



Impacts of long-term cassava-based conservation agriculture systems on soil greenhouse gas emissions in Cambodia

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ABSTRACT

Although cassava (*Manihot esculenta* Crantz) is regarded as an important food and energy crop, the effects of its cultivation on greenhouse gas (GHG) emissions remain poorly documented. This study, conducted in a tropical red Oxisol in Cambodia, quantified the effects of long-term cassava-based cropping systems on soil methane (CH₄) and nitrous oxide (N₂O) emissions using static chambers over two years (2022–24). Also accounting for measured change in soil organic carbon (SOC) stocks, the greenhouse gas balance (in CO₂-eq) of the systems was determined. Established in 2009, the replicated treatments included: (1) conventional tillage mono-cropping cassava (CTM-Cs), (2) no-till mono-cropping cassava with biomass retention (NTM-Cs), and (3) no-till bi-annual cassava-maize rotation with cover crops (NTR), where cassava (Cs) and maize (Mz) are grown in two separate plots: NTR1 and NTR2. CH₄-C emissions ranged from −123 to +141 μg CH₄-C m^{−2} hr^{−1}, with negligible cumulative emissions (−1.76 to +0.94 kg CH₄-C ha^{−1} yr^{−1}), depending on cropping systems and season. In cassava treatments, N₂O-N emissions peaked after mineral fertilizer application (up to +141 μg N₂O-N m^{−2} hr^{−1}), while maize treatment showed the higher peaks (up to +437.18 μg N₂O-N m^{−2} hr^{−1}) after cover crop termination under NTR. Cassava treatments had lower ($p < 0.05$) average cumulative N₂O-N emissions (0.74–0.87 kg N₂O-N ha^{−1} yr^{−1}) than maize (1.42 kg N₂O-N ha^{−1} yr^{−1}). With similar yield-scaled CH₄ and N₂O emissions, cassava yield under NTR-Cs was 20–30% higher ($p > 0.05$) than CTM-Cs and NTM-Cs, respectively. Accounting for CH₄ and N₂O emissions and annual SOC accumulation, NTM-Cs, NTR1 and NTR2 systems (2022–24) resulted in a net climate mitigation benefit by sequestering −3.52, −1.93 and −3.16 Mg CO₂-eq ha^{−1} yr^{−1}, respectively. Our results showed that while N₂O emissions were consistently higher in the treatment characterized by greater cover crop residue quantity and quality, they only slightly offset the climate benefits due to increased SOC stocks. Overall, the findings underscore the potential of NT systems for sustainable cassava production and climate change mitigation.

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1. Introduction

Agriculture, forestry, and other land uses (AFOLU) represented one of the main sources of anthropogenic greenhouse gas (GHG) emissions and accounted for 19%, equivalent to 10.90 Gt CO₂-eq, of the global net anthropogenic GHG emissions in 2020 (IPCC, 2023; Li et al., 2024, 2025). The significant sources of agricultural GHG emissions include forest conversion for farming, livestock production, manure management, mineral N fertilizer application, crop residues, and irrigation (Li et al., 2025). However, depending on management practices, agricultural soils can serve as either a source or a sink of GHG emissions. Conventional tillage (CT) (Lal, 1991; Krstić, 2024) and high use of inorganic and organic inputs are sources of GHG emissions (Choudhary et al., 2024). Agroforestry (Mutuo et al., 2005), the proper application rate of organic-based amendments (Bharali et al., 2021; Chau et al., 2023), low crop residues retention (Choudhary et al., 2024), along with right placement of mineral fertilizers were reported to reduce methane (CH₄) and nitrous oxide (N₂O) emissions (Bhuiyan et al., 2023; Islam et al., 2024). No-till (NT) cropping systems, which are part of conservation agriculture (CA), have been gaining momentum in practice and are widely promoted as a means of enhancing food security and mitigating climate change (Gonçalves et al., 2018; Gonzalez Sanchez et al., 2020). A recent review suggested that the benefit of CA for climate change adaptation and mitigation can only be achieved if all the CA principles are consistently implemented (Freitag et al., 2024). Among the key principles of CA, cover crops have the capacity to sequester soil organic carbon (SOC) and offer additional co-benefits (Poeplau and Don, 2015; Poeplau et al., 2024; Delgado et al., 2021). Despite numerous potential advantages of cover crops, comprehensive reviews showed that their effects on GHG emissions can be contrasted and variable (Daryanto et al., 2018; Van Eerd et al., 2023). Cover crops have been identified as a promising approach for reducing GHG emissions by concurrently reducing soil mineral nitrogen (N) concentration (Van Eerd et al., 2023), and preventing nitrate (NO₃) leaching (Nouri et al., 2022). On the other hand, from a systematic review of 377 studies, Daryanto et al. (2018) found that cover crops are significant sources of GHG emissions, with 49% higher N₂O emissions, when compared with non-cover cropping. However, the increased N₂O emissions induced by cover crops vary depending on cropping systems, cover crop species, seed rates, planting and termination dates, climatic conditions, soil types, and N fertilizer rate (Nouri et al., 2022; Li et al., 2023; Van Eerd et al., 2023). The decomposition of legume cover crop residues, particularly with a low C:N ratio, can generate higher N₂O emissions than non-leguminous cover crops by supplying labile C and N (Daryanto et al., 2018; Rigon et al., 2021) and releasing more NO₃ after termination, thus serving as the source of N₂O emissions (Mohammed et al., 2020). By contrast, the decomposition of non-legume cover crops occurs at slower rates due to a higher C:N ratio (Daryanto et al., 2018). Beside the use of cover crops, the retention of previous crop residues under CA systems could further increase N₂O emissions, especially on clayed soils (Shumba et al., 2023; Zheng et al., 2023). The evidence on the effects of CA on GHG emissions is often inconsistent and varies depending on the agroecological zone, soil types, space, time, and specific management strategies, requiring a need to quantify the impacts of CA on GHG emissions.

CH₄ and N₂O are potent greenhouse gases, with a global warming potential (GWP) of 27 and 273 times that of carbon dioxide (CO₂) for a 100-year timescale (IPCC, 2023). In crop production systems, paddy rice cultivation is a net source of CH₄ emissions, with greater variability influenced by agroecological zones and crop management practices (Chen et al., 2025), whereas the upland cropping systems could either emit or uptake CH₄, and typically exhibit less variability in emissions (Maucieri et al., 2021). Nitrous oxide emissions from agricultural land account for approximately 60% of the total global anthropogenic N₂O emissions (Reay et al., 2012; Tian et al., 2024). Reducing N₂O emissions is thus considered a key target to limit the global temperature to 1.5° and

2°C above preindustrial levels (Clark et al., 2020). Soils emit CO₂ through root respiration (also known as autotrophic respiration) and the biological decomposition of organic inputs and soil organic matter (SOM) (i.e., heterotrophic respiration). Although soil CO₂ emissions contribute to the overall GHG balance in agricultural systems, they only represent a part of the CO₂ balance, the other part being the assimilation of CO₂ by plants during photosynthesis. The net CO₂ balance can be estimated in large fields using eddy covariance measurements. However, in small plots of agronomic trials, this method cannot be used. In this case, field-scale net soil CO₂ emissions are recommended to be estimated based on the changes in SOC stock over an appropriate time period (IPCC, 2019).

Soil could act as a sink or a source of CH₄ depending on several major factors such as microbial activity, soil moisture, SOC content, and soil pH (Mosier et al., 1997; Dutaur and Verchot, 2007). Soil CH₄ fluxes are the net result of CH₄ production by methanogenesis under anaerobic conditions and CH₄ oxidation by methanotrophic processes taking place under aerobic conditions (Hütsch et al., 1996; Mosier et al., 1997; Dutaur and Verchot, 2007). In contrast, soil N₂O emissions result primarily from denitrification and nitrification processes (Bremner, 1997). The emissions of CH₄ and N₂O are governed by complex interactions between biotic and abiotic factors that regulate microbial activity and SOM mineralization (Adair et al., 2011; De Deyn et al., 2008). Key drivers of CH₄ and N₂O emissions include soil parameters such as water-filled pore space (WFPS), environmental factors, crop management practices, the amount and quality of C and N inputs from residues, and mineral N fertilizer application (Chen et al., 2013; Oertel et al., 2016; Muhammad et al., 2019). Crop residues are widely reported as a primary source of organic inputs for increasing SOC stock (Fujisaki et al., 2018; Shumba et al., 2024a; Leng et al., 2024). However, increasing SOC storage would also affect soil N₂O emissions by supplying readily mineralizable C and N, which enhance microbial activity and oxygen consumption, thereby stimulating nitrification and denitrification and increasing emissions from both soil mineral N and crop residue-derived N (Lesschen et al., 2011; Guenet et al., 2021). As organic matter is the major substrate for nitrification and denitrification, higher organic input retention can lead to higher production of soil mineral N and N₂O emissions compared to lower biomass retention (Parihar et al., 2018; Shumba et al., 2023; Sedghi et al., 2024).

Cassava (*Manihot esculenta* Crantz) is primarily cultivated by small-scale farmers in tropical regions worldwide. In Cambodia, the area of land under cultivation increased significantly from 0.02 to 0.76 × 10⁶ ha between 2002 and 2022 (FAO, 2024a). Cassava has become the country's second-largest cash crop for feedstock and bioenergy after rice, and Cambodia has become one of the top ten cassava producers in the world (RGC, 2020). At the global scale, cassava cultivated area has expanded substantially from 9.62 to 32.04 × 10⁶ ha between 1961 and 2022 and is regarded as the 21st-century most important food and energy crop after maize (FAO, 2024a). Due to its high resilience to drought and adaptability to poor soils, cassava is commonly grown in monoculture without proper soil fertility management, and rotation systems are often neglected. These practices degrade soil fertility, environmental quality, and biodiversity (Howeler, 1991; FAO and IFAD, 2001), making it necessary to explore alternative cassava cropping systems and assess their efficiency and performances towards sustainable cassava production in the context of changing climate (Kulkarni, 2024). Studies have investigated how different cropping systems, particularly CT and NT systems, influence GHG emissions and the GHG balance by evaluating the trade-off between SOC sequestration and cumulative non-CO₂ emissions under cereals production across a range of agroecosystems (Gong et al., 2021; Rigon et al., 2021; Shumba et al., 2024b). However, for cassava, field-scale research remains limited. A few studies have primarily investigated the effects of the application of organic and inorganic fertilizers on non-CO₂ emissions (Pengthamkeerati et al., 2014; Chirinda et al., 2021; Sriphirom et al., 2023), but none have evaluated how different cropping systems affect GHG emissions and the

overall GHG balance. The lack of studies exploring soil GHG has led the tropical cassava-producing countries to rely on the IPCC's default Tier 1 for the estimation of soil direct GHG emissions factors (Hergoualch et al., 2019). Quantifying the GHG emissions on the area-scaled (cumulative emissions per ha) and yield-scaled (GHG emissions per kg of product) emissions metrics (Graham et al., 2025) underscores the need for site- and crop-specific data to contribute to the proper estimation of the country's GHG emissions factors and global carbon footprint of cassava production. Our study aimed to i) quantify the impacts of long-term CT-based cassava mono-cropping compared with different NT systems with cassava mono-cropping or in bi-annual rotation with maize with the use of cover crops and their interactive effects on soil CH₄ and N₂O emissions in the tropical rainfed upland of Cambodia and ii) compute the net climate impact of the systems calculating the GHG balance (in CO₂-eq) considering the different GWP of each gas and by considering the additional SOC storage measured on the same site. We hypothesized that (i) CH₄ and N₂O emissions would increase under NT systems due to higher biomass retention, particularly in crop rotational systems with the use of cover crops; however (ii) the SOC accumulated under NT systems driven by greater biomass inputs and minimal soil disturbance would outweigh these non-CO₂ emissions, leading to an overall positive effect on climate change mitigation.

2. Materials and methods

2.1. Study site description

The study was conducted at the Bos Khnor Conservation Agriculture Research Station, the oldest CA research station in Southeast Asia, which belongs to the Department of Agricultural Land Resources Management, the General Directorate of Agriculture. It is located in Chamkar Leu district, Kampong Cham province (12°12'31.0"N, 105°19'07.0"E, 118 m above sea level). The detailed history of the research site was described in Hok et al. (2015). Briefly, the site was a natural tropical rainforest, which was then converted to perennial cropland in 1937. The crops included cashew, coffee, mango, mulberry, avocado, and rubber, which were planted soon after forest clearance. Because of the civil war (Khmer Rouge) between 1970 and 1982, the area was abandoned and taken over by several tree species which grew naturally. The farming was resumed, and cotton (*Gossypium hirsutum* L.) and banana (*Musa acuminata* spp.) were planted from 1982 to 2000. From 2000–2009, successive annual crops per year of cotton, followed by mung bean (*Vigna radiata* (L.) R. Wilczek), and sesame (*Sesamum indicum* L.), followed by soybean (*Glycine max* L.), were rotated under conventional plough-based management before the establishment of the experiment. Mineral fertilizers such as NPK (15–15–15), ammonium phosphate (16–20–0), and potassium chloride (0–0–60) were applied to the cotton and soybean without lime application.

The soil of the study site is classified as a red Oxisol (Soil Survey Staff, 2022) or a Ferralsol in the world reference base (WRB) for soil resources (IUSS Working Group WRB, 2022), with 1% sand, 29% silt, and 69% clay at the top 0–20 cm and gradually increasing with soil depth to 78% clay at 20–100 cm. The clay fraction is mainly made of kaolinite (Hok et al., 2015). The land on the site is flat, the slope is < 1%. Prior to the establishment of the experiment in 2009, the SOC and total nitrogen (TN) stocks at the top 0–20 cm layer were 33.2 Mg C ha⁻¹ and 3.33 Mg N ha⁻¹, respectively (Leng et al., 2024). The research site's climate is defined as tropical monsoon, corresponding to the Am Köppen climate classification, with two main seasons: the wet season from May to October and the dry season from November to April. The mean annual temperature from 2009 to 2023 was 28.7°C, while the average annual minimum and maximum temperatures were 19.2°C and 39.8°C, respectively. The annual rainfall from 2009 to 2023 varied between 1468 and 2039 mm with a mean of 1750 mm.

2.2. Experimental design

The soil GHG emissions were assessed throughout two whole successive cropping seasons; the first 2022–23 cropping season was from April 20, 2022, to April 11, 2023, and the second 2023–24 cropping season was from April 20, 2023, to April 20, 2024. The long-term experiment was designed to compare conventional tillage-based mono-cropping of cassava production (CT) with different no-till mulch-based cropping systems (NT), including cassava mono-cropping and bi-annual cassava-maize rotation with the use of cover crops. The details of the experimental design, treatment descriptions, and fertilizer application were reported in Hok et al. (2015) and Leng et al. (2024). Briefly, the experiment was arranged in a randomized complete-block design consisting of three treatments with three replicates. The elementary plot dimensions are 8 m × 37.5 m, equivalent to 300 m².

2.3. Treatment description

The three treatments included: (1) mono-cropping of cassava (Cs) under CT (CTM-Cs) with land preparation done by disc ploughing, which represents standard farmers' practices; (2) mono-cropping of cassava under NT system (NTM-Cs), in which the cassava was cropped in a single frequency pattern with no tillage and the retention of previous cassava biomass; and (3) bi-annual rotation of cassava with maize (Mz) (*Zea mays* L.) under NT systems with the use of diverse cover crop species grown prior to and after the maize cultivation (NTR), where the main crops were presented every year in two separate elementary plots designated as NTR1 and NTR2. In the season 2022–23, within the NTR systems, NTR1 was planted to maize (NTR1-Mz) and NTR2 to cassava (NTR2-Cs). In the season 2023–24, the crops were switched: NTR1 was planted to cassava (NTR1-Cs), and NTR2 with maize (NTR2-Mz).

In CTM-Cs, the plot was initially ploughed to a depth of 15–20 cm after a few early rains at the beginning of the rainy season, followed by a second ploughing prior to cassava cultivation. In the NT treatments that were planted to cassava, the crop was planted directly by a two-row NT planter (Plantcenter®), followed by the application of a mix of pre-emergent non-selective herbicides, i.e., glyphosate [N-(phosphonomethyl) glycine] and 2,4-D [2,4-dichloro-phenoxyacetic acid], at a rate of 960 and 720 g active ingredient (a.i) ha⁻¹, respectively, right after planting to control the weeds and/or cover crops that were established after maize harvest in the previous cropping season.

2.4. Crop management practice

The cassava was planted in early May and harvested about 10 months after in mid-February of the following year, whereas maize, with a life cycle of approximately 110 days, was seeded in the last week of June or the first week of July and harvested at the end of October. Cassava was planted at an inter-row spacing of 1 m and an in-row spacing of approximately 1 m to achieve a plant population of 10000 plants ha⁻¹. Prior to maize cultivation, at the beginning of the rainy season (in the mid of May), a mix of fast-growing species, i.e., pearl millet (*Pennisetum typhoides* (L.) Morrone), sunnhemp (*Crotalaria juncea* L.) and cowpea (*Vigna unguiculata* (L.) Walp.), at seed rates of 15, 20, and 25 kg ha⁻¹, respectively, was direct seeded by a NT seeder at 23 cm of the inter-row spacing. The cover crops were grown for approximately 60 days prior to maize cultivation as the main cycle crop. Maize was then directly seeded on the green-standing cover crops called "green sowing" by a NT seeder at an inter-row spacing of 0.6 m with a density of approximately 4 seeds per linear meter to achieve a plant population of 66000 plants ha⁻¹. To terminate the cover crops, right after sowing maize, they were crimped twice, followed by a spraying of a mix of pre-emergent non-selective herbicides, i.e., glyphosate and 2,4-D, at a rate of 960 and 720 g a.i ha⁻¹, respectively. Right after maize harvest, if sufficient rainfalls occurred in the late part of the wet season, a mix of fast-growing and drought-tolerant cover crop species, i.e., pearl millet,

cowpea, and rattlepod (*Crotalaria ochroleuca* G. Don) was direct seeded at seed rates of 15, 20, and 8 kg ha⁻¹, respectively, on the maize residues by the NT seeder at 23 cm inter-row spacing as cover crops crossing the dry season for the cassava in the next cropping season. For post-control of weeds on the cassava, manual hoe weeding was conducted whenever weeds were 10 cm tall or the spot of 10 cm in diameter for stoloniferous weeds. A selective herbicide, Mesotrione [2-[4-(Methylsulfonyl)-2-nitrobenzoyl]-cyclohexane-1,3-dione], was applied at 150 g a.i. ha⁻¹ at 12–15 days after sowing maize.

There were a few adjustments to the mineral fertilizer application during the experimental period, and the rate and types of mineral fertilizers applied to the experiment from 2009 to 2021 were reported in Hok et al. (2015) and Leng et al. (2024). During the GHG emissions assessment period, the mineral fertilizers were applied as basal and top dressing on each crop with different rates of nitrogen (N), phosphorus (P), and potassium (K) depending on the types and phenological stage of each crop. For the cassava, N and K, with a total amount of 46 and 50 kg ha⁻¹ yr⁻¹, respectively, were applied in the form of urea (46% N) and potassium chloride (60% K₂O) at 50 kg ha⁻¹ each as top dressings at 30 and 90 days after planting on the soil surface along the cassava rows with a distribution width of approximately 10 cm. On the cover crops, 25 kg K ha⁻¹ was applied 30 days after sowing (DAS). No mineral fertilizer was applied to the cover crops sown after the maize harvest. For maize, a total amount of 70 and 13 kg ha⁻¹ yr⁻¹ of N and P, respectively, were split 2 times; 150 kg ha⁻¹ of ammonium phosphate (16% N, 20% P) was applied as basal fertilizer by placing it below the maize sowing lines by NT planter at the same date of maize sowing, and 100 kg ha⁻¹ of urea was applied as top dressing at 25 DAS on the soil surface along the maize rows with a distribution width of approximately 10 cm.

In the 2022–23 cropping season, cassava was harvested earlier than usual due to a severe infestation of cassava witches' broom disease (CWBD) and resulted in a significant tuber yield loss ($\geq 40\%$). To mitigate this, we changed the cassava variety from KU50, which had been planted since the experimental setup (2009) until 2022, to Rayong 5 in the 2023–24 cropping season, which was observed to be less susceptible to CWBD.

2.5. Crop residue management

For the crop residue management, prior to tuber harvest, 50% of the healthy main stems from all cassava treatments were selected as planting materials for the following cropping season. After the harvest, the remaining 50% of the main stems, all the shoots, and original cuttings were completely removed from the plot under CTM-Cs treatment. Therefore, fallen leaves, surviving top leaves, branches and forks remained in the plot. This management represents the typical practice of the local farmers. In all the NT-Cs treatments, the remaining 50% of the main stems, all the shoots, original cutting, fallen leaves, survival top

leaves, branches, and forkings were redistributed evenly on the soil surface after harvest. For the maize-planted NTR rotational treatment (NTR1-Mz and NTR2-Mz), all biomass from cover crops and maize stalks was left on the soil surface. The annual cropping sequences, above-ground biomass inputs, and estimated C and N inputs retained to the soil in each treatment from 2009 to 2021 have been annually recorded since the start of the experiment and were reported in Leng et al. (2024). The details of crop sequences, plant productivity of the main crops, above-ground biomass inputs of the main and cover crops, and the measured C and N inputs of each treatment that were retained in the soil over the soil GHG emissions assessment period are presented in Table 1. Briefly, the aboveground biomass of cover crops was quantified 1 day prior to the termination by cutting vegetation at ground level within 2 m $\times$ 2 m quadrats (4 m²) at 5 sampling points in a diagonal "X" shape per elementary plot. The biomass was separated by species, chopped, and the fresh mass at field-moisture content was weighed. The moisture content of each species was determined by oven-drying five subsamples (each weighing ~ 200 g) to constant weight at 60°C. Maize aboveground biomass was quantified at physiological maturity at 5 sampling areas per elementary plot across 4 rows of 10 m length (24 m²). After harvesting the cobs, the stalks were cut at ground level, chopped, weighed fresh, and 5 subsamples (~ 200 g) were collected for moisture content determination. For cassava, dry fallen leaf biomass was measured several days prior to harvest using 2 m $\times$ 2 m quadrats. After harvest, cassava residues (branches, main stems, survival leaves, shoots, and original cuttings) under NT were evenly redistributed within their respective plots and crimped using a roller crimper. Remaining aboveground residues were then sampled using 2 m $\times$ 2 m quadrats at 5 points per elementary plot, weighed fresh, and 5 subsamples (~ 200 g) were collected for moisture content determination. All the dried biomass samples were finely ground, and C and N concentrations were determined by dry combustion using a LECO® CHN628 analyzer at the Sustainable Agroecosystems Laboratory, ETH Zurich, Switzerland. The C and N inputs were calculated using the C and N concentrations obtained from the dry combustion analysis of each crop's aboveground plant part retained to the soil.

2.6. Meteorological data

Temperature was recorded every hour from a weather station managed by the Kampong Cham provincial department of water resources and meteorology located approximately 28 km from the experimental site, while the daily rainfall data was collected manually from a rain gauge installed at the experimental station.

2.7. Soil GHG emissions measurement and calculation

We measured soil CH₄ and N₂O emissions from the 12 experimental

Table 1

Crop sequences, annual cumulative dry aboveground biomass inputs, and measured C- and N-inputs from the crop and cover crop residues retained to the soil during the GHG emissions monitoring, April 2022–April 2024.

Season	Treatments ^a	Crop sequences ^b	Cumulative dry biomass inputs (kg DM ha ⁻¹)	C inputs (kg C ha ⁻¹)	Organic N inputs (kg N ha ⁻¹)
2022–23	CTM-Cs	Cs	4612 (± 9)	1996 (± 280)	70 (± 9.6)
	NTM-Cs	Cs	3554 (± 61)	1539 (± 57)	55 (± 2.3)
	NTR1-Mz	Mi+Su+Co/Mz/Mi+Rp+Co	16149 (± 1083)	6961 (± 441)	136 (± 8.0)
	NTR2-Cs	Cs	4987 (± 104)	2162 (± 189)	79 (± 6.9)
2023–24	CTM-Cs	Cs	979 (± 140)	402 (± 53)	12 (± 1.7)
	NTM-Cs	Cs	3714 (± 623)	1609 (± 219)	58 (± 8.2)
	NTR1-Cs	Mi + Rp+Co/Cs	13223 (± 1196)	5614 (± 413)	146 (± 13.1)
	NTR2-Mz	Mi+Su+Co/Mz/Mi+Rp+Co	18729 (± 430)	7988 (± 262)	163 (± 53.0)

^a CTM-Cs: mono-cropping of cassava under conventional tillage; NTM-Cs: mono-cropping of cassava under no tillage system; and NTR: bi-annual rotation of cassava and maize under no-till systems with the use of cover crops represented by NTR1 and NTR2.

^b Co: cowpea; Cs: cassava; Mi: millet; Mz: maize; Su: sunnhemp; and Rp: rattlepod. The letters in bold and italicized indicate the main crops and cover crops, respectively. "+" indicates crops planted in association (same or staggered sowing dates); "/" indicates relay cropping with varying planting dates. Values in brackets indicate standard errors (n = 3).

plots using static chambers (Charteris et al., 2020; De Klein et al., 2020). The static chamber technique involves trapping gases emitted from the soil by a chamber, and gas samples were collected from the chamber headspace at a regular interval to determine the concentrations using gas chromatography (Rochette and Eriksen-Hamel, 2008; De Klein et al., 2020; Maier et al., 2022). The chamber comprised two main parts: the base ring and the headspace, both were made from PVC in a cylindrical shape. The base rings (height 0.18 m and inner diameter 0.20 m) were manufactured in an inner-manner joint extending at 0.05 m from the intersection with the lids. The lids (height 0.2 m and inner diameter 0.20 m) were manufactured in an outer-manner joint extending at 0.05 m from the intersection with the base rings, facilitating the reliable gas sampling. In addition, the lids were equipped with an electrical battery-powered fan (diameter 0.025 m) for mixing inside gases prior to the sampling, and with an airtight self-sealing rubber septa placed on the top center to enable gas sampling with a syringe. To reduce overheating, both the base rings and the lids were painted white. Each chamber covered an area of 0.0314 m² and had a headspace volume of 0.00628 m³.

To avoid possible leakage or contamination by lateral diffusion (Clough et al., 2020), the base rings were inserted into the soil to a depth of 0.13 m, leaving 0.05 m above the soil surface for inserting the lids at sampling. Because the main field operations (i.e., ploughing under the CTM-Cs, crimping the cover crops under NT treatments, and planting all the crops) were carried out mechanically using tractors, the base rings were removed prior to the mechanical field operation implementation and then immediately inserted right after the operation was completed. When mineral fertilizers were applied along the main crops' rows, Shumba et al. (2023) reported higher N₂O emissions in the rows than in the inter-row space. To account for this spatial heterogeneity, four base rings were installed at different locations in each treatment of the three replicates: two on the crops' rows ("row") and two between two rows of the crops ("inter-row"). The row and inter-row base rings were centrally positioned between the crops' plants and rows, respectively. For NTR-Mz, during the cover cropping before maize cultivation and after maize harvest, all four base rings were installed between the cover crops' rows since the row spacing was 0.23 m and there was no N mineral fertilizer applied to the cover crops. A total of 48 static chambers (4 treatments × 3 replicates × 4 chambers) was therefore used for the study.

To minimize the potential bias caused by the heterogeneity of the biomass within the same treatment in the three replicates, we standardized the amount of each crop biomass input regardless of replication and sampling positions (row and inter-row), with a proportional share of the total biomass input of each crop per treatment and cropping season as reported in Table 1. In addition, at every top-dressing event, the proportional share of mineral fertilizers to the application rates was placed inside the "row" chambers, while the "inter-row" chambers did not receive any mineral fertilizers.

During gas sampling, the row and inter-row chambers of an elementary plot were closed simultaneously by two people. At every gas sampling event, two air samples were collected at the beginning and at the end of a session, and averaged to quantify air GHG background samples (GC_0). Before closing the chambers, the contact area (the joint) between the base rings and the lids was covered with a thin layer of petroleum jelly to avoid any gas leakage. The gases from the treatments were collected into pre-evacuated 12 mL Exetainer® glass vials (Labco Ltd., Lampeter, United Kingdom) using a graduated 20 mL syringe after 48 min of gas trapping. On each sampling event, gas sampling was done between 9:00 a.m. and 11:30 a.m., as recommended by Alves et al. (2012) and Charteris et al. (2020). Gas diffusion theory predicted that an increase in gas concentration during chamber deployment had a negative impact on emissions rate at soil surface (Rochette et al., 2008; Venterea et al., 2020). We therefore conducted a linearity test one day after sowing maize by collecting gas at times 0, 15, 30, 48 and 60 min after closing the lid. Results showed that GHG emissions increased

linearly with time, even at 60 min and on maize rows where fertilizers were applied, suggesting that gas sampling at 48 min after the lid closure was appropriate for this study as emissions were linear and no saturation was observed (data not shown).

In each cropping season, GHG sampling was scheduled based on the major field operations, particularly land preparation in the CTM-Cs plot and the termination of cover crops in the NT treatments, crop types, and mineral fertilizer applications to the main crops. Since the rainy season usually begins early May, April 20th was set as the first GHG sampling date in each cropping season, regardless of treatments. For the treatments with cassava, we collected gas samples 7 days after the first ploughing. During the first month after planting cassava, gas sampling was collected once every week at 1, 7, 14, 21, and 30 days after planting (DAP). During the first month following each top dressing, we intensified the sampling frequency at 4, 7, 11, 14, 17, 20, 23, and 26 days after top dressing (DAT). In the second month after each top dressing, gas sampling was collected once every week at 33, 40, 47, and 54 DAT. In the dry season, gas sampling was collected once every month at 160, 190, 220, and 250 DAP. Gas samples were collected 1 day after cassava harvest (DAH), and then at 30 and 60 DAH to cover the whole cropping season. For the treatment that was sown to maize, gas samples were collected 1 and 30 DAS of the short cycle cover crops that were sown to produce biomass prior to maize cultivation. Gas sampling was carried out at 1 day before cover crop termination and maize planting. We intensified the sampling frequency during the three weeks after maize planting at 1, 2, 3, 4, 7, 11, 14 and 21 DAS. As the second top dressing on maize was applied at 25 DAS, we collected gas samples at 2, 4, 7, 11, 14, 18 and 21 DAT. Then gas sampling was done at 14-day intervals until maize harvest (+4 times). Gas sampling was done 1 day after sowing the cover crops, which were sown right after the maize harvest, and then at a 30-day interval (+6 times) during the dry season to cover the whole cropping season. In total, there were 38 and 29 gas sampling events for the treatments that were planted to cassava and maize, respectively.

Storage and shipment were assumed to result in negligible changes in gas concentration of the samples based on previous experiences with sealed Exetainer glass vials (Faust and Liebig, 2018; Harvey et al., 2020). The concentrations of CH₄ and N₂O were quantified by gas chromatography (Scienc 456®, Bruker Daltonics, Switzerland) using the thermal conductivity and flame ionization detectors and the electron capture detector, respectively (Gallarotti et al., 2021). Gas fluxes were calculated as the difference in concentrations between the 48-min trapped gas sampled from the chambers and the average air background samples using the following equation:

$$F = \frac{(GC_f - GC_0) \times V}{T \times A} \quad (1)$$

where F is the gas flux ($\mu\text{g CH}_4\text{-C}$ or $\mu\text{g N}_2\text{O-N m}^{-2} \text{ hr}^{-1}$), GC_f are the gas concentrations ($\mu\text{mol mol}^{-1}$) of the 48-min trapped gas sampled from the chambers, whereas GC_0 is the gas concentration ($\mu\text{mol mol}^{-1}$) of the background air samples the day of measurement, V is the chamber volume (mL), T is the duration of the chamber closure (hour), and A is the surface area covered by the static chamber (m²).

2.8. Cumulative GHG emissions and GHG balance

Cumulative CH₄ and N₂O emissions were computed using linear interpolation between sampling events by multiplying the mean flux of two successive sampling dates by the length of the period between sampling and adding that amount to the previous cumulative total (Dorich et al., 2020).

As mineral fertilizers were only applied along the main crops' rows with an application width of approximately 10 cm, we assumed that the chambers (0.2 m in diameter) in the main crops' rows were representative of the rows only. On the other hand, the inter-row chambers were assumed to be representative of the remaining 0.8 m and 0.4 m for

cassava and maize, respectively, where there were no main crops growing and no mineral fertilizers were applied (Shumba et al., 2023). We then weighted cumulative emissions per chamber position (row or inter-row) according to these proportions, which were 20% and 80% for cassava and 33% and 67% for maize contributions from row and inter-row emissions, respectively, to calculate total cumulative emissions per treatment and per hectare.

To better understand the cropping systems' climatic effects, we calculated the GHG balance accounting for the global warming potential (GWP) at a 100-year time scale (in CO₂ equivalent; Mg CO₂-eq ha⁻¹ yr⁻¹) of each gas in each cropping season.

$$CH_4 \text{ (Mg CO}_2\text{-eq ha}^{-1}\text{)} = \frac{16}{12} \times CH_4 \text{ (Mg CH}_4\text{ - C ha}^{-1}\text{)} \times 27 \quad (2)$$

where 12 is the molecular weight of C in CH₄ and 16 is the molecular weight of CH₄. The GWP of 1 kg CH₄ is equivalent to 27 kg CO₂ based on a 100-year time scale (IPCC, 2023).

$$N_2O \text{ (Mg CO}_2\text{-eq ha}^{-1}\text{)} = \frac{44}{28} \times N_2O \text{ (Mg N}_2O\text{ - N ha}^{-1}\text{)} \times 273 \quad (3)$$

where 28 is the molecular weight of N in N₂O and 44 is the molecular weight of N₂O. The GWP of 1 kg N₂O is equivalent to 273 kg CO₂ based on a 100-year time scale (IPCC, 2023).

The annual SOC stock change rate (Δ SOC) of each treatment measured between 2021 and 2011 and reported in Leng et al. (2024) was used to estimate CO₂ emissions.

$$CO_2 = \Delta SOC \times 3.67 \quad (4)$$

Therefore,

$$GHG \text{ balance} = CH_4 + N_2O + CO_2 \quad (5)$$

A GHG balance > 0 means the cropping system loses carbon. A GHG balance < 0 means the cropping systems sequesters carbon and contributes to climate change mitigation.

We then calculated for each cropping season the proportion of the climate change mitigation benefit due to additional SOC storage that was offset by cumulative CH₄ and N₂O emissions (all expressed as CO₂-eq) as described by Lugato et al. (2018) and Shumba et al. (2024b).

$$\text{non-CO}_2 \text{ mitigation offset (\%)} = \frac{\sum \Delta CH_4 + N_2O}{\Delta SOC} \times 100 \quad (6)$$

An offset of 50% means emissions of CH₄ and N₂O reduced by 50% the climate change mitigation benefits due to SOC sequestration.

To differentiate the seasonal effects of each main crop and the overall mitigation potential of NTR rotational systems, we computed the average cumulative CH₄ and N₂O emissions and the associated GHG balance on both a crop-specific (i.e., cassava and maize) and elementary plot (i.e., NTR1 and NTR2) basis for the full NTR rotational systems by averaging the annual cumulative emissions and GHG balance of the first and second cropping seasons.

2.9. Main crop yields and yield-scaled CH₄ and N₂O emissions

We measured cassava tuber yield by harvesting the tubers from the net elementary plots (8 m x 37.5 m) every season at a maturity of approximately 10 months old. The moisture content of the cassava dry tuber was determined by oven drying at 60 °C until reaching a constant weight. Maize grain yield was measured by harvesting the cobs from five samples per elementary plot in a diagonal "X" shape, each sample covering four maize rows and 10 m long (24 m²). The grain moisture content was measured by a multiple grain moisture tester (PM-390, Kett Electric Laboratory®, Japan) and the fresh weight was adjusted to 14% standard maize grain moisture. Yield-scaled CH₄ and N₂O emissions were determined as CH₄-C and N₂O-N emissions per unit of dry tuber or

grain yield (g CH₄-C and N₂O-N kg⁻¹ of dry tuber or grain) to quantitatively assess the potential trade-offs between CH₄ and N₂O emissions and crop yields (Grassmann et al., 2020; Rahman et al., 2024).

2.10. Soil sample collection for mineral N and water-filled pore space assessment

At every gas sampling event, we collected two soil samples from two positions: "row" and "inter-row" at 0–20 cm depth using a soil probe sampler (4 cm diameter) from each elementary plot. The samples that were collected from the same position and at the same depth were composited. The composite samples were used to determine soil moisture content, soil ammonium (NH₄-N), and soil nitrate (NO₃-N) concentrations. In the laboratory, gravimetric moisture content (θ_g) was determined as soil weight loss upon oven drying the soil samples at 105 °C for 24 h. The concentrations of soil ammonium (NH₄-N) and nitrate (NO₃-N) were determined using the Berthelot method as described by Searle (1984) and the spectrophotometric procedure described by Doane and Horwath (2003), respectively. Due to the heavy clay content of the soil at the site, a diachronic assessment of the impact of long-term no-till systems on SOC and N dynamics conducted by Leng et al. (2024) indicated that the bulk density of each treatment was insignificantly different between 2011 and 2021. Thus, we used the bulk density of individual layers 0–5, 5–10, 10–20 cm that were collected in 2021 for calculating the weighted bulk density for the 0–20 cm depth, respectively. In this Oxisol, there was no coarse fraction (i.e., gravels) left after sieving at 2 mm. Therefore, the bulk density of soil equals the bulk density of fine earth. The weighted bulk density was then used to calculate the mineral N content per unit area and the WFPS of the soil samples collected at each gas sampling occasion using the following equation:

$$WFPS (\%) = \frac{(\theta_g \times \rho_b)}{\left(1 - \frac{\rho_b}{\rho_D}\right)} \quad (7)$$

where θ_g is the gravimetric water content, ρ_b is the soil bulk density, and ρ_D is the soil particle density, given as 2.65 g cm⁻³.

2.11. Statistical analysis

Statistical analyses were conducted using R software, version 4.4.1 (R Core Team, 2024). Prior to analysis, data was checked for normality using both visual inspection (quantile-quantile plots and density distributions) and the Shapiro-Wilk test. Where necessary, data was log-transformed if there were no negative values, or cube root transformed in the case of some negative values (e.g., daily CH₄-C and N₂O-N emissions).

Linear mixed effect models were fitted on daily WFPS and soil mineral N and hourly CH₄-C and N₂O-N emissions using the *lmer* function from the *lme4* package (Bates et al., 2015), using as fixed effects the cropping season (2022–23 and 2023–24), the treatments, and the positions of the chambers (row vs. inter-row) as the random effect. The chamber number was considered a random factor. The final models were chosen based on the lowest Akaike information criterion (AIC) and the lowest Bayesian information criterion (BIC). A simple linear regression was performed to examine the interactive effects of soil mineral N and WFPS on hourly N₂O emissions. Model significance was tested using *t*-tests for the regression coefficients and an *F*-test from the ANOVA.

An analysis of variance (ANOVA) was then applied on the fitted models. Separation of means was done using the post hoc Tukey test at the 5% significance level using the *emmeans* function from the *emmeans* package (Bolker et al., 2009). A one-way ANOVA was carried out to establish any significant treatment effects on cumulative CH₄-C and N₂O-N fluxes, soil mineral N, maize grain- and cassava tuber-yield-scaled CH₄-C and N₂O-N emissions, the GHG balance, and the

percentage offset of SOC storage due to non-CO₂ GHG emissions for each cropping season, followed by a mean separation using Tukey's test. Furthermore, we performed one-sample *t*-tests at the 5% significance level to assess whether the GHG balance of each treatment, across different cropping seasons, significantly differed from zero.

3. Results

3.1. Weather conditions

During the study period, the annual rainfall at the site was 2039 mm in the 2022–23 cropping season, while it dropped to 1468 mm in the 2023–24 cropping season, of which 64% (1300 mm) and 82% (1199 mm) fell from the beginning of June to the end of October in the

2022–23 and 2023–24 cropping seasons, respectively (Figs. 1a and 1b). The average annual minimum and maximum temperatures were 24.76 and 32.66 °C and 25.74 and 34.08 °C, with a mean annual temperature of 28.22 and 29.37 °C in the 2022–23 and 2023–24 cropping seasons, respectively (Figs. 1a and 1b).

3.2. Soil water-filled pore space and soil mineral nitrogen

The fluctuations of soil WFPS across treatments and sampling positions throughout each cropping season were closely linked to the rainfall patterns (Figs. 1a and 1b and Figs. 2a and 2b). In both cropping seasons, the WFPS sharply increased at the onset of the rainy season, reaching its highest peaks during the high rainfall events in the wet season, then steadily declined to its normal stage at 25% in the dry season (Figs. 2a

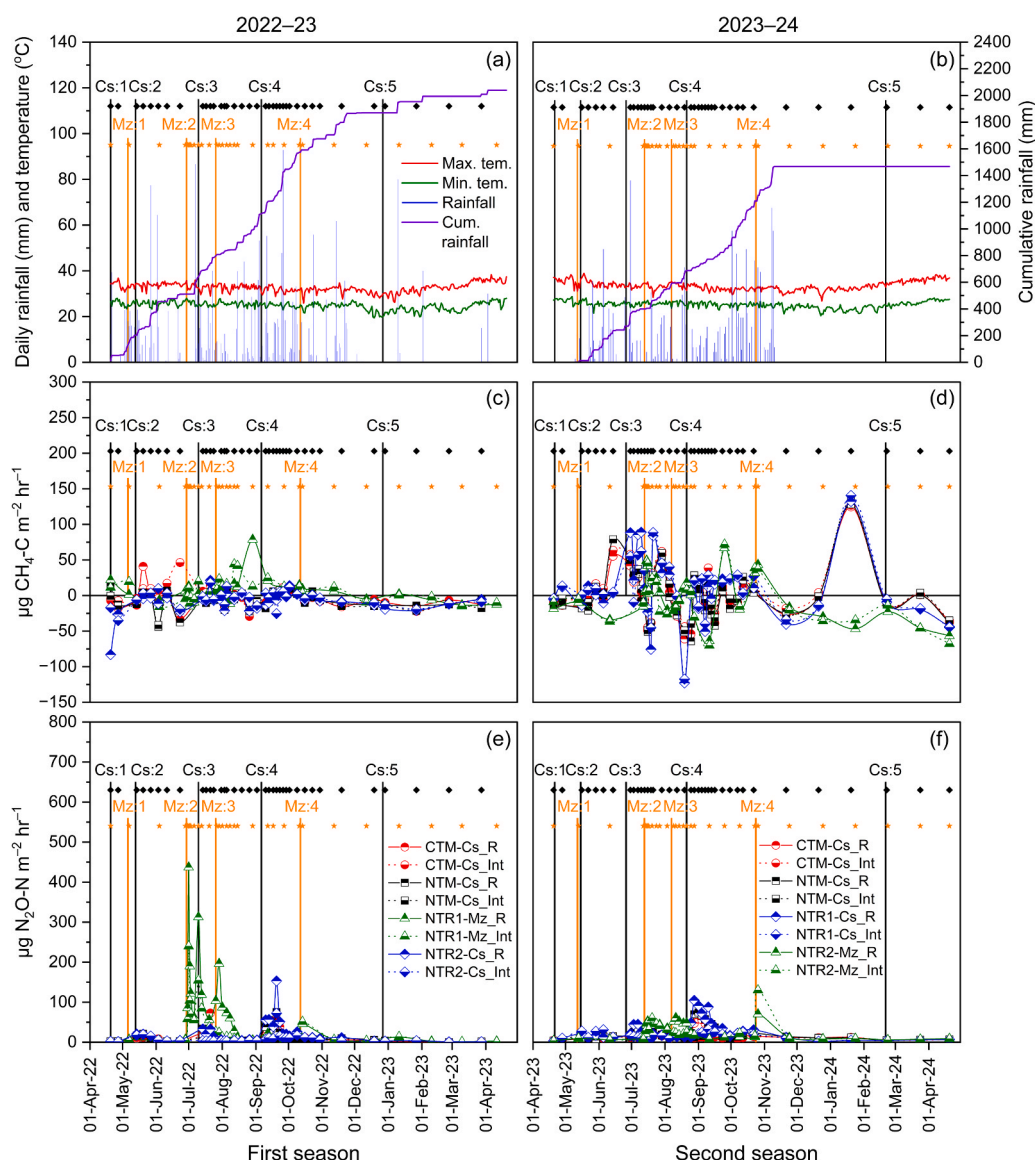


Fig. 1. Daily rainfall, cumulative rainfall, and temperature and hourly CH₄-C and N₂O-N emissions during the 2022–23 and 2023–24 cropping seasons. Cs:1–5 refer to the main field operations on the treatments planted to cassava: Cs:1–1st ploughing on CTM-Cs; Cs:2–2nd ploughing on CTM-Cs followed by cassava planting in the CTM-Cs and NT-Cs; Cs:3–1st top dressing of mineral fertilizer on cassava; Cs:4–2nd top dressing of mineral fertilizer on cassava; and Cs:5–harvest of cassava. Mz:1–4 refer to the main field operations on the NTR1-Mz & NTR2-Mz, with Mz:1–sowing of mixed cover crops prior to maize cultivation; Mz:2–green sowing maize by NT planter, along with the first top dressing of mineral fertilizer, followed by the termination of cover crops 1 day after sowing; Mz:3–2nd top dressing of mineral fertilizer on maize; and Mz:4–harvest of maize followed by sowing of mixed cover crops. CTM-Cs: mono-cropping of cassava under conventional tillage; NTM-Cs: mono-cropping of cassava under no tillage system; and NTR: bi-annual rotation of cassava and maize under no-till systems with the use of cover crops represented by NTR1 and NTR2 as described in Table 1. R (row) and Int (inter-row) refer to the positions of the sample collection on the rows and inter-rows of the cassava or maize. The black rhombuses and orange stars indicate gas sampling dates on cassava and maize, respectively.

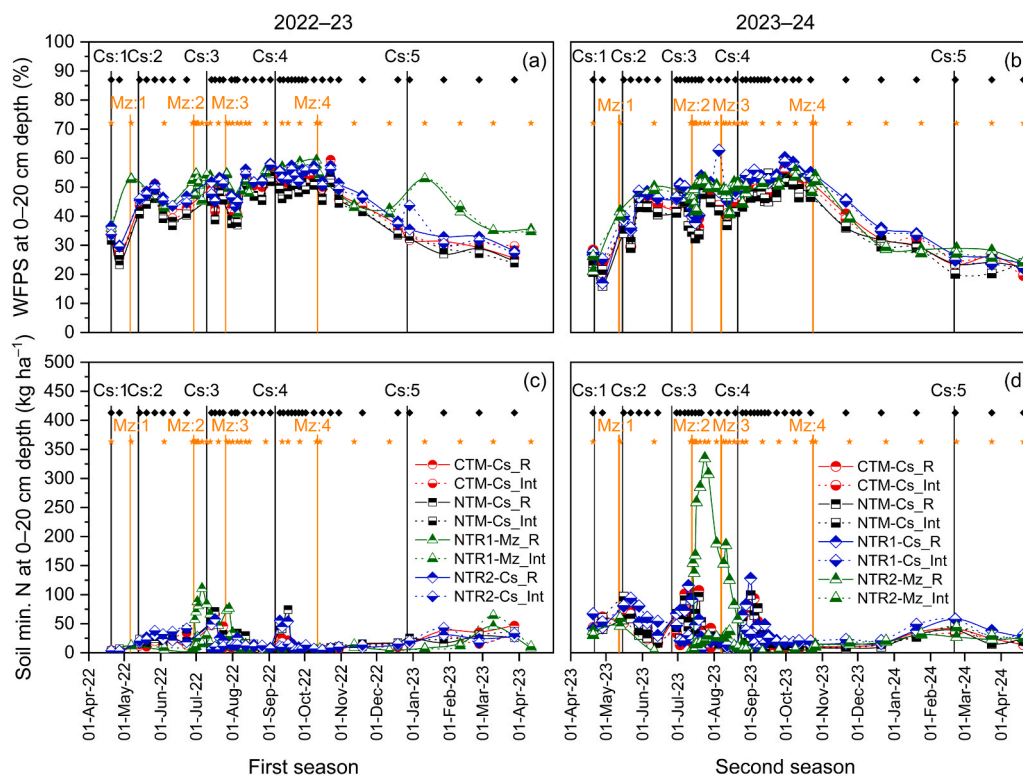


Fig. 2. Daily water-filled pore space (WFPS) and soil mineral N during the 2022–23 and 2023–24 cropping seasons. Cs:1–5 refer to the main field operational sequences implemented on the treatments planted to cassava, with: Cs:1–1st ploughing on the CTM-Cs plot; Cs:2–2nd ploughing on the CTM-Cs plot followed by cassava planting in the CTM-Cs and NT-Cs treatments; Cs:3–the 1st top dressing of mineral fertilizer application on cassava; Cs:4–the 2nd top dressing of mineral fertilizer application on cassava; and Cs:5–the harvest of cassava. Mz:1–4 refer to the main field operational sequences implemented on the NTR1-Mz & NTR2-Mz, with: Mz:1–sowing of mixed cover crops (pearl millet, sunnhemp, and cowpea) as short-cycle cover crops prior to maize cultivation; Mz:2–green sowing maize by NT planter, along with the first top dressing of mineral fertilizer applied localized on the maize sowing lines, followed by the termination of cover crops by crimping and spraying herbicides 1 day after sowing; Mz:3–the 2nd top dressing of mineral fertilizer on maize; and Mz:4–the harvest of maize followed by sowing of mixed cover crops (pearl millet, rattle pod, and cowpea). CTM-Cs: mono-cropping of cassava under conventional tillage; NTM-Cs: mono-cropping of cassava under no tillage system; and NTR: bi-annual rotation of cassava and maize under no-till systems with the use of cover crops represented by NTR1 and NTR2 as described in Table 1. R (row) and Int (inter-row) refer to the positions of the sample collection on the row and inter-row of the cassava or maize. The black rhombuses and orange stars indicate gas sampling dates on cassava and maize, respectively.

and 2b). Cropping season and treatment significantly ($p < 0.0001$) affected the WFPS, but it did not differ between the row and inter-row (Table S1).

In both seasons, soil mineral N ($\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$) concentrations were significantly ($p < 0.0001$) affected by cropping season, treatment, and sampling position (Table S2). The peaks of soil mineral N concentration on the rows of the cassava treatments (CTM-Cs, NTM-Cs, NTR1-Cs, and NTR2-Cs) were soon detected after every mineral fertilizer application as top dressing, then gradually declined at least 1 week after each application and tailed down from the last top dressing until the harvest of cassava (Figs. 2c and 2d). Under NTR1-Mz and NTR2-Mz, the peaks of soil mineral N on maize rows were detected after the successive field operations of maize cultivation with mineral fertilizer application at sowing followed by the cover crop termination. These peaks subsequently decreased within 2 weeks after cultivation. Noticeably, the peak of soil mineral N under NTR2-Mz in 2022–23 was 3 times lower than those recorded under NTR1-Mz in 2023–24 (Figs. 2c and 2d). The soil mineral N on the maize rows spiked again just after the mineral fertilizer application as the last top dressing on maize at 25 days after sowing and tailed off until maize harvest (Figs. 2c and 2d). For both cassava and maize, the soil mineral N content increased after harvest in both seasons (Figs. 2c and 2d).

3.3. Hourly soil CH_4 and N_2O emissions

The hourly $\text{CH}_4\text{-C}$ emissions were significantly ($p < 0.0001$) affected

by cropping season, treatment, sampling position, WFPS, and the interactive effects between cropping season and sampling position (Table S3). The hourly $\text{CH}_4\text{-C}$ emissions were very inconsistent and showed an unpredictable pattern across all the treatments, sampling positions, and seasons (Figs. 1c and 1d). In both cropping seasons, soils of all the treatments frequently acted as $\text{CH}_4\text{-C}$ sinks, with the exception during regular rainfalls (July to October) when the WFPS was higher than 55% (Figs. 1c and 1d and Figs. 2a and 2b). During the 2022–23 cropping season, the $\text{CH}_4\text{-C}$ emissions varied from -83.04 to $+78.76 \mu\text{g CH}_4\text{-C m}^{-2} \text{hr}^{-1}$ and -35.24 to $+46.35 \mu\text{g CH}_4\text{-C m}^{-2} \text{hr}^{-1}$ on the row and inter-row, respectively. The $\text{CH}_4\text{-C}$ emissions in the 2023–24 cropping season were two times higher than in 2022–23, ranging from -123 to $+132 \mu\text{g CH}_4\text{-C m}^{-2} \text{hr}^{-1}$ and -118 to $+141 \mu\text{g CH}_4\text{-C m}^{-2} \text{hr}^{-1}$ on the row and inter-row, respectively (Figs. 1c and 1d).

Cropping season, treatment, sampling position, WFPS, and soil mineral N significantly ($p < 0.0001$) affected the hourly $\text{N}_2\text{O-N}$ emissions. Furthermore, the $\text{N}_2\text{O-N}$ emissions were also significantly influenced by the interactive effects between WFPS and soil mineral N (Table S4). In both seasons, under the cassava treatments (CTM-Cs, NTM-Cs, and NTR2-Cs), $\text{N}_2\text{O-N}$ emissions peaked following each application of mineral fertilizer as top dressing. These peaks were generally higher in the row than in the inter-row and gradually decreased to lower levels within at least one week after the application (Figs. 1e and 1f). The $\text{N}_2\text{O-N}$ emissions under NTR systems that were sown to maize differed between the two cropping seasons. In 2022–23, $\text{N}_2\text{O-N}$ emissions under NTR2-Mz on the row sharply increased just after the successive field operational

implementations of maize cultivation along with the mineral fertilizer applied at sowing followed by the termination of cover crops. The emissions on the row fluctuated during the first two weeks after sowing maize, with the highest peak at $437 \mu\text{g N}_2\text{O-N m}^{-2} \text{ hr}^{-1}$ (Fig. 1e). The $\text{N}_2\text{O-N}$ emissions spiked again after the mineral N fertilizer applied as the top dressing at 25 days after sowing maize. In 2023–24, despite the fact that we detected the peaks of $\text{N}_2\text{O-N}$ emissions under NTR1-Mz after cover crop termination and maize cultivation, the highest peak of $\text{N}_2\text{O-N}$ emissions on the row was 7 times lower than in 2022–23, with only $57.77 \mu\text{g N}_2\text{O-N m}^{-2} \text{ hr}^{-1}$ (Figs. 1e and 1 f). We also detected peaks of $\text{N}_2\text{O-N}$ emissions under NTR1-Mz and NTR2-Mz after sowing cover crops following the maize harvest in both seasons (Figs. 1e and 1 f). $\text{N}_2\text{O-N}$ emissions of all the treatments in both seasons decreased to low levels at the end of the dry season (Figs. 1e and 1 f).

3.4. Cumulative soil CH_4 and N_2O emissions

The cumulative emissions of CH_4 varied between the two cropping seasons. In 2022–23, the soil of the cassava treatments (CTM-Cs, NTM-Cs, and NTR2-Cs) acted as a sink for CH_4 , while the soil of NTR1-Mz acted as a source of CH_4 (Fig. 3a). In 2023–24, the soil of NTR2-Mz acted as a sink for CH_4 , while the soils of all the cassava treatments (CTM-Cs, NTM-Cs, and NTR1-Cs) were the source of CH_4 (Fig. 3b). There was no significant difference in cumulative CH_4 emissions between the cassava systems in both cropping seasons. Averaged over the two seasons, the NTR-Mz soil (average of NTR1-Mz and NTR2-Mz) and the NTR2 (average of NTR2-Cs and NTR2-Mz) were significant sinks for CH_4 , with values of -0.65 and $-0.95 \text{ kg CH}_4\text{-C ha}^{-1} \text{ yr}^{-1}$, respectively. Meanwhile, the soils under cassava treatments, i.e., CTM-Cs, NTM-Cs, NTR-Cs (average of NTR1-Cs and NTR2-Cs), and NTR1 (average of NTR1-Cs and NTR1-Mz) were the source of CH_4 with cumulative emissions ranging from 0.08 to $0.66 \text{ kg CH}_4\text{-C ha}^{-1} \text{ yr}^{-1}$ (Fig. 3c).

Considering the proportion of the row and inter-row emissions, the

cumulative N_2O emissions of the cassava treatments varied between the two cropping seasons. In 2022–23, the cumulative N_2O emissions of the cassava treatments (CTM-Cs, NTM-Cs, and NTR2-Cs) ranged from 0.48 to $0.58 \text{ kg N}_2\text{O-N ha}^{-1} \text{ yr}^{-1}$, which were 2 times lower than in 2023–24 (CTM-Cs, NTR-Cs, and NTR1-Cs), with cumulative emissions ranging from 0.94 to $1.17 \text{ kg N}_2\text{O-N ha}^{-1} \text{ yr}^{-1}$ in 2023–24 (Figs. 3d and 3e). In contrast, the cumulative N_2O emissions under NTR systems that were sown to maize were similar between two seasons, with the emissions ranging from $1.39 \text{ kg N}_2\text{O-N ha}^{-1} \text{ yr}^{-1}$ under NTR1-Mz in 2022–23 and $1.46 \text{ kg N}_2\text{O-N ha}^{-1} \text{ yr}^{-1}$ under NTR2-Mz in 2023–24. This occurred despite the absence of N_2O emissions peaks following the basal application at maize sowing and cover crop termination in the cropping season 2023–24 (Figs. 1e and 1 f and Figs. 3d and 3e). Although the NTR1-Mz emitted significantly ($p < 0.05$) more cumulative N_2O emissions than the cassava treatments (CTM-Cs, NTM-Cs, and NTR2-Cs) in 2022–23, the cumulative emissions of NTR2-Mz did not differ from other NT cassava systems (NTM-Cs and NTR1-Cs) in 2023–24 (Fig. 3e).

Averaged over the two seasons, the cumulative N_2O emissions of NTR-Mz were significantly ($p < 0.05$) higher than CTM-Cs, NTM-Cs, and the NTR-Cs, while there was no significant difference with NTR1 and NTR2 (Fig. 3f). The average cumulative N_2O emissions under NTR1 was significantly ($p < 0.05$) higher than CTM-Cs, NTM-Cs, and NTR-Cs, but did not differ between NTR2 (Fig. 3f).

3.5. Soil drivers of $\text{N}_2\text{O-N}$ emissions

The $\text{N}_2\text{O-N}$ emissions were positively and significantly ($p < 0.0001$) associated with soil mineral N (Fig. 4a). However, the relationship with soil mineral N showed a very low R^2 value ($R^2 < 0.051$), indicating a weak explanatory power (Fig. 4a). In contrast, the relationship between $\text{N}_2\text{O-N}$ emissions and WFPS followed a bell-shape pattern, with peak emissions detected at 55% WFPS, suggesting an optimum moisture condition for $\text{N}_2\text{O-N}$ emissions (Fig. 4b).

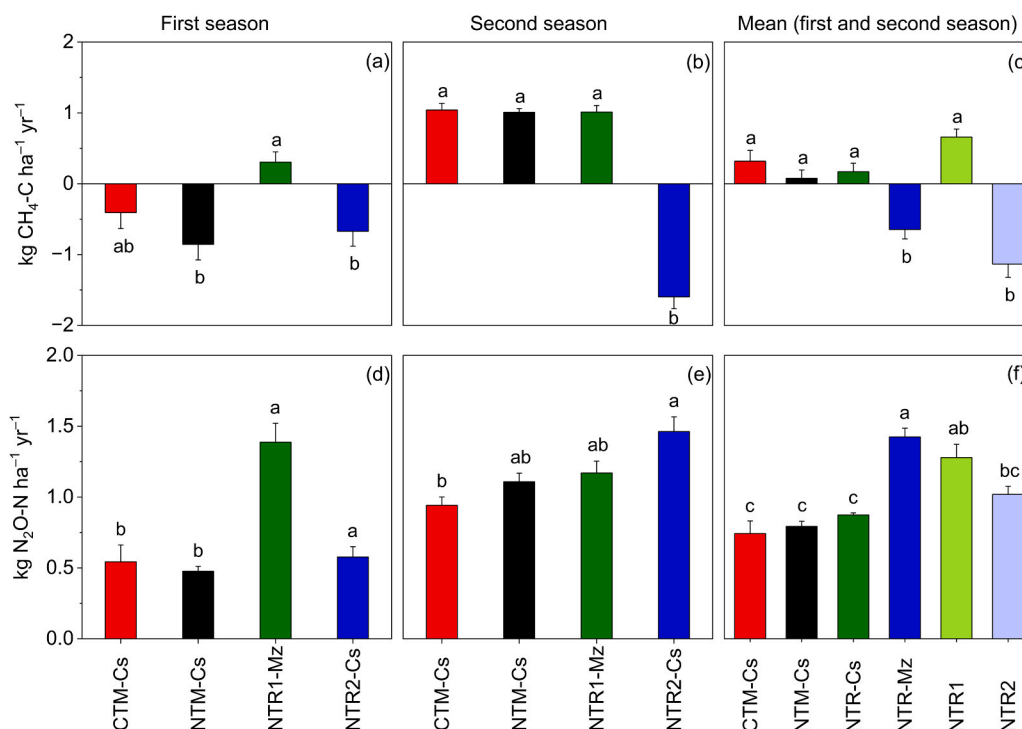


Fig. 3. Cumulative CH_4 and N_2O emissions in 2022–23 and 2023–24, and the two-season average cumulative emissions of each cropping system. CTM-Cs: mono-cropping of cassava under conventional tillage; NTM-Cs: mono-cropping of cassava under no tillage system; and NTR: bi-annual rotation of cassava and maize under no-till systems with the use of cover crops represented by NTR1 and NTR2 as described in Table 1. NTR-Cs represents the average cumulative emissions between NTR1-Cs and NTR2-Cs, while the NTR-Mz represents the average cumulative emission between NTR1-Mz and NTR2-Mz. Different lowercase letters within the same group indicate a significant difference (Tukey's test, $p < 0.05$) between treatments. Error bars represent standard errors (n = 3).

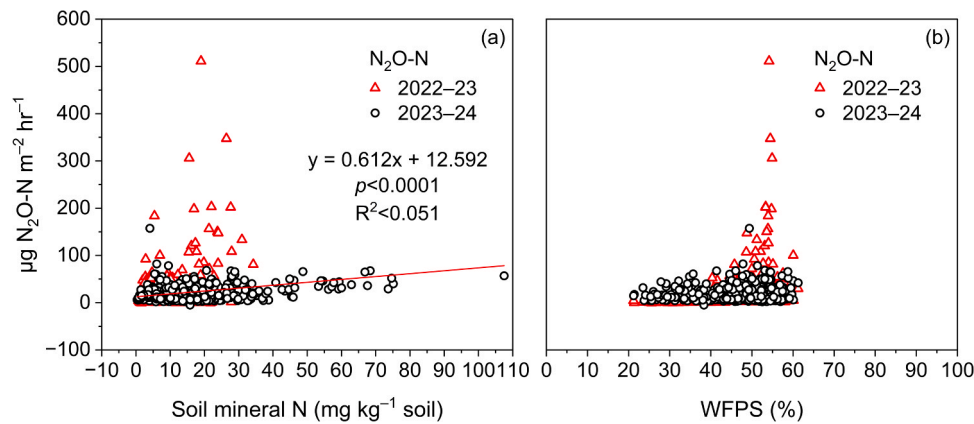


Fig. 4. Relationship between hourly N_2O -N emissions, daily soil mineral N and WFPS in 0–20 cm depth for the 2022–23 and 2023–24 cropping seasons.

3.6. Crop productivity and yield-scaled CH_4 and N_2O emissions

The severe infestation of cassava witches' broom disease during the rainy season in 2022–23 considerably affected cassava growth, caused a tuber yield loss estimated to be more than 40% (data not shown). Cassava productivity was not significantly different ($p > 0.05$) between the treatments in each cropping season; however, the tuber yield of all treatments in the 2023–24 cropping season was 32–50% higher than in 2022–23 (Table 2). When considering the average of both seasons' tuber yield, NTR-Cs produced 20% and 30% more ($p > 0.05$) than CTM-Cs and NTM-Cs, respectively (Table 2).

The yield-scaled CH_4 emissions of the main crops were totally reversed between the two cropping seasons. In 2022–23, the NTR1-Mz system emitted 0.05 g of CH_4 per kg of maize grain, whereas in 2023–24, NTR2-Mz became the CH_4 sink, consuming 0.22 g of CH_4 per kg of maize produced. In contrast, cassava production under all cropping systems in 2022–23 acted as a sink for CH_4 , consuming 0.05, 0.08, and 0.20 g CH_4 per kg of dry tuber under CTM-Cs, NTR2-Cs, and NTM-Cs, respectively. However, in 2023–24, cassava production across all the cropping systems (CTM-Cs, NTM-Cs, and NTR1-Cs) acted as a source for CH_4 , emitting 0.12 g CH_4 per kg of dry tuber (Table 2). Although NTR1-Mz was a CH_4 source in 2022–23, its yield-scale CH_4 emissions did not differ from CTM-Cs and NTR2-Cs, except that it was significantly ($p < 0.05$) higher than NTM-Cs. In 2023–24, the yield-scaled CH_4 emissions under NTR1-Mz was significantly ($p < 0.05$) lower than in the cassava treatments (Table 2). Considering the average of the both

seasons (2022–24), the yield-scaled CH_4 emissions under NTR-Mz was significantly ($p < 0.05$) lower than CTM-Cs and NTR-Cs but did not differ from NTM-Cs (Table 2).

With similar yield-scaled emissions of 0.22 g N_2O per kg of maize grain across the seasons, NTR-Mz showed significant ($p < 0.05$) higher grain yield-scaled N_2O emissions than all the cassava treatments' tuber yield-scaled N_2O emissions in 2022–23 and higher ($p < 0.05$) than CTM-Cs and NTR1-Cs in 2023–24, but did not differ ($p > 0.05$) from NTM-Cs (Table 2). Tuber yield-scaled N_2O emissions did not differ between the cassava treatments for both seasons (Table 2). Considering the average of both seasons, the yield-scaled N_2O emissions under NTR-Mz was significantly ($p < 0.05$) higher than in the cassava treatments (Table 2).

3.7. Greenhouse gas balance

Between 2011 and 2021, significant annual SOC accumulation rates in the 0–100 cm soil layer were 1.07, 0.95, and 0.70 $\text{Mg C ha}^{-1} \text{ yr}^{-1}$ under the NTM-Cs, NTR1, and NTR2 systems, respectively. There was no significant accumulation under CTM-Cs (Leng et al., 2024). These SOC accumulation rates correspond to a CO_2 removal from the atmosphere of -3.92 , -3.47 , and $-2.56 \text{ Mg CO}_2\text{-eq ha}^{-1} \text{ yr}^{-1}$ for NTM-Cs, NTR1, and NTR2, respectively (Table 3). For the period 2022–24, the average CO_2 removal from the atmosphere through SOC accumulation in the NTR systems (average of NTR1 and NTR2) was 3.01 $\text{Mg CO}_2\text{-eq ha}^{-1} \text{ yr}^{-1}$ (Table 3).

In both seasons, all the NT systems (i.e., NTM-Cs, NTR1-Cs, NTR2-Cs,

Table 2

Main crop yields, yield-scaled emissions of N_2O -N and CH_4 -C during the 2022–23 and 2023–24 cropping seasons, and average yield-scale emissions by cropping systems and main crops (2022–24).

Season	Treatment ^a	Main crop	Tuber or grain yield	Yield-scaled emissions	
			(kg ha^{-1})	($\text{g CH}_4\text{-C kg}^{-1}$)	($\text{g N}_2\text{O-N kg}^{-1}$)
2022–23	CTM-Cs	Cassava	6090 (± 797) a	$-0.05 (\pm 0.03)$ ab	$0.07 (\pm 0.02)$ b
	NTM-Cs	Cassava	4802 (± 251) a	$-0.20 (\pm 0.05)$ b	$0.11 (\pm 0.01)$ b
	NTR1-Mz	Maize	6517 (± 354)	$0.05 (\pm 0.02)$ a	$0.23 (\pm 0.02)$ a
	NTR2-Cs	Cassava	7522 (± 416) a	$-0.08 (\pm 0.03)$ ab	$0.07 (\pm 0.01)$ b
2023–24	CTM-Cs	Cassava	9438 (± 589) a	$0.12 (\pm 0.01)$ a	$0.11 (\pm 0.01)$ b
	NTM-Cs	Cassava	9632 (± 1310) a	$0.14 (\pm 0.01)$ a	$0.16 (\pm 0.01)$ ab
	NTR1-Cs	Cassava	11221 (± 1117) a	$0.11 (\pm 0.01)$ a	$0.13 (\pm 0.01)$ b
	NTR2-Mz	Maize	6273 (± 443)	$-0.22 (\pm 0.02)$ b	$0.20 (\pm 0.01)$ a
2022–24	CTM-Cs	Cassava	7764 (± 486) a	$0.03 (\pm 0.02)$ a	$0.09 (\pm 0.01)$ c
	NTM-Cs	Cassava	7217 (± 771) a	$-0.03 (\pm 0.03)$ ab	$0.13 (\pm 0.01)$ b
	NTR-Cs	Cassava	9371 (± 480) a	$0.01 (\pm 0.01)$ a	$0.10 (\pm 0.01)$ bc
	NTR-Mz	Maize	6395 (± 208)	$-0.09 (\pm 0.02)$ b	$0.22 (\pm 0.01)$ a

^a CTM-Cs: mono-cropping of cassava under conventional tillage; NTM-Cs: mono-cropping of cassava under no tillage system; and NTR: bi-annual rotation of cassava and maize under no-till systems with the use of cover crops represented by NTR1 and NTR2 as described in Table 1. NTR-Cs represents the average of NTR1-Cs and NTR2-Cs, while NTR-Mz represents the average of NTR1-Mz and NTR2-Mz. For the crop productivity, we considered only the cassava dry tuber yield for the statistical analysis, while all the treatments were considered for the comparison in the yield-scaled N_2O and CH_4 emissions. Different lowercase letters within the same column and season indicate a significant difference (Tukey's test; $p < 0.05$). Values in brackets indicate standard errors ($n = 3$).

Table 3

Greenhouse gas (GHG) balances using a global warming potential at a 100-year timescale of the different treatments due to cumulative CO₂ (estimated with SOC stock change between 2021 and 2011 at 0–100 cm depth) and CH₄ and N₂O emissions expressed as CO₂ equivalent (CO₂-eq). The non-CO₂ mitigation offset represents the ratio of (CH₄ + N₂O)/|SOC| in CO₂-eq. An offset of 50% means emissions of CH₄ and N₂O reduced by 50% the climate change mitigation benefits due to SOC sequestration.

Seasons	Treatments	CO ₂	CH ₄	N ₂ O	GHG balance	non-CO ₂ mitigation offset
			(Mg CO ₂ -eq ha ⁻¹ yr ⁻¹)			%
2022–23	CTM-Cs	−0.50 (±1.30) b	−0.016 (±0.009) ab	0.23 (±0.05) b	−0.28 (±1.35)	43.7
	NTM-Cs	−3.92 (±0.66) a	−0.034 (±0.009) b	0.20 (±0.01) b	−3.75 (±0.67)*	4.4
	NTR1-Mz	−2.56 (±0.39) a	0.012 (±0.006) a	0.59 (±0.06) a	−1.95 (±0.34)*	23.7
	NTR2-Cs	−3.47 (±0.26) a	−0.027 (±0.008) b	0.25 (±0.03) b	−3.25 (±0.25)*	6.4
2023–24	CTM-Cs	−0.50 (±1.30) b	0.152 (±0.014) a	0.40 (±0.03) b	0.06 (±1.32)	112.0
	NTM-Cs	−3.92 (±0.66) a	0.147 (±0.008) a	0.48 (±0.03) ab	−3.30 (±0.69)*	15.9
	NTR1-Cs	−2.56 (±0.39) a	0.147 (±0.013) a	0.50 (±0.04) ab	−1.91 (±0.39)*	25.4
	NTR2-Mz	−3.47 (±0.26) a	−0.233 (±0.024) b	0.63 (±0.04) a	−3.08 (±0.28)*	11.4
2022–24	CTM-Cs	−0.50 (±1.30) b	0.068 (±0.011) a	0.32 (±0.04) c	−0.11 (±1.34)	77.9
	NTM-Cs	−3.92 (±0.66) a	0.057 (±0.006) a	0.34 (±0.02) c	−3.52 (±0.68)*	10.1
	NTR-Cs	−3.01 (±0.31) a	0.060 (±0.008) a	0.37 (±0.01) c	−2.58 (±0.31)*	14.4
	NTR-Mz	−3.01 (±0.31) a	−0.110 (±0.014) b	0.61 (±0.03) a	−2.51 (±0.30)*	16.6
	NTR1	−2.56 (±0.39) a	0.080 (±0.009) a	0.55 (±0.04) ab	−1.93 (±0.36)*	24.6
	NTR2	−3.47 (±0.26) ^a	−0.130 (±0.016) b	0.44 (±0.02) bc	−3.16 (±0.26)*	8.9

^a CTM-Cs: mono-cropping of cassava under conventional tillage; NTM-Cs: mono-cropping of cassava under no tillage system; and NTR: bi-annual rotation of cassava and maize under no-till systems with the use of cover crops represented by NTR1 and NTR2 as described in Table 1. NTR-Cs represents the average of NTR1-Cs and NTR2-Cs, while NTR-Mz represents the average of NTR1-Mz and NTR2-Mz. Values in brackets indicate standard errors (n = 3). Different lowercase letters in the same column and seasons indicate significant (Tukey's test; $p < 0.05$) difference between the treatments within the same cropping season. Values of the GHG balance of the treatments with * indicate significant (One-sample t -test; $t < 0.05$) different from zero.

NTR1-Mz, and NTR2-Mz) contributed positively ($t < 0.05$) to climate change mitigation in relative to zero, while the GHG balance of CTM-Cs in both seasons were negligible (Table 3 and Table S6). Across both seasons, between 4% and 25% of the climate benefit due to the annual SOC accumulation rate ($t < 0.05$) under the NT systems (NTM-Cs, NTR-Cs, and NTR-Mz) were offset by the CH₄ and N₂O emissions. Considering the average over both seasons, only 9–25% of the climate benefit due to SOC accumulation rate ($t < 0.05$) under the NT systems were offset by the CH₄ and N₂O emissions (Table 3).

Considering the average across both seasons of each main crop and elementary plot, all the NT systems (NTM-Cs, NTR-Cs, NTR-Mz, NTR1, and NTR2) had a significant ($t < 0.05$) potential to contribute to climate change mitigation, with sequestration rates ranging from −1.93 to −3.52 Mg CO₂-eq ha⁻¹ yr⁻¹ (Table 3).

4. Discussion

4.1. Effects of seasonal and cropping systems on soil CH₄ emissions and uptake

In our study, the hourly CH₄ emissions were unpredictable and varied across the treatments and seasons (Figs. 1c and 1d). Such findings are not surprising as many studies reported high temporal variability in CH₄ fluxes, in which the soils can switch from a sink to source of CH₄ within hours (Drewer et al., 2017; McDaniel et al., 2019). This observation aligns with findings by Shumba et al. (2023), who reported CH₄ fluxes varied between −128.2 and +142.9 μg CH₄-C m⁻² hr⁻¹ depending on seasons and spatial sampling positions. In contrast, from a global meta-analysis covering 90 case studies, Maucieri et al. (2021) reported a much larger variation in CH₄ fluxes, ranging between −2883 and +41400 μg CH₄-C m⁻² hr⁻¹ under CT and −128 and +32550 μg CH₄-C m⁻² hr⁻¹ under NT systems, indicating the wide variability in CH₄ dynamics under different agroecosystems worldwide.

In 2022–23, the soil of the cassava treatments (CTM-Cs, NTM-Cs, and NTR2-Cs) was a net sink for CH₄, while it became a source of CH₄ in 2023–24 (Figs. 3a and 3b). This change coincided with warmer weather due to the El Niño phenomenon between July 2023 to May 2024 (FAO, 2024b), verified by a higher annual mean temperature of +1.15 °C in 2023–24 than in 2022–23 (Figs. 1a and 1b), which could accelerate the rates of the methanogenesis and anaerobic oxidation of CH₄ (Xu et al.,

2024). The variation in air temperature, which could alter microbial activity, might explain the CH₄ emissions recorded under these treatments (Xu et al., 2024).

Seasonal variation in rainfall distribution between seasons influenced the growth of mixed cover crops established prior to the maize cultivation under NTR-Mz, thereby leading to differences in N inputs from crop residues that varied by species and season (Table S5). In 2022–23, the N inputs from the grass (pearl millet) were significantly lower than from the legumes, particularly sunn hemp, with 22.7 and 55.4 kg ha⁻¹, respectively. However, this trend was reversed in 2023–24, with pearl millet contributing significantly to N inputs than the legumes—82.5 vs. 26.9 kg ha⁻¹, respectively (Table S5). The fact that in 2022–23, the soil under NTR1-Mz was a CH₄ source could be explained by the biochemical composition of legume cover crops, which were characterized by a low C:N ratio and contain high levels of soluble compounds with low lignin and polyphenol concentrations (Cobo et al., 2002; Gomes et al., 2009). These traits can accelerate C mineralization (Riffaldi et al., 1996), thus providing a readily available C substrate to methanogenic bacteria (Dutaur and Verchot, 2007). In contrast, in 2023–24, the NTR2-Mz soil became a CH₄ sink (Fig. 3b). This shift coincided with higher peaks of soil mineral N observed in 2023–24 (Fig. 2d), indicating increased N availability that could lower CH₄ oxidation in the soil (Hütsch et al., 1996; Acton and Baggs, 2011). This could potentially be due to changes in the structure of the microbial community (Acton and Baggs, 2011).

Overall, our results clearly indicated the difference in soil CH₄ fluxes among the treatments and cropping seasons, which were influenced by air temperature and the biochemical nature of crop residues. These findings align with other studies that underscored the influences of environmental conditions and residue quality in regulating soil CH₄ emissions (Cobo et al., 2002; Gomes et al., 2009; Xu et al., 2024).

4.2. Effect of cropping systems on soil N₂O emissions

The temporal dynamics of hourly N₂O emissions on all the treatments exhibited sharp peaks following each mineral fertilizer application, particularly on the rows of cassava and maize at WFPS > 55%, aligned with the studies from various croplands in tropical climate (Dos Santos et al., 2016; Shumba et al., 2023). These peaks indicate the localized effects of the mineral N fertilizers placement with high

moisture content, which increases soil N availability, known as the primary source of N_2O emissions (Shumba et al., 2023; Sedghi et al., 2024). Furthermore, applying mineral N fertilizer alongside the rows with higher C-inputs from residues, especially under NT systems, could increase nutrient availability, which stimulates microbial activities and accelerates nitrification and denitrification processes, leading to increased N_2O from the soils (Bremner, 1997; Hergoualch et al., 2019).

Under NTR-Mz, the hourly N_2O emissions pattern on the rows during the first three weeks after maize cultivation, along with mineral N fertilizer application at sowing followed by the cover crop termination, differed between the two cropping seasons, despite similar management systems (Figs. 1e and 1f). Despite these contrasting peaks of hourly N_2O emissions under NTR-Mz, our study showed that the cumulative N_2O emissions was similar between the two years, ranging from 1.39 to 1.46 kg $\text{N}_2\text{O-N ha}^{-1} \text{ yr}^{-1}$ (Fig. 3e). Crop residues could regulate N_2O emissions depending on their structural fractions, easily degradable fractions, N content, and their biochemical characteristics (Abalos et al., 2022). Studies on the effect of different cover crop species showed that soil N_2O emissions increased linearly as the amount of the N-rich legume residues increased compared to grass residues (Pimentel et al., 2015; Muhammad et al., 2019). The residues of legume cover crops favor the rapid microbial decomposition, especially in the tropical climates, contributing to the increase in soil mineral N content after the termination, contributing to N_2O emissions (Cobo et al., 2002; Perin et al., 2006; Gomes et al., 2009; Kandel et al., 2018; Delgado et al., 2021; Virk et al., 2022; Abalos et al., 2022). From a field-scale experiment in the tropical climate of Brazil, Perin et al. (2006) reported that although sunnhemp and pearl millet had the same dry matter decomposition half-life time of 39 days after termination, N release occurred much earlier under sunnhemp at 15 days, compared to 36 days under pearl millet. Gomes et al. (2009) reported the peaks of soil N_2O emissions in the first 45 days after termination of legume cover crops from long-term NT crop rotation experiments in Southern Brazil (semi-temperate climate). In contrast, residues from grass cover crops have a higher lignin, hemicellulose and cellulose content, a lower N content, a higher C:N ratio, and a higher lignin:N ratio, indicating potentially slower decomposition rate than legumes along with slower N release or even in immobilization of mineralized N from SOM (Thompson and Fillery, 2002; Perin et al., 2006; Pimentel et al., 2015; Daryanto et al., 2018). In addition, grass cover crops also showed the greatest capability in nitrate leaching reduction up to 52% (Nouri et al., 2022).

Studies measuring the effects of different cassava-based cropping systems on N_2O emissions are still limited. In our study, the average cumulative N_2O emissions over the two seasons under cassava treatments ranged from 0.74 to 0.87 kg $\text{N}_2\text{O-N ha}^{-1}$, which is comparable to the annual emissions of 0.84 kg $\text{N}_2\text{O-N ha}^{-1}$ with no soil amendment reported by Sriphirom et al. (2023) from a 47-year long-term experiment in Thailand. These emission rates were at least 47% lower than those reported by Chirinda et al. (2021), who observed annual N_2O emissions ranging from 1.28 kg $\text{N}_2\text{O-N ha}^{-1}$ under organic amendment to 1.74 kg $\text{N}_2\text{O-N ha}^{-1}$ under mineral fertilizer application in Colombia, and lower than the 1.79–3.37 kg $\text{N}_2\text{O-N ha}^{-1}$ range reported by Sriphirom et al. (2023) under various amendments in Thailand.

Differences in amount of the crop residues retained to the systems (Table 1) may account for the higher cumulative N_2O emissions under the NTR1-Mz in 2022–23 and the NTR systems (NTR1-Cs and NTR2-Mz) in 2023–24 when compared to CTM-Cs. Similar results were observed in field studies conducted in Sub-Saharan Africa, in which annual N_2O emissions were higher under the systems with residue addition (Zheng et al., 2023) and crop rotation (Shumba et al., 2023).

4.3. Yield-scaled CH_4 and N_2O emissions

Understanding the climate impacts of cropping systems in relation to their productivity requires evaluating yield-scaled CH_4 and N_2O emissions (Pittelkow et al., 2013; Rigon et al., 2021). Our results showed that

the highest yield-scaled CH_4 and N_2O emissions were 0.14 g $\text{CH}_4\text{-C kg}^{-1}$ and 0.16 g $\text{N}_2\text{O-N kg}^{-1}$ of dry tuber of cassava and 0.05 g $\text{CH}_4\text{-C kg}^{-1}$ and 0.23 g $\text{N}_2\text{O-N kg}^{-1}$ of dry maize grain across both cropping seasons (Table 3). While yield-scaled N_2O emissions have been investigated in cassava and maize production (Pengthamkeerati et al., 2014; Chirinda et al., 2021; Sriphirom et al., 2023), no published data is available for yield-scaled CH_4 emissions. In our study, the measured yield-scaled N_2O emissions of the cassava production were at least 60% lower than previously reported values, which ranged from 0.41 to 0.98 g $\text{N}_2\text{O-N kg}^{-1}$ dry tuber of cassava, depending on the types and amount of soil amendments applied to the crop (Sriphirom et al., 2023). In comparison to the findings reported from Sub-Saharan Africa, the maize yield-scaled N_2O emissions under NT systems in our study were among the highest recorded for NT systems, with emissions varying from 0.02 to 0.19 g $\text{N}_2\text{O-N kg}^{-1}$ maize grain, depending on cropping systems intensity, seasons, and soil type (Shumba et al., 2023).

To avoid overestimating the climate benefits of agricultural practices, it is important to accurately assess the trade-off between SOC sequestration and non- CO_2 GHG emissions (Guenet et al., 2021). Our on-site study clearly showed that field-scale CH_4 and N_2O emissions offset part of the climate benefit due to the increase in SOC stocks under NT systems (Table 3). This suggests that the primary climate benefit of NT systems in the tropical upland of Cambodia is primarily driven by SOC accumulation. These benefits are achieved through the combination of the three CA principles: minimal soil disturbance, biomass retention, and crop and cover crops diversification. Our findings are consistent with those of Shumba et al. (2024), who also reported that GHG emissions compensated the increased SOC stocks under NT alone.

4.4. Greenhouse gas balance

N_2O contributed much more to the GHG balance across cropping seasons than CH_4 (Table 3). Our findings suggested that, on average, SOC sequestration under NT systems could remove 2.51–3.52 Mg $\text{CO}_2\text{-eq ha}^{-1} \text{ yr}^{-1}$ from the atmosphere, higher than the estimation of the potential SOC sequestration in the tropics by Graham et al. (2021) at the rate of 0.04 Mg $\text{CO}_2\text{-eq ha}^{-1} \text{ yr}^{-1}$ and align with the predictions by Smith et al. (2008) and Ogle et al. (2019) ranging from 0.15 to 3.75 Mg $\text{CO}_2\text{-eq ha}^{-1} \text{ yr}^{-1}$. In contrast, there was no significant C removal under CTM-Cs (Table 3). These findings highlight the potential of NT systems as agricultural sustainable practices for food security and mitigating global warming.

4.5. Limitations and perspective

We acknowledge the limitations associated with the static chamber technique used in this study. Although extensively adopted, static chambers capture GHG fluxes only during short measurement intervals and are typically constrained by low sampling frequency. In this study, the highest frequency of gas sampling was once daily for maize and twice a week for cassava. In contrast, automated monitoring systems can detect variations and short-lived emission peaks continuously that static chambers may not capture.

Since NH_3 volatilization contributes to indirect N_2O emissions, the NH_3 effluxes should be integrated to have a better understanding of N cycling and to refine the emission factors of each cassava-based cropping system. Furthermore, modeling should be carried out to predict the impacts of each cropping system on the sustainability of cassava production in Cambodia and in the region.

5. Conclusion

Our study provides the first in-situ quantification of non- CO_2 GHG emissions and trade-offs with annual SOC accumulation under contrasting cassava-based cropping systems. Our findings showed that CH_4 emissions varied depending on cropping systems and seasons. In

contrast, N₂O emissions were generally greater under the treatments with higher residue quality and quantity rather than influenced by the seasons.

With similar rates of cassava tuber yield-scaled CH₄ and N₂O emissions, NT systems with cover crops resulted in positive climate mitigation benefits. Emissions of CH₄ and N₂O emissions offset between 4.4% and 25.4% of the climate mitigation benefit due to SOC sequestration under NT systems, while the offset varied between 43.7% and 112% under CT system. Considering the average of each main crop and elementary plot, NT systems substantially contributed to climate change mitigation by net removing 1.93–3.52 Mg CO₂-eq ha⁻¹ yr⁻¹. Our findings highlighted the potential of NT systems as sustainable agricultural practices for food security and climate change mitigation.

CRediT authorship contribution statement

Chhay Ngin: Writing – review & editing, Investigation. **Stéphane Boulakia:** Writing – review & editing, Investigation. **Vira Leng:** Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation. **Lyda Hok:** Writing – review & editing, Investigation. **Johan Six:** Writing – review & editing, Supervision, Investigation. **Pascal Lienhard:** Writing – review & editing, Investigation, Funding acquisition. **Phearum Mark:** Writing – review & editing, Data curation. **Rémi Cardinael:** Writing – review & editing, Supervision, Methodology, Data curation, Conceptualization. **Florent Tivet:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Prasad P. V. Vara:** Writing – review & editing, Investigation. **Vang Seng:** Writing – review & editing, Investigation. **Manuel Reyes:** Writing – review & editing, Investigation. **Laurent Thuriès:** Writing – review & editing, Supervision, Methodology, Data curation, Conceptualization. **Titouan Filloux:** Writing – review & editing, Validation, Formal analysis. **Try Yorn:** Writing – review & editing, Investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.agee.2026.110363](https://doi.org/10.1016/j.agee.2026.110363).

Data availability

The dataset used in this study is fully available in the Cirad Dataverse ([Leng et al., 2025](https://doi.org/10.1016/j.agee.2026.110363)).

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