ReGeo ISSN: 2177-3246

GREENHOUSE GAS EMISSIONS IN A YELLOW LATOSOL UNDER AGRICULTURAL MANAGEMENT IN PARAGOMINAS-PA

EMISSÕES DE GASES DE EFEITO ESTUFA EM UM LATOSSOLO AMARELO SOB MANEJO AGRÍCOLA EM PARAGOMINAS-PA

EMISIONES DE GASES DE EFECTO INVERNADERO EN UN LATOSOL AMARILLO BAJO MANEJO AGRÍCOLA EN PARAGOMINAS-PA

doi 10.56238/revgeov17n1-117

Raimundo Cosme de Oliveira Junior[1], Eduardo Jorge Maklouf Carvalho[2], Darlisson Bentes dos Santos[3], Carlos Alberto Costa Veloso[4], Arystides Resende Silva[5], Neusa Maria da Silva Ferreira[6]

ABSTRACT

Understanding greenhouse gas (GHG) dynamics in tropical agricultural systems is essential for improving national inventories and guiding low-emission management strategies. This study quantified soil–atmosphere nitrous oxide (N_2O) and methane (CH_4) fluxes in soybean fields managed under conventional tillage (CT) and no-tillage (NT) in very clayey Yellow Latosols of eastern Amazonia. Fluxes were measured across three phenological phases using static chambers, coupled with soil moisture and temperature monitoring. Overall, N_2O and CH_4 fluxes were low in both systems, reflecting the well-drained conditions, low water-filled pore space, and limited labile carbon characteristic of these Oxisols. N_2O emissions showed modest temporal variability but no statistical differences between CT and NT, and no rainfall-induced pulses were detected. CH_4 fluxes were negative or near zero throughout the season, indicating net atmospheric CH_4 uptake, with slightly higher consumption under NT during the late season. Soil moisture and temperature exhibited similar averages across systems, but their temporal dynamics helped explain gas-flux patterns. Collectively, the results demonstrate that microenvironmental controls exert stronger influence on GHG fluxes than tillage practices under these soil and climatic conditions. These findings provide empirical evidence to refine regional emission factors and improve the representation of tropical agricultural systems in Brazil's GHG inventory.

[1] Dr. in Environmental Geochemistry. Embrapa Amazônia Oriental. Pará, Brazil.
E-mail: raimundo.oliveira-junior@embrapa.br
[2] Dr. in Soil Science and Plant Nutrition. Embrapa Amazônia Oriental. Pará, Brazil.
E-mail: eduardo.maklouf@embrapa.br
[3] Master's degre in Energy in Agriculture. Embrapa Amazônia Oriental. Pará, Brazil.
E-mail: engenheirodbs@hotmail.com
[4] Dr. in Soil Science and Plant Nutrition. Embrapa Amazônia Oriental. Pará, Brazil.
E-mail: carlos.veloso@embrapa.br
[5] Dr. in Soil Science and Plant Nutrition. Embrapa Milho e Sorgo. Minas Gerais, Brazil.
E-mail: arystides.silva@embrapa.br
[6] Graduated in Food Technology. Embrapa Amazônia Oriental. Pará, Brazil.
E-mail: neusa.ferreira@embrapa.br

Keywords: Greenhouse Gas Emissions. No-Tillage. Yellow Latosol (Oxisol). Eastern Amazon. Soybean Cultivation.

RESUMO
Compreender a dinâmica dos gases de efeito estufa (GEE) em sistemas agrícolas tropicais é essencial para o aprimoramento dos inventários nacionais e para a orientação de estratégias de manejo de baixa emissão. Este estudo quantificou os fluxos de óxido nitroso (N_2O) e metano (CH_4) entre o solo e a atmosfera em áreas de cultivo de soja manejadas sob preparo convencional do solo (PC) e sistema de plantio direto (PD) em Latossolos Amarelos muito argilosos da Amazônia Oriental. Os fluxos foram medidos ao longo de três fases fenológicas, utilizando câmaras estáticas, associadas ao monitoramento da umidade e da temperatura do solo. De modo geral, os fluxos de N_2O e CH_4 foram baixos em ambos os sistemas, refletindo as condições de boa drenagem, o baixo espaço poroso preenchido por água e a limitada disponibilidade de carbono lábil característicos desses Latossolos. As emissões de N_2O apresentaram modesta variabilidade temporal, sem diferenças estatísticas entre PC e PD, e não foram observados pulsos induzidos por eventos de precipitação. Os fluxos de CH_4 foram negativos ou próximos de zero ao longo de todo o período avaliado, indicando consumo líquido de CH_4 atmosférico, com consumo ligeiramente maior sob PD no final do ciclo. A umidade e a temperatura do solo apresentaram médias semelhantes entre os sistemas, porém suas dinâmicas temporais contribuíram para explicar os padrões observados dos fluxos gasosos. Em conjunto, os resultados demonstram que os controles microambientais exercem influência mais significativa sobre os fluxos de GEE do que as práticas de preparo do solo sob essas condições edafoclimáticas. Esses achados fornecem evidências empíricas para o refinamento de fatores de emissão regionais e para o aprimoramento da representação dos sistemas agrícolas tropicais no inventário nacional de GEE do Brasil.

Palavras-chave: Emissões de Gases de Efeito Estufa. Plantio Direto. Latossolo Amarelo (Oxisol). Amazônia Oriental. Cultivo de Soja.

RESUMEN
Comprender la dinámica de los gases de efecto invernadero (GEI) en los sistemas agrícolas tropicales es fundamental para mejorar los inventarios nacionales y orientar estrategias de manejo de bajas emisiones. Este estudio cuantificó los flujos de óxido nitroso (N_2O) y metano (CH_4) entre el suelo y la atmósfera en áreas de cultivo de soja manejadas bajo labranza convencional (LC) y siembra directa (SD) en Latosoles Amarillos muy arcillosos de la Amazonía Oriental. Los flujos se midieron a lo largo de tres fases fenológicas mediante el uso de cámaras estáticas, junto con el monitoreo de la humedad y la temperatura del suelo. En general, los flujos de N_2O y CH_4 fueron bajos en ambos sistemas, lo que refleja las condiciones de buen drenaje, el bajo espacio poroso lleno de agua y la limitada disponibilidad de carbono lábil característicos de estos Oxisoles. Las emisiones de N_2O mostraron una variabilidad temporal moderada, sin diferencias estadísticas entre LC y SD, y no se detectaron pulsos inducidos por eventos de precipitación. Los flujos de CH_4 fueron negativos o cercanos a cero durante toda la temporada, lo que indica una absorción neta de CH_4 atmosférico, con un consumo ligeramente mayor bajo SD al final del ciclo. La humedad y la temperatura del suelo presentaron promedios similares entre los sistemas, aunque sus dinámicas temporales ayudaron a explicar los patrones de los flujos gaseosos. En conjunto, los resultados demuestran que los controles microambientales ejercen una influencia más fuerte sobre los flujos de GEI que las prácticas de labranza bajo estas condiciones edafoclimáticas. Estos hallazgos aportan evidencia empírica para refinar los factores de emisión regionales y mejorar la representación de los sistemas agrícolas tropicales en el inventario nacional de GEI de Brasil.

Palabras clave: Emisiones de Gases de Efecto Invernadero. Siembra Directa. Latosol Amarillo (Oxisol). Amazonía Oriental. Cultivo de Soja.

1 INTRODUCTION

The municipality of Paragominas, located in the northeastern region of the state of Pará, has stood out for adopting advanced technologies in agriculture, contrasting with the predominant scenario in many other municipalities of Pará, where traditional or conventional cultivation models still prevail. Despite technical advancements, the prevailing production model in the region is still dominated by often inadequate management practices, such as extensive deforestation, intensive soil tillage with heavy machinery, excessive use of synthetic fertilizers and pesticides, and the predominance of monoculture systems (Vieira et al, 2018; Alves et al., 2014). Such practices, widely disseminated in the eastern Amazon, have contributed to a range of negative environmental impacts, including soil degradation, loss of organic matter, increased compaction, and the intensification of erosive processes—with serious implications for biogeochemical cycles and the sustainability of agroecosystems. This combination of factors makes the eastern Amazon a space of high uncertainty in regional GHG inventories, due to the scarcity of local data on N_2O and CH_4 fluxes in agricultural systems (Gatti et al., 2021).

Although Paragominas cultivated approximately 148,000 ha in 2023 (IBGE, 2023) and consolidated itself as an agricultural hub, the adoption of conservation practices still occurs heterogeneously among properties, making it fundamental to understand the environmental implications of this variability, especially regarding greenhouse gas (GHG) emissions from the soil (FEARNSIDE, 2018; Armacolo et al., 2015). Therefore, the response of N_2O and CH_4 to management practices can be highly localized and dependent on the interaction between management, soil texture, and hydrology (Oertel et al., 2016; Shakoor et al., 2021).

Concern about GHG emissions, especially CO_2, N_2O, and CH_4, has grown substantially in recent decades, primarily due to their role in global warming and climate change (IPCC, 2021). Agriculture accounts for a significant portion of these emissions and is considered one of the main anthropogenic sources of N_2O and CH_4. Nitrous oxide is mainly emitted through microbial soil processes such as nitrification and denitrification, while methane is produced in anaerobic environments, often associated with livestock production and waterlogged soils (SYAKILA & KROEZE, 2011; TUBIELLO et al., 2013; TIAN et al., 2020). These differences reinforce the need for regional studies with high-resolution temporal monitoring to capture phenological and hydrological pulses that determine the magnitude of fluxes (Yue et al., 2023).

In this context, agricultural management systems strongly influence the dynamics of soil GHG emissions. Practices such as excessive soil disturbance, the use of nitrogen fertilizers, and the absence of vegetative cover directly affect microbial activity and the soil's physical and chemical conditions, thereby altering gas fluxes between the soil and atmosphere (**Horwath** & KUZYAKOV, 2018). On the other hand, conservation practices—such as no-tillage (NT), crop rotation, and green manuring—have proven to be effective strategies to mitigate these emissions, enhance carbon sequestration, and increase the resilience of production systems (Monteiro et al., 2024). Empirical data collected in tropical Latosols—with high clay content and low fertility—are particularly valuable for adjusting regional emission factors and reducing uncertainties in national and global models (MAPA, 2021).

In Brazil, efforts to quantify and mitigate GHG emissions from agriculture have been coordinated by institutions such as Embrapa through structured initiatives such as the Pecus project (focused on livestock systems), Saltus (focused on forest systems), and Fluxus (focused on agricultural crops, especially grains). These projects aim to build a robust national inventory of GHG emissions, supporting public policies and strategies for sustainable agricultural development in tropical regions (BERNDT et al., 2013; SILVA et al., 2013; Embrapa, 2014; Armacolo et al., 2015). Even so, the Amazon remains underrepresented in these inventories, especially regions of recent agriculture, such as Paragominas. This gap prevents safe extrapolations from data from the south-central part of the country and compromises the formulation of management recommendations aligned with both productivity and mitigation goals (da Cruz Corrêa et al., 2025; Coe et al., 2017; Quesada et al., 2020; Osis et al, 2019).

The state of Pará, particularly the region of Paragominas, presents edaphoclimatic conditions and land-use dynamics that demand specific regional studies. The very clayey Yellow Latosol that predominates in the region strongly influences structural stability, water retention, and gas diffusivity, factors closely tied to N_2O and CH_4 efflux. The interaction between very clayey texture, high rainfall regimes, and intensive management creates unique conditions that cannot be directly inferred from studies conducted in South-Central Brazil, where soils and climate differ substantially (Martins et al., 2021; Carvalho et al., 2010).

Systematic studies in the Amazon that comparatively evaluate the effects of different cultivation systems on GHG emissions in agricultural soils are still scarce. Most of the available data comes from the south-central region of Brazil, which limits the extrapolation of results to the Amazonian context, where soils, climate, and production systems have quite unique characteristics (FEARNSIDE, 2018; Sousa et al., 2021). Considering this gap, regional studies are crucial for understanding the specific dynamics of the Amazon.

Given the scarcity of systematic Amazonian studies evaluating GHG fluxes under contrasting cultivation systems, there is a critical gap in understanding how different agricultural practices modulate biogeochemical processes in very clayey Latosols of the region. Filling this gap is essential both for local decision-making and for strengthening Brazil's commitments under the Paris Agreement and its Nationally Determined Contributions (Brasil, 2020).

Given this context, this study evaluated N_2O and CH_4 fluxes in areas cultivated with soybeans in the municipality of Paragominas (PA), comparing conventional tillage (CT) and no-tillage (NT) systems in very clayey Yellow Latosol. The main hypothesis is that conservation practices (NT) reduce the net balance of GHG emissions when compared to conventional management, due to less soil disturbance, greater structural stability, and effects on aerobic microenvironments and surface labile carbon. It is expected that temporal differences—associated with fertilization, harvest, and re-wetting—explain a large part of the observed variability (Yue et al., 2023).

It is expected that the results will allow identifying agricultural practices with lower emission intensity, quantifying real differences between managements, improving estimates of regional GHG inventories in the Amazon, and directly contributing to mitigation strategies aligned with low-carbon agriculture.

2 MATERIALS AND METHODS

2.1 STUDY SITE AND CLIMATIC CHARACTERIZATION

This study was conducted in the second half of 2015 on an experimental field located in the municipality of Paragominas, southeastern Pará, Brazil (02°59′ S; 47°21′ W), at an average altitude of 89 m. The region has a tropical Aw climate (Köppen), with a well-defined dry season from July to November. Mean annual precipitation is approximately 1,743 mm, relative humidity averages around 85 %, and mean annual air temperature is 26.3 °C (Alves et al., 2014).

The predominant soil type is a dystrophic, very clayey Yellow Latosol (Oxisol), with high aggregate stability, rapid infiltration capacity, and inherently low fertility (RODRIGUES et al., 2003; Brazil, 2018). Prior to the experiment, the area had been cultivated with soybean for several consecutive years under locally adopted conventional tillage practices.

2.2 EXPERIMENTAL SETUP AND GAS SAMPLING

Two contrasting soil-management systems were evaluated: conventional tillage (CT), consisting of plowing and disking, and no-tillage (NT), defined by direct seeding without soil disturbance. Each system occupied a contiguous 1-ha plot positioned to minimize topographic and hydrological gradients.

Soybean (*Glycine max* L.) was planted at the onset of the rainy season. Fertilization followed regional recommendations, with N–P–K applied only at sowing (nutrient rates provided in Supplementary Table S1). Dolomitic lime had been applied two years before the study in both systems. Routine crop management—including weeding and pest control—followed local standard practices.

2.3 STATIC CHAMBER INSTALLATION AND GAS SAMPLING

Soil–atmosphere N_2O and CH_4 fluxes were quantified using non-flow static chambers following Hutchinson & Mosier (1981) and ISO 20951:2019 guidelines. Each chamber consisted of a cylindrical PVC collar (30 cm internal diameter; 12 cm height) and an airtight removable lid (20 cm height), fitted with a gas-sampling septum and a vent to equilibrate pressure.

Ten chambers were randomly distributed within each plot, maintaining at least 20 m between sampling points to reduce spatial autocorrelation. This resulted in a completely randomized design with 10 replicates per treatment.

Collars were installed at least 48 h before the first sampling. Aboveground residues inside collars were left intact. Chamber positioning minimized shading differences.

2.4 SAMPLING SCHEDULE AND FIELD MEASUREMENTS

Gas sampling was conducted across three phenological phases:

1. **Post-fertilization (Phase 1):** daily sampling for seven days after planting;
2. **Vegetative–reproductive phase (Phase 2):** weekly sampling;
3. **Harvest and post-harvest (Phase 3):** sampling on harvest day and for five subsequent days.

During each sampling event, chambers were closed and four headspace samples (20 mL) were collected at 1, 10, 20, and 30 min using gas-tight syringes. Samples were transferred to laminated airtight bags and analyzed within 24 h.

Chamber headspace temperature was recorded at each interval, and soil temperature at 2 cm depth and air temperature (shade) were recorded beside each chamber. Soil samples (0–10 cm) collected adjacent to chambers were used to determine gravimetric moisture via oven-drying at 105 °C for 48 h. Additional soil properties (pH, total C and N, texture) were determined according to Embrapa protocols (Brazil, 2017, 2018).

ISSN: 2177-3246

2.5 SOIL AND MICROCLIMATE MEASUREMENTS

Simultaneously with gas sampling, composite soil samples (0–10 cm) were collected adjacent to each chamber to determine gravimetric moisture by oven-drying at 105 °C for 48 h. Moisture (%) was computed as:

$$\text{Moisture} = \frac{W_w - W_d}{W_d} \times 100 \quad (1)$$

Where W_w is wet mass and W_d is dry mass.

Additional soil properties—including pH, total organic carbon, total nitrogen, and texture—were determined following standard Embrapa protocols (Brazil, 2017, 2018).

2.6 GAS CHROMATOGRAPHY AND CALIBRATION

N_2O and CH_4 concentrations were analyzed using a Shimadzu GC-8A gas chromatograph equipped with an Electron Capture Detector (N_2O) and a Flame Ionization Detector (CH_4), and a Porapak-Q packed column (1/8″ × 4′). Operating temperatures were 300 °C (ECD), 125 °C (FID), 60 °C (N_2O column), and 40 °C (CH_4 column); carrier gas was P-5 at 40 psi.

Daily calibrations were performed with NIST-traceable standards (308.1 and 753 ppb for N_2O; 0.884 and 1.75 ppm for CH_4). Calibration curves displayed $R^2 > 0.995$ and performance was checked using mid-level standards, duplicates (10% of samples), and blanks.

2.7 FLUX CALCULATIONS

Gas fluxes (μg m^{-2} h^{-1}) were calculated from the linear change in chamber concentration over time using equation 2. Fluxes were retained only when regressions exhibited $R^2 \geq 0.90$. Negative CH_4 fluxes were interpreted as net soil uptake.

$$F = \left(\frac{dC}{dt}\right) \times \frac{V}{A} \times \frac{M}{(273.15+T)} \quad (2)$$

Where:

- $\frac{dC}{dt}$= slope of concentration vs. time (ppmv min^{-1}),
- V= chamber headspace volume (m^3),
- A= soil area covered by chamber (m^2),
- M= molar mass of N_2O or CH_4,

- T= chamber air temperature (°C).

Fluxes were retained only when linear regressions showed $R^2 \geq 0.90$. Negative CH_4 fluxes were interpreted as net soil uptake.

2.8 STATISTICAL ANALYSES

Analyses were conducted using Statistica 7.0 (StatSoft). For each gas and phenological phase, CT and NT treatments were compared using one-way ANOVA (α = 0.05), followed by Tukey's test. Residuals were evaluated using Shapiro–Wilk (normality) and Levene's test (homoscedasticity); log transformations were applied when needed.

Simple linear regressions assessed relationships between fluxes and soil moisture or temperature. Outliers were identified using Cook's distance and removed only when supported by clear methodological evidence.

3 RESULTS AND DISCUSSION

Table 1 summarizes N_2O and CH_4 fluxes as well as soil moisture and temperature across soybean growth stages. Overall, absolute fluxes were low for both gases, consistent with the physical and biogeochemical characteristics of very clayey Yellow Latosols—deep, well-drained, acidic soils with rapid infiltration and limited labile C supply. Similar patterns of suppressed N_2O and CH_4 emissions have recently been reported for well-aerated tropical soils (Martins et al., 2021; Nascimento et al., 2020; Yue et al., 2023; Moraes et al., 2025).

Table 1

Mean values of N_2O and CH_4 fluxes, soil moisture, and temperature for the management systems at different soybean growth stages in the municipality of Paragominas, Pará State, Brazil

Growth stages	N_2O ± SEM $\mu g\ Nm^{-2}h^{-1}$	Soil Moisture %	CH_4 ± SEM $\mu g\ C^{-2}m^{-1}h$	Temperature °C
Conventional Planting				
Period 1	0,024 ± 0,028a	24,79 ± 1,67a	0,074 ± 0,07a	27,5 ± 0,8a
Period 2	0,014 ± 0,104a	25,65 ± 2,00b	0,02 ± 0,077b	27,2 ± 2,0a
Period 3	0,027 ± 0,0,037a	23,53 ± 1,22c	0,011 ± 0,08bc	26,5 ± 0,2a
Total	0,018 ± 0,08	25,07 ± 2,02	0,033 ± 0,078	27,1 ± 1,5
No-Till Planting				
Period 1	0,031 ± 0,043a	25,08 ± 0,94a	0,058 ± 0,10a	26,5 ± 0,4a
Period 2	0,013 ± 0,037a	25,34 ± 1,03a	0,028 ± 0,056a	27,2 ± 1,3a

Period 3	0,048 ± 0,039a	23,10 ± 0,78b	-0,005 ± 0,05a	28,2 ± 0,2b
Total	0,019 ± 0,039	25,07 ± 1,17	0,035 ± 0,072	27,1 ± 1,2

Note: Means followed by the same letters in the column, across periods, do not differ statistically from each other according to Tukey's test (5% significance level).

3.1 N_2O FLUXES

The average total N_2O fluxes did not differ statistically between the management systems, being 0.018 ± 0.08 μg N m^{-2} h^{-1} under CT (conventional tillage) and 0.019 ± 0.039 μg N m^{-2} h^{-1} under NT (no-tillage) (Table 1). In CT, a decrease in fluxes was observed during Period 2 (0.014 ± 0.104 μg N m^{-2} h^{-1}), after the initial crop establishment, followed by a subsequent increase in Period 3 (0.027 ± 0.037 μg N m^{-2} h^{-1}), corresponding to the harvest and post-harvest stage (Table 1). A comparable temporal pattern was observed in NT, with Period 3 (0.048 ± 0.039 μg N m^{-2} h^{-1}) showing the highest mean flux. Both systems showed modest temporal variability, with small increases during Period 3, coinciding with crop senescence and residue mineralization. These late-season increases are consistent with enhanced nitrification–denitrification following residue turnover and changes in soil aeration (Rubaiyat et al., 2023).

The absence of strong management effects contrasts with studies in temperate and subtropical systems, where NT often elevates N_2O emissions through increased soil moisture and the formation of anaerobic microsites. However, recent tropical evaluations emphasize that high clay content, rapid drainage, and low soil C availability strongly constrain denitrification (Martins et al., 2021; Lage Filho et al., 2022; Sousa et al., 2021).

In theory, NT can create conditions of higher soil moisture and anaerobic microsites due to the presence of crop residues and reduced soil disturbance, which may favor denitrification and, consequently, N_2O emissions (Xu et al., 2020; Maucieri et al., 2021; Liu et al., 2021).

The discrepancy with the literature may be associated with factors such as low soil water saturation, reduced levels of labile carbon in the soil, and the absence of prolonged anoxic events during the experimental period—conditions that are critical for the microbial activity responsible for denitrification. Nevertheless, the increased fluxes observed in Period 3 may be attributed to the mineralization of crop residues and the stimulation of microbial activity resulting from nitrogen release following crop senescence and harvest, promoting both nitrification and denitrification processes (Abalos et al., 2022; Mirzaei et al., 2022; Lashermes et al., 2022; Rubaiyat et al., 2023).

Moreover, it is important to consider that emission pulses, typically triggered by soil rewetting after dry periods or fertilizer application, often account for a large proportion of N losses in the form of N_2O over short time intervals (Krichels et al., 2022; Guo et al., 2014; BUTTERBACH-BAHL et al., 2013). Rainfall-driven N_2O pulses—dominant contributors to annual budgets in tropical agriculture—were not observed. This likely reflects the absence of saturating rainfall during the monitoring period. Contemporary meta-analyses show that >60% of cumulative N_2O emissions in tropical croplands occur in short-lived pulses linked to rewetting or fertilization (Xu et al., 2020; Yue et al., 2023).

In addition, **recent meta-analyses show that tropical N_2O emissions are strongly pulse-driven**, with a large portion of cumulative fluxes occurring in short windows after rainfall or fertilization (Kirkby et al., 2023; **Xu et al., 2020**). Although no large pulses were captured here, this may be due to the absence of intense rainfall events during the measurement window.

3.2 CH_4 FLUXES

Average CH_4 emissions were also low in both management systems, with values of 0.033 ± 0.078 μg N m⁻² h⁻¹ in CT and 0.035 ± 0.072 μg N m⁻² h⁻¹ in NT (Table 1). CH_4 fluxes were negative or near zero across systems, indicating net CH_4 uptake. NT showed slight CH_4 consumption in Period 3 (–0.005 ± 0.05 μg N m⁻² h⁻¹). This pattern is typical for well-drained upland soils and reflects dominance of methanotrophy over methanogenesis (Ma et al., 2020; Cowan et al., 2021).

Higher CH_4 emissions in CT during Period 1 may result from short-term microbial activation following soil disturbance, which increases labile C exposure and modifies oxygen diffusivity. However, these effects are transient, and the overall seasonal balance points to soils acting as CH_4 sinks—an important ecosystem service also observed in tropical agroecosystems under conservation management (Wu et al., 2020; Monteiro et al., 2024).

This behavior reinforces the hypothesis that soils under soybean cultivation, particularly under well-drained conditions, act as CH_4 sinks due to the presence of oxygen in the profile and the limited availability of substrate for methanogenesis (Covey et al., 2021; Venturini et al., 2022). Studies conducted in Eastern Amazonia, such as those by Venturini et al. (2022), also reported this pattern, with CH_4 emissions during soil preparation and uptake at the end of the crop cycle.

In the CT system, the increase in CH_4 flux during Period 1 (0.074 ± 0.07 μg N m⁻² h⁻¹) may be attributed to greater soil disturbance caused by mechanized tillage, which exposes organic matter to rapid mineralization and alters the microbiological balance of the rhizosphere (Mehra et al., 2018; Lage Filho et asl., 2023). Such disturbance favors, in the short term, CH_4 production, although this effect is usually transient. The activity of methanotrophic bacteria — important agents in CH_4 oxidation — may be favored by conservation practices such as NT, as these conditions tend to maintain soil structure stability and preserve the microbial trophic network (Kollah et al., 2020; Moanty et al., 2022). In this context, the net CH_4 balance may represent an important ecosystem service associated with sustainable soil management.

Recent global and tropical assessments also confirm the strong CH_4-sink behaviour of no-tillage systems (Ma et al., 2020; **Cowan et al., 2021; Wu et al., 2020**).

3.3 EDAPHIC PARAMETERS

Soil moisture showed similar averages between the systems (25.07 ± 2.02% in CT and 25.07 ± 1.17% in NT), with discrete seasonal variations. The decrease in moisture during Period 3, especially under NT (23.10 ± 0.78%), may be associated with increased crop evapotranspiration and greater soil exposure due to crop senescence.

Soil temperature was also similar on average between systems (27.1 °C for both CT and NT). However, a different trend was observed over time: in CT, there was a slight decrease in values across periods (from 27.5 ± 0.8 °C in Period 1 to 26.5 ± 0.2 °C in Period 3); in NT, temperature increased by approximately 1.5 °C from Period 1 (26.5 ± 0.4 °C) to Period 3 (28.2 ± 0.2 °C). This difference may be associated with a thicker residual plant cover in NT, which acts as a thermal insulator and influences the edaphic microclimate (Semenov et al., 2022).

The high sampling frequency allowed for an adequate characterization of the seasonal dynamics of trace gas emissions, showing that both management systems exhibited relatively low absolute fluxes of N_2O and CH_4. However, the temporal patterns observed reinforce the importance of specific events—such as fertilization, soil disturbance, and straw decomposition—as key modulators of emission peaks (Oliveira Junior et al., 2015).

Compared to studies conducted in humid tropical areas with poorly drained soils, where fluxes can be up to two orders of magnitude higher (Toteva et al., 2024), the results obtained here reflect the characteristics of well-drained, acidic, and low-fertility Oxisols in the Paragominas region (Rodrigues et al., 2003; Brasil, 2018). The low availability of labile carbon and rapid water infiltration in these soils help limit reductive processes and, consequently, the production of gases such as N_2O and CH_4.

These findings have important implications for greenhouse gas emission modeling in tropical agriculture, indicating that soil management may have a secondary effect compared to the influence of local microclimatic and biogeochemical factors. The integration of edaphic, climatic, and phenological data is essential for building effective mitigation strategies aligned with the productive reality of agriculture in the eastern Amazon.

The coupling between low WFPS and low labile carbon supply likely constrained denitrification, supporting the low N_2O levels observed. Similarly, rapid oxygen diffusion in clayey Oxisols and the absence of saturating rainfall likely promoted CH_4 oxidation throughout the season.

Soil moisture and temperature showed similar means across systems, but their temporal trajectories differed. NT had slightly lower moisture and higher temperature during Period 3, likely due to crop senescence and residue-mediated thermal buffering. Recent studies demonstrate that subtle shifts in moisture and thermal regimes can modulate microbial activity and trace-gas dynamics in tropical soils (Semenov et al., 2022; Oliveira et al., 2025).

These edaphic patterns help explain the low magnitude of both gases. Limited labile C and low water-filled pore space reduce the likelihood of anaerobic microsites, constraining denitrification and methanogenesis while favoring CH_4 oxidation.

3.4 INTEGRATED INTERPRETATION OF GREENHOUSE GAS DYNAMICS

Across the soybean cycle, microenvironmental factors dominated GHG regulation, while management system effects were minor. The predominance of CH_4 uptake and low N_2O emissions align with recent findings from Amazonian and Cerrado Oxisols, where hydrological and carbon constraints override management influences (Oliveira et al., 2025; Monteiro et al., 2024; Oliveira Junior et al., 2015).

NT enhanced CH_4 consumption slightly late in the season, suggesting modest mitigation potential, but differences between CT and NT remained small. This likely reflects the combination of well-drained soils, low N inputs, limited residue loads, and absence of extreme rainfall.

3.5 IMPLICATIONS FOR MITIGATION AND REGIONAL INVENTORIES

These findings offer several implications:

1. **Baseline emissions from soybean cultivation on Oxisols in the eastern Amazon are intrinsically low**, especially for CH_4.
2. NT presents small but meaningful mitigation potential via enhanced CH_4 oxidation.
3. Event-driven N_2O peaks, although absent here, remain critical for long-term assessments, demanding high-frequency monitoring.

4. The results contribute empirical evidence to refine **regional emission factors**, which remain among the least constrained in Brazil's NDC framework (Brasil, 2020).
5. The observed flux patterns align with mitigation strategies promoted by Embrapa's Fluxus program and the national ABC+ policy.

These insights reinforce the need for **long-term, event-driven monitoring campaigns** and the inclusion of tropical Amazonian Oxisols in future efforts to parameterize models of nitrogen cycling and soil GHG dynamics.

4 CONCLUSIONS

This study demonstrates that soybean production on very clayey Yellow Latosols in the eastern Amazon exhibits intrinsically low soil emissions of N_2O and CH_4 regardless of tillage system. The absence of strong differences between CT and NT reflects the overriding influence of soil physical and hydrological properties—particularly rapid drainage, low labile carbon availability, and restricted anaerobic microsites—which collectively limit both denitrification and methanogenesis. The predominance of CH_4 uptake further reinforces the role of these soils as atmospheric CH_4 sinks. Although NT enhanced CH_4 consumption slightly during the late season, management-driven contrasts remained small due to low nitrogen inputs, modest residue loads, and the absence of extreme rainfall events capable of generating short-lived emission pulses. The temporal patterns of soil moisture and temperature were key determinants of gas fluxes, underscoring the importance of microenvironment-driven controls in tropical agroecosystems. These results contribute critical empirical data for improving regional and national GHG inventories and highlight the need for high-frequency monitoring during rainfall and fertilization windows to capture the episodic events that dominate annual N_2O budgets in tropical agriculture.

ACKNOWLEDGEMENTS

We thank the Fluxus Project, from Embrapa Eastern Amazon, for the opportunity and financial support for this research. We are also grateful to technician Cleuton Pereira for his assistance and collaboration during field sampling.

REFERENCES

Abalos, D., Recous, S., Butterbach-Bahl, K., De Notaris, C., Rittl, T. F., Topp, C. F. E., Petersen, S. O., & et al. (2022). A review and meta-analysis of mitigation measures for nitrous oxide emissions from crop residues. Science of the Total Environment, 828, Article 154388. https://doi.org/10.1016/j.scitotenv.2022.154388

Alves, L. W. R., Carvalho, E. J. M., Silva, L. G. T., Martorano, L. G., Siviero, M. A., Tourne, D. C. M., Vieira, S. B., Fitzjarrald, D. R., Vettorazzi, C. A., Brienza Júnior, S., Yeared, J. A. G., Meyering, É., & Lisboa, L. S. S. (2014). Diagnóstico agrícola do município de Paragominas, PA (Boletim de Pesquisa e Desenvolvimento No. 91). Embrapa Amazônia Oriental.

Armacolo, N. M., Mombach, M. A., da Silveira, J. G., Romeiro, S. O., & Rodrigues, R. A. R. (2015). Emissões de gases de efeito estufa em sistema agroflorestal na região da Amazônia Matogrossense. In Anais do 35º Congresso Brasileiro de Ciência do Solo. Sociedade Brasileira de Ciência do Solo; Embrapa Solos.

Berndt, A., & et al. (2013). Dados de inventários nacionais de GEE no setor agropecuário [Relatório institucional]. Embrapa / SEEG.

Brasil. Embrapa Solos. (2017). Manual de métodos de análise de solo (3ª ed. rev. e ampl.). Embrapa Solos.

Brasil. Embrapa Solos. (2018). Sistema brasileiro de classificação de solos (5ª ed. rev. e ampl.). Embrapa. ISBN 978-85-7035-817-2

Brasil. Ministério da Ciência, Tecnologia e Inovações. (2020). Quarta comunicação nacional do Brasil à Convenção-Quadro das Nações Unidas sobre Mudança do Clima. MCTI. ISBN 978-65-87432-18-2

Butterbach-Bahl, K., Baggs, E. M., Dannenmann, M., Kiese, R., & Zechmeister-Boltenstern, S. (2013). Nitrous oxide emissions from soils: How well do we understand the processes and their controls? Philosophical Transactions of the Royal Society B: Biological Sciences, 368(1621), Article 20130122. https://doi.org/10.1098/rstb.2013.0122

Carvalho, J. L. N., Avanzi, J. C., Silva, M. L. N., Mello, C. R., & Cerri, C. E. P. (2010). Potencial de sequestro de carbono em diferentes biomas do Brasil. Revista Brasileira de Ciência do Solo, 34(2), 277–289. https://doi.org/10.1590/S0100-06832010000200001

Coe, M. T., Brando, P. M., Deegan, L. A., Macedo, M. N., Neill, C., & Silvério, D. V. (2017). The forests of the Amazon and Cerrado moderate regional climate and are the key to the future. Tropical Conservation Science, 10. https://doi.org/10.1177/1940082917720671

Covey, K., Soper, F. M., Pangala, S. R., Bernardino, A. F., Pagliaro, Z., & et al. (2021). Carbon and beyond: The biogeochemistry of climate in a rapidly changing Amazon. Frontiers in Forests and Global Change, 4, Article 618401. https://doi.org/10.3389/ffgc.2021.618401

Cowan, N., Maire, J., Krol, D., Cloy, J. M., Hargreaves, P., Murphy, R., Carswell, A., & et al. (2021). Agricultural soils: A sink or source of methane across regions. European Journal of Soil Science, 72(6), 1842. https://doi.org/10.1111/ejss.13075

da Cruz Corrêa, D. C., Poccard-Chapuis, R., Blanfort, V., Bochu, J.-L., & Lescoat, P. (2025). Impacts of cattle farming practices and associated livestock systems on energy balances and greenhouse gas emissions in the municipality of Paragominas - State of Pará - Amazonia. Deleted Journal, 15, Article 14461. https://doi.org/10.3389/past.2025.14461

Embrapa – Empresa Brasileira de Pesquisa Agropecuária. (2014). Projetos estruturantes para mitigação de gases de efeito estufa: Pecus, Saltus e Fluxus. Embrapa Meio Ambiente; Embrapa Agricultura Digital.

Fearnside, P. M. (2018). Brazil's Amazonian forest carbon: The key to Southern Amazonia's significance for global climate. Regional Environmental Change, 18(1), 47–61. https://doi.org/10.1007/s10113-016-1007-2

Gatti, L. V., Basso, L. S., Miller, J. B., & et al. (2021). Amazonia as a carbon source linked to deforestation and climate change. Nature, 595(7867), 388–393. https://doi.org/10.1038/s41586-021-03629-6

Guo, X.-B., Drury, C. F., Yang, X., Reynolds, D., & Fan, R. (2014). The extent of soil drying and rewetting affects nitrous oxide emissions, denitrification, and nitrogen mineralization. Soil Science Society of America Journal, 78(1), 194–204. https://doi.org/10.2136/sssaj2013.06.0219

Horwath, W., & Kuzyakov, Y. (2018). The potential for soils to mitigate climate change through carbon sequestration. In Advances in agronomy (Vol. 150, pp. 185–230). Elsevier. https://doi.org/10.1016/B978-0-444-63865-6.00003-X

Hutchinson, G. L., & Mosier, A. R. (1981). Improved soil cover method for field measurement of nitrous oxide fluxes. Soil Science Society of America Journal, 45(2), 311–316. https://doi.org/10.2136/sssaj1981.03615995004500020017x

Instituto Brasileiro de Geografia e Estatística. (2023). Produção agrícola municipal (PAM) 2023 e Levantamento sistemático da produção agrícola (LSPA). SIDRA/IBGE.

International Organization for Standardization. (2019). Soil quality — Guidelines for measurement of greenhouse gases from soils using chamber technique (ISO 20951:2019). https://www.iso.org/standard/69534.html

Intergovernmental Panel on Climate Change. (2021). Climate change 2021: The physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. https://doi.org/10.1017/9781009157896

Kirkby, R., Friedl, J., Takeda, N., & et al. (2023). Nonlinear response of N_2O and N_2 emissions to increasing soil nitrate availability in a tropical sugarcane soil. Journal of Soils and Sediments, 23(7), 2065–2071. https://doi.org/10.1007/s11368-023-03482-2

Kollah, B., Bakoriya, M., Dubey, G., & et al. (2020). Methane consumption potential of soybean-wheat, maize-wheat and maize-gram cropping systems under conventional and no-tillage agriculture in a tropical vertisol. The Journal of Agricultural Science, 158(1-2), 38–46. https://doi.org/10.1017/S0021859620000416

Krichels, A. H., Homyak, P. M., Aronson, E. L., Sickman, J. O., Botthoff, J., Shulman, H., Piper, S., & Andrews, H. M. (2022). Rapid nitrate reduction produces pulsed NO and N_2O emissions following wetting of dryland soils. Biogeochemistry, 158(2), 233–250. https://doi.org/10.1007/s10533-022-00896-x

Lage Filho, N. M., Cardoso, A. d. S., Azevedo, J. C. d., Faturi, C., da Silva, T. C., Domingues, F. N., Ruggieri, A. C., Reis, R. A., & do Rêgo, A. C. (2022). Land use, temperature, and nitrogen affect nitrous oxide emissions in Amazonian soils. Agronomy, 12(7), Article 1608. https://doi.org/10.3390/agronomy12071608

Lage Filho, N. M., Cardoso, A. S., Azevedo, J. C., & et al. (2023). How does land use change affect the methane emission of soil in the Eastern Amazon. Frontiers in Environmental Science, 11, Article 1244152. https://doi.org/10.3389/fenvs.2023.1244152

Lashermes, G., Recous, S., Alavoine, G., Janz, B., Butterbach-Bahl, K., Ernfors, M., & Laville, P. (2022). N_2O emissions from decomposing crop residues are strongly linked to their initial soluble fraction and early C mineralization. Science of the Total Environment, 806(Pt 4), Article 150883. https://doi.org/10.1016/j.scitotenv.2021.150883

Liu, X., Wu, X., Liang, G., Zheng, F., Zhang, M., & Li, S. (2021). A global meta-analysis of the impacts of no-tillage on soil aggregation and aggregate-associated organic carbon. Land Degradation & Development, 32(18), 5292–5305. https://doi.org/10.1002/ldr.4109

Ma, L., & et al. (2020). In situ measurements and meta-analysis reveal land management controls on soil CH_4 uptake. Science of the Total Environment, 712, Article 136048. https://doi.org/10.1016/j.scitotenv.2019.136048

Ministério da Agricultura, Pecuária e Abastecimento. (2021). Plano setorial para adaptação à mudança do clima. MAPA.

Martins, M. dos S., & et al. (2021). Physical-hydraulic properties of the soil in areas with different land uses in the eastern Amazon region, Brazil. Revista Brasileira de Ciência do Solo, 45, Article e0200142.

Maucieri, C., Tolomio, M., McDaniel, M. D., Zhang, Y., Robatjazi, J., & Borin, M. (2021). No-tillage effects on soil CH_4 fluxes: A meta-analysis. Soil and Tillage Research, 212, Article 105042. https://doi.org/10.1016/j.still.2021.105042

Mehra, P., Baker, J., Sojka, R. E., Bolan, N., Desbiolles, J., Kirkham, M. B., Ross, C., Gupta, R., & et al. (2018). A review of tillage practices and their potential to impact the soil carbon dynamics. In Advances in agronomy (Vol. 150, pp. 185–230). Elsevier. https://doi.org/10.1016/bs.agron.2018.03.002

Monteiro, A., Barreto Mendes, L., Fanchone, A., Morgavi, D. P., Pedreira, B. C., Magalhães, C. A. S., Abdalla, A. L., & Eugène, M. (2024). Crop-livestock-forestry systems as a strategy for mitigating greenhouse gas emissions and enhancing the sustainability of forage-based livestock systems in the Amazon biome. Science of the Total Environment, 906, Article 167396. https://doi.org/10.1016/j.scitotenv.2023.167396

Mirzaei, M., Gorji Anari, M., Taghizadeh-Toosi, A., Zaman, M., Saronjic, N., Mohammed, S., Szabo, S., & Caballero-Calvo, A. (2022). Soil nitrous oxide emissions following crop residues management in corn-wheat rotation under conventional and no-tillage systems. Air, Soil and Water Research, 15(1). https://doi.org/10.1177/11786221221128789

Moraes, L. M., Lage Filho, N. M., Abreu, N. L., Ruggieri, A. C., Faturi, C., Silva, T. C., & Rêgo, A. C. (2025). Soil greenhouse gas emissions under different land uses in the Eastern Amazon. Revista Brasileira de Agroambiente, 19. https://doi.org/10.18227/1982-8470ragro.v19i00.8578

Nascimento, A. F., Rodrigues, R. A. R., Silveira, J. G., Silva, J. J. N., Daniel, V. C., & Segatto, E. R. (2020). Nitrous oxide emissions from a tropical Oxisol under monocultures and an integrated system in the Southern Amazon – Brazil. Revista Brasileira de Ciência do Solo, 44, Article e0190123. https://doi.org/10.36783/18069657rbcs20190123

Oertel, C., Matschullat, J., Zurba, K., Zimmermann, F., & Erasmi, S. (2016). Greenhouse gas emissions from soils—A review. Geochemistry, 76(3), 327–352. https://doi.org/10.1016/j.chemer.2016.04.002

Oliveira Junior, R. C., Keller, M., Crill, P., Beldini, T., van Haren, J., & Camargo, P. (2015). Trace gas fluxes from intensively managed rice and soybean fields across three growing seasons in the Brazilian Amazon. African Journal of Agricultural Research, 10(39), 3748–3758. https://doi.org/10.5897/AJAR2015.10241

Oliveira, A. D. de, Antonini, J. C. dos A., Santos, M. V. A. dos, Andrade, A. C. M. de, Malaquias, J. V., Carvalho, A. M. de, Muller, A. G., Delvico, F. M. d. S., Mendes, I. d. C., & Chagas, J. H. (2025). Sustainable irrigation management of winter wheat and effects on soil gas emissions (N_2O and CH_4) and enzymatic activity in the Brazilian Savannah. Sustainability, 17(17), Article 7734. https://doi.org/10.3390/su17177734

Osis, R., Laurent, F., & Poccard-Chapuis, R. (2019). Spatial determinants and future land use scenarios of Paragominas municipality, an old agricultural frontier in Amazonia. Journal of Land Use Science, 14(3), 258–279. https://doi.org/10.1080/1747423X.2019.1643422

Quesada, C. A., Paz, C., Oblitas Mendoza, E., Phillips, O. L., Saiz, G., & Lloyd, J. (2020). Variations in soil chemical and physical properties explain basin-wide Amazon forest soil carbon concentrations. SOIL, 6(1), 53–88. https://doi.org/10.5194/soil-6-53-2020

Rodrigues, T. E., Silva, R. das C., Silva, J. M. L. da, Oliveira Junior, R. C. de, Gama, J. R. N. F., & Valente, M. A. (2003). Caracterização e classificação dos solos do município de Paragominas, Estado do Pará (Documentos No. 162). Embrapa Amazônia Oriental. https://ainfo.cnptia.embrapa.br/digital/bitstream/item/63746/1/Oriental-Doc162.PDF

Rubaiyat, A., Hossain, M. L., Kabir, M. H., Sarker, M. M. H., Salam, M. M. A., & Li, J. F. (2023). Dynamics of greenhouse gas fluxes and soil physico-chemical properties in agricultural and forest soils. Journal of Water and Climate Change, 14(10), 3791–3809. https://doi.org/10.2166/wcc.2023.338

Semenov, V. M., Lebedeva, T. N., Zinyakova, N. B., Khromychkina, D. P., Sokolov, D. A., Lopes de Gerenyu, V. O., Kravchenko, I. K., Li, H., & Semenov, M. V. (2022). Dependence of soil organic matter and plant residues decomposition on temperature and moisture in the long-term incubation experiments. Eurasian Soil Science, 55(7), 926–939. https://doi.org/10.1134/S1064229322070080

Shakoor, A., Shakoor, S., Rehman, Ashraf, F., Abdullah, M., Shahza, S. M., Farooq, T. H., Ashraf, M., Manzoor, M. A., Altaf, M. M., & Altaf, M. A. (2021). Effect of animal manure, crop type, climate zone, and soil attributes on greenhouse gas emissions from agricultural soils - A global meta-analysis. Journal of Cleaner Production, 278, Article 124019. https://doi.org/10.1016/j.jclepro.2020.124019

Silva, E. V. da, & et al. (2013). O Projeto Saltus: Subsídios para a elaboração do inventário brasileiro de emissões antrópicas de gases de efeito estufa em sistemas florestais. In Anais do 18º Congresso Brasileiro de Agrometeorologia. Embrapa Amazônia Oriental.

Sousa, T. R., Ramos, M. L. G., Figueiredo, C. C., & Carvalho, A. M. (2021). N_2O emissions from soils under different uses in the Brazilian Cerrado - A review. Revista Brasileira de Ciência do Solo, 45, Article e0210093. https://doi.org/10.36783/18069657rbcs20210093

StatSoft Inc. (2004). STATISTICA (data analysis software system) (Version 7.0). Tulsa.

Syakila, A., & Kroeze, C. (2011). The global nitrous oxide budget revisited. Greenhouse Gas Measurement and Management, 1(1), 17–26. https://doi.org/10.3763/ghgmm.2010.0007

Tian, H., Xu, R., Canadell, J. G., & et al. (2020). A comprehensive quantification of global nitrous oxide sources and sinks. Nature, 586(7828), 248–256. https://doi.org/10.1038/s41586-020-2780-0

Toteva, G. Y., Reay, D., Jones, M. R., Cowan, N., Deshpande, A., Weerakoon, B., Nissanka, S., & Drewer, J. (2024). Nitrous oxide and nitric oxide fluxes differ from tea plantation and tropical forest soils after nitrogen addition. Frontiers in Forests and Global Change, 7, Article 1335775. https://doi.org/10.3389/ffgc.2024.1335775

Tubiełło, F. N., & et al. (2013). The FAOSTAT database of greenhouse gas emissions from agriculture. Environmental Research Letters, 8(1), Article 015009. https://doi.org/10.1088/1748-9326/8/1/015009

Venturini, A. M., Dias, N. M. S., Gontijo, J. B., Yoshiura, C. A., Paula, F. S., Meyer, K. M., Nakamura, F. M., da França, A. G., Borges, C. D., Barlow, J., Berenguer, E., Nüsslein, K., Rodrigues, J. L. M., Bohannan, B. J. M., & Tsai, S. M. (2022). Increased soil moisture intensifies the impacts of forest-to-pasture conversion on methane emissions and methane-cycling communities in the Eastern Amazon. Environmental Research, 212, Article 113139. https://doi.org/10.1016/j.envres.2022.113139

Vieira, I. C. G., Toledo, P. M., Melo, A. W. F., & Veríssimo, A. (2018). Deforestation, land use and environmental governance in Pará: Dynamics of agricultural expansion in eastern Amazonia. Land Use Policy, 76, 103–112. https://doi.org/10.1016/j.landusepol.2018.05.020

Wu, J., & et al. (2020). Asymmetric response of soil methane uptake rate to land degradation and restoration. Global Change Biology. https://doi.org/10.1111/gcb.15315

Xu, R., & et al. (2020). Global N_2O emissions from cropland driven by nitrogen inputs. Global Biogeochemical Cycles. https://doi.org/10.1029/2020GB006698

Yue, K., & et al. (2023). No-tillage decreases GHG emissions with no crop yield penalty: A meta-analysis. Agriculture, Ecosystems & Environment. https://doi.org/10.1016/j.still.2023.105643