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Efeito de sistemas de gerenciamento nas emissões de gases de efeito estufa em uma cultura de grãos no município de Macapá-AP

Effect of management systems on greenhouse gas emissions in a grain crop in the municipality of Macapá-AP

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RESUMO

A expansão da agricultura na região Amazônica levanta preocupações sobre sua contribuição para as emissões de Gases de Efeito Estufa (GEE). Este estudo avaliou os fluxos de dióxido de carbono (CO_2), óxido nitroso (N_2O) e metano (CH_4) no cultivo de soja sob sistemas de Plantio Convencional (PC) e Plantio Direto (PD) em um Latossolo Amarelo argiloso em Macapá-AP, Brasil. A amostragem de gases foi realizada utilizando câmaras estáticas e analisada por cromatografia gasosa. Os resultados indicaram que o PC apresentou maiores emissões médias de N_2O (0,18 ± 0,17 µg-N m^{-2} h^{-1}) em comparação ao PD (0,007 ± 0,002), com um declínio temporal significativo pós-adubação. O PC exibiu uma captura líquida de CO_2 (-816 ± 852,9 mg-C m^{-2} h^{-1}), enquanto o PD mostrou emissões líquidas (733,9 ± 1459,8 mg-C m^{-2} h^{-1}), atribuídas à decomposição dos resíduos culturais. Ambos os sistemas atuaram como fracos sumidouros de CH_4, sem diferenças significativas entre eles. A temperatura do solo permaneceu estável (27,1 ± 1,5 °C) entre os tratamentos. Os resultados sugerem que a adoção de curto prazo (dois anos) do PD nesta região tropical ainda não conferiu vantagens significativas de mitigação para N_2O e CH_4 em comparação com o PC, destacando a importância da fase de adaptação do sistema. A alta variabilidade nos fluxos de CO_2 ressalta a complexa interação entre o manejo de resíduos e a respiração microbiana. Estudos de longo prazo são essenciais para avaliar com precisão o potencial de mitigação de GEE das práticas conservacionistas na fronteira agrícola amazônica.

Palavras-chave: Mudanças Climáticas, Manejo do Solo, Plantio Direto, Plantio Convencional, Câmara Estática, Amazônia.

ABSTRACT

The expansion of agriculture in the Amazon region raises concerns about its contribution to greenhouse gas (GHG) emissions. This study evaluated the fluxes of carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) in soybean cultivation under conventional tillage (CT) and no-till (NT) systems on a clayey Yellow Latosol in Macapá-AP, Brazil. Gas sampling was performed using static chambers and analyzed by gas chromatography. The results indicated that CT showed higher mean N_2O emissions (0.18 ± 0.17 µg-N m^{-2} h^{-1}) compared to NT (0.007 ± 0.002), with a significant temporal decline post-fertilization. CT exhibited a net CO_2 uptake (-816 ± 852.9 mg-C m^{-2} h^{-1}), while NT showed net emissions (733.9 ± 1459.8 mg-C m^{-2} h^{-1}), attributed to residue decomposition. Both systems acted as weak CH_4 sinks, with no significant differences between them. Soil temperature remained stable (27.1 ± 1.5 °C) across treatments. The findings suggest that the short-term adoption (two years) of NT in this tropical region did not yet confer significant mitigation advantages for N_2O and CH_4 compared to CT, highlighting the importance of the system's adaptation phase. The high variability in CO_2 fluxes underscores the complex interplay between residue management and microbial respiration. Long-term studies are essential to accurately assess the GHG mitigation potential of conservation practices in the Amazonian agricultural frontier.

Keywords: Climate Change, Soil Management, No-Till, Conventional Tillage, Static Chamber, Amazon.

RESUMEN
La expansión de la agricultura en la región amazónica genera preocupación por su contribución a las emisiones de gases de efecto invernadero (GEI). Este estudio evaluó los flujos de dióxido de carbono (CO_2), óxido nitroso (N_2O) y metano (CH_4) en el cultivo de soja bajo sistemas de labranza convencional (CT) y labranza cero (NT) en un latosol amarillo arcilloso en Macapá, AP, Brasil. El muestreo de gases se realizó utilizando cámaras estáticas y se analizó por cromatografía de gases. Los resultados indicaron que CT presentó mayores emisiones promedio de N_2O (0,18 ± 0,17 µg-N m^{-2} h^{-1}) en comparación con NT (0,007 ± 0,002), con una disminución temporal significativa después de la fertilización. El PC exhibió una captura neta de CO_2 (-816 ± 852,9 mg-C m^{-2} h^{-1}), mientras que el PD mostró emisiones netas (733,9 ± 1459,8 mg-C m^{-2} h^{-1}), atribuidas a la descomposición de residuos de cultivo. Ambos sistemas actuaron como sumideros débiles de CH_4, sin diferencias significativas entre ellos. La temperatura del suelo se mantuvo estable (27,1 ± 1,5 °C) entre los tratamientos. Los resultados sugieren que la adopción a corto plazo (dos años) del PD en esta región tropical aún no ha conferido ventajas de mitigación significativas para N_2O y CH_4 en comparación con el PC, lo que destaca la importancia de la fase de adaptación del sistema. La alta variabilidad en los flujos de CO_2 resalta la compleja interacción entre el manejo de residuos y la respiración microbiana. Los estudios a largo plazo son esenciales para evaluar con precisión el potencial de mitigación de GEI de las prácticas de conservación en la frontera agrícola amazónica.

Palabras clave: Cambio Climático, Manejo del Suelo, Agricultura sin Labranza, Labranza Convencional, Cámara Estática, Amazonía.

1 INTRODUÇÃO

The agricultural sector is recognized as one of the main contributors to global greenhouse gas (GHG) emissions, particularly carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4). While CO_2 is released in the largest quantities, N_2O and CH_4 exhibit much higher global warming potentials (GWP) — approximately 296 and 23 times greater, respectively, when compared to CO_2 (IPCC, 2001; Moreira and Siqueira, 2006).

In Brazil, the AFOLU sector (Agriculture, Forestry, and Other Land Use) represented nearly 74% of the country's total GHG emissions in 2021, with agriculture alone accounting for roughly 25%. At the same time, conservation practices such as no-till systems have contributed to a net removal of approximately − 67.5 Mt CO_2e (Soares *et al.*, 2025). These figures highlight the urgent need to develop and validate sustainable agricultural practices that can both mitigate emissions and sustain productivity in tropical biomes (Rodrigues *et al.*, 2024).

Globally, agriculture is responsible for 25–30% of anthropogenic GHG emissions, with N_2O and CH_4 dominating the sector's contribution (IPCC, 2019; Smith *et al.*, 2014). Emissions of N_2O, primarily associated with nitrogen fertilizer use and manure management, represent the largest single agricultural source, while CH_4 arises largely from rice paddies and enteric fermentation in ruminants. However, cropland soils under intensive management also contribute significantly, particularly in regions with expanding agricultural frontiers such as the tropics.

Meta-analyses indicate that N_2O emissions increase exponentially rather than linearly with nitrogen application (Shcherbak, Millar and Robertson, 2014; Wang *et al.*, 2021), suggesting that even moderate reductions in fertilizer inputs, combined with improved soil management, can yield disproportionally large mitigation benefits. These findings reinforce the need to integrate precision agriculture with conservation practices to reduce emissions without compromising crop productivity.

For CH_4, the role of agricultural soils is dualistic: depending on management intensity and soil redox conditions, they may act as either net sources or sinks. No-till systems tend to improve soil structure, enhance aeration, and stimulate methanotrophic bacteria, leading to increased CH_4 oxidation (Six *et al.*, 2004). Yet, in tropical soils, hydrological variability and episodic waterlogging can suppress CH_4 uptake or even generate CH_4 emissions. This highlights the necessity of site-specific studies in tropical regions, where results are not easily extrapolated from temperate contexts.

Carbon dioxide fluxes are closely tied to soil respiration and organic carbon (SOC) balance. Conventional tillage accelerates SOC mineralization, while no-till enhances SOC storage, particularly in surface horizons (West and Post, 2002). Nevertheless, the permanence of these carbon gains in tropical soils is debated, as high temperatures and rainfall accelerate organic matter turnover and may limit long-term sequestration (Chambers *et al.*, 2016).

Brazilian studies contribute important evidence to this debate. For example, Passianoto *et al.* (2003) e Bayer and Bertol (2003) found that conventional tillage increased CO_2 emissions by 37% within two months, while no-till limited the increase to only 7%. Similarly, long-term experiments (over 40 years) in southern Brazil revealed that incorporating cover crops in no-till rotations could reduce net GHG emissions by 40% to over 100%, with legumes such as pigeon pea and lablab leading to negative net emissions (−1.2 Mg CO_2e ha^{-1}) while increasing maize productivity (Soares *et al.*, 2025). In Paraná, no-till systems were also observed to function as CH_4 sinks, with the highest oxidation rates occurring under alfalfa–maize rotations (Albuquerque, 2012a).

Despite these advances, the knowledge base on GHG mitigation potential in tropical agricultural systems remains fragmented and insufficient (Chung *et al.*, 2008; Albuquerque, 2012b). Most robust long-term data come from temperate regions, where soil characteristics, climate, and management differ significantly. In the Amazon, highly weathered soils, acidity, and rapid organic matter turnover create unique dynamics that are still poorly understood, particularly concerning N_2O emissions and the balance between CH_4 uptake and release.

In response, Brazil has launched ambitious low-carbon agriculture programs (ABC+), with a mitigation target of 164.3 million Mg CO_2e between 2020 and 2030. However, realizing this potential requires robust scientific validation based on in situ measurements of GHG fluxes. These measurements are crucial to parameterize and validate process-based simulation models such as Rothamsted, Century, and DayCent, which are widely used to estimate GHG emissions at larger scales (Rodrigues *et al.*, 2024). Yet, without adequate field data from tropical regions, the predictive capacity of these models remains limited.

Recognizing these challenges, Embrapa has launched large-scale projects — PECUS (livestock), SALTUS (forestry), and FLUXUS (grains) — to generate comprehensive national datasets on GHG emissions under different land uses and management systems. These initiatives are particularly relevant in the Amazon, where expanding croplands pose both a risk of increased emissions and an opportunity for mitigation through sustainable intensification.

2 METODOLOGIA

2.1 STUDY AREA AND CLIMATE CHARACTERISTICS

The experiment was carried out in 2016 in an experimental field located in Macapá, Brazil (0.0342° S, 51.0664° W). The region is classified as a tropical monsoon climate (Köppen Aw), with well-defined rainy and dry seasons. Annual precipitation averages 1,743 mm, with approximately 85% relative humidity and a mean annual temperature of 26.3 °C (Rodrigues *et al.*, 2000). Rainfall is concentrated from December to June, whereas a distinct dry period occurs between July and November. The predominant soil type in the experimental site is a clayey Yellow Latosol (Oxisol), characterized by low natural fertility but favorable physical attributes, such as good structure and drainage, which make it suitable for mechanized cultivation (Rodrigues *et al.*, 2000).

2.2 EXPERIMENTAL DESIGN

The study was designed to compare two contrasting soil management systems under soybean (*Glycine max*) cultivation. In the no-till (NT) system, soybeans had been grown for two consecutive years without soil disturbance, maintaining surface crop residues as a protective layer. In contrast, the conventional tillage (CT) system involved mechanical soil preparation through plowing and harrowing prior to planting. These treatments were selected to represent typical management strategies used in soybean production across the Amazonian frontier, allowing the evaluation of their effects on greenhouse gas (GHG) fluxes.

2.3 GAS SAMPLING PROTOCOL

Greenhouse gas emissions were quantified using the static chamber method. For each management system, ten chambers were randomly installed in the field, totaling 20 chambers across treatments. Each chamber was equipped with four sampling ports, enabling the collection of 40 gas samples per treatment at each sampling event. Sampling followed a stratified temporal scheme to capture both short-term and long-term dynamics. Immediately after fertilization, samples were collected daily for eight consecutive days in order to detect emission peaks associated with fertilizer application. Subsequently, from the ninth day until crop harvest, samples were taken weekly to encompass variations linked to different phenological stages of soybean.

To complement gas flux measurements, ancillary environmental variables were monitored at each sampling. Soil temperature was recorded at 2 cm depth using a Taylor digital thermometer, while air temperature was measured in shaded conditions adjacent to the chambers. These measurements provided context for interpreting GHG dynamics and allowed the assessment of potential correlations with environmental drivers.

2.4 LABORATORY ANALYSIS

Collected gas samples were transported to the laboratory and analyzed by gas chromatography (GC-2014, Shimadzu) for the determination of carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) concentrations. Gas fluxes were calculated according to the procedures described by Oliveira Junior *et al.* (2015), which account for chamber headspace volume, sampling time, and concentration gradients. This methodology is widely validated for agricultural systems and ensures comparability with similar studies.

2.5 DATA PROCESSING AND STATISTICAL ANALYSIS

Prior to statistical analyses, flux data for N_2O and CH_4 were transformed [log (N_2O

+ 60) and log (CH_4 + 650)] to correct deviations from normality and stabilize variances, as commonly recommended for skewed ecological datasets. Treatment effects were evaluated using one-way analysis of variance (ANOVA), followed by Tukey's test (α = 0.05) to detect pairwise differences between management systems. In addition, simple linear regressions were performed to investigate the influence of soil temperature and moisture on gas fluxes. All analyses were conducted using STATISTICA 7.0 software (StatSoft Inc.), ensuring rigorous statistical control.

2.6 QUALITY CONTROL

To minimize diurnal variability, gas samples were systematically collected in the morning, between 08:00 and 10:00. Blank samples were also taken during each sampling campaign to correct for potential background contamination and ensure accuracy in gas concentration measurements. These procedures provided robust quality control and reliability to the dataset, strengthening the validity of the results.

3 RESULTADOS E DISCUSSÕES

3.1 GREENHOUSE GAS FLUXES AND SOIL TEMPERATURE DYNAMICS

Table 1 presents the mean fluxes of N_2O, CO_2 e CH_4, and soil temperature across soybean growth stages under conventional tillage (CT) and no-till (NT) systems in Macapá, AP.

Table 1. Mean fluxes (with standard error, SEM) of N_2O, CO_2, CH_4, and soil temperature under different management systems

Stadium	N_2O ± SEM µg-N m^{-2} h^{-1}	CO_2 ± SEM mg-C m^{-2} h^{-1}	CH_4 ± SEM µg-C m^{-2} h^{-1}	Temp °C
		Conventional Tillage		
Period 1	-0,07 ± 0,05a	24,21 ± 110,97a	0,95 ± 1,02a	27,5 ± 0,8a
Period 2	-0,001 ± 0,005b	128,12 ± 57,27a	0,001 ± 0,007b	27,2 ± 2,0a
Total	-0,0108 ± 0,009	113,79 ± 51,62	0,13 ± 0,14	27,1 ± 1,5
		No-till		
Period 1	-0,015 ± 0,03a	-2,70 ± 14,45a	-0,10 ± 0,09a	26,5 ± 0,4a
Period 2	-0,002 ± 0,004a	78,63 ± 33,42a	-0,01 ± 0,007a	27,2 ± 1,3a
Total	-0,004 ± 0,006	67,54 ± 29,06	-0,006 ± 0,01	27,1 ± 1,2

Means followed by the same lowercase letter (within columns) or uppercase letter (comparing systems) do not differ significantly (Tukey's test, $p < 0.05$). SEM = Standard Error of the Mean. Source: Prepared by the authors.

Table 2 presents the average results of the CH4, CO2 and N2O gas fluxes and soil temperature during the corn crop cycle.

Table 2. Average values of CH4 fluxes, N2O flux, and CO2 flux (with standard error of the mean), and soil temperature, for the management systems studied, at different stages of soybean crop development, in the municipality of Macapá-AP

Stadium	N_2O ± SEM µg-N m^{-2} h^{-1}	CO_2 ± SEM mg-C m^{-2} h^{-1}	CH_4 ± SEM µg-C m^{-2} h^{-1}	Temp °C
		Conventional Tillage		
Period 1	1,21 ± 1,22aA	20,10 ± 11,05a	-0,006 ± 0,02a	27,5 ± 0,8a
Period 2	0,01 ± 0,004b	-948 ± 987,6a	-0,008 ± 0,006a	27,2 ± 2,0a
Total	0,18 ± 0,17	-816 ± 852,9	-0,008 ± 0,005	27,1 ± 1,5
		No-till		
Period 1	-0,003 ± 0,004aB	-1,80 ± 6,09a	-0,006 ± 0,009a	26,5 ± 0,4a
Period 2	-0,008 ± 0,002a	850,1 ± 1691,4a	-0,004 ± 0,003a	27,2 ± 1,3a
Total	0,007 ± 0,002	733,9 ± 1459,8	-0,004 ± 0,003	27,1 ± 1,2

Means followed by the same lowercase letters in the column between periods do not differ statistically from each other, according to Tukey's test (5% significance). SEM = standard error of the mean. Means followed by the same uppercase letters in the column do not differ statistically from each other, according to Tukey's test (5%) and compare periods between systems. Source: Prepared by the authors.

3.2 N_2O FLUXES

The results indicate that CT showed higher mean N_2O emissions (0.18 ± 0.17 µg-N m^{-2} h^{-1}) compared to NT (0.007 ± 0.002). Importantly, CT presented a significant decline in N_2O fluxes from Period 1 (post-fertilization) to Period 2 (harvest) ($p < 0.05$), reflecting the rapid depletion of mineral nitrogen after initial fertilization. In contrast, NT maintained fluxes close to zero throughout the cycle.

These findings diverge from several long-term studies reporting higher N_2O emissions under NT due to the accumulation of crop residues and enhanced denitrification potential (Oliveira Junior *et al.* (2015); Ciampitti *et al.*, 2008; Yang and Cai, 2005). A plausible explanation lies in the short adoption period of NT (two years) in the study area, which may not have been sufficient for the stabilization of soil microbial communities and for structural changes in soil organic matter (Fireston and Davidson, 1989; Franchini *et al.*, 2009).

The temporal dynamics observed reinforce the importance of considering the adaptation phase of NT systems. Long-term NT has been shown to enhance soil aggregation and organic matter stabilization, conditions that typically increase denitrification potential and N_2O fluxes (Snyder *et al.*, 2009; Huang *et al.*, 2018). However, under short-term NT, lower emissions can occur due to limited residue decomposition and reduced microbial activity (Baggs, 2011).

3.3 CO_2 FLUXES

CT exhibited an overall net CO_2 uptake (-816 ± 852.9 mg-C m^{-2} h^{-1}), while NT showed net emissions (733.9 ± 1459.8 mg-C m^{-2} h^{-1}). The high variability observed under NT suggests sporadic peaks of microbial respiration associated with residue decomposition and micro-environmental heterogeneity (Johnson *et al.*, 2005; Watanabe, 1999).

The contrasting results between CT and NT may reflect different soil C dynamics. In CT, soil disturbance through tillage enhances aeration and initial mineralization but also accelerates organic matter depletion, which in some cases results in temporary CO_2 uptake due to changes in soil-atmosphere diffusion gradients (Reicosky and Archer, 2007). In NT, residue accumulation at the soil surface promotes labile organic inputs that stimulate microbial activity and, consequently, CO_2 release (Oliveira Junior *et al.*, 2015; Six *et al.*, 2004).

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This dual role of NT—as both a potential C sink via residue retention and a C source via microbial respiration—emphasizes the complexity of interpreting soil CO_2 fluxes. Long-term monitoring and integrated C balance approaches are required to assess whether NT in tropical conditions leads to net sequestration or emission (Lal, 2004).

3.4 CH_4 FLUXES

Both systems acted as weak CH_4 sinks, with no significant statistical differences ($p > 0.05$). Mean fluxes were slightly lower in NT (-0.004 ± 0.003 mg-CH_4 m^{-2} h^{-1}) than in CT (-0.008 ± 0.005 mg-CH_4 m^{-2} h^{-1}). These results are consistent with studies demonstrating that well-drained tropical soils generally act as net CH_4 sinks (Smith *et al.*, 2003).

The slightly lower uptake in NT is consistent with the hypothesis that residue cover and reduced soil disturbance can reduce gas diffusivity into the soil matrix, limiting methanotrophic activity (Pimentel *et al.*, 2019). This effect tends to be more pronounced in poorly aerated soils or under high residue accumulation, conditions not predominant in the sandy soils of Macapá.

3.5 SOIL TEMPERATURE

Soil temperature remained relatively stable across treatments (27.1 ± 1.5 °C), indicating limited influence of tillage management on thermal regimes during the study period. However, the presence of residue cover in NT can buffer diurnal fluctuations and protect soil microclimate in longer-term scenarios (Al-Kaisi and Licht, 2004). Such microclimatic stabilization may indirectly influence greenhouse gas emissions by affecting microbial activity and soil moisture dynamics (Merino *et al.*, 2004).

3.6 INTEGRATED DISCUSSION

Overall, the absence of significant differences in GHG fluxes between CT and NT under short-term adoption conditions highlights the importance of long-term experimental assessments. Several studies conducted in tropical and subtropical regions indicate that NT only reaches its full potential for soil C sequestration and GHG mitigation after more than five years of continuous use (Franchini *et al.*, 2009; Lal, 2004; Six *et al.*, 2004).

Furthermore, fertilizer management plays a critical role in modulating GHG emissions, especially N_2O. Synchronizing N supply with crop demand, combined with NT adoption, has been shown to reduce cumulative emissions (Snyder *et al.*, 2009).

Thus, while the present results provide valuable insights into the early-phase dynamics of NT adoption in the Amazonian context, they also underscore the need for extended monitoring, with integrated measurements of soil C stocks, microbial community shifts, and GHG balances at seasonal and interannual scales.

4 CONCLUSION

The results demonstrate that greenhouse gas (GHG) dynamics in soybean and maize systems are strongly influenced by crop type and management practices. In soybean, nitrous oxide (N_2O) fluxes varied significantly over time under conventional tillage (CT), with higher emissions after planting compared to harvest, whereas no-till (NT) maintained stable emissions throughout the cycle. Methane (CH_4) fluxes also showed temporal variation under CT, decreasing at harvest, but remained unchanged under NT. Carbon dioxide (CO_2) fluxes did not differ between systems or periods, suggesting limited influence of tillage practices on this gas.

In maize, N_2O emissions showed temporal differences under CT and a significant contrast between CT and NT after planting, with higher fluxes under CT. In contrast to soybean, CH_4 emissions remained stable across periods and systems. As with soybean, CO_2 fluxes showed no significant differences between systems or periods, reinforcing the limited sensitivity of this gas to soil management.

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Overall, conventional tillage showed greater sensitivity to temporal variation in N_2O and CH_4 emissions, particularly in soybean. The absence of CO_2 differences suggests that environmental factors, such as soil moisture and temperature, exert greater control over fluxes than tillage systems. The contrasting responses between soybean and maize highlight the importance of crop-specific assessments when evaluating GHG emissions under different agricultural management practices.

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