most significant influence on N_2O emissions.

Soil moisture is a crucial variable for N_2O emissions. Aerated soils with water-filled pore space (WFPS) between 35 and 60 % promote the formation of N_2O as a by-product of

Table 1. Relation of variables associated with soil N_2O emissions in the Cerrado

Factors associated with N_2O emissions in the soil	Reference
Watter-filled pore space	Metay et al. (2007), Cruvinel et al. (2011), Carvalho et al. (2013), Martins et al. (2015), Carvalho et al. (2016), Correa et al. (2016), Nogueira et al. (2016), Santos et al. (2016), Petter et al. (2016), Carvalho et al. (2017), Sato et al. (2017), Silva et al. (2017), Campanha et al. (2019), Oliveira Filho et al. (2020), Carvalho et al. (2021) and Oliveira et al. (2021).
Mineral N	Cruvinel et al. (2011), Carvalho et al. (2013), Martins et al. (2015), Carvalho et al. (2016), Correa et al. (2016), Santos et al. (2016), Sato et al. (2017), Silva et al. (2017), Figueiredo et al. (2018), Campanha et al. (2019), Oliveira Filho et al. (2020) and Carvalho et al. (2021).
Sources of N	Nogueira et al. (2016) and Oliveira Filho et al. (2020).
Soil temperature	Correa et al. (2016), Nogueira et al. (2016), Santos et al. (2016) and Figueiredo et al. (2018).

nitrification. The WFPS above 60 % favors denitrification reactions with greater emission of this gas, and anaerobiosis favors losses in the form of N_2 or N_2O (Davidson et al., 2000; Jantalia et al., 2007). Soil water content is essential in this process as it controls the transport of oxygen and the escape of gases such as NO, N_2O and N_2 to the atmosphere (Baggs and Philippot, 2010). In addition, the presence of water and fertilizers increases the productivity of the production system, which also leads to a greater potential for N_2O emissions (Liu et al., 2011). However, the adaptation, duration, and quantity of water in these systems can mitigate N_2O emissions (Scheer et al., 2008).

Another important factor is soil temperature. Its increase causes an increase in the metabolic rates of denitrifying bacteria, producing more N_2O up to an optimal soil temperature (Braker et al., 2010). The temperature in conjunction with soil moisture affects N_2O fluxes, and N conversion rates are low at mild temperatures (around 14 °C) and increase with increasing temperature (23-30 °C) (Liu et al., 2011).

Agricultural systems

Adoption of practices that enhance soil conservation is essential for the development of sustainable agriculture. Agricultural systems such as no-till (NT), Integrated Crop-Livestock (ICL), Integrated Crop-Livestock Forestry (ICLF), consortium, crop succession and crop rotation are sustainable alternatives that are increasingly used in the Cerrado region. Studies show their benefits in reducing N_2O (Cruvinel et al., 2011; Carvalho et al., 2016, 2017; Santos et al., 2016).

No-tillage system does not disturb the soil and form straw, promoting land cover and depends on rotation and/or intercropping for straw production (Santos et al., 2014; Carvalho et al., 2016). In the Cerrado, soil losses under this production system are minimal, between 0.01 and 1.15 Mg ha^{-1} yr^{-1} (Anache et al., 2018). As a result, there is an increase in the production capacity of farming systems (Soares et al., 2019). The increase in N_2O emissions in CT can be associated with plowing the soil, as the decomposition of crop residues is accelerated and anaerobic sites are created, causing peaks in N_2O emissions (Ussiri and Lal, 2013). Some studies in Cerrado reported lower N_2O emissions in NT than in CT (Sato et al., 2017, 2019), while others observed higher NT emissions (Liu et al., 2007).

Abdalla et al. (2014) compared reduced cropping in conjunction with cover crops under NT. They concluded that the efficiency of the minimum cropping system in mitigating GHG depends mainly on the carbon sequestration by the cover crop species used in the system, through higher carbon input and increases in carbon dioxide uptake by the cover crop. Furthermore, Silva (2020) observed that during corn crop season cultivated in succession to *Cajanus cajan,* N_2O emissions were higher (0.985 kg ha^{-1}) than with *Crotalaria juncea (*0.772 kg ha^{-1}), indicating that N_2O emissions also depend on plant species.

One strategy to mitigate GHG emissions is the sustainable intensification of agricultural systems. The ICLF is one of the technologies included in Brazil's voluntary commitments to reduce GHG emissions at the 15th Conference of the Parties (COP-15) to the United Nations Framework Convention on Climate Change in Paris (Brasil, 2010). Its use was highlighted as a sustainable agricultural system that avoids deforestation and considers the growing demand for food and energy (Smith, 2015). In addition, these systems optimize the biological cycles of plants and animals and inputs and cultural residues. They offer significant benefits to the land, such as water conservation, wood production and animal welfare (Cordeiro et al., 2015). However, it is necessary to assess the impact of this system on N_2O emissions (Carvalho et al., 2017) as all ICLF components compete for resources, water, light and nutrients (Franchini et al., 2014).

In the Cerrado, ICL is an alternative to reverse pasture degradation and improve soil quality and organic matter content (Vilela et al., 2012), depending on the profile and objectives of each agricultural plot, alternating crop species with livestock and making the system more diversified and complex (Cordeiro et al., 2015). They are efficient systems for recycling nutrients, improving soil quality (Salton et al., 2014) and reducing N_2O emissions (Carvalho et al., 2017; Sato et al., 2017, 2019).

THE CASE OF THE BRAZILIAN CERRADO

Different agricultural systems affect soil N_2O emissions. Obtaining direct standards for N_2O emissions from soils in different agrosystems in the Brazilian Cerrado is necessary for GHG mitigation in this region. Of the 36 studies evaluated in the Cerrado, the average cumulative N_2O emissions from agroecosystems were less than 5 kg ha^{-1} for changes in land use, agricultural system, fertilizer use, and soil properties (Figure 3). In the results obtained, emissions differed mainly with the cropping system, soil preparation, differences in crop rotation, and fertilization strategies (Table 2).

The N_2O emissions ranged from 0.001 to 4.84 kg ha^{-1} in different agricultural systems (Figure 3), with the lowest values in the native Cerrado, which is not a natural source of N_2O (Metay et al., 2007; Cruvinel et al., 2011; Carvalho et al., 2017). These results show that N_2O emissions in agroecosystems are related to different combinations, such as soil tillage, water regime, crop rotation and fertilizer use. It is important to note that all articles published on N_2O emissions were performed on clay soils. Therefore, studies in soils with medium and sandy textures are also relevant and should be a direction for future researches.

The highest N_2O emissions were obtained from dry corn cultivation at CT (4.84 kg ha^{-1}), and N fertilizer application of 32 kg ha^{-1} at planting and 112.5 kg N ha^{-1} in topdressing as urea, followed by corn at NT (3.36 kg ha^{-1}) with the same N fertilizer application on CT (Campanha et al., 2019). These authors associated N_2O fluxes with mineral N in the soil, with a dominance of NH_4^+, together with WFPS (about 66 %); total accumulated N_2O (cropping cycle + fallow) was 10 times higher in upland corn with fertilizer at CT and NT than in upland corn treatments without fertilizer use. Nitrous oxide emissions were 30 % lower under NT than CT (Campanha et al., 2019).

Several studies presented an increase in N_2O emissions after using N fertilizers (Signor and Cerri, 2013; Piva et al., 2014; Martins et al., 2015; Santos et al., 2016). Santos et al. (2016) determined higher peak N_2O fluxes (260 µg m^{-2} h^{-1}) after nitrogen fertilization as urea and in soils with higher moisture content, with WFPS with maximum values of 90 %. The authors also related these fluxes to changes in soil NO_3^- contents; in the rainy season, NO_3^- contents varied from 0 to 18.70 mg kg^{-1} and 14.71 mg kg^{-1} in CT and NT, respectively.

Lower N_2O emissions in NT have been identified in several studies (Santos et al., 2016; Sato et al., 2017, 2019; Figueiredo et al., 2018), highlighting the differences between cropping systems. Sato et al. (2019), in a continuous cropping system (CC) with pronounced soil preparation, presented 1.80 and 0.90 kg ha^{-1} in 146 days when intercropping sorghum with *Brachiaria brizantha* at CT and NT, respectively, and 0.79 kg ha^{-1} under ICL. The same plot presented 2.55 kg ha^{-1} in 375 days in CC at CT and 1.90 kg ha^{-1} in CC at NT, and 1.52 kg ha^{-1} under ICL (Sato et al., 2017). In long-term systems, cumulative N_2O emissions are greater under CT than under NT, and ICL is an alternative to low-carbon agriculture in GHG mitigation. However, other studies showed no differences in N_2O emissions between different cropping systems (Metay et al., 2007; Carvalho et al., 2016), with values below the detection limit of 0.6 ng cm^{-2} h^{-1} (Carvalho et al., 2006; Jantalia et al., 2008).

In sugarcane cultivation in the Cerrado, the combination of vinasse (V) and mineral N (N) promoted higher values of N_2O emissions (2.1 kg ha^{-1}) compared to the use

Table 2. Cumulative N_2O fluxes from soils under different systems in the Brazilian Cerrado

Reference	Geographical location	Treatment	Agricultural System	Cumulative N_2O
Poth et al. (1995)	15° 55’ 58” S, 47° 51’ W	CER		0.40 ng m^{-2} s^{-1}
Poth et al. (1995)		CER + burned		1.37 ng m^{-2} s^{-1}
Anderson and Poth (1998)	15° 55’ 58” S, 47° 51’ 02” W	CER + burned (45 d and 20 y)		<0.6 ng cm^{-2} h^{-1}
Pinto et al. (2002)	15° 56’ S, 47° 51’ W	CER SS and CER SS + burned		<0.6 ng cm^{-2} h^{-1}
Carvalho et al. (2006)		C-5 d N (Crop rotation C-S crop sucession CP) 6 y old	NT/CT	<0.6 ng cm^{-2} h^{-1}
Metay et al. (2007)		OFF (Rotation R-BA-S-CJ) 5 y old		0.035 kg ha^{-1}
Metay et al. (2007)		DMC (Rotation R-BA-S-CJ) 5 y old	NT	0.031 kg ha^{-1}
Cruvinel et al. (2011)		S-NF (Rotation) + 10 y old	NT	0.1 kg ha^{-1}
Cruvinel et al. (2011)		CO-BA + 10 y old	NT	0.1 kg ha^{-1}
Cruvinel et al. (2011)		C+BA-B(I) + 10 y old	NT	0.2 kg ha^{-1}
Cruvinel et al. (2011)		CER		-0.2 kg ha^{-1}
Carvalho et al. (2013)	16° 29’ 17” S, 49° 17’ 57” W	B(I) (Crop rotation; cultivated residues corn)	NT	0.094 kg ha^{-1}
Carvalho et al. (2013)		B(I) + MU (Crop rotation)	NT	0.213 kg ha^{-1}
Carvalho et al. (2013)		B(I) + NPK (Crop rotation; cultivated residues corn)	NT	0.107 kg ha^{-1}
Carvalho et al. (2013)		B(I) + MU + NPK (Crop rotation)	NT	0.229 kg ha^{-1}
Carvalho et al. (2013)		CER		0.001 kg ha^{-1}
Carvalho et al. (2014)		Crops (Plant sucession CO-S-C-PG-NF) 20 y old	NT	0.57 kg ha^{-1}
Carvalho et al. (2014)		Crops (Crop rotation S-C + BA-CO-NF) 9 y old	NT	2.0 kg ha^{-1}
Carvalho et al. (2014)		P 23 y of use		1.67 kg ha^{-1}
Buller et al. (2015)	19° 16’ 46.90” S, 4° 36’ 2.35” W	P (Crop rotation with biennial crops)	NT	1.043 kg ha^{-1}
Buller et al. (2015)		ICLF (Integrated system SW-C-P-E planting 1-2 old)	NT	1.043 kg ha^{-1}
Buller et al. (2015)		ICL + Fe (Integrated system SW-C-P)	NT	3.886 kg ha^{-1}
Buller et al. (2015)		ICLF + NPK + Fe (Integrated system SW-CC-P-E 1-2 old)	NT	1.600 kg ha^{-1}
Buller et al. (2015)		ICL + NPK + Fe (Integrated system SW-CC-P)	NT	1.302 kg ha^{-1}
Martins et al. (2015)	12° 00’ S, 46° 03’ W	C + RU (Crop rotation) C-S) 11 y old	NT	0.0013 ± 0.0005 kg ha^{-1}
Martins et al. (2015)		C + UZ (Crop rotation) C-S) 11 y old	NT	0.0020 ± 0.0002 kg ha^{-1}
Martins et al. (2015)		C + CN (Crop rotation) C-S) 11 y old	NT	0.0020 ± 0.0006 kg ha^{-1}
Martins et al. (2015)		C + AS (Crop rotation C-S) 11 y old	NT	0.0027 kg ha^{-1}
Carvalho et al. (2016)	15° 39’ S, 47° 44’ W	C-CJ (Sucession) 6 y old	NT	0.7 kg ha^{-1}
Carvalho et al. (2016)		C-MP (Sucession) 6 y old	NT	1.0 kg ha^{-1}
Carvalho et al. (2016)		C-NF (Sucession) 6 y old	NT	0.9 kg ha^{-1}
Carvalho et al. (2016)		C-CJ/MP (Sucession) 6 y old	CT	0.9 kg ha^{-1}
Carvalho et al. (2016)		C-NF (Sucession) 6 y old	CT	0.5 kg ha^{-1}

Continue

Continuation

Correa et al. (2016)	16° 29′ 59″ S, 49° 17′ 35″ W	P-ILC (Annual crop rotation) 10 y		1.64419 kg ha^{-1}
Meurer et al. (2016)		Biome CER		0.14 kg ha^{-1}
Nogueira et al. (2016)	11° 51′ S, 55° 35′ W	E 1 y old	F	0.165 kg ha^{-1}
Nogueira et al. (2016)		S/C+BA (Crop rotation S-C) 1 y old		1.401 kg ha^{-1}
Nogueira et al. (2016)		P 1 y old		0.298 kg ha^{-1}
Nogueira et al. (2016)		ICLF (Crop rotation S/C-BA-E) 1 y old		0.367 kg ha^{-1}
Petter et al. (2016)	14° 34′ 50″ S, 52° 24′ 01″ W	R (UR) 5 y after the application	NT	0.17 kg ha^{-1} (112 d)
Petter et al. (2016)		R + N (UR) 5 y after the application	NT	0.33 kg ha^{-1} (112 d)
Petter et al. (2016)		R + 0BI (UR) 5 y after the application	NT	0.0016 kg ha^{-1} (112 d)
Petter et al. (2016)		R + 8BI (UR) 5 y after the application	NT	0.0037 kg ha^{-1} (112 d)
Petter et al. (2016)		R + 16BI (UR) 5 y after the application	NT	0.0043 kg ha^{-1} (112 d)
Petter et al. (2016)		R + 32BI (UR) 5 y after the application	NT	0.97 kg ha^{-1} (112 d)
Santos et al. (2016)	15° 33′ 33.99″ S, 47° 44′ 12.32″ W	S-SO (Crop rotation; sucession) 19 y old	NT	1.00 kg ha^{-1}
Santos et al. (2016)		C-B (Crop rotation; sucession) 19 y old	NT	0.70 kg ha^{-1}
Santos et al. (2016)		S-NF (Monoculture) 19 y old	CT	1.36 kg ha^{-1}
Santos et al. (2016)		CER		0.27 kg ha^{-1}
Carvalho et al. (2017)	15° 35′ 30″ S, 14° 42′ 30″ W	ICL (Crop rotation BA-SG-L-SO-G-SO-BA) 5 y old	NT	2.84 kg ha^{-1} (2 y)
Carvalho et al. (2017)		ICLF (Crop rotation, SO-G-SO-BA-E) 5 y old	NT	2.05 kg ha^{-1} (2 y)
Carvalho et al. (2017)		Continuous P 5 y old	NT	0.41 kg ha^{-1} (2 y)
Carvalho et al. (2017)		CER		-0.05 kg ha^{-1}
Sato et al. (2017)	15° 39′ S, 47° 44′ W	CC (Crop rotation; sucession) 24 y old	NT	1.90 kg ha^{-1} (375 d)
Sato et al. (2017)		CC (Crop rotation; sucession) 24 y old	CT	2.55 kg ha^{-1} (375 d)
Sato et al. (2017)		ICL (4 y crop/pasture rotation)	NT	1.52 kg ha^{-1} (375 d)
Sato et al. (2017)		CER		0.55 kg ha^{-1} (375 d)
Silva et al. (2017)	15° 36′ 17.76″ S, 47° 42′ 35.51″ W	SC-NR third ratoon	NT	0.57 kg ha^{-1}
Silva et al. (2017)		SC-VR third ratoon	NT	0.59 kg ha^{-1}
Silva et al. (2017)		SC-NVR third ratoon	NT	2.34 kg ha^{-1}
Silva et al. (2017)		SC-N75 third ratoon	NT	0.78 kg ha^{-1}
Silva et al. (2017)		SC-V75 third ratoon	NT	0.50 kg ha^{-1}
Silva et al. (2017)		SC-NV75 third ratoon	NT	2.91 kg ha^{-1}
Figueiredo et al. (2018)	15° 33′ 33.99″ S, 47° 44′ 12.32″ W	S-SO (Crop rotation; sucession) 19 y old	NT	± 0.99 kg ha^{-1}
Figueiredo et al. (2018)		C-B (Crop rotation; sucession) 19 y old	NT	± 0.67 kg ha^{-1}
Figueiredo et al. (2018)		S-NF (Monoculture) 19 y old	CT	± 1.36 kg ha^{-1}
Figueiredo et al. (2018)		CER		± 0.26 kg ha^{-1}

Continue

Continuation

Campanha et al. (2019)	19° 29′ 6″ S, 44° 10′ 46″ W	C+N (Monoculture; UR) 2 y old	CT	4.84 kg ha^{-1}
Campanha et al. (2019)		C (Monoculture; UR) 2 y old	CT	0.29 kg ha^{-1}
Campanha et al. (2019)		C+N (Monoculture; UR) 2 y old	NT	3.36 kg ha^{-1}
Campanha et al. (2019)		C (Monoculture; UR) 2 y old	NT	0.29 kg ha^{-1}
Nascimento et al. (2019)	11° 51′ 38″ S, 55° 36′ 3″ W	E 3 y old		0.64 kg ha^{-1}
Nascimento et al. (2019)		S-C + BA (Crop rotation S-C)	NT	2.75 kg ha^{-1}
Nascimento et al. (2019)		P (‘Marandu’ grass) 3 y old	NT	2.4 kg ha^{-1}
Nascimento et al. (2019)		FF (initial secondary species)	F	1.19 kg ha^{-1}
Oliveira Filho et al. (2020)		S (exclusive) (Crop sucession S-PG) 1 y old	NT	0.42 kg ha^{-1}
Oliveira Filho et al. (2020)		C (exclusive) (Crop sucession S-PG) 1 y old	NT	1.57 kg ha^{-1}
Oliveira Filho et al. (2020)		C+BA (Crop sucession S-PG) 1 y old	NT	1.24 kg ha^{-1}
Oliveira Filho et al. (2020)		CER		0.11 kg ha^{-1}
Carvalho et al. (2021)	15° 36′ 17.76″ S, 47°42′ 35.51″ W	SC-R% fifth ratoon	NT	1.05 kg ha^{-1}
Carvalho et al. (2021)		SC-T17% fifth ratoon	NT	1.10 kg ha^{-1}
Carvalho et al. (2021)		SC-T46% fifth ratoon	NT	1.22 kg ha^{-1}
Carvalho et al. (2021)		SC-T75% fifth ratoon	NT	1.33 kg ha^{-1}
Oliveira et al. (2021)	15° 53′ 06.44″ S, 47° 39′ 37.10″ W	E (E1; E2)		≤0.85 kg ha^{-1}
Oliveira et al. (2021)		CER		0.32 kg ha^{-1}

The soils are classified as a Oxisols with clayey texture. CER: Cerrado; SS: Cerrado *stricto sensu;* d: days; y: years; C-5 d N: Corn, up to five days after the first nitrogen broadcasting fertilization with urea in a corn field, the level of nitrogen broadcasting fertilization was of 60 kg ha^{-1}; C-S: Corn-Soybean; CP: Cover plants; NT: no-tillage; CT: conventional tillage; PS: pig slurry application (40 m^3 ha^{-1}) on soil about a quantity of oat straw (3.6 Mg ha^{-1}); MT: minimum tillage; OFF: Offset or disc harrowing treatment in which soil was tilled only to 0.15 m depth; R-BA-S-CJ: Rice-Brachiaria-Soybean-*Crota laria juncea;* DMC: direct seeding mulch based treatment with cover crops of Brachiaria; S-NF: Soybean-Natural fallow; CO-BA: Cotton planting over Brachiaria; C+BA-B(I): Corn consortium with brachiaria-irrigated Bean; B(I): Irrigated bean, cultivated residues corn; MU: mulching; NPK: mineral fertilization; MU+NPK: mulching with mineral fertilization; CO-S-C-PG-NF: Cotton-Soybean-Corn-*Pennisetum glaucum*-Natural fallow; S-C+BA-CO-NF: Soybean-Corn consortium with brachiaria-Cotton-Natural fallow; P: Pastures; ICLF: integrated crop–livestock forest; SW-C-CC-E: swine-corn-continuous crop-pasture-Eucalyptus; ICL: integrated crop–livestock; Fe: fertigation; SW-C-CC: swine-continuous crop-pasture; NPK+Fe: Fertigation with mineral fertilization; C+RU: Corn with regular urea; C+UZ: Corn with urea + zeolite; C+CN: Corn with calcium nitrate; C+AS: Corn with ammonium sulfate; C-CJ*:* Corn consortium with *Crotalaria juncea*; C-MP: Corn consortium with *Mucuna pruriens*; C-NF: Corn consortium with Natural fallow; P-ILC: Pasture in an integrated crop–livestock; E: Eucalyptus; S/C-BA: Soybean/Corn-Brachiaria; S/C-BA-E: Soybean/Corn-Brachiaria-Eucalyptus; R (UR): Rice, under rainfed; R+N (UR): Rice 100 kg de N, under rainfed; 0BI, 16BI and 32BI: doses of biochar: 0, 8, 16 and 32 Mg ha^{-1}; S-SO: Soybean-Sorghum; C-B: Corn-Bean; BA-SG-L-SO-G-BA: Brachiaria-*Stylosanthes guianensis*-*Leucaena leucocephala*-Sorghum biocolor-*Glycine max*-Brachiaria; SO-G-SO-BA-E: *Sorghum biocolor-Glycine max-Sorghum biocolor*-Brachiaria-Eucalyptus; CC: Continuous crop; SC-NR: Sugarcane with nitrogen under no irrigation; SC-VR: Sugarcane with vinasse without irrigation; SC-NVR: Sugarcane with nitrogen plus vinasse without irrigation; SC-N75: Sugarcane with nitrogen under 75 % of crop evapotranspiration replacement.; SC-V75: Sugarcane with vinasse under 75 % of crop evapotranspiration replacement; SC-NV75: Sugarcane with nitrogen plus vinasse under 75 % of crop evapotranspiration replacement; C+N (UR): Corn with nitrogen, under rainfed; S-C+BA: Soybean-Corn consortium with brachiaria; FF: Forest Fragment; S: Soybean exclusive; C: Corn exclusive; S-PG: Soybean-*Pennisetum glaucum;* C+BA: Corn consortium with brachiaria; SCR%: Sugarcane with Rescue irrigation; T17%, T46% and T75%: 17%, 46% and 75% Sugarcane with of crop evapotranspiration replacement; E1: *Eucalyptus urophyll*a, planting 2 years; E2: *Eucalyptus grandis* planting 4 years.

of separately applied fertilizers: nitrogen fertilization only (0.78 kg ha^{-1}) or vinasse application only (0.50 kg ha^{-1}) (Silva et al., 2017). Nitrogen fertilizer was applied at a dose of 100 kg ha^{-1} as ammonium nitrate, and fresh vinasse was applied at 150 m^3 ha^{-1} immediately after the ammonium nitrate application. The authors found that the combination NV promoted emissions on average three times higher than when V or N applied separately. Vinasse used as the main fertilizer may benefit GHG mitigation.

Regarding water regimes in sugarcane, no relationship was found between N_2O emissions and water regimes: Rescue irrigation - R (1.05 kg ha^{-1}), 17 % (1.10 kg ha^{-1}), 46 % (1.22 kg ha^{-1}) and 75 % (1.33 kg ha^{-1}) of the crop water requirement, but the water regime

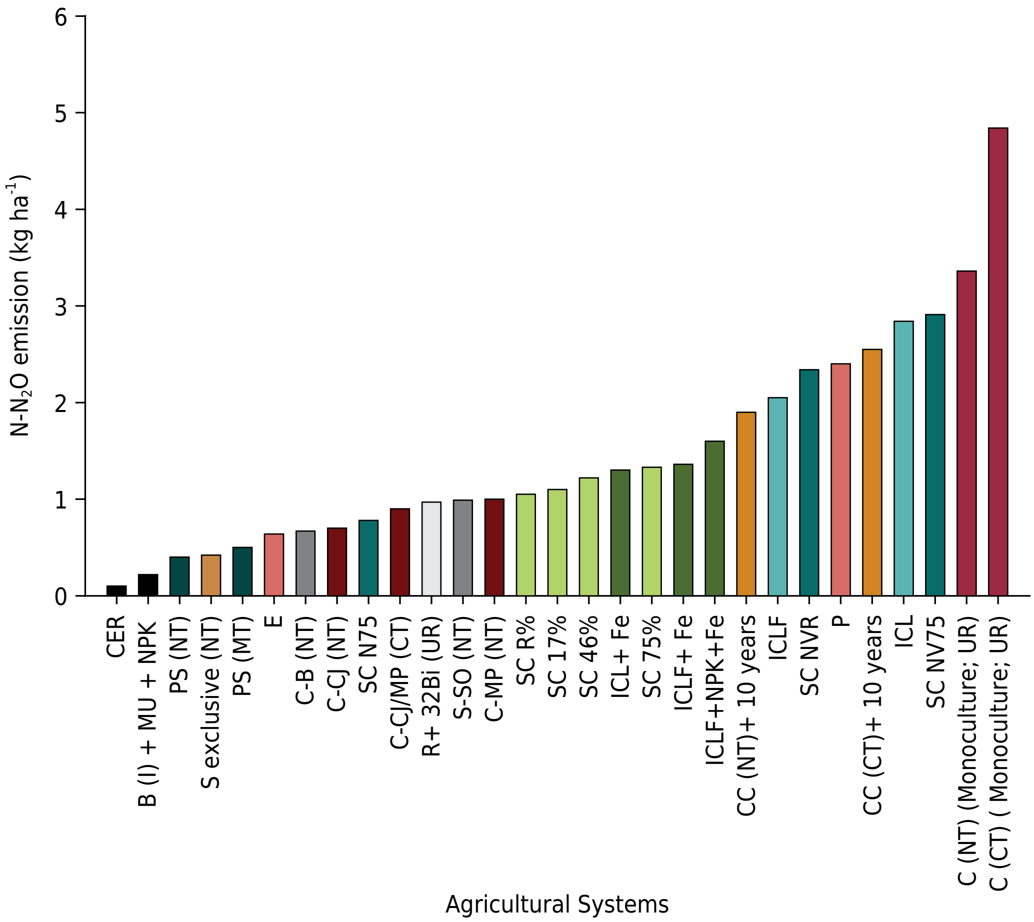

Figure 3. Cumulative N_2O emissions in different agricultural systems in the Brazilian Cerrado. Equal colours refer to data collected in the same study. CER: Native Cerrado; NT: no-tillage; CT: conventional tillage; B(I)+MU+NPK: Common bean (*Phaseolus vulgaris*), with mulching (*Urochloa ruziziensis*) and mineral fertilization (400 kg ha^{-1} N-P-K), applied at planting, and 200 kg ha^{-1} of urea was applied via fertigation; PS(NT): Pig Slurry application (40 m^3 ha^{-1}) on soil with oat straw (3.6 Mg ha^{-1}); S(NT): Soybean exclusive, crop succession soybean-*Pennisetum glaucum* with 1 year old; PS(MT): Pig Slurry application (40 m^3 ha^{-1}) on soil with oat straw (3.6 Mg ha^{-1}); E: *Eucalyptus urograndis*, 3 years of planting; C-B(NT): Corn crop rotation (corn-soybean) with succession corn-common bean with 19 y old; C-CJ(NT): Corn succession cover plants (succession with *Crotalaria juncea*) with 6 years old; SCN75: Sugarcane with applied nitrogen under 75 % of crop evapotranspiration replacement; C-CJ/MP(CT): corn in succession to cover crops (*Crotalaria juncea and Mucuna pruriens*) with 6 years; R+32Bi: Rice + 32 Mg ha^{-1} of biochar 5 years after application biochar to the soil; UR: rice under rainfed; S-SO(NT): soybean crop rotation corn, (sucession soybean-sorghum) with 19 y old; C-MP(NT): corn succession cover plants (corn succession *Mucuna pruriens*) with 6 years old no-tillage; SCR%: Sugarcane with rescue irrigation; SC17 %, SC46 %: Sugarcane, 17 % and 46 % of crop evapotranspiration replacement, respectively; ICL+Fe: Integrated crop-livestock with fertigation (swine-crop-pasture, with cultivated pasture in rotation with crops), 2 years integrated system; SC75 %: Sugarcane, 75 % of crop evapotranspiration replacement; ICLF+Fe: Integrated crop-livestock-forest with fertigation (swine-crop-pasture-eucalyptus, with cultivated pasture in rotation with crops and rows of eucalyptus with no-tillage management), 2 years integrated system; ICLF+NPK+Fe: Integrated crop-livestock-forest with mineral fertilizer (NPK) and fertigation (swine-crop-pasture-eucalyptus, with pasture in rotation with crops and rows of eucalyptus with no-tillage management), 2 years integrated system; CC(NT)+10 years: Continuous crop, crop rotation and succession of leguminous and grasses and fallow with +10 years; ICLF: Integrated crop-livestock-forest (*Brachiaria brizantha* cv. Piatã, planting of an annual crop with no-tillage- *Eucalyptus urograndis*, 3 years integrated system); SCNVR: Sugarcane with nitrogen plus vinasse with rescue irrigation; P: Pasture (Marandu' grass (*Urochloa brizantha)* with 3 years; CC(CT)+10 years: Continuous crop, crop rotation and succession of leguminous, grasses and fallow with +10 years; ICL: Integrated crop-livestock (planting of an annual crop with no-tillage, *Brachiaria brizantha* cv. with 3 years integrated system); SCNV75: sugarcane with nitrogen plus vinasse with 75 % of crop evapotranspiration replacement; C(NT) (Monoculture, UR), and C(CT) (Monoculture, UR): corn under rainfed, 2 years of planting).

with 75 % replacement of crop evapotranspiration showed higher yields compared to the other water regimes (Carvalho et al., 2021).

Although native Cerrado is not a naturally emitting source of N_2O (Metay et al., 2007; Cruvinel et al., 2011; Santos et al., 2016; Carvalho et al., 2017; Sato et al., 2017), studies have shown that conversion of native vegetation to agricultural systems (Martins et al., 2015; Sato et al., 2017; Silva et al., 2017; Carvalho et al., 2017; Campanha et al., 2019) can emit up to 4.84 kg ha^{-1} (Campanha et al., 2019). Cerrado soils are characterized by acidity and high drainage, which, along with acid pH (5.2), is one of the reasons for the low N_2O emissions in soils from the native areas (Martins et al., 2015).

In general, the higher the soil moisture, the higher the N_2O emissions due to the influence of soil water content stimulating microbial activity (Luo et al., 2010; Signor and Cerri, 2013). The increase in N_2O emissions after rainy periods is reported in studies due to the rise in WFPS, favoring denitrifying activity induced by reducing O_2 diffusion in the soil (Jantalia et al., 2008; Martins et al., 2015).

Varella et al. (2004) compared degraded *Brachiaria brizanta* pastures with areas of native Cerrado, and N_2O emissions were below the detection limit in both cases (0.6 μg m^{-2} h^{-1}). Low levels (0.44 kg ha^{-1}) were also observed in a study with permanent pasture in NT (Carvalho et al., 2017), conditions possibly related to good drainage and aeration of the soils, which limit denitrification (Signor and Cerri, 2013).

As with ICL systems, N_2O emissions may increase with animals in the environment, as feces and urine increase N_2O emissions. Lessa et al. (2014) evaluated the effect of urine and cattle feces application on a pasture; the addition of urine promoted significantly higher N_2O emissions (0.026 g g^{-1}) than those found with fecal application treatments (0.0011 g g^{-1}) over 37 days. Giacomini et al. (2006) observed an increase in N_2O fluxes with pig manure in NT and minimum tillage (MT), 40.6 and 50.9 mg m^{-2}, respectively, compared to the treatment without application of 9.5 and 13.2 mg m^{-2}.

In ICLF systems, N_2O emissions were low (0.36 kg ha^{-1}), showing the promising potential to mitigate N_2O emissions compared to the crop, the rotation soybean-corn with Brachiaria (1.401 kg ha^{-1}), pasture (0.298 kg ha^{-1}) and eucalypt plantation (0.165 kg ha^{-1}); emissions were related to rainfall and N availability (Nogueira et al., 2016).

Biological nitrogen fixation contributes to the reduction of N_2O emissions in soybean crop (NT), and low fluxes were observed (0.42 kg ha^{-1}) compared to the systems with intercropping of corn and brachiaria (1.24 kg ha^{-1}) and corn only (1.57 kg ha^{-1}) (Oliveira Filho et al., 2020). The authors observed that the highest N_2O emissions in the intercropping system of corn with brachiaria were due to nitrogen fertilizer application related to N availability and soil moisture. Siqueira-Neto et al. (2020) observed similar cumulative emissions in CT and NT with two crops grown in the same year: Soybean/Sorghum; Soybean/Millet; and Corn/Sorghum, with mean values of 0.13 g m^{-2} yr^{-1}. However, Figueiredo et al. (2018) found that emissions were higher when soybean was grown at CT followed by fallow (1.36 kg ha^{-1}) than when soybean was grown at NT followed by sorghum (0.99 kg ha^{-1}).

In corn cultivation with different N sources, cumulative emissions were similar, and higher emissions were observed with the application of ammonium sulfate (171 g of N_2O per Mg of grain) compared to the control treatment (108 g of N_2O per Mg of grain) (Martins et al., 2015). In corn and cover crop succession, N_2O emissions were higher in legumes (1.0 kg ha^{-1}) than in fallow (0.5 kg ha^{-1}). Still, it is crucial to evaluate the changes of C and N from soil to obtain the emission factor when considering the effectiveness of GHG mitigation (Carvalho et al., 2016).

Eucalyptus plantations in the Cerrado showed cumulative emissions below 0.86 kg ha^{-1}, which is close to the values of Native Cerrado (0.33 kg ha^{-1}). During the dry season, N_2O inflows were observed in association with low NO_3^- levels in the soil (Oliveira et al., 2021). This influx into native vegetation may be associated with a predominantly ammonia mineral N content (Martins et al., 2015; Santos et al., 2016; Carvalho et al., 2017; Sato et al., 2017). In addition, inhibition of soil microbial and enzymatic activity (Chen et al., 2013) may contribute to low soil N_2O fluxes under Eucalyptus in the Cerrado (Oliveira et al., 2021).

In contrast to the Amazon and Atlantic forests, where N_2O emissions range from 0.38 to 16 kg ha^{-1}, with the highest value in the Amazon forest, and the maximum emission of the Atlantic forest is below 3.42 kg ha^{-1} (Meurer et al., 2016). Soils under natural Cerrado vegetation showed very low and even negative values, with a median emission of 0.14 kg ha^{-1} and often below the detection limit, as shown in several studies (Metay et al., 2007; Cruvinel et al., 2011; Bustamante et al., 2012; Carvalho et al., 2013; Martins et al., 2015; Santos et al., 2016; Silva et al., 2017; Carvalho et al., 2017; Sato et al., 2017; Oliveira Filho et al., 2020).

In general, the average N_2O emissions in Brazilian Cerrado soils at CT showed the highest cumulative N_2O emissions (1.58 kg ha^{-1}) compared to NT (0.82 kg ha^{-1}) and Native Cerrado (0.15 kg ha^{-1}) (Figure 4). These data show the importance of NT, its benefits in soil, production system, and GHG mitigation.

As for ICL and ICLF in Brazilian Cerrado, among the cumulative averages of N_2O, ICL had the highest overall average of N_2O emissions (1.68 kg ha^{-1}), compared to ICLF (1.20 kg ha^{-1}) and eucalypt forests (0.48 kg ha^{-1}) (Figure 5). Studies have shown lower soil N_2O emissions in conservation systems than monoculture systems (Carvalho et al., 2014; Abdalla et al., 2014).

In general, wastes from agricultural livestock systems are directly applied to pastures and may behave as pollutants in the atmosphere due to higher N_2O emissions (Giacomini et al., 2006). However, Carvalho et al. (2017) observed lower N_2O emissions in ICLF (2.05 kg ha^{-1}) compared to ICL (2.84 kg ha^{-1}) under NT.

N_2O emissions and soil organic matter in Cerrado

Global data analysis on N_2O emissions suggests that increases in organic C content in cropping systems are associated with N_2O emissions (Stehfest and Bouwman, 2006). Table 3 shows soil organic matter (SOM) content in the Cerrado in different tillage systems and native vegetation. The results show the variation from the lowest to the highest value in the soil layers, 0.00-0.05 m (33-38 g kg^{-1}), 0.00-0.10 m (4.6-35.48 g kg^{-1}) and 0.00-0.20 m (10-41.2 g kg^{-1}) (Table 3). Soil organic matter rates were not directly related

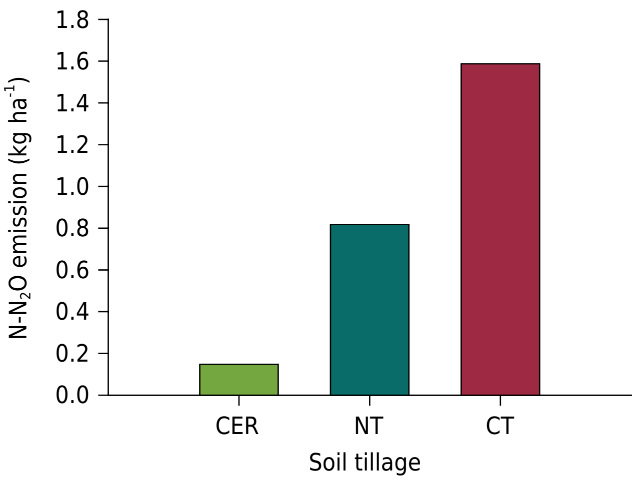

Figure 4. Overall average of cumulative N_2O fluxes in no-tillage (NT), conventional tillage (CT) and Native Cerrado (CER).

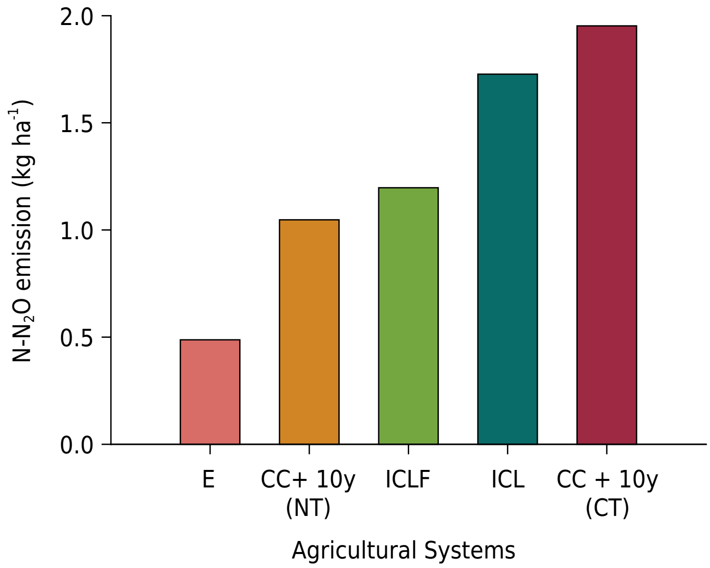

Figure 5. Averages of the cumulative N_2O fluxes in forests of Eucalyptus (E) with 1-4 years planting, compared to continuous crop with +10 years, crop/pasture rotation, successions of leguminous, grasses and natural fallow, under no-tillage CC +10 y (NT); integrated crop-livestock forest, crop/pasture rotation and Eucalyptus with 1-3 years planting (ICLF); the integrated crop-livestock, crop/pasture rotation 1-3 years planting (ICL), and Continuous crop with +10 years, crop/pasture rotation natural fallow conventional tillage CC+10 y (CT) in the Brazilian Cerrado.

to N_2O emissions (Wu et al., 2016). In general, fractionation of SOM makes it possible to understand the dynamics of N in the soil (Sá et al., 2015), usually due to a higher proportion of fractions in the SOM combined with a high N supply (Wu et al., 2016). In a single study in the Cerrado, NT was more efficient in accumulating stable and labile C fractions and was directly related to lower N_2O emissions (Figueiredo et al., 2018).

In the context of climate change, soils represent the largest C reservoir on the Earth's surface and can reduce GHG emissions (Chenu et al., 2019). Conservation systems in Brazilian Cerrado, including crop rotations (Santos et al., 2016), cover crops (Carvalho et al., 2014), and ICL (Sato et al., 2017; Carvalho et al., 2017), have shown a greater potential to mitigate N_2O emissions from agriculture. However, the relationship between the farming system and N_2O emissions is complex, and results are often contradictory (Smith et al., 2008). The relationship between soils under natural vegetation and conservation tillage systems with high C contents and low N_2O emissions is not fully understood in Brazilian Cerrado (Martins et al., 2015).

Natural ecosystems in the Cerrado are conservative in regards to N and limit the supply of this nutrient (Bustamante et al., 2006) and the high C/N ratio of plant residues (Soares et al., 2019) and the predominance of NH_4^+ relative to NO_3^- are factors that contribute to the maintenance of low soil N levels (Bustamante et al., 2012).

Conservation practices contribute to the conservation and formation of SOM and consequently reduce GHG emissions (Lal, 2004; Buller et al., 2015). Considering that 98 % of the total N in soil is in organic form (Stevenson, 1994), N availability and dynamics are influenced by the C/N ratio of crop residues (Kong et al., 2009; Carvalho et al., 2012). Carbon availability in the soil from less complex sources (e.g., glucose) favors the production of N_2O (Miller et al., 2008). The ability to protect and stabilize C depends on soil management (plowing, use of cover crops, crop succession, crop rotation, etc.) and soil properties (Bayer et al., 2011). The accumulation of C in its more stable forms is related to the greater degree of stabilization of SOM (Plaza-Bonilla et al., 2014). The more protected SOM, the less it is exposed to mineralization, the lower the loss of SOM in the form of GHG to the atmosphere, such as N_2O (Lal, 2004; Sato et al., 2019).

Table 3. Literature review of organic matter contents in soils under different management systems in Brazilian Cerrado

Reference	Treatments	Soil tillage	Depth	Organic matter
			m	g kg^{-1}
Carvalho et al. (2006)	C-N	NT	0.20	27.0
Carvalho et al. (2006)	C-N	CT	0.20	27.0
Metay et al. (2007)	OFF		0.10	16.0
Metay et al. (2007)	DMC		0.10	17.6
Lessa et al. (2014)	P		0.20	10.4
Correa et al. (2016)	ICL	P	0.10	34.3
Correa et al. (2016)	CER		0.10	35.5
Santos et al. (2016)	S-SO	NT	0.20	30.0
Santos et al. (2016)	C-B	NT	0.20	30.0
Santos et al. (2016)	S-NF	CT	0.20	30.0
Santos et al. (2016)	CER		0.20	34.0
Carvalho et al. (2017)	ICL	NT	0.20	28.6
Carvalho et al. (2017)	ICLF	NT	0.20	28.6
Meurer et al. (2017)	CER		0.10	18.8
Meurer et al. (2017)	GF		0.10	4.6
Meurer et al. (2017)	P		0.10	14.2
Meurer et al. (2017)	Crops		0.10	31.6
Meurer et al. (2017)	F		0.10	14.9
Meurer et al. (2017)	O-P		0.10	18.3
Meurer et al. (2017)	MA-P		0.10	23.9
Meurer et al. (2017)	Y-P		0.10	14.5
Figueiredo et al. (2018)	S-SO	NT	0.20	30.0
Figueiredo et al. (2018)	C-B	NT	0.20	30.0
Figueiredo et al. (2018)	S	CT	0.20	30.0
Figueiredo et al. (2018)	CER		0.20	34.0
Campanha et al. (2019)	C-N and NN	NT	0.20	41.2
Campanha et al. (2019)	C-N and NN	CT	0.20	38.9
Nascimento et al. (2019)	E		0.10	24.0
Nascimento et al. (2019)	Crops		0.10	23.0
Nascimento et al. (2019)	P		0.10	26.0
Nascimento et al. (2019)	F		0.10	46.0
Oliveira Filho et al. (2020)	S	NT	0.20	20.0
Oliveira Filho et al. (2020)	C	NT	0.20	20.0
Oliveira Filho et al. (2020)	C-BA	NT	0.20	20.0
Carvalho et al. (2021)	SC	NT	0.20	8.7
Oliveira et al. (2021)	E1		0.05	33.0
Oliveira et al. (2021)	E2		0.05	30.0
Oliveira et al. (2021)	CER		0.05	38.0

NT: no-tillage; CT: conventional tillage; P: Pastures; N: application of N fertilizer; NN: no N fertilizer application; CER: Native Cerrado; ICL: integrated crop-livestock; ICLF: integrated crop-livestock-forest; C: Corn; BA: Brachiária; S: Soybean; SO: Sorghum; B: Bean; SC: Sugarcane; E: Eucalyptus; E1: *Eucalyptus urophylla*; E2: *Eucalyptus grandis*; F: Forest; GF: Gallery Forest; NF: Natural fallow; OFF: Offset or disc harrowing treatment in which soil was tilled only to 0.15 m depth; DMC: direct seeding mulch based treatment with cover crops of Brachiaria; O-P: old pasture; MA-P: medium-aged pasture; Y-P: young pasture.

Soil fertility improvement depends on the quantity and quality of SOM (Sheehy et al., 2015). Soil organic matter is one crucial component in characterizing agricultural systems, and its efficient management can contribute to GHG mitigation (Lal, 2004; Figueiredo et al., 2018; Sato et al., 2019). In tropical regions, soils are predominantly weathered, and the strong organic-mineral interaction can contribute to SOM stabilization and consequently reduce N_2O emissions from soils under native vegetation (Martins et al., 2015; Santos et al., 2016).

Differences among agricultural systems and their interaction with cumulative N_2O fluxes cannot be explained based on SOM contents alone (Table 3). Studies relating soil N_2O emissions to fractions of SOM are needed, especially in Brazilian Cerrado, to understand better the dynamics of SOM associated with N_2O emissions. An integrated effect of management systems (crop rotation, crop succession, and no-tillage system), cultural residues, and SOM fractions can contribute to understanding N_2O emissions in the soil, as reported by Figueiredo et al. (2018) and Sato et al. (2019) in agroecosystems in the Cerrado.

CONCLUSIONS

In the Cerrado, cumulative N_2O emissions in cropping systems are less than 5 kg ha^{-1}, and the introduction of conservation systems, such as integrated crop-livestock (ICL), is essential to mitigate N_2O emissions. In general, N_2O emissions were higher in conventional cropping systems than in the no-till system. The ICL had the highest average of N_2O emissions among the integrated systems compared to ICLF and eucalypt plantations.

The relationship between soil organic matter and N_2O fluxes to the atmosphere is not fully elucidated in the Brazilian Cerrado, and further studies are needed. In the present study, it was not possible to obtain a direct relationship between the total content of SOM and N_2O emissions. Thus, further studies should consider the different SOM fractions.

ACKNOWLEDGEMENTS

To Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), for the scientific productitvity fellowships granted to Maria Lucrecia Gerosa Ramos, Cícero Célio de Figueiredo and Arminda Moreira de Carvalho. Furthermore, to Coordenação de Aperfeiçoamento de Pessoal de Nível Superior for the Masters scholarship to Thais Rodrigues de Sousa. We also acknowledge to Professor Concepta McManus Pimentel for revising the paper.

AUTHOR CONTRIBUTIONS

Conceptualização: Thais Rodrigues de Sousa (equal), Maria Lucrecia Gerosa Ramos (equal) and Cícero Célio de Figueiredo (equal).

Methodology: Thais Rodrigues de Sousa (equal), Maria Lucrecia Gerosa Ramos (equal) and Cícero Célio de Figueiredo (equal).

Formal analysis: Thais Rodrigues de Sousa (equal), Maria Lucrecia Gerosa Ramos (equal), Cícero Célio de Figueiredo (equal) and Arminda Moreira de Carvalho (equal).

Writing – original draft: Thais Rodrigues de Sousa (equal), Maria Lucrecia Gerosa, Ramos (equal), Cícero Célio de Figueiredo (equal) and Arminda Moreira de Carvalho (equal).

REFERENCES

Abdalla M, Hastings A, Helmyc M, Prescher A, Osbor NB, Lanigane G, Forristal D, Killi D, Maratha P, Williams M, Rueangritsarakul K, Smith P, Nolan P, Jones MB. Assessing the combined use of reduced tillage and cover crops for mitigating greenhouse gas emissions from arable ecosystem. Geoderma. 2014;223:9-20. https://doi.org/10.1016/j.geoderma.2014.01.030

Almeida RF, Naves ER, Silveira CH, Wendling B. Emissão de óxido nitroso em solos com diferentes usos e manejos: Uma revisão. Rev Agroneg Meio Ambient. 2015;8:441-61. https://doi.org/10.17765/2176-9168.2015v8n2p441-461

Anache JAA, Flanagan DC, Srivastava A, Wendland EC. Land use and climate change impacts on runoff and soil erosion at the hillslope scale in the Brazilian Cerrado. Sci Total Environ. 2018;622:140-51. https://doi.org/10.1016/j.scitotenv.2017.11.257

Anderson IC, Poth MA. Controls of fluxes of trace gases from Brazilian Cerrado soils. J Environ Qual. 1998;27:1117-24. https://doi:10.2134 /jeq1998.00472425002700050017x

Baggs EM, Philippot L. Microbial terrestrial pathways to nitrous oxide. In: Smith K, editor. Nitrous oxide and climate change. London: Routledge; 2010. p. 4-35.

Bayer C, Amado TJC, Tornquist CG, Cerri CEC, Dieckow J, Zanatta JA, Nicolos RS. Estabilização do carbono no solo e mitigação das emissões de gases de efeito estufa na agricultura conservacionista. In: Klauberg Filho O, Mafra AL, Gatiboni LC, editores. Tópicos em ciência do solo. Viçosa, MG: Sociedade Brasileira de Ciência do Solo; 2011. v. 7. p. 55-118.

Beuchle R, Grecchi RC, Shimabukuro YE, Sellinger R, Eva HD, Sano E, Achard F. Land cover changes in the Brazilian Cerrado and Caatinga biomes from 1990 to 2010 based on a systematic remote sensing sampling approach. Appl Geophys. 2015;58:116-27. https://doi.org/10.1016/j.apgeog.2015.01.017

Bonanomi J, Tortato FR, Gomes RSR, Penha JM, Bueno AS, Peres CA. Protecting forests at the expense of native grasslands: Land-use policy encourages open habitat loss in the Brazilian Cerrado biome. Perspect Ecol Conserv. 2019;17:26-31. https://doi.org/10.1016/j.pecon.2018.12.002

Braker G, Schwarz J, Conrad R. Influence of temperature on the composition and activity of denitrifying soil communities. FEMS Microbiol Ecol. 2010;73:134-48. https://doi.org/10.1111/j.1574-6941.2010.00884.x

Brasil. Plano agrícola e pecuário 2010-2011. Brasília, DF: Ministério da Agricultura, Pecuária e Abastecimento / Secretaria de Política Agrícola; 2010 [cited 2016 May 10]. Available from: https://www.gov.br/agricultura/pt-br/assuntos/politica-agricola/todas-publicacoes-de-politica-agricola/plano-agricola-pecuario/plano-agricola-e-pecuario-2010-2011.pdf.

Brasil. Plano setorial de mitigação e de adaptação às mudanças climáticas para a consolidação de uma economia de baixa emissão de carbono na agricultura: plano ABC (Agricultura de Baixa Emissão de Carbono). Brasília, DF: Ministério da Agricultura, Pecuária e Abastecimento / Ministério do Desenvolvimento Agrário, coordenação da Casa Civil da Presidência da República; 2012 [cited 2017 Out 18]. Available from: https://www.gov.br/agricultura/pt-br/assuntos/sustentabilidade/plano-abc/arquivo-publicacoes-plano-abc/download.pdf

Bronick CJ, Lal R. Soil structure and management: A review. Geoderma. 2005;124:3-22. https://doi.org/10.1016/j.geoderma.2004.03.005

Buller LS, Bergier I, Ortega E, Moraes A, Bayma-Silva G, Zanetti MR. Soil improvement and mitigation of greenhouse gas emissions for integrated crop-livestock systems: Case study assessment in the Pantanal savanna highland, Brazil. Agr Syst. 2015;137:206-19. https://doi.org/10.1016/j.agsy.2014.11.004

Bustamante MMC, Medina E, Asner GP, Nardoto GB, Garcia-Montiel DC. Nitrogen cycling in tropical and temperate savannas. Biogeochemistry. 2006;79:209-37. https://doi.org/10.1007/s10533-006-9006-x

Bustamante MMC, Nardoto GB, Pinto AS, Resende JCF, Takahashi FSC, Vieira LCG. Potential impacts of climate change on biogeochemical functioning of Cerrado ecosystems. Braz J Biol. 2012;72:655-71. https://doi.org/10.1590/S1519-69842012000400005

Cameron KC, Di HJ, Moir JL. Nitrogen losses from the soil/plant system: A review. Ann Appl Biol. 2013;162:145-73. https://doi.org/10.1111/aab.12014

Campanha MM, Oliveira AD, Marriel IE, Neto MMG, Malaquias JV, Landau EC, Carvalho AM. Effect of soil tillage and N fertilization on N_2O mitigation in corn in the Brazilian cerrado. Sci Total Environ. 2019;692:1165-74. https://doi.org/10.1016/j.scitotenv.2019.07.315

Carneiro MAC, Souza ED, Reis EF, Pereira HS, Azevedo WR. Atributos físicos, químicos e biológicos do solo de cerrado sob diferentes sistemas de uso e manejo. Rev Bras Cienc Solo. 2009;33:147-57. https://doi.org/10.1590/S0100-06832009000100016

Carvalho AM, Bustamante MMC, Kozovits AR, Vivaldi L, Souza DM. Emissão de óxidos de nitrogênio associada à aplicação de uréia sob plantio convencional e direto. Pesq Agropec Bras. 2006;41:679-85. https://doi.org/10.1590/S0100-204X2006000400020

Carvalho AM, Bustamante MMC, Marchão RL, Malaquias JV. Nitrogen oxides and CO_2 from an Oxisol cultivated with corn in succession to cover crops. Pesq Agropec Bras. 2016;51:1213-22. https://doi.org/10.1590/S0100-204X2016000900021

Carvalho AM, Coelho MC, Dantas RA, Fonseca OP, Guimarães Júnior R, Figueiredo CC. Chemical composition of cover plants and its effect on maize yield in no-tillage systems in the Brazilian savana. Crop Pasture Sci. 2012;63:1075-81. https://doi.org/10.1071/CP12272

Carvalho AM, Oliveira AD, Coser TR, Sousa TR, Lima CA, Ramos MLG, Malaquias JV, Gonçalves ADMA, Ribeiro Júnior WQ. N_2O emissions from sugarcane fields under contrasting watering regimes in the Brazilian Savannah. Environ Technol Innov. 2021;22:101470. https://doi.org/10.1016/J.Eti.2021.101470

Carvalho AM, Oliveira WRD, Ramos MLG, Coser TR, Oliveira AD, Pulronik K, Marchão RL. Soil N_2O fluxes in integrated production systems, continuous pasture and Cerrado. Nutr Cycl Agroecosys. 2017;108:69-83. https://doi.org/10.1007/s10705-017-9823-4

Carvalho JLN, Raucci GS, Frazão LA, Cerri CEP, Bernoux M, Cerri CC. Crop-pasture rotation: a strategy to reduce soil greenhouse gas emissions in the Brazilian Cerrado. Agric Ecosyst Environ. 2014;183:167-75. https://doi.org/10.1016/j.agee.2013.11.014

Carvalho MTM, Madari BE, Leal WGO, Costa ARM, Machado PLOA, Silveira PMS, Moreira JAA, Heinemann AB. Nitrogen fluxes from irrigated common-bean as affected by mulching and mineral fertilization. Pesq Agropec Bras. 2013;48:478-86. https://doi.org/10.1590/S0100-204X2013000500003

Chen H, Li G, Hu F, Shi W. Soil nitrous oxide emissions following crop residue addition: A meta-analysis. Glob Chang Biol. 2013;19:2956-64. https://doi.org/10.1111/gcb.12274

Chenu C, Angers D, Barré P, Derrien D, Arrouays D, Balesdent J. Increasing organic stocks in agricultural soils: Knowledge gaps and potential innovations. Soil Till Res. 2019;188:41-52. https://doi.org/10.1016/j.still.2018.04.011

Cordeiro LAM, Vilela L, Marchão RL, Kluthcouski J, Martha Junior GB. Integração lavoura-pecuária e integração lavoura-pecuária-floresta: estratégias para intensificação sustentável do uso do solo. Cad Cienc Tecnol. 2015;32:15-43.

Correa 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

Cruvinel EBF, Bustamante MMC, Kozovitsc AR, Zeppd RG. Soil emissions of NO, N_2O and CO_2 from croplands in the savanna region of central Brazil. Agric Ecosyst Environ. 2011;144:29-40. https://doi.org/10.1016/j.agee.2011.07.016

Davidson EA, Bustamante MMC, Pinto AS. Emissions of nitrous oxide and nitric oxide from soils of native and exotic ecosystems of the Amazon and Cerrado regions of Brazil. Thescientificworldjo. 2001;1:312-9. https://doi.org/10.1100/tsw.2001.261

Davidson EA, Keller M, Erickson HE, Verchot LV, Veldkamp E. Testing a conceptual model of soil emissions of nitrous and nitric oxides: using two functions based on soil nitrogen availability and soil water content, the hole-in-the-pipe model characterizes a large fraction of the observed variation of nitric oxide and nitrous oxide emissions from soils. Bioscience. 2000;50:667-80. https://doi.org/10.1641/0006-3568(2000)050[0667:TACMOS]2.0.CO;2

De La Vega E, Chalk TB, Wilson P, Bysani RP, Foster GL. Atmospheric CO_2 during the mid piacenzian warm period and the M2 glaciation. Sci Rep-UK. 2020;10:11002. https://doi.org/10.1038/s41598-020-67154-8

Ferreira EAB, Bustamante MMC, Resck DVS, Figueiredo CC, Pinto AS, Malaquias JV. Carbon stocks in compartments of soil organic matter 31 years after substitution of native cerrado vegetation by agroecosystems. Rev Bras Cienc Solo. 2016;40:e0150059. https://doi.org/10.1590/18069657rbcs20150059

Figueiredo CC, Oliveira AD, Santos IL, Ferreira EAB, Malaquias JV, Sá MAC, Carvalho AM, Santos Júnior JDG. Relationships between soil organic matter pools and nitrous oxide emissions of agroecosystems in the Brazilian cerrado. Sci Total Environ. 2018;618:1572-82. https://doi.org/10.1016/J.Scitotenv.2017.09.333

Fourier J. Mémoire sur les températures du globe terrestre et des espaces planétaires. Mémoires de l'Académie Royale des Sciences de l'Institut de France. 1827;7:569-604.

Franchini JC, Balbinot Junior AA, Sichieri FR, Debiasi H, Conte O. Yield of soybean, pasture and wood in integrated crop-livestock-forest system in Northwestern Paraná state, Brazil. Rev Cienc Agron. 2014;46:1006-13. https://doi.org/10.1590/S1806-66902014000500016

Galaz V, Crona B, Dauriach A, Scholtens B, Steffen W. Finance and the Earth system - exploring the links between financial actors and non-linear changes in the climate system. Glob Environ Change. 2018;53:296-302. https://doi.org/10.1016/j.gloenvcha.2018.09.008

Gardi C, Angelini M, Barceló S, Comerma J, Cruz Gaistardo C, Jones A, Krasilnikov P, Mendonça SBML, Montanarella L, Muniz UO, Schad P, Vara RMI, Vargas R. Atlas de suelos de América Latina y el Caribe, Comision Europea. Luxemburgo: Oficina de publicaciones de la Union Europea; 2014.

Giacomini SJ, Jantalia CS, Aita C, Urquiaga SS, Alves BJR. Emissão de óxido nitroso com a aplicação de dejetos líquidos de suínos em solo sob plantio direto. Pesq Agropec Bras. 2006;41:1653-61. https://doi.org/10.1590/S0100-204X2006001100012

Goldman JAL, Bender ML, Morel FMM. The effects of pH and pCO_2 on photosynthesis and respiration in the diatom *Thalassiosira weissflogii*. Photosyn Res. 2017;132:83-93. https://doi.org/10.1007/s11120-016-0330-2

Hirsch PR, Mauchline TH. The importance of the microbial N cycle in soil for crop plant nutrition. Adv Appl Microbiol. 2015;93:45-71. https://doi.org/10.1016/bs.aambs.2015.09.001

Hungria M, Nogueira MA, Araujo RS. Inoculation of *Brachiaria* spp. with the plant growth-promoting bacterium *Azospirillum brasilense*: An environment-friendly component in the reclamation of degraded pastures in the tropics. Agric Ecosyst Environ. 2016;221:125-31. https://doi.org/10.1016/j.agee.2016.01.024

Intergovernmental Panel on Climate Change - IPCC. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Prepared by the National Greenhouse Gas Inventories Programme, Eggleston HS, Buendia L, Miwa K, Ngara T, Tanabe K, editors. Japan: IPCC/IGES; 2006 [cited 2015 Dec 12]. Available from: https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/0_Overview/V0_0_Cover.pdf.

Intergovernmental Panel on Climate Change – IPCC. Climate Change 2014: Synthesis Report. Contribution of working groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change. Geneva, Switzerland, 2014 [cited 2016 Fev 18]. Available from: https://archive.ipcc.ch/pdf/assessment-report/ar5/syr/SYR_AR5_FINAL_full_wcover.pdf

Intergovernmental Panel on Climate Change – IPCC. Climate Change and Land: an IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. Summary for Policymakers. In: Shukla J, Skea E, Calvo Buendia V, Masson-Delmotte HO, Pörtner DC, Roberts P, Zhai R, Slade S, Connors R, van Diemen M, Ferrat E, Haughey S, Luz S, Neogi M, Pathak J, Petzold J, editors. Press, 2019 [cited 2017 Nov 18]. Available from: https://www.ipcc.ch/site/assets/uploads/sites/4/2020/02/SPM_Updated-Jan20.pdf

Jantalia CP, Resck DVS, Alves NJR, Zotarelli L, Urquiaga S, Boddey RM. Tillage effect on C stocks of a clayey Oxisol under a soybean-based crop rotation in the Brazilian Cerrado region. Soil Till Res. 2007;95:97-109. https://doi.org/10.1016/j.still.2006.11.005

Jantalia CP, Santos HP, Urquiaga S, Boddey RM, Alves BJR. Fluxes of nitrous oxide from soil under different crop rotations and tillage systems in the south of Brazil. Nutr Cycl Agroecosys. 2008;82:161-73. https://doi.org/10.1007/s10705-008-9178-y

Kong AYY, Fonte SJ, Van Kessel C, Six J. Transitioning from standard to minimum tillage: trade-offs between soil organic matter stabilization, nitrous oxide 114. Emissions, and n availability in irrigated cropping systems. Soil Till Res. 2009;104:256-62. https://doi.org/10.1016/j.still.2009.03.004

Lal R. Soil carbon sequestration to mitigate climate change. Geoderma. 2004;123:1-22. https://doi.org/10.1016/j.geoderma.2004.01.032

Lessa ACR, Madari BE, Paredes DS, Boddey RM, Urquiaga S, Jantalia CP, Alves BJR. Bovine urine and dung deposited on Brazilian savannah pastures contribute differently to direct and indirect soil nitrous oxide emissions. Agric Ecosyst Environ. 2014;190:104-11. https://doi.org/10.1016/j.agee.2014.01.010

Liu C, Wang K, Meng S, Zheng X, Zhou Z, Han S, Chen D, Yang Z. Effects of irrigation, fertilization and crop straw management on nitrous oxide and nitric oxide emissions from a wheat-maize rotation field in northern China. Agric Ecosyst Environ. 2011;140:226-33. https://doi.org/10.1016/j.agee.2010.12.009

Liu XJ, Mosier AR, Halvorson AD, Reule CA, Zhang FS. Dinitrogen and N_2O emissions in arable soils: effect of tillage, N source and soil moisture. Soil Biol Biochem. 2007;39:2362-70. https://doi.org/10.1016/j.soilbio.2007.04.008

Luo J, De Klein CAM, Ledgard SF, Saggar S. Management options to reduce nitrous oxide from intensively grazed pasture: A review. Agric Ecosyst Environ. 2010;136:282-91. https://doi.org/10.1016/j.agee.2009.12.003

Martins MR, Jantalaia CP, Polidoro JC, Batista JN, Alves BJR, Boddey RM, Urquiaga S. Nitrous oxide and ammonia emission from N fertilization of maize crop under no-till in a Cerrado soil. Soil Till Res. 2015;151:75-81. https://doi.org/10.1016/j.still.2015.03.004

Metay A, Oliver R, Scopel E, Douzet JM, Moreira JAA, Maraux F, Feigl BJ, Feller C. N_2O and CH_4 emissions from soils under conventional and no-till management practices in Goiânia (*Cerrados*, Brazil). Geoderma. 2007;141:78-88. https://doi.org/10.1016/j.geoderma.2007.05.010

Meurer KHE, Franco U, Spott O, Schützenmeister K, Niehaus E, Stangeand CF, Jungkunst HF. Missing hot moments of greenhouse gases in southern Amazonia. Erdkunde. 2017;71:195-211. https://doi.org/10.3112/Erdkunde.2017.03.03

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

Miller MN, Zebarth BJ, Dandie CE, Burton DL, Goyer C, Trevors JT. Crop residue influence on denitrification, N_2O emissions and denitrifier community abundance in soil. Soil Biol Biochem. 2008;40:2553-62. https://doi.org/10.1016/j.soilbio.2008.06.024

Mosier AR, Halvorson AD, Reule CA, Liu XJJ. Net global warming potencial and greenhouse gas intensity in irrigated cropping systems in northastern Colorado. J Environ Qual. 2006;35:1584-98. https://doi.org/10.2134/jeq2005.0232

Myhre G, Shindell D, Bréon FM, Collins W, Fuglestvedt J, Huang J, Koch D, Lamarque JF, Lee D, Mendoza B, Nakajima T, Robock A, Stephens G, Takemura T, Zhang H. Anthropogenic and natural radiative forcing. In: Climate Change 2013 - The Physical Science Basis. Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press; 2013;659–740. https://doi.org/10.1017/CBO9781107415324.018

Nascimento AF, Rodrigues RAR. Sampling frequency to estimate cumulative nitrous oxide emissions from the soil. Pesq Agropec Bras. 2019;54:e00211. https://doi.org/10.1590/S1678-3921.pab2019.v54.00211

National Oceanic and Atmospheric Administration - NOAA. Teacher background: the greenhouse effect [internet]. Estados Unidos: U.S Departament of Commerce; 2020 [cited 2019 Dec 14] Available from: https://www.noaa.gov/education/resource-collections/climate

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

Norse D. Low carbon agriculture: Objectives and policy pathways. Environ Dev. 2012;1:25-39. https://doi.org/10.1016/j.envdev.2011.12.004

Oertel C, Matschullat J, Zurbaa K, Zimmermanna F, Erasmi S. Greenhouse gas emissions from soil - A review. Geochemistry. 2016;76:327-52. https://doi.org/10.1016/j.envdev.2011.12.004

Oliveira AD, Ribeiro FP, Ferreira EAB, Malaquias JV, Gatto A, Zuim DR, Pinheiro LA, Pulrolnilk K, Soares JPG, Carvalho AM. CH_4 and N_2O fluxes from planted forests and native Cerrado ecosystems in Brazil. Sci Agric. 2021;78:e20180355. https://doi.org/10.1590/1678-992X-2018-0355

Oliveira Filho EG, Medeiros JC, Rosa JD, Souza HA, Deon DS, Madari BE. Nitrous oxide (N_2O) emissions in Savanah agrosystems. Australian J Sci. 2020;14:1970-6. https://doi: 10.21475/ajcs.20.14.12.2846

Petter FA, Lima LB, Marimon Júnior BH, Morais LA, Marimon BS. Impact of biochar on nitrous oxide emissions from upland rice. J Environ Manage. 2016;169:27-33. https://doi.org/10.1016/j.jenvman.2015.12.020

Pinto AS, Bustamante MC, Kisselle K, Burke R, Zepp R, Viana LT, Varella RF, Molina M. Soil emissions of N_2O, NO, and CO_2 in Brazilian Savannas: effects of vegetation type, seasonality, and prescribed fires. J Geophys Res. 2002;107:8089. https://doi.org/10.1029/2001JD000342

Piva JT, Dieckow J, Bayer C, Zanatta JA, Moraes A, Tomazi M, Pauletti V, Barthe G, Piccolo MC. Soil gaseous N_2O and CH_4 emissions and carbon pool due to integrated crop-livestock in a subtropical Ferralsol. Agric Ecosyst Environ. 2014;190:87-93. https://doi.org/10.1016/j.agee.2013.09.008

Plaza-Bonilla D, Álvaro-Fuentes J, Cantero-Martínez C. Identifying soil organic carbon fractions sensitive to agricultural management practices. Soil Till Res. 2014;139:19-22. https://doi.org/10.1016/j.still.2014.01.006

Poth MA, Anderson HS, Miranda AC, Miranda, Riggan, PJ. The magnitude and persistence of soil NO, N_2O, CH_4, and CO_2 fluxes from burned tropical savanna in Brazil. Global Biogeochem Cycles. 1995;9:503-13. https://doi.org/10.1029/95GB02086

Rada N. Assessing Brazil's Cerrado agricultural miracle. Food Policy. 2013;38:146-55. https://doi.org/10.1016/j.foodpol.2012.11.002

Ren FX, Zhang J, Liu N, Sun L, Wu Z, Li M. A synthetic analysis of greenhouse gas emissions from manure amended agricultural soils in China. Sci Rep. 2017;7:8123. https://doi.org/10.1038/s41598-017-07793-6

Sá JCM, Séguy L, Tivet F, Lal R, Bouzinac S, Borszowskei PR, Briedis C, Santos JB, Hartman DC, Bertoloni CG, Rosa J, Friedrich T. Carbon depletion by plowing and its restoration by no-till cropping systems in Oxisols of subtropical and tropical agro-ecoregions in Brazil. Land Degrad Dev. 2015;26:531-43. https://doi.org/10.1002/ldr.2218

Salton JC, Mercante FM, Tomazi M, Zanatta JA, Concenço G, Silva WM, Retore M. Integrated crop-livestock system in tropical Brazil: Toward a sustainable production system. Agric Ecosyst Environ. 2014;190:70-9. https://doi.org/10.1016/j.agee.2013.09.023

Sano EE, Rodrigues AA, Martins ES, Bettiol GM, Bustamante MMC, Bezerra AS. Cerrado ecorregions: A spatial framework to assess and prioritize Brazilian savana environmental diversity for conservation. J Environ Manage. 2019;232:818-28. https://doi.org/10.1016/j.jenvman.2018.11.108

Santos IL, Caixeta CF, Sousa AATC, Figueiredo CC, Ramos MLG, Carvalho AM. Cover plants and mineral nitrogen: effects on organic matter fractions in an Oxisol under no tillage in the Cerrado. Rev Bras Cienc Solo. 2014;38:1874-81. https://doi.org/10.1590/S0100-06832014000600022

Santos IL, Oliveira AD, Figueiredo CC, Malaquias JV, Santos Junior JDG, Ferreira EAB, Sá MAC, Carvalho AM. Soil N_2O emissions from long-term agroecosystems: interactive effects of rainfall seasonality and crop rotation in the Brazilian Cerrado. Agric Ecosyst Environ. 2016;233:111-20. https://doi.org/10.1016/j.agee.2016.08.027

Sato JH, Carvalho AM, Figueiredo CC, Coser TR, Sousa TR, Vilela L, Marchão LR. Nitrous oxide fluxes in a Brazilian clayey Oxisol after 24 years of integrated crop-livestock management. Nutr Cycl Agroecosys. 2017;108:55-68. https://doi.org/10.1007/s10705-017-9822-5

Sato JH, Figueiredo CC, Marchão RL, Oliveira AD, Vilela L, Delvico FM, Alves BJR, Carvalho AM. Understanding the relations between soil organic matter fractions and N_2O emissions in a long-term integrated crop-livestock system. Eur J Soil Sci. 2019;70:1183-96. https://doi.org/10.1111/ejss.12819

Scheer C, Wassmann R, Kienzler K, Ibragimov N, Eschanov R. Nitrous oxide emissions from fertilized, irrigated cotton. (*Gossypium hirsutum* L.) in the Aral Sea Basin, Uzbekistan: Influence of nitrogen applications and irrigation practices. Soil Biol Biochem. 2008;40:290-301. https://doi.org/10.1016/j.soilbio.2007.08.007

Shakoor A, Ashraf F, Shakoor S, Mustafa A, Rehman A, Altaf MM. Biogeochemical transformation of greenhouse gas emissions from terrestrial to atmospheric environment and potential feedback to climate forcing. Environ Sci Pollut R. 2020;27:38513-36. https://doi.org/10.1007/s11356-020-10151-1

Sheehy J, Regina K, Alakukku L, Six J. Impact of no-till and reduced tillage on aggregation and aggregate-associated carbon in Northern European agroecosystems. Soil Till Res. 2015;150:107-13. https://doi.org/10.1016/j.still.2015.01.015

Signor D, Cerri CEP. Nitrous oxide emissions in agricultural soils: a review. Pesq Agropec Trop. 2013;43:322-38. https://doi.org/10.1590/S1983-40632013000300014

Silva JF, Carvalho AM, Rein TA, Coser TR, Ribeiro-Júnior WQ, Vieira DL, Coomes DA. Nitrous oxide emissions from sugarcane fields in the Brazilian Cerrado. Agric Ecosyst Environ. 2017;246:55-65. https://doi.org/10.1016/j.agee.2017.05.019

Silva JMC, Bates JM. Biogeographic patterns and conservation in the South American Cerrado: a tropical savanna hotspot. Bio Sci. 2002;52:225-34. https://doi.org/10.1641/0006-3568(2002)052[0225:BPACIT]2.0.CO;2

Silva MA, Arantes MT, Rhein AFL, Gava GJC, Kolln OT. Potencial produtivo da cana-de-açúcar sob irrigação por gotejamento em função de variedades e ciclos. Rev Bras Eng Agr Amb. 2014;18:241-9. https://doi.org/10.1590/S1415-43662014000300001

Silva VG. Fluxos de óxido nitroso, N mineral e frações de carbono no solo cultivado com milho em sucessão a plantas de cobertura [tese]. Brasília, DF: Universidade de Brasília; 2020.

Siqueira-Neto M, Popin GV, Piccolo MC, Corbeels M, Scopel E, Camargo PB, Bernoux M. Impacts of land use and cropland management on soil organic matter and greenhouse gas emissions in the Brazilian Cerrado. Soil Sci. 2020;72:1431-46. https://doi.org/10.1111/ejss.13059

Sistema de Estimativas de Emissões e Remoções de Gases de Efeito Estufa-Seeg-Brasil. Análise das emissões brasileiras de gases de efeito estufa e suas implicações para as metas de clima do Brasil 1970-2018. São Paulo. Observatório do Clima; 2019 [cited 10 May 2021]. Available from: https://www.oc.eco.br/wp-content/uploads/2019/11/OC_SEEG_Relatorio_2019pdf.pdf

Sistema de Estimativas de Emissões e Remoções de Gases de Efeito Estufa- Seeg-Brasil. Análise das emissões brasileiras de gases de efeito estufa e suas implicações para as metas de clima do Brasil 1970-2019. São Paulo. Observatório do Clima; 2020 [cited 15 Jun 2021]. Available from: http://seeg-br.s3.amazonaws.com/Documentos%20Analiticos/SEEG_8/SEEG8_DOC_ANALITICO_SINTESE_1990-2019.pdf

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 Trans R Soc Lond B, Biol Sci. 2008;363:789-813. https://doi.org/10.1098/rstb.2007.2184

Smith P. Malthus is still wrong: we can feed a world of 9-10 billion, but only by reducing food demand. Proc Nutri Soc. 2015;74:187-90. https://doi.org/10.1017/S0029665114001517

Soares DS, Ramos MLG, Marchão RL, Maciel GA, Oliveira AD, Malaquias JV, Carvalho AM. How diversity of crop residues in long-term no-tillage systems affect chemical and microbiological soil properties. Soil Till Res. 2019;194:104316. https://doi.org/10.1016/j.still.2019.104316

Soterroni AC, Ramos FM, Mosnier A, Fargione J, Andrade PR, Baumgarten L, Pirker J, Obersteiner M, Kraxner F, Câmara G, Carvalho AXY, Polasky S. Expanding the soy moratorium to Brazil's Cerrado. Sci Adv. 2019;5:eaav7336. https://doi.org/10.1126/sciadv.aav7336

Stehfest E, Bouwman L. N_2O and NO emission from agricultural fields and soils under natural vegetation: summarizing available measurement data and modeling of global annual emission. Nutr Cycl Agroecosys. 2006;74:207-28. https://doi.org/10.1007/s10705-006-9000-7

Stevenson FJ. Humus Chemistry: genesis, composition, reactions. 2nd ed. New York. John Wiley & Sons; 1994.

Strassburg BBN, Brooks T, Feltran-Barbieri R, Iribarrem A, Crouzeilles R, Loyola R, Latawiec AE, Oliveira Filho FJB, Scaramuzza CAM, Scarano FR, Soares-Filho B, Balmford A. Moment of truth for the Cerrado hotspot. Nat Ecol Evol. 2017;1:0099. https://doi.org/10.1038/s41559-017-0099

Strassburg BB, Latawiec AE, Barioni LG, Nobre CA, Silva VP, Valentim JF, Vianna M, Assad ED. When enough should be enough: Improving the use of current agricultural lands could meet production demands and spare natural habitats in Brazil. Glob Environ Change, 2014;28:84-97. https://doi.org/10.1016/j.gloenvcha.2014.06.001

Thomson AJ, Giannopoulos G, Pretty J, Baggs EM, Richardson DJ. Biological sources and sinks of nitrous oxide and strategies to mitigate emissions. Philos Trans R Soc Lond B. 2012;367:1157-68. https://doi.org/10.1098/rstb.2011.0415

United Nations World Water Assesment Programme – WWAP. The United Nations World Water Development Report 2015: Water for a Sustainable World. Paris, UNESCO. 2015 [cited 2016 Aug 20]. Available from: https://books.google.com.br/books?id=zQV1CQAAQBAJ&printsec=frontcover&hl=pt-BR&source=gbs_ge_summary_r&cad=0#v=onepage&q&f=false

Ussiri D, Lal R. Formation and release of nitrous oxide from terrestrial and aquatic ecosystems. In: Ussiri D, Lal R, editors. Soil emission of nitrous oxide and its mitigation. Dordrecht: Springer; 2013. p. 63-89. https://doi.org/10.1007/978-94-007-5364-8_3

Varella RF, Bustamante MMC, Pinto AS, Kisselle KW, Santos RV, Burke RA, Zepp RG, Viana LT. Soil fluxes of CO_2, CO, NO, and N_2O from an old pasture and from native savanna in Brazil. Ecol Appl. 2004;14:221-31. https://doi.org/10.1890/01-6014

Vilela L, Martha Jr GB, Marchão RL. Integração lavoura-pecuária-floresta: Alternativa para intensificação do uso da terra. Rev UFG. 2012;13:92-9.

Wu Y, Lin S, Liu T, Wan T, Hu R. Effect of crop residue returns on N_2O emissions from red soil in China. Soil Use Manag. 2016;32:80-8. https://doi.org/10.1111/sum.12220

Zanatta JA, Alves BJR, Bayer C, Tomazi M, Fernandes AHBM, Costa FS, Carvalho AM. Protocolo para medição de gases de efeito estufa do solo. Colombo, PR: Embrapa Florestas; 2014 [cited 2021 May 20]. Available from: https://ainfo.cnptia.embrapa.br/digital/bitstream/item/123470/1/Doc.-265-Protocolo-Josileia.pdf