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Special Issue

Effects of crop rotation and tillage on CO_2 and CH_4 fluxes in paddy fields

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ABSTRACT: Rice is a staple food for much of the global population, but its traditional cultivation methods, particularly prolonged flooding, contribute to significant methane (CH_4) emissions. Introducing a rice-maize rotation system has the potential to reduce greenhouse gas (GHG) emissions. This study compared double-cropping rice fields with rice-maize rotation systems, with and without tillage, over two consecutive growing periods. The closed chamber method was employed to measure carbon dioxide (CO_2) and CH_4 fluxes in each field, assessing GHG emissions across different cropping systems. Results indicate that tillage is an effective management practice for reducing emissions in double-cropping rice systems. The total net carbon absorption (CO_2 + CH_4) over two periods ranked as follows: double-cropping rice in field A (AR1-AR2) at 4.93 t C/ha > rice-no-tilled maize in field B (BR1-BNTC2) at 3.46 t C/ha > rice-till maize in field B (BR1-BTC2) at 3.41 t C/ha > rice-no-till maize in field C (CR1-CNTC2) at 2.24 t C/ha > rice-tilled maize in field C (CR1-CTC2) at 1.79 t C/ha. The global warming potential (GWP) of the rice-maize rotation systems was notably lower than that of double-cropping rice, primarily due to the high CH_4 emissions from waterlogged conditions in control fields. Among treatments, the rice-no-till maize system exhibited the lowest GWP and greenhouse gas intensity (GHGI) while also achieving the highest crop yield, implying it the most environmentally and economically sustainable option.

KEY WORDS: Greenhouse gas emissions, greenhouse gas intensity, global warming potential, climate-smart agriculture.

INTRODUCTION

The growing global population, combined with increasing food demand and intensifying impacts of climate change due to rising greenhouse gas (GHG) emissions, poses significant challenges in environmental science. Agriculture plays a pivotal role, contributing around 12% of total GHG emissions, primarily from soil cultivation and crop production. It is also the leading source of non-carbon dioxide GHG emissions from human activities (IPCC, 2021; Raihan and Tuspekova, 2022). Reducing GHG emissions in agricultural systems is essential for mitigating the greenhouse effect and moving toward carbon neutrality. Between 2000 and 2010, non-CO_2 GHG emissions averaged 4.6 to 5.1 billion tonnes of CO_2-equivalent per year, with nitrous oxide (N_2O) accounting for 57% and methane (CH_4) 43% of these emissions (FAO, 2019). Rice (*Oryza sativa* L.), a staple food for nearly half of the global population (Wang *et al*., 2017), is a significant source of agricultural GHG emissions. Rice paddies contribute approximately 55% of total agricultural soil GHG emissions and 6-11% of anthropogenic CH_4 emissions, with about 90% of these emissions originating in Asia (FAO, 2019). Globally, paddy fields released an estimated 22-25 million tonnes of CH_4 annually between 2000 and 2010 (FAO, 2013b). Rice cultivation has a higher global warming potential (GWP) compared to crops like maize and wheat, largely due to CH_4 emissions generated by methanogenic bacteria in flooded soils (Linquist *et al*., 2012). Net greenhouse gas intensity (GHGI) refers to the net GWP per unit of crop yield, which is determined by the exchange of CH_4 and CO_2 between soils and the atmosphere (Shang *et al*., 2011). CH_4 has a GWP 27.2 times greater than CO_2 over a 100-year time horizon (IPCC, 2023). Given agriculture's significant contribution to GHG emissions, improving farming practices and management strategies is critical for reducing global warming impacts while maintaining high crop productivity (Follett *et al*., 2011; Pao *et al*., 2025).

Climate-smart agriculture (CSA) has been globally advocated as an approach to maintain or enhance food production while mitigating agricultural GHG emissions and minimizing other environmental impacts (FAO, 2013a). Among the key factors influencing soil and atmospheric GHG exchanges is tillage. The amount of soil CO_2 emitted from tilled farmlands can vary depending on factors such as the region, soil type, and local environmental conditions (Forte *et al*., 2017; Hou *et al*., 2014). Studies have shown that tilled soils emit approximately 21% more CO_2 than no-till soils, largely due to differences in soil bulk density and aggregate stability (Abdalla *et al*., 2016; Chaplot *et al*., 2015).No-tillage practices have been recommended as part of CSA strategies (Lipper *et al*., 2014), as no-till systems tend to have greater carbon sequestration potential, improved soil structure, and enhanced soil fertility and crop productivity compared to conventionally tilled fields. These benefits help prevent soil degradation, increase soil organic matter, and reduce GHG emissions (Krauss *et al.*, 2017; Li *et al.*, 2023; Stewart *et al.*, 2016). In Taiwan, the adoption of no-tillage or reduced tillage practices remains relatively limited, primarily due to the prevalence of small-scale farms, high-intensity farming systems, and a lack of awareness or access to no-tillage equipment. Furthermore, traditional farming methods, including tillage, are often preferred due to perceived advantages in pest control, weed and crop residue management. Nonetheless, recent initiatives have aimed to promote no-tillage practices by demonstrating their benefits in reducing soil erosion, enhancing water retention, and contributing to carbon sequestration. These efforts are particularly relevant in areas facing soil degradation and frequent extreme weather events. However, the effects of no-tillage on soil GHG emissions remain contested, with studies reporting mixed outcomes (Zhao *et al.*, 2016). Therefore, further research is needed to better understand the impact of tillage practices on GHG emissions, particularly under Taiwan's unique agricultural conditions and diverse cropping systems. By addressing these challenges, no-tillage systems could play a more prominent role in advancing CSA strategies in Taiwan.

To enhance food production and promote environmental sustainability, it is crucial to develop effective field management practices that minimize net global warming potential (GWP) and greenhouse gas intensity (GHGI) while maintaining high productivity. The relationship between net GWP and GHGI and the timing of tillage, in conjunction with crop yields, warrants further exploration. Crop rotation in paddy fields has been shown to optimize land use, although its impact on GHG emissions varies across different rotation systems (Yang *et al.*, 2024; Zhou *et al.*, 2014). Such variations affect the rate of organic matter decomposition and soil organic carbon accumulation. Some studies have classified maize fields as either methane (CH_4) sinks or sources, depending on long-term climatic and irrigation conditions (Linquist *et al.*, 2012), while others report that maize fields act as weak CH_4 sources, particularly during irrigation (Weller *et al.*, 2015, 2016).

In Asia, rice paddies are the dominant form of crop cultivation, but water shortages due to industrial and domestic demands, exacerbated by climate change, are increasingly limiting rice production. As a result, many farmers are transitioning from double-cropping rice systems (R-R) to rice-maize (Zea mays L.) rotations (Timsina *et al.*, 2010). The rising demand for livestock feed and bioenergy has also driven the conversion of paddy fields into dryland crops, such as maize and sorghum, which are more drought-tolerant and require less irrigation. These crops, with shorter growing periods and lower water needs, make rice-maize rotations a sustainable approach to intensive agriculture (FAO, 2016). Compared to double-cropping rice, rice-maize rotations yield higher productivity, greater economic value, lower energy consumption, and reduced water use (Jat *et al.*, 2019). Implementing crop rotations in paddy fields has also improved land use efficiency and reduced GHG emissions, as CH_4 emissions increase under anoxic conditions, while nitrous oxide (N_2O) emissions decline due to denitrification (Datta *et al.*, 2011; Linquist *et al.*, 2012). Maize fields, however, tend to sequester more carbon than paddy fields (Janz *et al.*, 2019). Rotating rice with maize or sorghum has been shown to increase soil organic carbon while reducing annual GHG emissions by 68–78% compared to continuous rice cropping systems (Cha-un *et al.*, 2017).

In Taiwan, promoting crop rotations such as rice-maize systems has been identified as a priority for enhancing agricultural resilience and environmental sustainability. The government has actively encouraged the transition to mixed cropping systems, particularly through subsidies and pilot projects aimed at increasing the cultivation of drought-tolerant grains like maize, millet, and sorghum. These initiatives align with the need to adapt to water scarcity challenges and reduce CH_4 emissions from flooded rice fields. Despite these efforts, barriers such as farmers' preference for traditional rice cultivation. Nevertheless, the shift toward diversified cropping systems offers promising opportunities for improving land-use efficiency and mitigating GHG emissions. The conversion of paddy fields to dryland crops, such as maize and sorghum, has been shown to effectively reduce CH_4 emissions. However, this transition necessitates addressing potential trade-offs, including increased N_2O emissions and reductions in soil carbon stocks resulting from enhanced oxygen availability (Stevens and Quinton, 2009). Achieving greenhouse gas (GHG) neutrality requires the identification of farm management practices tailored to local conditions. Such practices include optimized water management strategies, precise fertilizer application techniques, and the development of robust market support mechanisms to ensure the economic sustainability of dryland crop systems in Taiwan (Pao *et al.*, 2025). Furthermore, long-term research is critical to evaluate the impacts of rice-to-dryland crop rotations on GHG emissions and soil health, particularly within the context of Taiwan's diverse agricultural landscapes.

In this study, our objectives were to: (1) quantify methane (CH_4) and carbon dioxide (CO_2) absorption and emissions over consecutive growing periods, and (2) assess the differences in crop yields between double-cropping rice cultivation (used as the control) and a rice-maize rotation system, with both tilled and no-till treatments. The findings of this study identified specific combinations of tillage methods and crop rotation systems as promising strategies for mitigating GHG emissions. Moreover, the GWP and GHGI results offer insights into the environmental impacts of these agricultural practices and could inform future efforts to minimize GHG emissions in crop production systems.

MATERIALS AND METHODS

Experimental site and planting design

This experiment was carried out between March 2023 and January 2024 at the Taoyuan District Agricultural Research and Extension Station (TDARES, 24°57'11.3"N, 121°01'41.3"E). The study spanned two cropping periods, with three experimental fields assigned to different planting schemes, as outlined in Table S1. All fields were initially prepared as paddy fields before the first growing period. One field, planted with rice (AR1), served as the control group, while the other two fields were designated for rice-corn rotation systems. Prior to rice transplanting, the rotation fields underwent conventional tillage (BR1 and CR1), involving mouldboard ploughing to a depth of 20 cm. Each experimental field (20 m × 20 m) during the first growing period had a cultivation period of 140 days, from March to July 2023. The experimental sites were selected based on previously harvested areas for each crop regime plan, accounting for spatial variations in factors such as temperature, aridity, and growing days, all of which influence crop yield. Rice seeds were initially sown in a seedling nursery and transplanted into the fields at the three- to four-leaf stage. After harvesting the first period's rice crop, the control field was tilled again and planted with a second rice crop (AR2), while the two rotation fields were planted with maize. The rotation fields from the first period (BR1 and CR1) were further divided before the second growing period (August to November 2023), depending on whether the fields were tilled for corn planting. This resulted in tilled corn (BTC2 and CTC2) and no-till corn (BNTC2 and CNTC2) treatments in the same fields. Each experimental field during the second period had a growing period of 110 days. The rice and maize varieties used in this study were Taoyuan No.3 and Tainan No.7, respectively. Taoyuan No.3 is a widely cultivated rice variety in Taiwan, known for its high nutritional value, while Tainan No.7 maize is popular for consumption as a fresh vegetable. The experimental schedule and data collection times for each field are detailed in Table S1. Prior to transplanting or sowing, each field received a basal application of fertilizer (50 kg P_2O_5 ha^{-1} and 30 kg K_2O ha^{-1}), which was broadcast onto the soil. Additionally, two rounds of topdressing were applied during the growing period, at the tillering and panicle stages, to provide supplementary nutrients for optimal crop growth.

Water management in all fields during the growing periods relied on natural drainage. No pesticides were applied throughout the study, and fields were drained and re-irrigated during the second growing period. Over the two crop rotation cycles (growth periods 1 and 2), total precipitation amounted to 2230 mm and 2491 mm, with average temperatures of 26.1°C and 30.4°C, respectively. The soil at the site is classified as a typical Haplaquept, consisting of 18.2% clay, 31.3% silt, and 50.5% sand. The 0–20 cm soil layer has a bulk density of 1.13 g cm^{-3}, a pH of 5.74, an organic carbon content of 16.9 g kg^{-1}, and a total nitrogen content of 1.62 g kg^{-1}. It is assumed that the tested crops were uniformly influenced by these soil characteristics.

Measurements of CH_4 and CO_2 flux

Steel rings and closed chambers were utilized to monitor CH_4 and CO_2 flux changes at predetermined intervals, allowing for the analysis of the effects of plant growth stages, treatment conditions, and light exposure on organic gas emissions from the plants and fields (Cha-un *et al*., 2017; Pao *et al*., 2025). Methane concentrations were measured using the ABB GLA-131 (ASEA Brown Boveri, Switzerland), while CO_2 levels were determined with the CR-800 (LICOR Biosciences, CA, USA). During chamber closure, an automated sampling system extracted headspace air from each chamber and directly injected it into gas chromatographs located on-site. Three replicates were randomly sampled from each experimental field. Methane concentrations were recorded every 10 seconds for a duration of 5 minutes, while CO_2 data were collected under both full shade and natural light conditions to simulate day and night, with measurements taken every 30 seconds for a period of 2 minutes. The resulting data were used to compute various metrics related to gas flux.

Net ecosystem exchange (NEE)

Net ecosystem exchange (NEE) was measured as the net amount of greenhouse gases (e.g., CO_2) exchanged between the atmosphere and the ecosystem per unit area and per unit time (Reichstein *et al*., 2005; Chapin *et al*., 2006; Pao *et al*., 2025). The CO_2 flux data were analyzed specifically after tillage, when soil respiration was the primary source of CO_2 emissions. In this study, NEE is expressed in milligrams per square meter per hour. Negative values indicate greenhouse gas absorption by soil and organisms (net carbon sink), whereas positive values represent emissions (net carbon source). Larger absolute values reflect greater absorption or emission capacities.

NEE for CO_2 and methane (CH_4) was recorded as mg C/m^2·h and mg CH_4/m^2·h, respectively. NEE was calculated using the average slope derived from linear regression, which tracked changes in greenhouse gas flux during the measurement period and converted them into appropriate experimental units (Weller *et al*., 2015, 2016). The formula used for these calculations is as follows:

$$NEE\ (\mathrm{mg/\ m^2 \cdot h}) = \frac{S \times V_r \times 60 \times M_g \times n}{V_m \times 1000 \times 0.7}$$

Table 1. Net flux of CO_2 equivalents of CO_2 and CH_4 in each experimental field over two consecutive growth periods.

Field	Period 1-CO_2	t CO_2 e/ha	Period 2	t CO_2 e/ha	Total (t CO_2 e/ha)
A	Rice (AR1)	-19.60	Rice (AR2)	-1.79	-21.39
B	Rice (BR1)	-15.09	Tilled Corn (BTC2)	1.50	-13.59
			No-tilled Corn (BNTC2)	1.33	-13.76
C	Rice (CR1)	-8.97	Tilled Corn (CTC2)	1.70	-7.27
			No-tilled Corn (CNTC2)	0.06	-8.91
Field	Period 1-CH_4	t CO_2 e/ha	Period 2	t CO_2 e/ha	Total (t CO_2 e/ha)
A	Rice (AR1)	2.36	Rice (AR2)	28.34	30.70
B	Rice (BR1)	7.02	Tilled Corn (BTC2)	0.66	7.68
			No-tilled Corn (BNTC2)	0.69	7.71
C	Rice (CR1)	2.09	Tilled Corn (CTC2)	0.23	2.32
			No-tilled Corn (CNTC2)	0.16	2.25

Positive values indicate net emissions, while negative values indicate net absorption.
Each experimental field during first and second growing periods had growth periods of 110 and 140 d, respectively.

S: The average slope of the flux change regression line, with units of mg/ m²·h (rate of carbon flux change over time).
Vr: The volume of the steel ring cover, with units of m^3 or L (depending on the experimental setup; ensure consistent units).
Mg: The molecular weight of the gas, with units of g/mol.
n: The recording frequency per minute, unitless (typically expressed as the number of recordings per minute).
Vm: The molar volume of the gas at standard conditions, with units of L/mol. Winter value is 24.50 L/mol and summer value is 24.86 L/mol.

Global warming potential (GWP)

Global warming potential (GWP) for each growth period was quantified based on the greenhouse gas impact on global warming, following the guidelines set by the Intergovernmental Panel on Climate Change (IPCC, 2023). GWP was assessed over specific time horizons (e.g., 20 years or 100 years), as recommended by the IPCC, to compare the relative contributions of different greenhouse gases to global warming, relative to CO_2. This study adopted GWP100 values from the IPCC (2021), where GWP for CO_2 is set at 1 and for CH_4 at 27.2. GWP calculations were based on NEE data, as well as day and night durations recorded by the agricultural meteorological station at TDARES. CO_2 flux, CH_4 flux, and GWP were computed separately using the following formulas:

$$CO_2\,flux\ (\text{t CO}_2\ /\ \text{ha}) = \frac{(NEE_d \times T_d + NEE_n \times T_n) \times 44}{12 \times 10^5}$$

$$CH_4 flux(\text{t CH}_4/\text{ha}) = \frac{NEE_m \times 24}{10^5}$$

$$GWP\ (\text{t CO}_2\text{e / ha}) = CO_2 flux + CH_4 flux \times 27.9$$

Where NEE_d, NEE_n, and NEE_m separately represent daytime NEE (mg C/m² h) of CO_2, nighttime NEE (mg C/m² h) of CO_2, and NEE (mg CH_4/m² h) of CH_4. T_d and T_n separately represent daytime duration (h) and night time duration (h).

Greenhouse gas intensity (GHGI)

Greenhouse gas intensity (GHGI) was calculated as the total greenhouse gas emissions per unit of crop yield (in tons). This metric was determined by dividing the net GWP by the total crop yield. Crop yield was measured as dry weight per unit area, and this value was used in combination with the GWP for the specified period to compute the GHGI. The formula used for this calculation is:

$$GHGI(\text{t CO2 e / t yield}) = \frac{GWP}{Y}$$

Where Y represents crop yield (t yield / ha).

RESULTS

Prevalence of microplastics in feces

Table 1 presents the net CO_2 equivalent flux in each experimental field across two growth periods, comparing a control group of double-cropping rice with rice-maize rotation fields under both tilled and no-till conditions. During the first growing period, all fields exhibited net CO_2 absorption. The net absorption in the rice rotation field (BR1) in field B was 15.09 t CO_2 e/ha, which was 68.23% higher than the rice rotation field (CR1) in field C, which recorded 8.97 t CO_2 e/ha, and 23.01% lower than the rice-planted control field (AR1) in field A, which absorbed 19.60 t CO_2 e/ha. In the second growing period, following the first period of rice cultivation in both BR1 and CR1 fields, all fields shifted to a net CO_2 emission state. The net emission in the rice-tilled corn rotation field (BR1-BTC2) in field B was 1.50 t CO_2 e/ha, 12.78% higher than the rice-no-tilled corn rotation field (BR1-BTC2), which emitted 1.33 t CO_2 e/ha. In contrast, the rice-tilled corn rotation field (CR1-CTC2) in field C recorded a net emission of 1.70 t CO_2 e/ha, 2733.33% higher than the rice-no-tilled corn rotation field (CR1-CNTC2) in field 3, which emitted only 0.06 t CO_2 e/ha. Comparing fields with different treatments during the first period but similar treatments in the second, CR1-CTC2 (1.70 t CO_2 e/ha) in field C had 13.33% higher emissions than BR1-BTC2 (1.50 t CO_2 e/ha) in field B. Conversely, CR1-CNTC2 (0.06 t CO_2 e/ha) in field C showed 95.49% lower emissions than BR1-BNTC2 (1.33 t CO_2 e/ha) in field B. Notably, the control rice field during the second period (AR2), which was replanted on the same field as AR1, exhibited net CO_2 absorption of

1.79 t CO_2 e/ha. Over both growth periods, the net CO_2 absorption, ranked from highest to lowest, was as follows: double-cropping rice (R1-R2, control, 21.39 t CO_2 e/ha in field 1) >BR1-BNTC2 (13.76 t CO_2 e/ha in field 2) >BR1-BTC2 (13.59 t CO_2 e/ha in field 2) >CR1-CNTC2 (8.91 t CO_2 e/ha in field 3) >CR1-CTC2 (7.27 t CO_2 e/ha in field 3).

The closed chamber method was used to measure changes in CO_2 and CH_4 fluxes across the experimental fields, allowing for a comparison of greenhouse gas flux differences under various planting configurations. Table 1 presents the net methane carbon flux (in CO_2 equivalents) for each field over the two growing periods, with all fields exhibiting net emissions. During the first growing period, the rice field B (BR1) had the highest methane carbon flux, with net emissions of 7.02 t CO_2 e/ha—197.46% and 235.89% higher than the rice field (AR1) at 2.36 t CO_2 e/ha and the rice field C (CR1) at 2.09 t CO_2 e/ha, respectively. In the second period, following the first period, rice field A (AR2) recorded the highest methane emissions at 28.34 t CO_2 e/ha, whereas emissions in the rotation fields (fields B and C) remained below 0.69 t CO_2 e/ha. Comparing fields B and C in the second period, field B (BNTC2: 0.69 t CO_2 e/ha; BTC2: 0.66 t CO_2 e/ha) had higher methane emissions than field C (CTC2: 0.23 t CO_2 e/ha; CNTC2: 0.16 t CO_2 e/ha). When combining the methane carbon flux over both growth periods, the control treatment (AR1-AR2) in field A had substantially higher net methane emissions than the rotation fields, with the order from highest to lowest as follows: AR1-AR2 (30.70 t CO_2 e/ha) >BR1-BNTC2 (7.71 t CO_2 e/ha) >BR1-BTC2 (7.68 t CO_2 e/ha) >CR1-CTC2 (2.32 t CO_2 e/ha) >CR1-CNTC2 (2.25 t CO_2 e/ha).

After collecting the net carbon flux data for CO_2 and CH_4 (Table 1) from both growth periods, the total carbon flux for each period was calculated and compared across the experimental fields, as shown in Tables 2 and 3. During the first growth period, CO_2 was the primary source of carbon absorption in all fields, with the following absorption amounts (from highest to lowest): AR1 at 5.26 t C/ha, BR1 at 4.03 t C/ha, and CR1 at 2.32 t C/ha (Table 2). Additionally, total carbon flux (CO_2 and CH_4) across all fields indicated net absorption, ranked as follows: AR1 at 5.20 t C/ha, BR1 at 3.84 t C/ha, and CR1 at 2.26 t C/ha. In the second period, only the AR2 field showed a net carbon absorption (CO_2), at 0.49 t C/ha, while the other rotation fields exhibited net carbon emissions (CO_2) ranging from 0.02 to 0.46 t C/ha (Table 2). Notably, AR2 had significantly higher emissions at 0.76 t C/ha, compared to corn rotation fields ranging from 0.004 to 0.02 t C/ha, with CH_4 being the main source of emissions. The total combined carbon flux (CO_2 + CH_4) for the corn rotation fields and the control, ranked from highest to lowest, was as follows: CTC2 at 0.47 t C/ha, BTC2 at 0.43 t C/ha, BNTC2 at 0.38 t C/ha, AR2 at 0.27 t C/ha, and CNTC2 at 0.02 t C/ha. When combining

Table 2. Net carbon flux of each experiment field in the first and second growth periods

	CO_2 resource (t C/ha)	CH_4 resource (t C/ha)	CO_2 + CH_4 (t C/ha)
first			
AR1	-5.26	0.06	-5.20
BR1	-4.03	0.19	-3.84
CR1	-2.32	0.06	-2.26
second			
AR2	-0.49	0.76	0.27
BTC2	0.41	0.02	0.43
BNTC2	0.36	0.02	0.38
CTC2	0.46	0.006	0.47
CNTC2	0.02	0.004	0.02

Positive values indicate net emissions, while negative values indicate net absorption.

Table 3. Summation of total net carbon flux (CO_2 + CH_4) of each experiment field from both periods

	Periods 1 + 2 (t C/ha)
AR1-AR2	-4.93
BR1-BTC2	-3.41
BR1-BNTC2	-3.46
CR1-CTC2	-1.79
CR1-CNTC2	-2.24

Negative values indicate net absorption.

Table 4. Global warming potential (GWP), crop yield, and greenhouse gas intensity (GHGI) of each experiment field in the first and second growth periods.

	GWP (t CO_2 e/ha)	Yield (t/ha)	GHGI (t CO_2 e/t yield)
first			
AR1	-16.99	7.87	-2.16
BR1	-7.75	6.60	-1.17
CR1	-6.43	6.85	-0.94
second			
AR2	26.55	4.32	6.15
BTC2	2.16	5.30	0.41
BNTC2	2.03	5.30	0.38
CTC2	1.93	6.76	0.29
CNTC2	0.22	5.30	0.04

Positive values indicate net emissions, while negative values indicate net absorption.

results from both growth periods, the total net absorption of CO_2 + CH_4 across the rotation fields and the control, from highest to lowest, was: AR1-AR2 (4.93 t C/ha) >BR1-BNTC2 (3.46 t C/ha) >BR1-BTC2 (3.41 t C/ha) >CR1-CNTC2 (2.24 t C/ha) >CR1-CTC2 (1.79 t C/ha) (Table 3).

Tables 4 and 8 present the global warming potential (GWP), crop yield, and greenhouse gas intensity (GHGI) for each experimental field during both growth periods. Table 4 indicates that all fields during the first growth period exhibited negative GWP and GHGI values. The GWP for AR1 in the first period was -16.99 t CO_2 e/ha, which was 119.23% and 164.23% lower than the BR1 (7.75 t CO_2 e/ha) and CR1 (6.43 t CO_2 e/ha) fields,

Table 5. Total GWP, crop yield, and GHGI of each experiment field over two consecutive growth periods

	GWP ($t\ CO_2$ e/ha)	Yield (t/ha)	GHGI ($t\ CO_2$ e/t yield)
AR1-AR2	9.56	12.19	0.78
BR1-BTC2	-5.59	11.9	-0.47
BR1-BNTC2	-5.72	11.9	-0.48
CR1-CTC2	-4.5	13.61	-0.33
CR1-CNTC2	-6.21	12.15	-0.51

Positive values indicate net emissions, while negative values indicate net absorption.

respectively. The crop yield for AR1 was 7.87 t/ha, 19.24% higher than BR1 (6.60 t/ha) and 14.89% higher than CR1 (6.85 t/ha). GHGI rankings for the first period, from lowest to highest, were as follows: AR1 (-2.16 t CO_2 e/t yield) >BR1 (-1.17 t CO_2 e/t yield) >CR1 (-0.94 t CO_2 e/t yield).

Table 4 shows that in the second growth period, all rotation fields had positive GWP and GHGI values. For AR2, the GWP was 26.55 t CO_2 e/ha, crop yield was 4.32 t/ha, and GHGI was 6.15 t CO_2 e/t yield. Among the rotation fields in the second period, fields B consistently showed higher GWP and GHGI values than fields C. For example, the GWP for BTC2 and BNTC2 was 2.16 and 2.03 t CO_2 e/ha, respectively, higher than CTC2 (1.93 t CO_2 e/ha) and CNTC2 (0.22 t CO_2 e/ha). The GHGI for BTC2 and BNTC2 was 0.41 and 0.38 t CO_2 e/t yield, respectively, compared to CTC2 (0.29 t CO_2 e/t yield) and CNTC2 (0.04 t CO_2 e/t yield). Additionally, the GWP, crop yield, and GHGI for CTC2 were 1.93 t CO_2 e/ha, 6.76 t/ha, and 0.29 t CO_2 e/t yield, respectively, representing 10.65% lower GWP, 27.55% higher crop yield, and 31.71% lower GHGI compared to BTC2, which had 2.16 t CO_2 e/ha, 5.30 t/ha, and 0.41 t CO_2 e/t yield.

When combining the calculations from both growth periods, all experimental fields exhibited negative GWP and GHGI values, with the exception of the A field (AR1-AR2), which had net emission values of 9.56 t CO_2 e/ha and 0.78 t CO_2 e/t yield, respectively (Table 5). Among the four rice-maize rotation fields, the GWP values, ranked from lowest to highest, were: CR1-CNTC2 (-6.21 t CO_2 e/ha) >BR1-BNTC2 (-5.72 t CO_2 e/ha) >BR1-BTC2 (-5.59 t CO_2 e/ha) >CR1-CTC2 (-4.50 t CO_2 e/ha). GHGI values followed a trend similar to GWP: CR1-CNTC2 (-0.51 t CO_2 e/t yield) >BR1-BNTC2 (-0.48 t CO_2 e/t yield) >BR1-BTC2 (-0.47 t CO_2 e/t yield) >CR1-CTC2 (-0.33 t CO_2 e/t yield). Crop yields over both growth periods, from highest to lowest, were as follows: CR1-CTC2 (13.61 t/ha) >AR1-AR2 (12.19 t/ha) >CR1-CNTC2 (12.15 t/ha) >BR1-BTC2 and BR1-BNTC2 (11.90 t/ha).

DISCUSSION

Rice is a staple food for much of the global population, but its cultivation, which involves prolonged flooding, is associated with significant CH_4 emissions. A major source of GHG emissions in agricultural systems is CH_4, particularly from enteric fermentation, making it essential to adopt sustainable land management practices (Valujeva *et al.*, 2022). Tilled paddy fields tend to emit more CO_2 and CH_4 compared to no-till systems, such as rice-corn rotations, which significantly reduce both CO_2 absorption and CH_4 emissions (Table 1) during the growing periods. Similarly, Li *et al.* (2013) observed that no-tillage methods substantially decrease CH_4 emissions during rice cultivation compared to conventional tillage. Increased CO_2 emissions in tilled fields are linked to enhanced microbial degradation of soil organic carbon (Mangalassery *et al.*, 2014). Shifting from continuous rice cropping to a rice (wet season) - maize (dry season) rotation has been shown to significantly reduce CH_4 emissions due to improved soil aeration (Weller *et al.*, 2015). Tillage practices have potential for GHG mitigation through carbon sequestration, as soils managed with these practices can act as carbon sinks. Soil carbon sequestration, through the incorporation of organic materials like rice straw, can help mitigate rising atmospheric CO_2 levels by increasing soil carbon stocks (Lal, 2004, 2015). However, incorporating crop residues in waterlogged paddy soils can increase overall GHG emissions (Romasanta *et al.*, 2017). Janz *et al.* (2019) found that aerobic rice and maize during the dry season resulted in the greatest GWP reductions, with CH_4 contributing over 80% of the GWP in paddy systems. Transitioning from flooded rice cultivation to well-aerated soils significantly reduces CH_4 emissions, potentially saving up to 248.5 Mg CH_4 annually compared to traditional rice-rice systems. He *et al.* (2017) reported that introducing maize during the dry season in continuous rice systems initially increased nitrogen and dissolved organic carbon losses due to soil organic matter decomposition, which could adversely affect the GHG balance. Large-scale conversion from rice double cropping to rice-maize rotations could pose risks to groundwater quality and atmospheric balance. Tillage also reduces soil's ability to absorb CH_4 compared to pre-tillage conditions (Peterson *et al.*, 2019).

The GHG footprints for the entire crop rotation cycle were compared across growth periods, rather than focusing on individual seasonal emissions or absorptions, to account for the cumulative effects of previous crop cultivation on GHG exchange. Therefore, the results presented in Tables 2 and 3 were derived by summing the data for each experimental field over both growth periods, as reported in Table 1. Soil GHG emissions, particularly CO_2, were highly sensitive to tillage management. The variations in GHG emissions across growth periods likely stem from the timing of tillage practices, which influenced soil carbon storage and organic matter decomposition, particularly for methanogenesis (Table 2). Both CO_2 and CH_4 may have been incorporated into the soil through tillage after rice harvest, creating anoxic conditions that promoted methanogenesis during organic matter decomposition, which subsequently increased GHG absorption over the two periods (Table 3). Additionally, the impact of tillage on soil CO_2 and CH_4 absorption in crop rotation fields was likely due to its influence on the soil microclimate, affecting aeration and gas diffusion.

Moreover, calculating net carbon flux reflects the overall carbon dynamics in the fields but does not capture the relative contribution of different greenhouse gases to global warming. Therefore, the GWP calculations for each field across both growth periods (Tables 4 and 5) were used to determine which planting systems were most effective in mitigating global warming. Since GWP was calculated on a per-unit-area basis, it only considered the field's total potential impact on global warming, without accounting for crop yield. To address this, GHGI was also calculated based on crop yield, offering a more accurate assessment of which treatments were more effective at reducing global warming impacts. Although CH_4 is a short-lived greenhouse gas, urgent action is needed to reduce all GHG emissions. Achieving net-zero GHG emissions requires substantial reductions and achieving net negative CO_2 emissions (IPCC, 2023). Over two growth periods, the rice control fields acted as net carbon sources with positive GWP and GHGI values, whereas the rice-maize rotation fields demonstrated negative values (Table 5), indicating their potential as carbon sinks. Future studies should focus on evaluating soil organic matter losses in rice-maize rotations in these experimental fields.

The net GWP and GHGI were significantly reduced by altering the timing of tillage, CR1-CNTC2 showed the lowest GWP and GHGI among treatments. The GWP and GHGI of the double-cropping rice control (AR1 + AR2) were significantly higher than those of the rice-maize rotation treatments (BR1 + BTC2, BR1 + BNTC2, CR1 + CTC2, and CR1 + CNTC2), primarily due to the high CH_4 emissions from prolonged flooding in the control fields, which created anaerobic conditions conducive to methanogenic microorganisms (Smith *et al*., 2021). Yang *et al*. (2018) also found that tillage combined with low stubble incorporation during the winter significantly reduced net GWP and GHGI by sequestering more soil organic carbon, while still maintaining high rice yields in double-cropping systems.

In addition to reducing net GWP and GHGI, this study aimed to maintain high crop yields while minimizing these metrics. The crop yields for AR1, BR1, and CR1 during the first growth period (Table 4) were higher than those of the rotation fields during the second growth period (Table 4), although CR1-CTC2 achieved the highest crop yield compared to the other treatments and control (Table 5). Consequently, when considering both environmental and economic factors, the rice with no-tilled maize system proved to be the most optimal cropping model, exhibiting the lower GWP and GHGI while producing the higher yield. The rice with the no-tilled maize system supports sustainable food production and security.

However, it should be noted that this study utilized only one field for the control and each treatment, which imposes limitations on the generalizability of the results due to the lack of replicates. This constraint increases the potential for site-specific effects or anomalies to influence the findings. To further validate these results and expand on the insights gained, future research should incorporate additional replicates for each treatment, as well as explore a broader range of locations, crop types, and tillage practices. Moreover, incorporating an analysis of the economic benefits associated with tillage practices would provide a more comprehensive understanding of their viability. Several climate models predict increased frequency of heatwaves, floods, and droughts (Pryor *et al*., 2013), which may negatively impact yields of crops like corn and rice.

Additionally, IPCC guidelines for estimating CH_4 emissions from rice paddies currently do not account for emissions during land preparation. Furthermore, the CO_2 fluxes in this study were estimated using linear equations without accounting for potential emission or absorption peaks, which could have biased the measurements. Future research should consider additional factors such as weather conditions, sunshine duration, soil temperature, and atmospheric pressure at the time of sampling to better understand crop-ecosystem interactions and greenhouse gas fluxes. Long-term monitoring, with more frequent measurements across various planting designs and locations, will provide crucial data to guide decision-making at the national level.

CONCLUSION

This study focused on the changes in soil CO_2 and CH_4 absorption and emissions in response to different tillage treatments and crop rotations. Specifically, we examined rice-corn rotation cycles at a single site-season to provide a method for scaling up local estimates of net CO_2 and CH_4 fluxes over the course of growth periods within a specific region. The results indicated that GHG emissions were highly sensitive to tillage management, while crop rotations significantly contributed to reducing emissions and had a synergistic effect on crop production. Developing strategies to minimize agricultural GHG emissions remains a critical goal in transforming agricultural systems towards net-zero emissions. The rice and no-tilled corn cropping system showed significant reductions in GWP and GHGI, demonstrating its potential as a sustainable approach for enhancing agroecosystem productivity and economic profitability. However, further long-term field trials incorporating a broader range of variables are needed to validate these findings and ensure the reliability of GHG and GHGI reductions over time.

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