

Improving net carbon balance and irrigation water productivity of subtropical organic double-rice cropping through a near-saturation water-saving management

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ABSTRACT

Organic rice farming sustains soil productivity but risks elevated greenhouse gas (GHG) emissions from organic inputs, which can be mitigated by optimizing water-saving irrigation and implementing regenerative practices like cover cropping. Compared to the most common water-saving irrigation (-15 cm water level threshold), a more conservative near-saturation approach (reflooding at 0 cm) offers a potential paradigm for stabilizing yields; however, its integrated impact on the net carbon (C) outcomes remains poorly understood. This study evaluated a near-saturation water-saving strategy and winter cover cropping [*Tartary buckwheat* (*Fagopyrum tataricum*)] to improve net C balance characteristic of subtropical organic double-rice systems in Taiwan (2023–2024). Compared to continuous flooding (CF), the near-saturation threshold significantly reduced cumulative CH₄ emissions and net GHG intensity by approximately 29% (1.37 vs. 0.97 Mg CO₂-eq Mg⁻¹ grain) while maintaining stable grain yield (~5.24 Mg ha⁻¹). Irrigation water productivity improved by 16.5% (0.92 vs. 0.79 kg grain m⁻³ irrigated water) under this near-saturation management. Furthermore, the near-saturation strategy resulted in a 17.3% reduction (CF: 23.32 Mg CO₂-eq ha⁻¹ vs. water-saving: 19.28 Mg CO₂-eq ha⁻¹) in the net ecosystem C source strength (net GHG emissions minus soil organic C sequestration) through the substantial CH₄ mitigation over the two-year period. Winter cover crop incorporation did not significantly influence GHG dynamics or crop productivity. These results demonstrate that a precision near-saturation threshold optimizes the environmental footprint of organic rice farming by significantly reducing net C source strength and improving water performance without compromising yield stability.

1. Introduction

Sustainable frameworks for rice production such as the System of Rice Intensification (SRI) prioritize the integration of organic amendments and enhanced water-use efficiency to maintain soil productivity with minimal chemical dependency (Berkhout et al., 2015; Gathorne-Hardy et al., 2016). Organic fertilizers and biological inputs, including compost and straw return, significantly improve soil physicochemical health and microbial diversity, supporting yield increases of 7–35% compared to conventional mineral fertilization (Liu et al., 2021;

Tang et al., 2022; Qaswar et al., 2020). These regenerative practices are increasingly viewed as essential for “net-zero” agricultural transitions because anaerobic paddy conditions facilitate soil organic carbon (SOC) sequestration, often exceeding adjacent upland carbon (C) stocks (Qin et al., 2013). However, the implementation of these organic strategies presents a critical environmental trade-off. The influx of external organic matter provides methanogens with abundant labile substrates, such as dissolved organic C (DOC), which can boost methane (CH₄) emissions by 50–300% (Liao et al., 2023; Song et al., 2019). The surge CH₄, a potent greenhouse gas (GHG) with a 100-year global warming

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potential (GWP) of ~ 27.9 , is often sufficient to offset the climate-mitigation benefits gained from enhanced SOC sequestration (Song et al., 2024; Zhang et al., 2022). Consequently, identifying the optimized drainage management, such as alternate wetting and drying (AWD), is vital for mitigating these emissions spikes in organic-rich paddy systems (Wu et al., 2022; Yao et al., 2015).

The AWD practice is established as a robust strategy for reconciling water-saving irrigation with CH_4 mitigation in rice systems. By introducing controlled aerobic periods, well-managed AWD typically reduces irrigation water use by 19–34% and CH_4 emissions by 30–70% (Carrijo et al., 2017; Wang et al., 2020; Zhao et al., 2024). Although periodic drainage events can stimulate the pulses of nitrous oxide (N_2O) and carbon dioxide (CO_2) via nitrification and enhanced aerobic respiration, the net impact remains climate-positive, with total GHG emissions and GWP decreasing by approximately 36–55% (Gao et al., 2024; Jiang et al., 2019; Wang et al., 2020; Wu et al., 2022). Consequently, the GHG intensity, which scales total emissions by grain yield, often declines by 38–52% in AWD-managed fields compared to continuous flooding (CF) management (Xing et al., 2025). However, these mitigation benefits are frequently tempered by trade-offs in SOC stability and yield security. The redox oscillations inherent in AWD can accelerate heterotrophic mineralization, increasing CO_2 emissions by nearly 45% and potentially undermining long-term SOC sequestration (Livsey et al., 2019). Furthermore, intensive AWD, especially employing water level thresholds less than -15 cm, carries a high risk of moisture stress during sensitive growth stages such as panicle initiation and anthesis, leading to significant yield penalties (Carrijo et al., 2017; Ishfaq et al., 2020). While “safe” AWD (typically drying to -15 cm) was designed to minimize moisture stress, significant yield reductions are still frequently reported compared to the CF practice across various subtropical environments (Huda et al., 2016; Ishfaq et al., 2020; Kar et al., 2018).

These intensive water regimes are often incompatible with the unique constraints of organic farming systems, where nutrient mineralization lags and weed pressure is heightened due to reduced water saturation and the absence of herbicides, resulting severely compromise yield loss from poor crop establishment (Jiang et al., 2019). Although the SOC farming practice such as winter cover cropping is also beneficial to disrupt weed cycles and relieve weed pressure (Hwang et al., 2017; Qiu et al., 2024), their integration with water-saving irrigation system creates a complex biogeochemical tension. Specifically, while AWD is necessary to counteract the massive CH_4 spikes triggered by organic inputs, the associated redox oscillations may accelerate SOC mineralization and stimulate N_2O pulses, potentially negating the benefits of SOC sequestration. Furthermore, recent studies have identified substantial N_2O uptake (sink behavior) in organic-amended paddies under anaerobic conditions, but the stability and magnitude of this sink remain poorly understood when subjected to AWD-induced aeration (Kong et al., 2024; Zhong et al., 2023). Despite the documented benefits of individual management practices, their combined and potentially confounding impacts on the net C balance and yield stability of organic double-rice cropping in subtropical monsoon areas remain a critical knowledge gap.

The central scientific question of this study is whether a precision water-saving strategy, specifically a near-saturation threshold (reflooding at 0 cm), can resolve the yield-emissions conflict inherent in high-input organic rice systems. This study tested the hypothesis that a 0 cm irrigation threshold acts as a biogeochemical “sweet spot” by maintaining enough soil moisture to safeguard yields and stabilize SOC, while providing sufficient aeration to suppress the massive CH_4 spikes characteristic of organic fertilization, thereby improving the net ecosystem C balance. The overarching aim of this research was to establish the technical feasibility and mechanistic efficacy of this near-saturation management as a scalable model for optimizing the climate-mitigation potential of regenerative rice production and to characterize its associated GHG dynamics, including the potential for N_2O sink activity. To evaluate these concepts, this study compared the

CF practice against a near-saturation irrigation strategy, integrated with winter cover cropping as green manure. The specific objectives were to (i) quantify the dynamic trade-offs between $\text{CH}_4/\text{N}_2\text{O}$ emissions and SOC sequestration to determine the net ecosystem C source strength; (ii) evaluate impact on grain yield and irrigation water productivity; and (iii) establish a resource-efficient management model that maximizes the environmental resilience of subtropical organic rice systems.

2. Materials and methods

2.1. Site and climate description

The field study was conducted during the 2023 and 2024 annual cycles at the university research station in central Taiwan (Taichung City, $24^{\circ}04'41''$ N; $120^{\circ}42'18''$ E) with a continuous rice cropping history. Each growing cycle consisted of a double-rice paddy season followed by a winter fallow season. The site is characterized by a subtropical monsoon climate with a 30-year average (1995–2024) annual temperature of 23.5°C and annual precipitation of 1621 mm (Central Weather Administration, Taichung Station). During the study period, the monthly temperature patterns followed the 30-year average (Fig. 1b). However, cumulative precipitation in both 2023 and 2024 was substantially lower than the historical average (Fig. 1c). While the 2023 precipitation pattern mirrored the long-term trend, 2024 was characterized by distinct extremes, including significantly higher rainfall in July ($\sim 67\%$ above average) and lower rainfall in August ($\sim 52\%$ below average). The soil at the experimental site is classified as Udorthents with a predominantly loamy texture (Chen et al., 2015). Prior to the initiation of the experiment, soil pH was slightly acidic ($5.35 \sim 6.03$) with low organic matter content ($1.2 \sim 2.1\%$). While soil textures were uniform across the three blocks, the north plot (B1) exhibited slightly lower pH (~ 5.35) and higher organic matter ($\sim 1.96\%$) compared to the central (B2) and south (B3) blocks (Table 1). Essential nutrients were also at similar levels. For the winter cover crop (Tartary buckwheat), dry matter biomass reached 1.91 Mg ha^{-1} in 2023 and 2.67 Mg ha^{-1} in 2024 (Fig. 1d); production was influenced by year-to-year climatic variation rather than the preceding rice-season water management.

2.2. Experimental design

Two water management practices (i.e., CF and a near-saturation water-saving strategy) were implemented in the continuously organic fertilized rice systems. During the winter fallow season from November to January, Tartary buckwheat (*Fagopyrum tataricum*) was implemented as the cover crop and used as green manure in the following spring. Two factors (i.e., water management $\times$ winter cover crop) were arranged in a split-plot design within a randomized complete block design with three blocks, where water management served as the main plot factor and cover crop as the sub-plot factor (Fig. 1a). For each treatment, the plot size was approximately 658 m^2 . The CF treatment followed the business-as-usual practices to maintain the water level of 5–10 cm above soil surface besides the mid-season drainage and final drainage before harvesting. The near-saturation water-saving treatment was conducted by re-flooding the field while the water level dropped to surface level (i.e., 0 cm) to avoid potential yield risk resulting from aggressive AWD practice (e.g., -15 cm) and began 3–4 weeks after transplanting to minimize the weed pressure at the establishment stage. In each plot, water levels were monitored using four PVC tubes and one solar-powered water level loggers (Chungten Technology Co., Taiwan). Each PVC tube had a diameter of 15.3 cm and height of 30 cm, and holes (~ 0.5 cm in diameter) were drilled every 2 cm from 0 to 20 cm to allow free water flow. After transplanting, the tubes were inserted 20 cm into the soil (until no holes were visible), and the soil inside was removed to a depth of 20 cm for observation. Total volume of the supplied irrigation water was precisely quantified for each plot using mechanical turbine flow meters (Model: T100, RedStar Instruments Co., Ltd., Taichung,

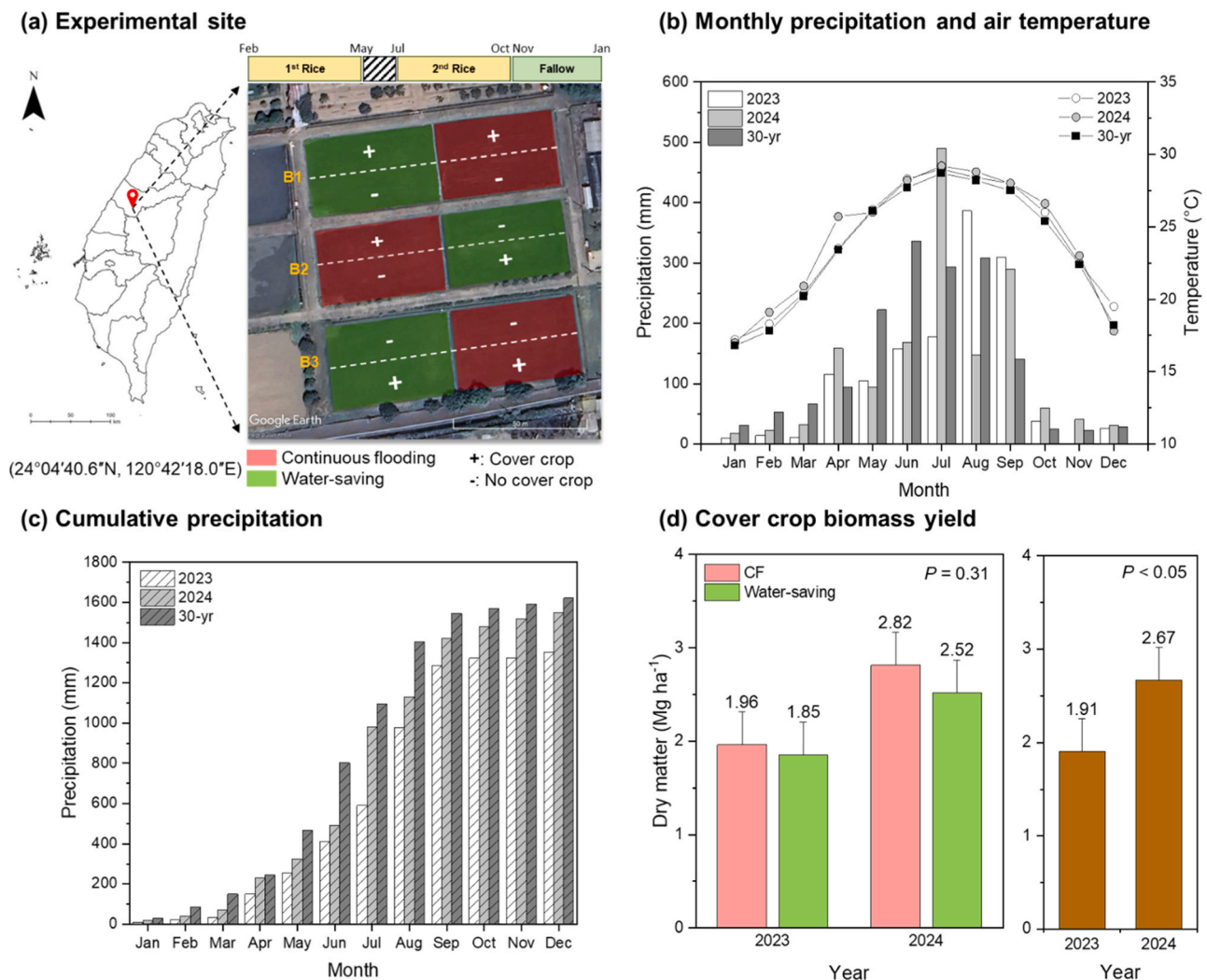


Fig. 1. Overview of the research site: (a) location in central Taiwan and field layout showing continuous flooding (CF), near-saturation water-saving irrigation, and winter cover crop treatments across three replicated blocks (B1–B3); (b) monthly precipitation and air temperature; (c) cumulative precipitation; (d) cover crop biomass yield during the double-cropping rice and cover crop periods in 2023 and 2024 (Image source: © Google Earth, 2025).

Table 1

Initial physicochemical properties of soils in each block prior to the field experiment.

Soil properties	Location		
	North (B1)	Central (B2)	South (B3)
Texture	loam	loam	loam
BD (g cm ⁻³)	1.31	1.59	1.51
pH (1:1)	5.35	5.94	6.03
EC (dS m ⁻¹)	0.10	0.09	0.06
OM (%)	1.96	1.22	1.15
Total C (g kg ⁻¹)	11.37	7.09	6.67
Total N (g kg ⁻¹)	1.23	0.91	0.76
Avail. P (mg kg ⁻¹)	2.10	2.11	2.67
Exch. K (mg kg ⁻¹)	47.0	53.0	46.0
Exch. Mg (mg kg ⁻¹)	261.0	240.0	241.0
Exch. Ca (mg kg ⁻¹)	807.0	764.0	802.0

BD: bulk density; EC: electrical conductivity (soil: water = 1:5); Total C and N: total carbon and nitrogen (dry-combustion method); OM: organic matter (conversion factor of 1.742 from the measured total C); Avail. P: available phosphorus (direct colorimetric method). Exch. K, Mg, and Ca: Exchangeable potassium, magnesium, and calcium determined by the Mehlich–3 method.

Taiwan) installed at the individual irrigation inlets. Tartary buckwheat was one of the common crops used for cover crop cultivation during the

winter fallow season in Taiwan due to its rapid growth characteristic. The seeds were evenly broadcasted with the seeding rate of 60 kg ha⁻¹ over the surface and lightly raked into soil (~ 1 cm) right after the second season harvest event around end-October. After approximately 70 days, the buckwheat was incorporated into the soil around three weeks before rice transplanting.

2.3. Field management

Prior to transplanting, the seedbed preparation included ploughing, puddling, and field levelling using a standard rotary tiller. The primary ploughing occurred approximately 2–3 weeks before transplanting to incorporate weeds and other leftover residues. Around 2–5 days before planting, the puddling practice and final levelling was performed to facilitate efficient transplanting operations. Rice was transplanted using a mechanical transplanter, with a spacing of 30 × 18.5 cm between rows and plants. For the first growing season, rice was planted in early February and harvested in the end of May; for the second season, rice was planted in early August and harvested in the end of October (Table 2). No basal fertilizer was applied to the experimental plots. Instead, a split fertilizer strategy was employed, consisting of three top-dressing applications: two side-dressing during the tillering stage and one panicle fertilizer application. Specifically, the first tillering fertilizer

Table 2
Rice cultivation and management schedule from 2023 and 2024.

Field management	2023		2024	
	Cropping season (growing period)			
	1st (109 days)	2nd (84 days)	1st (102 days)	2nd (85 days)
Primary tillage*	30-Nov	8-Jun	15-Jan	10-Jun
Secondary tillage*	13-Jan	30-Jun	31-Jan	22-Jul
Land levelling*	1-Feb	26-Jul	1-Feb	25-Jul
Transplanting	9-Feb	1-Aug	6-Feb	29-Jul
First tillering fertilizer [§]	22-Feb	7-Aug	19-Feb	5-Aug
Second tillering fertilizer [§]	6-Mar	24-Aug	4-Mar	20-Aug
Midseason drainage	1-Apr	8-Sep	1-Apr	2-Sep
Reflooding	14-Apr	21-Sep	13-Apr	12-Sep
Panicle fertilizer [†]	17-Apr	22-Sep	14-Apr	20-Sep
Final drainage	17-May	22-Oct	18-May	15-Oct
Harvest	29-May	30-Oct	30-May	29-Oct

Notes:

*: Primary tillage was performed under the non-flooded conditions, followed by secondary tillage and land levelling under submerged conditions.

§: Tillering fertilizer: N(5%)-P₂O₅(3%)-K₂O(2%)-SOM(75%); pH~6

†: Panicle fertilizer: N(4%)-P₂O₅(2%)-K₂O(6%)-SOM(70%); pH~8

was applied between 6–13 days after transplanting (DAT), followed by a second application at 22–27 DAT, and a final panicle fertilizer application at 45–68 DAT, depending on the season and year. The tillering fertilizers consisted of a commercial organic blend primarily composed of oilseed meal (including soybean, peanut, and sesame) and rice bran (N-P₂O₅-K₂O-SOM: 5–3–2–75; pH~6). The panicle fertilizer was a distinct commercial blend composed of sesame meal, palm ash, and peat (N-P₂O₅-K₂O-SOM: 4–2–6–70; pH~8). Each of the three applications was supplied at a rate of approximately 618.6 kg ha⁻¹. This regime resulted in a total seasonal nutrient input of 80.3 kg-N ha⁻¹, 68.0 kg-P₂O₅ ha⁻¹, and 55.6 kg-K₂O ha⁻¹ (Table 2).

2.4. Data collection, analysis, and calculations

2.4.1. Gas emissions

Greenhouse gas emissions were measured using the static closed-chamber method. To account for spatial variability, three replicate chambers were installed in each plot, resulting in a total of 36 chambers across the 12 experimental plots (Hwang et al., 2017; Minamikawa et al., 2015; Zaman et al., 2021). The chamber was made of transparent acrylic (45 cm length × 45 cm width × 110 cm height) and equipped with an internal fan, thermometer, and a two-way stopcock for gas sampling. The chamber was placed on a stainless-steel base frame (45 cm × 45 cm × 10 cm), which had a 2 cm deep groove along the upper edge. The groove was not fully sealed at the welding joints, allowing water to freely flow in and out. Gas sampling was conducted weekly between 09:00 and 11:00 a.m., with three chambers across field per experimental plot. During each sampling event, the chamber was placed over rice plants, and gas samples were collected at 0, 10, 20, and 30 min using pre-evacuated headspace vials. The collected gas samples were analyzed the GHG concentrations using a gas chromatograph (Agilent 8890, Agilent Technologies Inc., USA) equipped with a flame ionization detector (FID) for CH₄ and an electron capture detector (ECD) for N₂O. Gas fluxes (mg m⁻² hr⁻¹) were calculated using Eq. (1), which determines emission rates based on the slope of gas concentration change over time within the chamber headspace (Minamikawa et al., 2015).

$$\text{Flux} = \rho \times \frac{V}{A} \times \frac{\Delta C}{\Delta t} \times \frac{273}{273 + T} \quad (1)$$

where ρ is the gas density at 0 °C (CH₄ = 0.717 kg m⁻³, N₂O = 1.977 kg m⁻³), V is the volume of the chamber (m³), A is the surface area of the chamber (m²), $\frac{\Delta C}{\Delta t}$ is the slope of the linear regression of gas

concentration versus time (mg min⁻¹), T is the temperature inside the chamber (°C). Measured fluxes (mg m⁻² h⁻¹) were converted to daily averaged emissions (DAE) to estimate seasonal cumulative emissions. Missing DAE values were linearly interpolated between consecutive observations, and cumulative emissions were calculated by summing both measured and interpolated DAEs over the growing season (Hwang et al., 2017; Minamikawa et al., 2015).

The net GHG emissions (Mg CO₂-eq ha⁻¹) during the growing season were calculated using Eq. (2), based on the cumulative seasonal emissions of CH₄ and N₂O:

$$\text{Net GHG Emissions} = (\text{CH}_4 \times 27.9) + (\text{N}_2\text{O} \times 273) \quad (2)$$

where CH₄ and N₂O are the cumulative seasonal emissions (Mg ha⁻¹), and 27.9 and 273 are the 100-year GWP factors for CH₄ and N₂O, respectively, based on the IPCC AR6 values (IPCC, 2023).

2.4.2. SOC stocks

For soil C analysis, the initial sampling was conducted in November, 2022, prior to the experiment's initiation. Soil samples were collected annually from the 0–30 cm profile using a grid sampling strategy. Samples were specifically taken at two depths, 0–10 cm and 10–30 cm, to align with the Food and Agriculture Organization of the United Nations (FAO) Global Soil Organic Carbon Monitoring, Reporting, and Verification (GSOC-MRV) Protocol for continuous SOC monitoring (FAO, 2020). This design distinguished between the highly active plow layer (0–10 cm), characterized by intensive root activity and organic matter incorporation, and the underlying tillage pan and subsoil (10–30 cm). To account for soil spatial heterogeneity and ensure the reliability of the SOC stock calculations, intensive sampling was performed within each plot. For each plot, four intact soil cores were collected at both depths using soil sample ring kits (07.53.SC, Eijkkelkamp, Nederland). The rings featured a core diameter of approximately 5.3 cm and were used to determine the soil bulk density (BD). These cores were oven-dried at 105 °C to a constant weight and cooled to 30 °C in a desiccator before weighing to prevent moisture absorption from ambient air. After weighing, samples were crushed and sieved (10-mesh) to weigh the gravel fraction (>2 mm).

Simultaneously, four composite samples, each consisting of four individual cores collected with a 2.5-cm diameter probe, were obtained for SOC analysis. These probe-collected samples were air-dried for five days, after which large soil aggregates were gently crushed and sieved to 2 mm to remove root residues and plant debris. For SOC analysis, a subsample of approximately 100 mg was finely ground and passed through a 0.5-mm sieve before being analyzed with a total organic C analyzer (Soli TOC cube, Elementar, Germany). The measurement principle involves high-temperature catalytic combustion at 550 °C in an oxygen-rich environment, which oxidizes all C forms in the soil to CO₂. The resulting CO₂ is then quantified via a high-sensitivity non-dispersive infrared (NDIR) detector. The SOC stock (Mg ha⁻¹) was calculated using Eq. (3) (Liu et al., 2021; Ratnayake et al., 2017).

$$\text{SOC stock} = \text{SOC} \times \text{BD} \times \text{Depth} \times (1 - \delta_{2\text{mm}}) \times 100 \quad (3)$$

where SOC (%) is the SOC concentration, BD (Mg m⁻³) is the bulk density, Depth (m) is the soil sampling depth, $\delta_{2\text{mm}}$ is the fractional coarse fragment content, and 100 is the conversion factor.

2.4.3. Production efficiency

To determine crop performance, six random sampling points were selected within each plot. Each sampling unit measured 0.74 × 1.2 m², containing 12 rice plants. The rice was harvested, threshed, and oven-dried to 14–15% moisture content, then cleaned with an air blower and weighed to calculate grain yield per unit area. The rice straw biomass remaining after harvest within the sampled area was also collected and weighed. Measure grain yields were also used to evaluate the net GHG intensity and water productivity.

The net GHG intensity ($\text{Mg CO}_2\text{-eq Mg}^{-1}$ grain), or yield-scaled emissions, was calculated following the method of Song et al., (2024) using the Eq. (4) to quantify net GHG emissions ($\text{Mg CO}_2\text{-eq ha}^{-1}$) per unit of grain yield (Mg ha^{-1}) during growing season.

$$\text{GHG intensity} = \frac{\text{Net GHG Emissions}}{\text{GY}} \quad (4)$$

where GY is the grain yield (Mg ha^{-1}) obtained from the field measurements.

Irrigation water productivity (kg m^{-3}), representing the grain yield produced per unit of applied irrigation water, was calculated following the methodology of Zhou et al. (2017) and Wang et al. (2020) using Eq. (5).

$$\text{Irrigation water productivity} = \frac{\text{GY}}{W_i} \quad (5)$$

where GY is the grain yield (kg ha^{-1}) and W_i is the total volume of irrigation water supplied ($\text{m}^3 \text{ha}^{-1}$) measured by mechanical flow meters. This calculation focused on the efficiency of the irrigation water supply and did not account for total water inputs (precipitation) or subsurface hydrological losses, consistent with agronomic evaluations of water-saving practices.

2.5. DNDC model simulation

In addition to chamber-based measurements, CH_4 and N_2O fluxes were also estimated using the process-based DeNitrification-DeComposition (DNDC) model (version 9.5). The DNDC model consists of two components. The first one included the soil climate, crop growth, and decomposition sub-models, predicts the primary environmental drivers (e.g., soil temperature, moisture, pH, redox potential, and substrate concentration) based on ecological drivers (e.g., climate, soil, and management). The second component consists of the fermentation, nitrification, and denitrification sub-models, which simulate the biogeochemical processes leading to trace gas production, consumption, and transport. By integrating these modules, DNDC can predict C and N dynamics under various management practices (Li et al., 2004; Zhao et al., 2020).

To minimize the influence of initial conditions and stabilize soil C and N pools, a 3-year spin-up period (2020–2022) was conducted prior to simulating the experimental years, using the detailed management and crop parameters provided in Table S1. The simulation was grounded in measured site-specific soil properties, including a loamy texture, bulk density of $1.31\text{--}1.59 \text{ Mg m}^{-3}$, initial SOC of $0.67\text{--}1.14 \text{ kg C kg}^{-1}$, and a pH range of $5.35\text{--}6.03$. The model was then applied to simulate daily gas fluxes for each plot during the 2023 and 2024 seasons, incorporating measured cropping system data (e.g., climate, soil, and management) as detailed in Table S2. This included crop parameters such as a maximum biomass production of $1800\text{--}2400 \text{ kg C ha}^{-1}$ for rice and $486\text{--}1231 \text{ kg C ha}^{-1}$ for cover crop (i.e., Tartary buckwheat), respectively, and specific C/N ratios of $50\text{--}70$. Management inputs were synchronized with field logs, including tillage to a 20-cm depth and organic fertilization ($19\text{--}31 \text{ kg N ha}^{-1}$ and $186\text{--}232 \text{ kg C ha}^{-1}$ per application). While the field experiment employed a near-saturation water-saving treatment (maintaining a water level between 0 and 5 cm), the DNDC model architecture (v9.5) primarily supports the AWD with a default oscillation between -5 and $+5$ cm. To approximate the experimental conditions, the irrigation module was customized by specifying the exact dates of re-flooding, mid-season, and final drainage derived from field logs.

Model calibration and validation were performed using high-quality field-measured CH_4 fluxes and grain yield from the CF treatment across four growing seasons. Due to the structural differences in water level thresholds mentioned above, the comparison between field-measured and modelled gas fluxes focused on the CF treatment to ensure a standardized baseline for model validation. We anticipated that the simulated AWD would show a more substantial reduction in CH_4 emissions

compared to the field-measured near-saturation results. An interleaved data-splitting approach ensured the model represented the distinct environmental drivers of both the first and second rice crops. The calibration dataset (2023 2nd and 2024 1st seasons) was used to tune physiological parameters, while the validation dataset (2023 1st and 2024 2nd seasons) enabled an independent assessment of predictive reliability. Model performance was quantified using the coefficient of determination (R^2), root mean square error (RMSE), and Nash-Sutcliffe efficiency (NSE), with full details of input parameters provided in Supplementary Table S3.

2.6. Statistical analysis

Treatment effects on GHG emissions, crop production, and productivity were analyzed using the three-way repeated-measures analysis of variance (ANOVA) using the PROC MIXED procedure in SAS 9.2 Software (SAS Institute Inc, 2009). The water management (CF vs. water-saving), cover crop [no CC (control) vs. CC], two growing seasons [1st season (S1) vs. 2nd season (S2)], and their interactions were considered fixed factors, while the replicates were considered random factors. The sampling day was used as the repeated factor, and each plot was considered a subject in the repeated measurement. The data homogeneity and normality were assessed by the modelled residuals using equal-variance and Shapiro-Wilk tests to meet the ANOVA assumption. All significant differences were determined at $P \leq 0.05$ level. Pairwise mean comparisons were made using the Tukey method for p -value adjustment.

3. Results

3.1. Field-measured and modelled gas flux dynamics

Temporal variations of CH_4 and N_2O fluxes were characterized by distinct seasonal cycles and a strong response to water management regimes (Fig. 2). Field-measured CH_4 emissions followed a consistent pattern across both years, with flux increases occurring primarily during the early growth stages. Peaked CH_4 release typically preceded mid-season drainage events, particularly under the prolonged flooded conditions (i.e., CF). Following drainage, CH_4 emissions declined rapidly and remained at low rates for the remainder of the season, with the exception of a transient increase observed in May 2023. A significant seasonal contrast was observed, as CH_4 emissions during the second growing seasons (S2; July – October) were substantially higher than those in the first season (S1), especially within the CF management. In contrast, N_2O emissions exhibited lower temporal variation and were characterized by episodic spikes. These peaks coincided with soil-drying phases during mid-season drainage and fertilization events (black arrows in Fig. 1c), a pattern most pronounced under the near-saturation water-saving management.

The DNDC model performance was evaluated by comparing simulated daily CH_4 fluxes and biomass C yield with field observations from the CF treatment. During the calibration phase, the model showed a satisfactory fit to temporal observations with an NSE ranging from 0.59 to 0.62 and a strong correlation ($R^2 = 0.83\text{--}0.87$), a predictive capacity that was maintained during the independent validation phase (NSE = $0.41\text{--}0.57$; $R^2 = 0.65\text{--}0.66$; Fig. S1). Although validation errors (RMSE $\sim 3.84\text{--}32.42 \text{ mg m}^{-2} \text{hr}^{-1}$) reflected the stochastic nature of daily CH_4 ebullition, the model effectively tracked the broader experimental trends. Also, the crop growth sub-model demonstrated high accuracy in predicting biomass C yield all experimental plots and seasons ($R^2 = 0.99$ and NSE = 0.66; Fig. S2), providing a calibrated foundation for simulating C substrate availability. As a results, the DNDC-modelled CH_4 fluxes was capable of capturing the seasonal trajectories and characteristic spikes by showing flux increases from the beginning of the season toward a maximum prior to mid-season drainage. However, a notable contrast occurred after reflooding, where the model produced

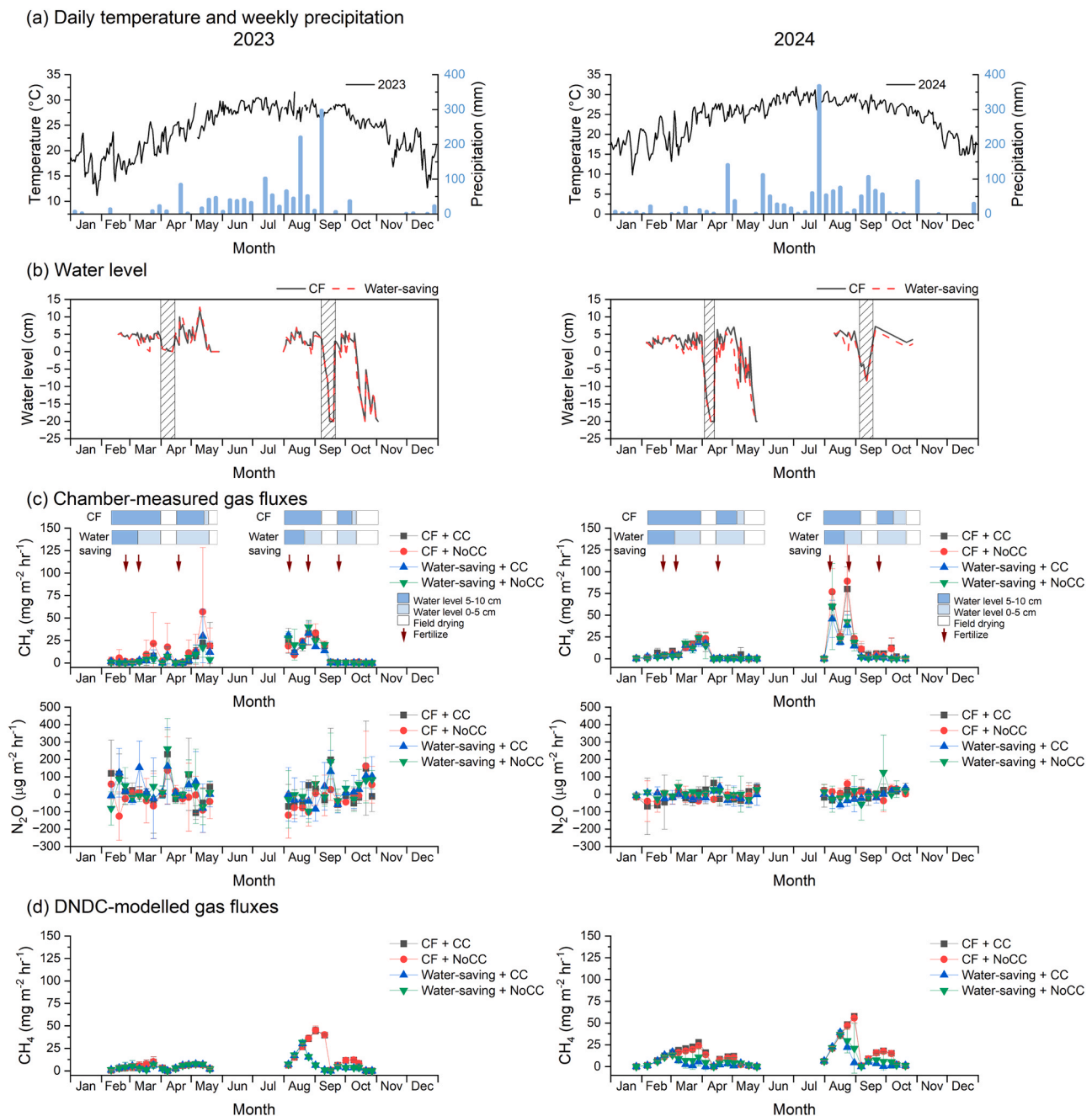


Fig. 2. Seasonal variation in (a) daily air temperature and weekly precipitation, (b) field water level under continuous flooding (CF) and near-saturation water-saving irrigation, (c) chamber-measured CH₄ and N₂O fluxes under CF and water-saving treatments with (CC) and without (NoCC) winter cover crop incorporation, and (d) DNDC-modelled CH₄ fluxes during the 2023 and 2024 growing seasons. Error bars indicate standard deviation.

more pronounced post-drainage CH₄ peaks compared to the field-measured data (Fig. 2d). For N₂O, DNDC produced substantial emission peaks corresponding specifically to mid-season drainage; beyond these pulses, modelled N₂O fluxes remained near or below the minimum detection limit.

3.2. Average and cumulative GHG emissions

Water management and cropping season significantly affected both average and cumulative CH₄ fluxes as well as net GHG emissions, whereas cover crop implementation and all interaction terms were not statistically significant (Table 3). Compared to CF, the near-saturation management significantly reduced both average CH₄ and seasonal

cumulative emissions (Table 4). These reductions in CH₄ contributed to lower seasonal net GHG emissions relative to the CF baseline (5.2 vs. 7.14 Mg CO₂-eq ha⁻¹). Cropping season exerted a consistent and pronounced effect on C loss; S2 resulted in substantially higher CH₄ releases for both average and seasonal cumulative emissions, leading to higher net GHG emissions compared to S1 (7.34 vs. 5.0 Mg CO₂-eq ha⁻¹). Although individual factors and their interactions did not significantly affect mean N₂O fluxes, a seasonal effect was observed in the cumulative data, with higher total N₂O recorded in S1 than in S2. The DNDC-modelled CH₄ fluxes followed statistical trends similar to the field-measured data (Table 5). Water management, cropping season, and their interaction significantly influenced both average and cumulative CH₄ fluxes, while cover crop effects remained non-significant. The

Table 3

Analysis of variance (ANOVA) showed the effects of water management (WM), cover crop (CC), cropping season (CS), and interactions on field measurements, including greenhouse gas (GHG) fluxes for both (averages and seasonal cumulation), net GHG emissions, grain yield, straw biomass, net GHG intensity, and irrigation water productivity with significance level of 0.05.

Factor	WM	CC	CS	WM × CC	WM × CS	CC × CS	WM × CC × CS
Average GHG fluxes							
CH ₄	**	ns	****	ns	ns	ns	ns
N ₂ O	ns	ns	ns	ns	ns	ns	ns
Net GHG	**	ns	****	ns	ns	ns	ns
Seasonal GHG fluxes							
Cumulative CH ₄	*	ns	*	ns	ns	ns	ns
Cumulative N ₂ O	ns	ns	**	ns	ns	ns	ns
Seasonal net GHG	*	ns	*	ns	ns	ns	ns
Productions							
Grain yield	ns	ns	****	ns	ns	ns	ns
Straw biomass	ns	ns	****	ns	ns	ns	ns
Productive efficiency							
Net GHG intensity	*	ns	ns	ns	ns	ns	ns
Water productivity	*	ns	****	ns	ns	ns	ns

Level-1 (*): $0.05 < p < 0.01$; Level-2 (**): $0.01 < p < 0.001$; Level-3 (***): $0.001 < p < 0.0001$; Level-4 (****): $p < 0.0001$; ns: not significant.

maximum CH₄ emissions were observed under the CF treatment in the

Table 4

Analyses of grain yield, straw biomass, averages and seasonal cumulations of greenhouse gas (GHG) fluxes and net GHG emissions, GHG intensity, and irrigation water productivity, influenced by water management [continuous flooding (CF) vs. water-saving], cover crop [cover crop cultivation (yes) vs. control (no)], cropping season [spring season (S1) vs. summer season (S2)]. Lowercase letters indicate mean separation at $\alpha = 0.05$ organized by highest to lowest value for each column with modelled standard error (SE). Notes: no mean separations were applied if the variable effect was not significant.

Factors	Water management		Cover crop		Cropping season	
	CF	Water-saving	Yes	No	S1	S2
Average GHG fluxes						
CH ₄ (mg m ⁻² hr ⁻¹)	10.95a	8.05b	8.92	10.08	5.32b	13.68a
SE	2.19		2.19		2.19	
N ₂ O (ug m ⁻² hr ⁻¹)	1.72	11.87	9.33	4.27	10.83	2.77
SE	9.27		9.27		9.25	
Net GHG (mg CO ₂ -eq m ⁻² hr ⁻¹)	307.11a	228.60b	252.23	283.47	151.93b	383.78a
SE	59.03		59.03		58.90	
Seasonal GHG fluxes						
Cumulative CH ₄ (kg ha ⁻¹)	253.74a	179.48b	198.89	234.32	169.50b	263.71a
SE	40.05		40.05		39.68	
Cumulative N ₂ O (kg ha ⁻¹)	1.03	1.28	1.23	1.08	1.51a	0.81b
SE	0.42		0.41		0.43	
Seasonal net GHG (Mg CO ₂ -eq ha ⁻¹)	7.14a	5.2b	5.71	6.63	5.0b	7.34a
SE	1.10		1.09		1.11	
Productions						
Grain yield (Mg ha ⁻¹)	5.20	5.28	5.21	5.27	4.87b	5.60a
SE	0.16		0.15		0.14	
Straw biomass (Mg ha ⁻¹)	4.95	5.05	4.99	5.01	4.37b	5.62a
SE	0.25		0.25		0.25	
Productive efficiency						
Net GHG intensity (Mg CO ₂ -eq Mg ⁻¹ grain)	1.37a	0.97b	1.10	1.24	1.02	1.31
SE	0.20		0.20		0.22	
Water productivity (kg grain m ⁻³)	0.79b	0.92a	0.84	0.87	0.55b	1.16a
SE	0.25		0.25		0.25	

2024 S2 (Table 5), and the two-year average showed that the DNDC-modelled CH₄ fluxes (11.90 mg m⁻² hr⁻¹) were in strong agreement with the field-measured CH₄ (10.95 mg m⁻² hr⁻¹) under the CF treatment. Simulated results also demonstrated that the water-saving practice (reflood at -5 cm) substantially reduced cumulative CH₄ emissions by more than 50% compared to CF (123.96 vs. 268.46 kg ha⁻¹). The model also reflected the seasonal disparity observed in the field, predicting higher CH₄ emissions for S2 than for S1 (Table 5).

3.3. Rice production, net GHG intensity, and water productivity

The ANOVA results showed that both grain yield and straw biomass were only influenced by crop seasons (Table 3). Averages across all treatments showed that grain yield in S2 (5.60 Mg ha⁻¹) was significantly higher than in S1 (4.87 Mg ha⁻¹) by approximately 15%, as was straw biomass. Regarding production efficiency, water management significantly influenced both net GHG intensity and irrigation water productivity. The near-saturation water-saving practice significantly reduced net GHG intensity by around 29% compared to CF (i.e., 0.97 vs. 1.37 Mg CO₂-eq Mg⁻¹ grain). Additionally, the irrigation water productivity was significantly higher under the near-saturation threshold compared to the CF baseline (i.e., 0.92 vs. 0.79 kg grain m⁻³).

3.4. SOC sequestration and net GHG budget

Both mean (black square) and median (black solid line) SOC stocks exhibited a positive trajectory across all experimental treatments over the two-year study period (Figs. 3a and 3c). Due to the high spatial

Table 5
Effects of water management [continuous flooding (CF) vs. water-saving], cover crop [cover crop cultivation (yes) vs. control (no)], cropping season [spring season (S1) vs. summer season (S2)], and interactions on the DNDC-modelled CH₄ fluxes, including the seasonal averages and cumulations. Lowercase letters indicate mean separation at $\alpha = 0.05$ organized by highest to lowest value for each column with modelled standard error (SE) Notes: no mean separations were applied if the variable effect was not significant.

	Water management		Cover crop		Cropping season		Cropping season $\times$ Water management			
	CF	Water-saving	Yes	No	S1	S2	S1 CF	Water-saving	S2 CF	Water-saving
Average CH ₄ (mg m ⁻² hr ⁻¹)	11.90a	6.79b	8.59b	10.10a	5.05b	13.63a	5.63c	4.48c	18.17a	9.09b
SE	1.34		1.34		1.34		2.64			
P-value	< 0.0001		0.03		< 0.0001		< 0.0001			
Cumulative CH ₄ (kg ha ⁻¹)	268.46a	123.96b	199.36	193.06	122.01b	270.42a	163.16b	80.86c	373.77a	167.06b
SE	35.75		34.90		34.90		36.38			
P-value	< 0.0001		0.52		< 0.0001		< 0.0001			

heterogeneity inherent in paddy soils, regressions based on individual raw observations yielded low coefficients of determination. However, a secondary regression performed on annual treatment means resulted in higher correlation values for both the CF and near-saturation water-

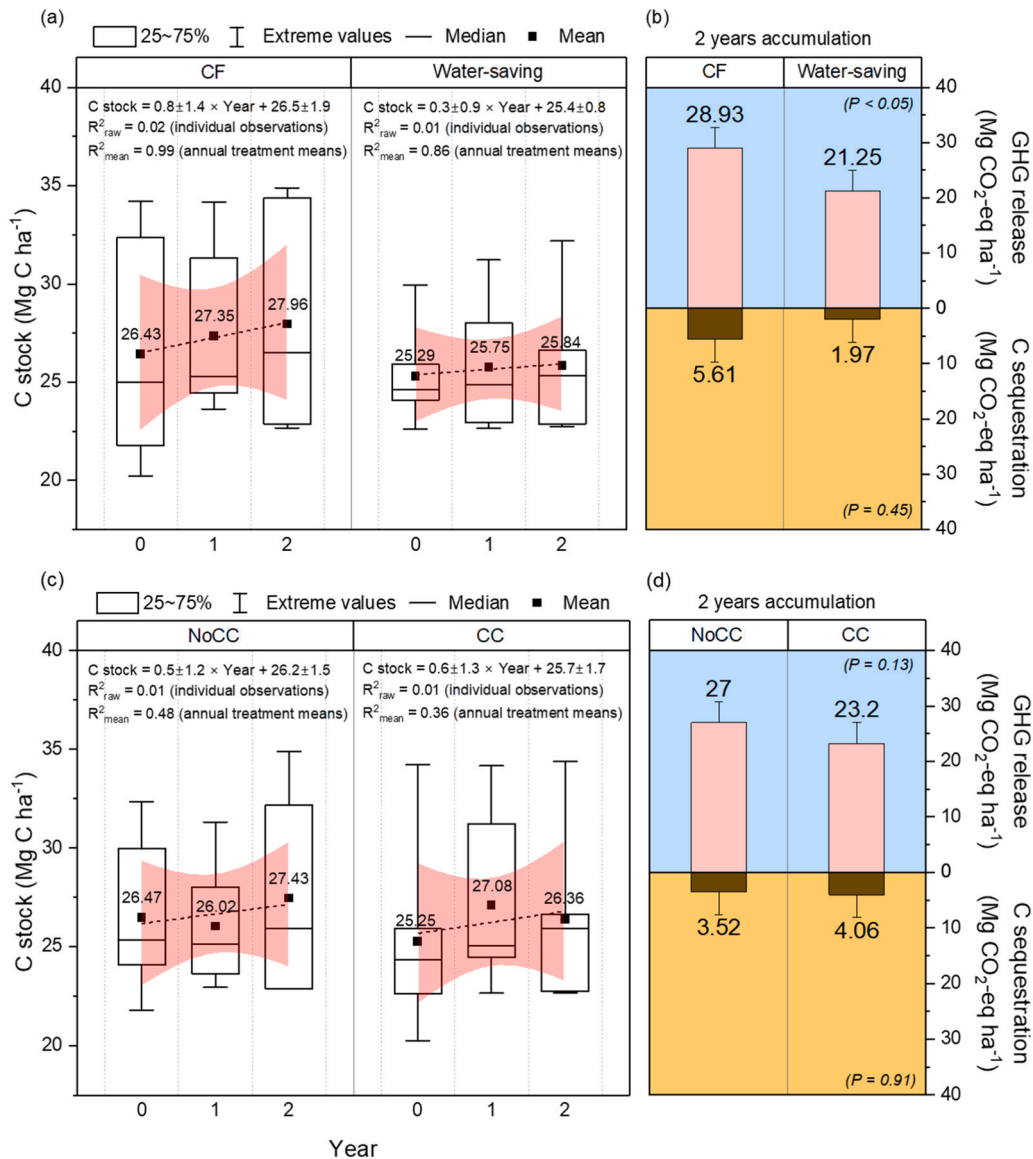


Fig. 3. Effects of water management and winter cover crop on soil organic carbon (SOC) sequestration and carbon balance. Boxplots show changes in SOC stocks and estimated sequestration rates under continuous flooding (CF) and near-saturation water-saving irrigation, and with (CC) or without (NoCC) winter cover crop. Bar charts show two-year cumulative greenhouse gas (GHG) emissions, SOC sequestration, and net carbon balance. Error bars indicate standard errors; P-values denote treatment effects.

saving treatments with positive SOC sequestration rate (i.e., CF: $0.8 \pm 1.4 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ vs. water-saving: $0.3 \pm 0.9 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$; Fig. 3a). The two-year net ecosystem C balance, representing the balance between cumulative gaseous releases and the SOC sequestration, identified both irrigation treatments as net C sources (Fig. 3b). Although no significant differences in SOC sequestration were observed between CF and near-saturation threshold treatments ($P = 0.45$), this precision water-saving practice resulted in significantly lower net GHG emissions compared to CF ($P < 0.05$). Consequently, the near-saturation management significantly reduced the net ecosystem C source strength (i.e., CF: $23.32 \text{ Mg CO}_2\text{-eq ha}^{-1}$ vs. water-saving: $19.28 \text{ Mg CO}_2\text{-eq ha}^{-1}$, $P < 0.05$). Regarding regenerative practices, winter cover crop implementation did not significantly shift SOC sequestration rate or the cumulative two-year C balance compared to the control plot (Fig. 3d).

3.5. Distribution of N_2O fluxes

The frequency distribution and variability of N_2O fluxes recorded across thirty-six sampling chambers are shown in Fig. 4. Both irrigation regimes exhibited high variability in N_2O dynamics, with the soil acting as both an atmospheric source and sink throughout the monitoring period. To investigate the mechanistic drivers behind these dynamics, N_2O effluxes (positive) and influxes (negative) were analyzed separately using distribution-based t -tests. This analysis showed that the near-saturation water-saving treatment led to significantly higher N_2O effluxes ($133.90 \pm 163.70 \mu\text{g m}^{-2} \text{ hr}^{-1}$) compared to the CF treatment ($104.34 \pm 134.78 \mu\text{g m}^{-2} \text{ hr}^{-1}$; $P = 0.01$). In contrast, even though substantial N_2O influxes were observed under both water management practices, no significant treatment effect was detected in the magnitude of these sink events ($P = 0.43$). These results showed that the higher net emissions frequency observed under the near-saturation threshold is primarily driven by an intensification of N_2O production events rather than a reduction in the soil's capacity for N_2O consumption.

4. Discussion

4.1. Near-saturation water-saving performances

The field-measured results in this study demonstrated that a near-saturation water-saving strategy, specifically reflooding at 0 cm, yielded a 26.5% reduction in average CH_4 emissions and a 29.3% reduction in seasonal cumulative CH_4 compared to CF. These reductions

contributed to a 27.2% decrease in net GHG emissions and a $\sim 29\%$ reduction in GHG intensity without compromising grain yield. While substantial, these mitigation rates are relatively modest compared to global meta-analyses of standard AWD (reflooding at -15 cm), which report CH_4 , net GHG, and GHG intensity reductions of approximately 57.8%, 44.9%, and 57.7%, respectively (Wang et al., 2020; Wu et al., 2022). Furthermore, when coupled with organic fertilization, standard AWD has been shown to achieve maximum reductions in yield-scaled GHG of up to 52.5% compared to the conventional flooding with chemical N fertilizer system (Liao et al., 2023; Livsey et al., 2019). The discrepancy between the field-measured reductions in this study and those reported for standard AWD was partially explained by the DNDC modeling results. Under the default model AWD threshold (reflooding at -5 cm), DNDC predicted a much higher CH_4 reduction magnitude ($\sim 42.9\%$ for average and $\sim 53.8\%$ for cumulative fluxes). This suggested that the saturation-based management applied in the field provided a more buffered redox environment than the drying phases typical of standard AWD or those simulated by default model parameters.

A primary contribution of this research involved the net ecosystem C balance (net GHG emissions minus SOC sequestration). Although SOC stocks followed a consistent upward trajectory, high spatial variability and the two-year duration limited the statistical significance of raw sequestration rates. However, the near-saturation water-saving practice effectively improved the net ecosystem C balance by 17.3% because the significant reduction in CH_4 emissions outweighed the slightly lower SOC gains. This finding is significant given that traditional AWD is often associated with negative impacts on long-term soil health (Livsey et al., 2019; Xu et al., 2017). Previous studies have indicated that water-saving irrigation can increase soil-to-atmosphere C flux by 25%, leading to an approximately 5.2% depletion of SOC over time (Livsey et al., 2019). In certain instances, the loss of SOC sequestration capacity under intermittent irrigation can entirely offset the climate mitigation benefits of reduced CH_4 , resulting in a net increase in the total GHG budget (Shang et al., 2021). The results here suggested that a near-saturation threshold preserves SOC stability more effectively than intensive drainage while still providing meaningful CH_4 mitigation.

Regarding resource efficiency, the near-saturation practice stabilized grain yield while significantly improving irrigation water productivity by $\sim 16.5\%$. Although this improvement is lower than the 26–40% gains reported for standard AWD (Carrizo et al., 2017; Zhao et al., 2024), the saturation-based approach avoids the moisture-stress risks associated with deeper water table thresholds. By resolving the conflict between

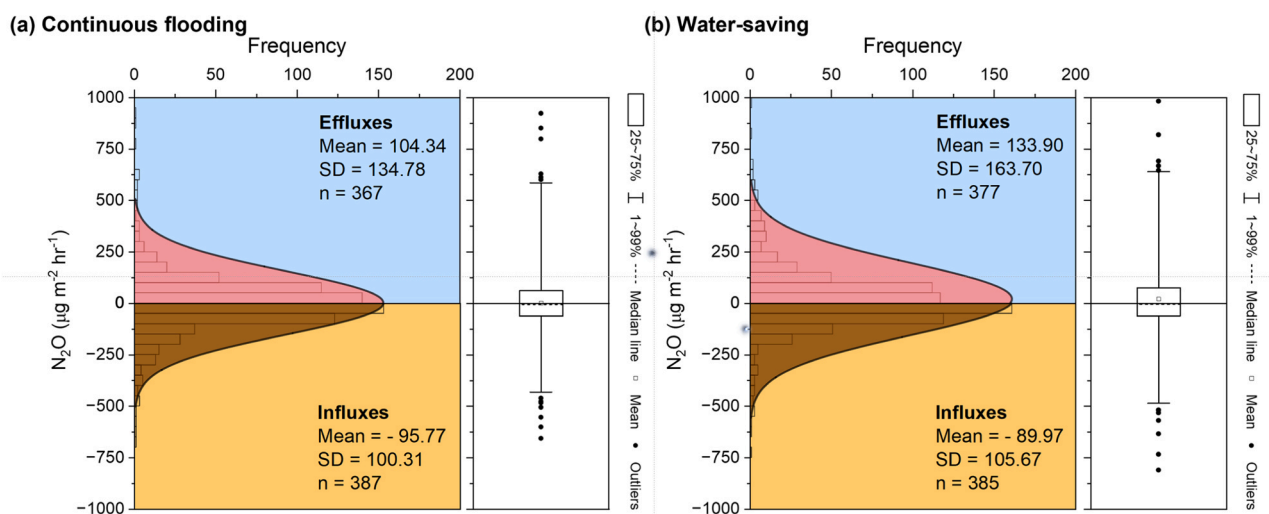


Fig. 4. Frequency distribution and variability of the field-measured N_2O fluxes from each chamber under (a) continuous flooding and (b) near-saturation water-saving irrigation across two growing seasons (2023–2024). Positive values indicate N_2O effluxes (emissions), while negative values indicate N_2O influxes (uptake). Boxplots summarize flux variability.

water conservation and yield security, this near-saturation threshold provides a technically feasible model for optimizing the climate-mitigation potential of organic rice systems.

4.2. GHG dynamics and seasonal variations

4.2.1. Methane

Methane emissions in this study followed distinct “single-peak” and “double-peak” patterns corresponding to irrigation management and substrate availability. Under both treatments, emissions increased from transplanting through the tillering stage as field flooding stimulated the methanogenic degradation of residual straw and root debris. This trend was further amplified during the panicle initiation stage, where maximum root activity and rhizodeposition provided abundant labile substrates for methanogenesis (Chen et al., 2019; Kimura et al., 2004; Vo et al., 2018; Qian et al., 2023). Under CF, reflooding after mid-season drainage typically triggered a secondary CH₄ peak. This “flush effect” results from the rapid mineralization of labile-C accumulated during the aerobic phase and the reestablishment of anaerobic conditions (Hang et al., 2014; Raheem et al., 2022). In contrast, the near-saturation water-saving strategy effectively suppressed this secondary rebound by maintaining a slightly more aerated soil profile through intermittent saturation.

Seasonal variations significantly influenced the magnitude of these emissions. The late cropping season (S2) consistently exhibited higher CH₄ and net GHG emissions than the early season (S1). This discrepancy was attributed to warmer ambient temperatures in S2, which accelerated rice growth and root biomass development, thereby enhancing root exudation and plant-mediated CH₄ transport (Li et al., 2013). Furthermore, the incorporation of rice straw from the preceding season provided a critical substrate surge. Modelled results indicated that the late-season increase in CH₄ was noticeably amplified under CF (~18.17 mg m⁻² hr⁻¹ for the average and 373.77 kg ha⁻¹ for cumulative emissions), suggesting that straw incorporation can exacerbate GHG emissions when coupled with prolonged flooding and high temperatures (Zhao et al., 2020). The amplified CH₄ emissions under the warmer and anoxic environment also suggested that the water-saving practice was potentially more efficient for CH₄ mitigation compared to the baseline-intensive in S2. Moreover, as S2 produced significantly higher grain yields than S1, the implementation of a near-saturation threshold during the late season effectively optimized GHG intensity by combining higher productivity with substantial CH₄ suppression.

4.2.2. Nitrous oxide

Unlike CH₄, N₂O emissions were episodic and primarily driven by fertilization events and drainage-rewetting cycles (Kritee et al., 2018; Qian et al., 2023; Sander et al., 2014). Significant N₂O spikes were observed during mid-season drainage and following panicle fertilizer applications, where the transient oxic-anoxic interface facilitated sequential nitrification and denitrification (Zou et al., 2005; Verhoeven et al., 2018). Seasonally, cumulative N₂O was ~86% lower in S2 than S1, presumably due to the depletion of labile N from plant uptake and prior gaseous losses, as well as increased plant N uptake under warmer S2 conditions (Wang et al., 2018). Interannual variations also played a role; the lower precipitation in 2023 compared to 2024 resulted in more pronounced N₂O emission events, as drier soil conditions favored nitrification.

Despite periodic emission spikes, both CF and near-saturation systems frequently acted as atmospheric N₂O sinks. The prevalence of negative N₂O fluxes highlights the high potential for N₂O reduction to N₂ in these organic-rich environments (Domeignoz-Horta et al., 2018). In this study, the negative N₂O fluxes observed were consistent with a high labile C environment, which potentially facilitated complete denitrification. Although we did not directly measure N₂O reductase activity or *nosZ* gene abundance, the presence of organic amendments likely provided the necessary electron donors to favor the N₂O → N₂

reduction pathway under reduced conditions (Hu et al., 2024; Kong et al., 2024; Tang et al., 2023). Additionally, evidence suggested that the rice plants themselves may have facilitated this sink behavior. By acting as a conduit, the aerenchyma may allow atmospheric N₂O to reach the rhizosphere, where high N₂O-reducing microbial activity thrives (Kim et al., 2021; Zhong et al., 2023). This dual role of organic substrate supply and plant-mediated transport suggested that near-saturation water-saving could maintain a net-negative N₂O balance even while mitigating CH₄ surges.

4.3. Limitations and research suggestions

4.3.1. Technical limitations of flux measurements

Discrepancies between field-measured CH₄ patterns and DNDC simulations, specifically the more pronounced secondary peak predicted by the model after reflooding, may be attributed to inherent limitations of the static chamber method. Static chambers sample a relatively small surface area (~1 m²), which may fail to capture heterogeneous gas release through discrete pathways, such as ebullition vents and desiccation cracks, that dominate flux during rapid wet-dry transitions (Chaichana et al., 2018; Charteris et al., 2020). Mid-season drainage commonly induces crack networks that function as preferential conduits for both gas transport and the export of DOC upon reflooding (Zhang et al., 2014). This export can deplete the labile substrates necessary for methanogenesis, a process not fully accounted for in model assumptions of uniform soil and substrate continuity (Fuhrmann et al., 2019). Furthermore, while weekly sampling is a standard protocol, the temporal resolution may have failed to capture high-frequency, episodic N₂O pulses, as linear interpolation between sampling dates could underestimate cumulative emissions during rapid “hot moments” such as fertilization or initial soil rewetting. Consequently, the divergence between simulated and measured CH₄ rebounds and the potential underestimation of N₂O likely reflects the chamber's inability to capture these localized “hot spots” of gas exchange.

4.3.2. Biogeochemical modelling constraints

In the DNDC simulations, N₂O fluxes consistently remained below detection limits, with discernible peaks occurring only during the most oxic phases of mid-season drainage (Fig. S3). This behavior was attributed to the biochemical nature of organic fertilizers and the near-saturation soil environment. The slow-release nature of organic nitrogen and the split-fertilizer regime likely resulted in small inorganic N pools that were rapidly assimilated by the crop, leaving insufficient substrate for simulated N₂O pulses (Kong et al., 2024). Crucially, DNDC version 9.5 failed to capture the observed atmospheric N₂O sink behavior. This discrepancy likely resulted from the model's empirical *Eh* sub-model, which lacks the sensitivity to simulate the complete reduction of N₂O to N₂ under fluctuating redox conditions, and the absence of a bi-directional gas diffusion module (Fumoto et al., 2008). Therefore, even when internal consumption exceeds production, the algorithm is designed to report zero values rather than the negative fluxes recorded in the field.

4.3.3. Temporal and spatial considerations

The two-year experimental duration and high spatial variability of SOC limited the statistical significance of observed sequestration trajectories. Although SOC stocks followed an upward trend, the near-saturation practice appeared to marginally slow sequestration relative to continuous flooding, likely due to enhanced mineralization driven by redox oscillations (Han et al., 2023; Livsey et al., 2019; Xu et al., 2017). Similarly, the lack of a detectable signal from winter cover cropping contrasts with literature reporting substantial GHG responses to green manure. While additional biomass from non-legume covers like Tartary buckwheat can stimulate CH₄ production, the benefits of SOC stabilization and CH₄ oxidation often develop gradually, with detectable shifts in the net C balance potentially requiring over 15 years of consistent

implementation (Mezzari et al., 2023; Liang et al., 2025). In this short-term study, the perturbation of the C and redox environment was likely too small to overcome statistical noise, suggesting that long-term monitoring is essential to confirm the environmental efficacy of integrated regenerative practices.

5. Conclusions

This study demonstrates that the implementation of a precision near-saturation irrigation threshold (0 cm) fundamentally shifts the biogeochemical trajectory of subtropical organic rice paddies by disrupting prolonged anaerobic conditions. The process-based significance of this research lies in the tactical introduction of soil aeration, which suppresses methanogenesis enough to achieve substantial climate mitigation (a ~29.3% reduction in cumulative CH₄). Crucially, this reduction is robust enough to outweigh minor short-term fluctuations in SOC sequestration and N₂O fluxes, effectively improving the net ecosystem C balance (a ~17.3% reduction in the net C source strength) over the two-year period. Consequently, the 0 cm reflooding threshold functions as a biogeochemical “sweet spot” for high-input organic systems. It successfully resolves the inherent conflict between resource intensification and environmental impact by safeguarding grain yields while simultaneously optimizing agricultural water conservation (a ~16.5% improvement in irrigation water productivity). Although winter cover crop did not yield significant immediate shifts in GHG dynamics and SOC sequestration, the integrated efficacy of the precision near-saturation irrigation model provides a mechanistic foundation for a scalable, low-risk strategy that maximizes the environmental resilience of regenerative rice production under increasing global water scarcity.

Disclaimer

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CRedit authorship contribution statement

Cheng-Hsien Lin: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Yi-Ting Hsu:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Jang-An Tai:** Resources, Methodology, Data curation. **Li-Yan Lin:** Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Ching-Wen Wang:** Resources, Conceptualization. **Yu-Ren Lin:** Resources, Methodology, Data curation. **Yu-Yu Kung:** Writing – review & editing, Visualization, Software, Resources, Methodology, Formal analysis, Data curation, Conceptualization. **Sung-Ching Lee:** Writing – review & editing, Validation, Resources, Methodology, Conceptualization.

Declaration of Competing Interest

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no other relevant affiliation or financial interest of the authors with any organization with a financial interest in or financial conflict with the subject matter or materials discussed in the manuscript, other than those that are disclosed.

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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.agwat.2026.110502](https://doi.org/10.1016/j.agwat.2026.110502).

Data availability

Data will be made available on request.

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