



Effect of post-harvest practices on greenhouse gas emissions in rice paddies: flooding regime and straw management

María Belenguer-Manzanedo · Carles Alcaraz ·
Antonio Camacho · Carles Ibáñez ·
Mar Català-Forner · Maite Martínez-Eixarch 

Received: 25 May 2021 / Accepted: 15 November 2021
© The Author(s) 2022

Abstract

Aims To assess 1) the effect of the combination of flooding (winter flooding vs. non-winter flooding; WFL vs NWF) and timing of straw incorporation (early vs late straw incorporation; ESI vs LSI) in the post-harvest of paddy agrosystem, on a year-round global balance of greenhouse gases (GHG) exchanges, i.e. methane (CH₄), carbon dioxide (CO₂) and nitrous oxide (N₂O); 2) the impact on the net ecosystem carbon balance (NECB) and 3) the resulting net global warming potential (GWP).

Methods A field experiment was conducted with fortnightly samplings of main GHG emissions. Effect of the studied factors on GHG emissions was seasonally assessed. The net GWP is estimated from the balance between GHG (CH₄ and N₂O) and NECB.

Results NWF-LSI reduced net GWP by 206% compared to conventional post-harvest management (WFL-ESI). NECB was similar in all treatments. Avoiding winter flooding reduced CH₄ emissions significantly in the post-harvest and next growing seasons, while delay straw incorporation prevented CH₄ and CO₂ emissions during post-harvest. None of the treatments increased N₂O emission. Environmental implications of post-harvest management options are discussed.

Conclusions Post-harvest management affects net GWP of the paddy rice cultivation by modifying GHG emissions in post-harvest and next growing season without compromise sequestration C budget. The combination of non-winter flooding and late straw incorporation strategies were more effective in reducing both CH₄ and CO₂ emissions, due to avoiding higher temperatures at the time of the straw incorporation during post-harvest and increasing soil Eh conditions at the following growing season.

Responsible Editor: Rémi Cardinael.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s11104-021-05234-y>.

M. Belenguer-Manzanedo · C. Alcaraz · C. Ibáñez ·
M. Martínez-Eixarch (✉)
IRTA Institute of Agrifood Research and Technology,
Marine and Continental Waters, Ctra. Poble Nou, km. 5.5,
E-43540 Sant Carles de la Ràpita, Spain
e-mail: maite.martinezexarch@irta.cat

M. Belenguer-Manzanedo (✉) · A. Camacho
Cavanilles Institute for Biodiversity and Evolutionary
Biology, University of Valencia, E-46980 Paterna, Spain
e-mail: maria.belenguer@irta.cat

Present Address:
C. Ibáñez
EURECAT, Climate change research, Area
of Sustainability, C. Lligallo de Lorente, 3,
E-43870 Amposta, Spain

M. Català-Forner
IRTA Institute of Agrifood Research and Technology,
Extensive crops. Ctra. Balda km. 1, 43870 Amposta, Spain

Keywords Fallow season management · Greenhouse gas emission · Rice straw management · Winter flooding management · Paddy rice · Net GWP

Abbreviations

CH ₄	methane
CO ₂	carbon dioxide
N ₂ O	nitrous oxide
GHG	greenhouse gas
GWP	global warming potential
NECB	net ecosystem carbon balance
C	carbon
N	nitrogen
SO ₄	sulphate
OM	organic matter
WL	water level
WFL	winter flooding
NWF	non-winter flooding
ESI	early straw incorporation
LSI	late straw incorporation
SE	standard error
NPP	net primary production.

Introduction

Worldwide cultivation of rice (*Oryza sativa* L.) contributes to about 9 – 11% of greenhouse gas (GHG) emissions in agriculture (Smith et al., 2014). Main GHGs emitted are methane (CH₄), carbon dioxide (CO₂) and nitrous oxide (N₂O) being one of the crops with the highest GHG intensity (Carlson et al., 2016; Linquist et al., 2012). Methane emissions are especially relevant in rice cultivation. Methane and N₂O have a 28 and 265 times higher warming potential than CO₂, respectively (Smith et al., 2014), thus their impact on GWP is larger. Particularly in rice paddies, CH₄ may dominate the net GWP of the crop (Naser et al., 2019). Flooding conditions for rice cultivation are one of the main driving factors of CH₄ production (Neue et al., 1996). Returning straw to the soil, which has become more common in recent decades because of the benefits it brings in soil fertility and carbon stock (Chivenge et al., 2020; Lu et al., 2008; Pan et al., 2004), is also associated with a boosting effect on CH₄ emissions from the crop (Huang et al., 2013). Consequently, reducing CH₄ emissions from flooding and straw decomposition practices are recognized as effective measures to decrease GWP from

rice cultivation (Hussain et al., 2015; Smith & Conen, 2004).

Temperature and moisture have been identified as key factors in regulating soil organic matter (OM) and rice straw decomposition and, subsequently, GHG emissions (Devèvre & Horwath, 2000; Huang et al., 2015). Increments in temperature have been associated with increased OM decomposition and C emissions (Devèvre & Horwath, 2000; von Lützow & Kögel-Knabner, 2009). Besides, soil moisture determines oxygen diffusion and substrate mobility (Linn & Doran, 1984; Moyano et al., 2013). In the case of flooded soils, such as in rice paddies, anaerobic conditions are promoted which are related to lower mineralisation rates (Devèvre & Horwath, 2000; Huang et al., 2015; Xu & Hosen, 2010). Several studies on the combined effect of temperature and moisture on rice straw decomposition and organic matter mineralisation have been conducted by assessing the amount of C emitted (Devèvre & Horwath, 2000; Huang et al., 2015). However, these studies are mostly under controlled conditions and more effort should be put in upscaling to field experimental studies.

In Ebro Delta (Spain), mono-crop rice cultivation is employed. The growing season lasts from May to September and the rest of the year the field is left in fallow. Fields are commonly flooded in early October as it previously was an agri-environmental measure to promote bird diversity (Ibáñez et al., 2010) and maintaining low levels of soil salinity by keeping the phreatic layer in deeper layers. In addition, it is also when a significant amount of organic matter from post-harvest above-ground plant residues, i.e. stubble and straw, is incorporated into the soil. In a previous study conducted in Ebro Delta (Martínez-Eixarch et al., 2018, 2021), it was concluded that around two-thirds of the annual CH₄ emissions are released during the fallow season and that the main drivers of fallow CH₄ emissions were water table depth, soil temperature and straw management. They attributed large CH₄ fluxes in the fallow season to the combined effect of a large amount of readily decomposable organic matter in the soil derived from straw, anaerobic conditions given by flooded fields and high temperature. According to this, it was suggested that delaying the incorporation of the straw to late fallow season could mitigate fallow CH₄ emissions. However, the final annual budget of carbon (C) emissions is unclear, because decomposition of SOM and straw could result in high

CO₂ emissions under unflooded field conditions (Lee et al., 2020; Li et al., 2013) and/or in CH₄ emissions when the fields are flooded in for the next growing season (Nakajima et al., 2015). Therefore, this motivated our study to evaluate the effect of delaying straw input to late fallow season combined with winter flooding or unflooded field on the annual net ecosystem carbon budget (NECB) and net GWP in order to minimize GHG emissions while maintaining the agronomic and environmental benefits of straw addition into the soil.

Agricultural practices are a valuable resource for controlling the GHG emissions (Hussain et al., 2015; Smith et al., 2010a) but the trade-off between processes during the entire crop should be contemplated. Flood management and straw incorporation in the fallow season have received some attention in terms of their role on methane production (Cai et al., 2003; Fitzgerald et al., 2000; Xu et al., 2000; Xu & Hosen, 2010; Zhang et al., 2010). One of the most efficient practices to decrease CH₄ emissions and mitigate the GWP of the crop is the reduction of the flooding period. Fields which were drained in the fallow season emitted less CH₄ in the following growing season than those which were permanently flooded (Cai et al., 2003; Xu et al., 2000; Zhang et al., 2010). For straw management, incorporating straw after harvest reduces CH₄ emissions during the following crop compared to incorporating it before transplanting (Song et al., 2019; Xu et al., 2000). Several of these studies monitor CH₄ and N₂O emission responses to crop practices, but ignore CO₂, thus neglecting possible impact on the carbon balance and net GWP. Therefore, is still not fully understood whether the post-harvest agricultural management of combined straw incorporation and flooding management will lead GHG emissions throughout post-harvest and following growing season and the effect on net carbon balance and net GWP of the crop.

This study was conducted 1) to quantify the combined effects of different flooding regimes and timing of straw incorporation during fallow and cropping seasons on CH₄, CO₂ and N₂O exchanges, 2) to assess their influence on global GHG balances throughout the annual cycle of the rice crop, including the post-harvest, pre-growing period and the rice growing period and 3) to evaluate the net global warming potential (GWP) and greenhouse gas intensity per unit of grain yield (GHGI) computing CH₄, N₂O

fluxes and NECB of the different post-harvest management options in the mono-crop Ebro Delta cultivation system.

Material & Methods

Study site and experiment design

The study was conducted at the IRTA experimental station (40°42'27.5"N 0°37'59.8"E) in the Ebro Delta (Spain), from October 2017 to December 2018, comprising a post-harvest season in 2017 and pre-growing, growing, and post-harvest seasons of 2018. The climate of the region is Mediterranean, with annual average temperature ranges 9 – 25 °C (mean annual temperature (16.9 ± 5.1) and precipitation annual average is around 600 mm with large interannual variation from 251 to 1054 mm in last 30 years. Summers are dry and warm, generally, July mean temperatures are the highest (25 °C) and accumulated precipitation is the lowest (13 mm). Precipitation is mostly distributed around the spring and autumn months. Winters are mild with lowest mean monthly temperatures around 9.5 °C in January. The paddy soils were similar in characteristics, poorly drained, where the proportions of silt, clay and sand in the arable layer (~20 cm) were 62.4, 30.6 and 7%, respectively. At the beginning of the experiment, bulk density was 1305 kg m⁻³; elemental C 6.66%; organic matter 2.43%; total organic C 1.1%; elemental nitrogen 0.17% and sulphate (SO₄) 0.16%.

The experiment included two factors, water management during the fallow season and timing of straw incorporation, with two levels each, winter flooding (WFL) vs non-winter flooding (NWF) and early (ESI) vs late (LSI) straw incorporation, respectively. Among the four resulting treatments (WFL-ESI, WFL-LSI, NWF-ESI and NWF-LSI), WFL-ESI is representative of the conventional post-harvest management applied in Ebro Delta rice fields. The experimental design was two plots divided in two subplots with three sampling points as replicates wherein the main plot represented the water management and the subplot the timing of straw incorporation. The experiment was laid out in two adjacent experimental fields of 106 × 10 m each (subplots: 53 × 10 m) (Fig. S1). Each plot had its own water inlet so that the irrigation was managed independently. The experiment started

Table 1 Crop treatments and field management during the experiment

Season	Date	Crop treatments or field management
Post-harvest	18-Sep-17	Harvest
	28-Sep-17	Flooding WFL plot
	6-Oct-17	Early straw incorporation (ESI) in WFL and NWF plots
	30-Nov-17	Late straw incorporation (LSI) in WFL and NWF plots
	29-Dec-17	Irrigation cut
Pre-growing	23-Apr-18	Fertilization (70 kg N ha ⁻¹)
	25-Apr-18	Flooding NWF and WFL
	26-Apr-18	Herbicide treatment (Ronstar)
Growing	3-May-18	Sowing (var. Gleva; 500 seeds m ⁻²)
	1-Jun-18	Herbicide treatment (Viper + Permit)
	4-Jun-18	Fertilization (Urea 60 kg N ha ⁻¹)
	2-Jul-18	Herbicide treatment (Basagran SG + MCPA)
	5-Jul-18	Fertilization (ammonium sulphate 60 kg N ha ⁻¹)
	23-Jul-18	Rice heading
	24-Jul-18	Fungicide treatment (Procloraz)
	6-Aug-18	Fungicide treatment (Azosistrobin)
	Post-harvest	1-Oct-18
9-Oct-18		Flooding WFL plot
18-Oct-18		Early straw incorporation (ESI) in WFL and NWF plots
29-Nov-18		Late straw incorporation (LSI) in WFL and NWF plots
30-Dec-18		Irrigation cut

in the post-harvest of 2017. For WFL treatment, the plot was permanently flooded from October to mid-December. In NWF plot, the irrigation was cut in October, which naturally drain in few days. To ensure dry conditions in NWF, a drainage channel was constructed in between the two main plots along to avoid water seepage from the flooded field. Regarding straw treatment, after the harvest the straw was left on the field. In ESI, straw was incorporated in soil by mechanically ploughing in mid-October while in LSI, the straw was mixed with the soil in late November. In the first year, the same amount (8.8 Mg ha⁻¹ dry weight) of straw was applied in the four treatments, which was estimated from the average of random sampling of the two fields. The resulting harvest index was 0.5, coinciding with Matías et al. (2019). In the second year, the quantity of incorporated straw was calculated from the grain yield and assuming the same harvest index as the preceding year.

During the growing season, rice was cultivated identically in the four treatments following the standard agricultural practices of the region in the Ebro Delta (Table 1). In brief, all plots were flooded in mid-April and sown (500 seed m⁻²) at the beginning

of May. Water depth was maintained around 5 – 15 cm depth during the cultivation period until September, when plots were drained for harvest. Three fertilization applications were applied plus three herbicide applications and two fungicide treatments along growing seasons (Table 1). Previous to this study, the experimental plots had been cultivated following the standard practices for more than 10 years.

Field sampling and laboratory procedures

Greenhouse gas emissions were measured using the dark non-steady state chamber gas following the sampling method described by Altor and Mitsch (2008). The chambers consisted of a squared based prism (dimensions: 0.35 × 0.35 × 0.74; volume = 0.093 m³) of polyvinylchloride (PVC) covered with a reflective layer to avoid photosynthesis. Two ports for thermometer and syringe insertion were sealed with rubber septa to avoid gas exchange while samples were taken. Chambers were placed and removed every sampling day. The base of the chamber was covered with foams which allowed to place the chambers floating without disturbing the soil when the paddy

fields were flooded. In soil dry conditions, the foam was removed, and chambers were placed carefully on the soil, with humid towels around the base to prevent gas exchange.

Measures were taken on a bi-weekly basis in each subplot during all the experimental period except in March and April, when soil labouring (ploughing and levelling) take place thus causing soil disturbance. Gas sampling was performed simultaneously in the three replicates in each treatment. Gas samples were taken after flushing the syringe to mix headspace air, and then, 30 ml sample of gas was collected and transferred overpressured to glass vacuum 12.5 ml vials (Labco Ltd., Buckinghamshire, UK) and sent to the laboratory. Samples of gas were extracted every 10 min over a 30-min period resulting in 4 measures per sampling event. Air temperature inside the chamber was monitored with each gas sample. Concentration of CH₄, CO₂ and N₂O gases was determined using Agilent 8860 GC System (Agilent USA) gas chromatograph equipped with a flame ionization detector (FID) and an electron capture detector (GC-ECD) connected in series with a valve system. The calibration of the gas chromatograph was carried out using a CH₄, CO₂ and N₂O standard in nitrogen provided by Carbueros Metalicos S.A. (Spain). The working range of the calibration curve was adjusted depending on the CH₄ concentration, from 3 to 30 ppm for the samples of low concentration, and from 30 to 600 ppm for the samples of high concentration. For CO₂ the calibration curve was adjusted from 50 to 2000 ppm and for N₂O from 0.1 to 2.0 ppm. The associated error of the gas standards ranged 5 – 10%.

Gas emission rates were calculated from a linear regression between gas concentration and time. Gas concentration of each sample was corrected for the increase of temperature in the headspace of the chamber according to the ideal gas law, since the pressure was kept constant through a pipe connecting the headspace to the outside. Only significant linear regressions ($P < 0.05$ and $R^2 > 0.80$) were accepted to represent changes in gas emission, and non-significant regressions were considered as zero emission rates. The cumulative emission (whole study period, post-harvest, pre-growing and growing seasons) were calculated by assuming constant emission rates between sampling events (Martínez-Eixarch et al., 2018, 2021).

$$\text{Cumulative emission (kg ha}^{-1}\text{)} = \sum_{i=1}^{n=3} \text{Emission rate}_{(n)} \times T$$

Where the emission rate is calculated from the fluxes of the chambers per sampling day multiplied by the time (T) elapsed until the next sampling event (hours) and n is each replication.

Simultaneously to gas sampling, environmental soil conditions (air temperature, soil temperature, soil pH, soil electrical conductivity and soil Eh potential) were measured next to each gas-sampling chamber at ca.10 cm depth by triplicate. The probes Hanna HI9126 for soil pH and Eh, and FieldScout Direct Soil EC Meter 2265FSTP for soil conductivity, were used. Climatic data was acquired from a meteorological station located in the experimental centre (GPS coordinates 40°42'27.9"N 0°37'55.6"E) pertaining to the Web of Agrometeorological Station of Weather Services of Catalonia (Catalan Government).

Estimation of net ecosystem carbon balance (NECB), net global warming potential (GWP) and greenhouse gas intensity (GHGI)

To estimate the carbon balance for each treatment, the net ecosystem carbon balance (NECB) for an entire year, from post-harvest 2017 to rice harvest 2018, was calculated based on the difference between carbon inputs and outputs (Haque et al., 2015; Ma et al., 2013).

$$\text{NECB}(\text{kgCha}^{-1}\text{yr}^{-1}) = \Sigma\text{Cinput} - \Sigma\text{Coutput} = (\text{NPP} + \text{Amendment}) - (\text{Rh} + \text{Harvest})$$

Sources considered as C input included rice plant biomass of the 2018 growing season as net primary production (NPP) and the straw biomass from 2017 crop season applied as organic amendment. The C outputs were determined as C losses through flux balance estimations of CO₂-C and CH₄-C and the C of the aboveground biomass harvested in 2018 (i.e., grain and straw). Carbon content of grain and straw was estimated considering a 39% and 37% of C by dry weight, respectively (Huang et al., 2007). Root, litter and rhizodeposits were estimated as 10% of aboveground biomass (Huang et al., 2007), 5% of the above ground and root biomass (Kimura et al., 2004), and 15% of the total biomass (Mandal et al., 2008), respectively.

Net global warming potential (GWP) estimations was calculated considering NECB, CH₄ and N₂O. Methane and N₂O was transformed to carbon equivalents (CO₂-eq) over a 100-year time scale (Smith et al., 2014) using IPCC factors, 28 and 265, respectively.

$$\text{NetGWP}(\text{kgCO}_{2\text{-eq}}\text{ha}^{-1}\text{yr}^{-1}) = 28 \times \text{CH}_4 + 265 \times \text{N}_2\text{O} - \text{NECB} \times \frac{44}{12}$$

To yield-scale net GWP, the greenhouse gas intensity (GHGI) was calculated dividing net GWP by the rice grain yield (Lee et al., 2020; Mosier et al., 2006):

$$\text{GHGI} (\text{kg CO}_{2\text{-eq}} \text{kg}^{-1} \text{ grain yield}) = \frac{\text{Net GWP}}{\text{Grain yield}}$$

Data analysis

Greenhouse gas emission rates (CH₄, CO₂ and N₂O) and soil properties (soil electrical conductivity, water level (WL) and soil temperature) were compared among two level factors (flooding regime and timing of straw incorporation) throughout the studied period and for each season (post-harvest, pre-growing and growing season) with repeated measures of variance analysis (RM-ANOVA). All factors were considered as fixed effects and, in addition to p-values (statistical significance), we also reported partial eta-squares (η^2) as a measure of effect size (i.e., importance of factors) where values ranges 0 – 1, meaning no effect to strong effect size of the factor, respectively. A conventional one-way ANOVA was performed for each treatment to compare the differences among of treatments for accumulated GHGs, grain yield, quantities of straw incorporated and GWP estimations. Correlation between emission rates and environmental parameters were evaluated with Pearson's coefficient (*r*). All statistical analyses were performed with SPSS 23 (SPSS Inc., Chicago IL, USA).

Results

Grain yield and environmental conditions

Post-harvest treatments did not affect the yield in 2018 ($5.2 \pm 0.2 \text{ Mg ha}^{-1}$ ($F=0.71$, $P=0.563$)). Soil temperature was similar between treatments

(Table S1). At the moment of straw incorporation, temperature in ESI was higher, ($20.7 \pm 0.3 \text{ }^\circ\text{C}$ in 2017 and $17.6 \pm 1.2 \text{ }^\circ\text{C}$ in 2018), compared with LSI ($9.2 \pm 0.3 \text{ }^\circ\text{C}$ and $12.5 \pm 0.5 \text{ }^\circ\text{C}$ in 2017 and 2018, respectively) (Fig. 1). The accumulated precipitation during the post-harvest season in 2017 was 33.2 mm, ca. 10 times lower than during the same period in 2018 (296.4 mm) (Fig. 1).

The Eh values were mainly associated to flooding regime (Fig. 1), showing lower values with the presence of a layer of standing water (Fig. 1). The overall post-harvest soil Eh was lower in 2018 than in 2017. The differences between WFL and NWF were more evident in 2017 (-120.1 ± 52.1 and $-16.4 \pm 13.1 \text{ mV}$, respectively) than in 2018 (-182.6 ± 51.8 and $-160.9 \pm 75.4 \text{ mV}$, respectively) because of the higher rainfall in the latter (Fig. 1). Also, in 2018, more marked differences were found in NWF treatments between ESI ($-172.5 \pm 109.3 \text{ mV}$) and LSI ($-149.5 \pm 46.7 \text{ mV}$). At pre-growing season, Eh could only be measured in WFL, where the soil had enough moisture, being the mean Eh values $-196.7 \pm 31.8 \text{ mV}$. The lowest soil Eh values of all treatments were reached in the growing season, which ranged from -286.1 to -257.4 mV . Eh values decreased along the growing season, but WFL treatments started from lower values ($-210.9 \pm 10.9 \text{ mV}$) than NWF ($-167.4 \pm 21.1 \text{ mV}$) and maintained those differences until July. Soil conductivity during the 2017 post-harvest was increased under NWF treatments and remained higher in NWF-ESI throughout the subsequent pre-growing and growing seasons which was supported by a significant effect of the flooding regimen (Table 2; Table S1). Thereafter, differences among the treatments were vanished in the 2018 post-harvest, coinciding with more rainfall in this season. Soil pH showed a seasonal variation with values around 7 (6.94 – 7.48) in post-harvest and pre-growing and between 6.5 and 7 in the growing season (Table S1) without differences across the treatment.

GHG emissions

CH₄ emissions

Overall, CH₄ emission rates were lower in both post-harvest (-0.03 – $2.50 \text{ mg CH}_4\text{-C m}^{-2} \text{ h}^{-1}$) and pre-growing (-0.01 – $0.00 \text{ mg CH}_4\text{-C m}^{-2} \text{ h}^{-1}$) seasons than in the

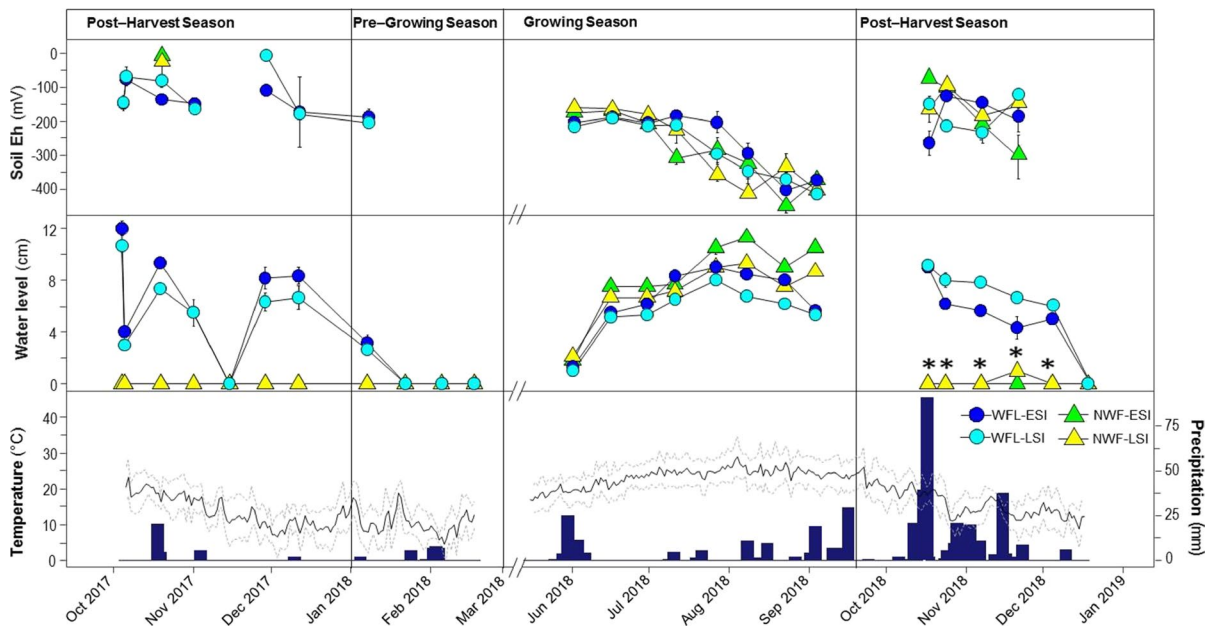


Fig. 1 Soil Eh (top) and water level (middle) under different post-harvest managements and climate graph (bottom) of the studied period divided by crop season (error bars are the mean \pm SE; $n=3$). Treatments are WFL-ESI, winter flooding and early straw incorporation; WFL-LSI, winter flooding and late straw incorporation; NWF-ESI, non-winter flooding and early

straw incorporation; NWF-LSI, non-winter flooding and late straw incorporation. For climate graph maximum, minimum (grey dotted lines), mean temperature (black line) and accumulated precipitation (bars) during the studied period are represented. Asterisks (*) indicate that the soil was saturated

growing season ($3.10 - 7.26 \text{ mg CH}_4\text{-C m}^{-2} \text{ h}^{-1}$) (Fig. 2) as supported by significant time effect among cropping seasons (Table 2). Straw and water management during the fallow season affected CH_4 fluxes in the post-harvest and subsequent growing season (Table 2).

The pattern of CH_4 emission rates was influenced by the timing of straw incorporation with a peak consistently found 5 weeks after straw input under ESI treatments as opposed to the lack of response in LSI, wherein the CH_4 emissions remained low throughout both post-harvest seasons. In 2017 post-harvest, the effect of winter flooding was significant, as was the interaction between incorporation timing and flooding, resulting in increased emission rates in WFL-ESI treatment. Emission rates in 2018 were more variable (Fig. 2) and consequently statistical analysis did not show significant treatment effects. Comparing both post-harvest seasons, CH_4 emission rates in ESI were higher in 2018 than in 2017; by 6 times in WFL-ESI treatment (0.39 and $2.5 \text{ mg CH}_4\text{-C m}^{-2} \text{ h}^{-1}$, in 2017 and 2018, respectively) and 200 times in NWF-ESI

(0.01 and $2.02 \text{ mg CH}_4\text{-C m}^{-2} \text{ h}^{-1}$, in 2017 and 2018, respectively).

The correlation analysis between CH_4 and the environmental factors by season indicated that, overall, CH_4 emission rates in NWF-ESI were negatively correlated with Eh ($P < 0.05$) while in WFL-ESI correlated negatively with soil conductivity ($P < 0.05$). In addition, CH_4 emission rates showed a positive correlation with soil temperature and water level ($P < 0.01$) (Table 3).

Post-harvest water and straw management affected CH_4 emissions during the subsequent growing season. The η^2 provided by the RM-ANOVA revealed that the importance of the individual effect of each factor ($\eta^2 = 0.39$) was larger than the interaction ($\eta^2 = 0.22$). During the growing season, CH_4 emission rates showed an overall increasing trend with two peaks at 4 and 8 weeks after sowing (Fig. 2) in all treatments: the first was larger under WFL than NWF (9.43 ± 1.2 vs $2.18 \pm 0.9 \text{ mg CH}_4\text{-C m}^{-2} \text{ h}^{-1}$) whereas the second one was explained by the timing

Table 2 Effect of flooding regime and straw incorporation time on GHG emissions, soil conductivity (Cond) and soil temperature (Temp): between-subject factors (Huynh-Feldt corrections) of repeated measures analysis of variance

Crop season (Year)	Time																	
	Winter Flooding Regime					Straw Incorporation Moment					Winter Flooding Regime x Straw Incorporation Moment							
	df	Error	F	P	partial η^2	df	F	P	partial η^2	df	F	P	partial η^2	df	F	P	partial η^2	
All seasons	CH ₄	4	35	16.2	<0.001	0.67	4	1.9	0.127	0.19	4	2.4	0.065	0.23	4	0.8	0.514	0.10
	CO ₂	15	118	153.6	<0.001	0.95	15	1.2	0.257	0.13	15	1.3	0.225	0.14	15	2.2	0.012	0.21
	N ₂ O	9	71	1.2	0.314	0.13	9	0.6	0.798	0.07	9	0.8	0.618	0.09	9	0.9	0.509	0.10
	Cond	24	192	9.1	<0.001	0.53	24	5.4	<0.001	0.40	24	2.5	<0.001	0.24	24	3.3	<0.001	0.29
	Temp	16	128	6355.0	<0.001	1.00	16	15.8	<0.001	0.66	16	1.3	0.182	0.14	16	3.1	<0.001	0.28
Post-harvest (2017)	CH ₄	2	14	3.8	0.052	0.32	2	4.3	0.038	0.35	2	3.5	0.063	0.30	2	3.9	0.048	0.33
	CO ₂	5	38	4.2	0.004	0.34	5	5.1	0.001	0.39	5	2.8	0.030	0.26	5	2.5	0.052	0.23
	N ₂ O	6	48	1.8	0.122	0.18	6	1.6	0.164	0.17	6	1.9	0.093	0.20	6	1.4	0.252	0.14
	Cond	6	45	11.8	<0.001	0.60	6	4.0	0.003	0.33	6	1.9	0.105	0.19	6	4.0	0.003	0.34
	Temp	6	48	8227.2	<0.001	1.00	6	6.2	<0.001	0.44	6	1.6	0.182	0.16	6	4.4	0.001	0.35
Pre-growing (2018)	CH ₄	3	23	1.1	0.382	0.12	3	2.4	0.100	0.23	3	0.1	0.974	0.01	3	3.6	0.031	0.31
	CO ₂	2	20	0.3	0.810	0.03	2	0.1	0.971	0.01	2	0.8	0.510	0.09	2	0.5	0.683	0.05
	N ₂ O	3	24	6.5	0.002	0.45	3	0.3	0.827	0.04	3	0.7	0.562	0.08	3	2.3	0.103	0.22
	Cond	2	16	2.3	0.138	0.22	2	4.4	0.031	0.35	2	2.2	0.147	0.21	2	1.8	0.198	0.18
	Temp	3	24	1988.3	<0.001	1.00	3	3.1	0.046	0.28	3	1.1	0.350	0.13	3	21.6	<0.001	0.73
Growing (2018)	CH ₄	7	56	48.5	<0.001	0.86	7	5.4	<0.001	0.40	7	5.0	<0.001	0.38	7	2.2	0.044	0.22
	CO ₂	7	53	86.7	<0.001	0.92	7	0.8	0.574	0.09	7	0.7	0.688	0.08	7	2.1	0.068	0.20
	N ₂ O	6	48	1.3	0.260	0.14	6	0.9	0.491	0.10	6	0.9	0.507	0.10	6	0.9	0.490	0.10
	Cond	7	56	8.3	<0.001	0.51	7	2.6	0.022	0.24	7	2.3	0.043	0.22	7	2.9	0.012	0.27
	Temp	6	49	321.6	<0.001	0.98	6	7.5	<0.001	0.48	6	0.9	0.517	0.10	6	1.0	0.446	0.11
Post-harvest (2018)	CH ₄	3	26	1.2	0.344	0.13	3	0.7	0.590	0.08	3	1.1	0.354	0.12	3	0.7	0.594	0.08
	CO ₂	5	40	1.6	0.188	0.16	5	0.9	0.507	0.10	5	0.5	0.774	0.06	5	0.8	0.576	0.09
	N ₂ O	2	18	1.0	0.387	0.11	2	0.2	0.827	0.03	2	0.4	0.696	0.05	2	1.0	0.406	0.11
	Cond	5	38	3.8	0.007	0.32	5	1.4	0.233	0.15	5	1.0	0.416	0.11	5	2.0	0.109	0.20
	Temp	5	40	5937.7	<0.001	1.00	5	73.3	<0.001	0.90	5	5.9	<0.001	0.42	5	4.6	0.002	0.37

Significant effects are highlighted in bold type

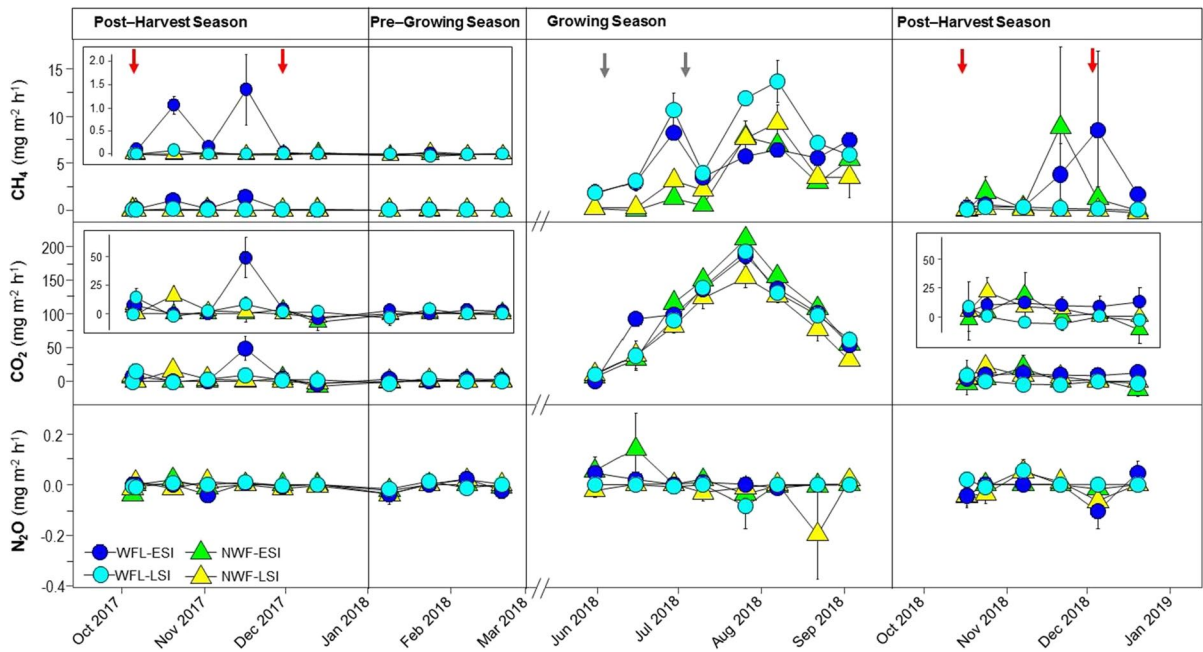


Fig. 2 GHG emission rates under different post-harvest managements of the studied period divided by crop season (error bars are the mean \pm SE; $n=3$). Additional graphs are provided with a higher resolution of the rate emissions scale. Red arrows point to the timing of the straw incorporation and grey arrows

to fertilization application. Treatments are WFL-ESI, winter flooding and early straw incorporation; WFL-LSI, winter flooding and late straw incorporation; NWF-ESI, non-winter flooding and early straw incorporation; NWF-LSI, non-winter flooding and late straw incorporation

of straw incorporation, with lower rates under ESI (6.66 ± 0.3 mg $\text{CH}_4\text{-C m}^{-2} \text{ h}^{-1}$ vs 11.51 ± 2.2 $\text{CH}_4\text{-C m}^{-2} \text{ h}^{-1}$). The rank of growing season mean CH_4 emission rates across the treatments was, from highest to lowest: $7.3 \pm 4.5 > 5.2 \pm 2.4 > 3.7 \pm 3.6 > 3.1 \pm 3.2$ mg $\text{CH}_4\text{-C m}^{-2} \text{ h}^{-1}$ for WFL-LSI, WFL-ESI, NWF-LSI and NWF-ESI, respectively (Fig. 2; Table S1).

For the whole study period, cumulative CH_4 emissions ranged from 116.1 to 262.8 kg C ha^{-1} . In all treatments, main contribution was at the growing season (117.6 – 226.0 kg C ha^{-1}) and the remaining at post-harvest (-3.7 – 68.7 kg C ha^{-1}), while pre-growing cumulative emissions contributed $<0.05\%$ (-0.1 – 0.05 kg C ha^{-1}) (Fig. 3).

Regarding overall cumulative emissions, WFL-ESI treatment, which is the conventional management, emitted more CH_4 (262.8 ± 54.82 kg ha^{-1}) than the alternative managements WFL-LSI, NWF-ESI

and NWF-LSI by 12.9, 39.5 and 55.8%, respectively. Cumulative CH_4 emission responded differently to post-harvest managements across the cropping seasons. In post-harvest 2017, higher CH_4 emission rates in WFL-ESI (Fig. 2; Table S1) resulted in significantly more cumulative emissions (Fig. 3) whereas in 2018, the main differences were found between LSI and ESI (-3.7 – 2.7 kg C ha^{-1} vs 40.8 – 68.7 kg ha^{-1}) (Fig. 3). At the growing season, WFL treatments emitted significantly more CH_4 than NWF (205.6 ± 20.4 vs 118.7 ± 1.1 kg C ha^{-1} , respectively), reducing emissions by 35 – 48% (Fig. 3). Besides, no significant effect of timing of straw incorporation was found.

CO₂ emissions

Emission rates of CO_2 varied between the growing (95.2 \pm 5.2 mg $\text{CO}_2\text{-C m}^{-2} \text{ h}^{-1}$), post-harvest

Table 3 Pearson's correlation coefficients (r) showing the relationship between fluxes of GHG and soil properties (soil conductivity (Cond), soil temperature (Temp), water level (WL) and soil Eh (Eh)) in each treatment per cropping

Crop season (Year)	Variables	WFL-ESI			WFL-LSI			NWF-ESI			NWF-LSI		
		CH ₄	CO ₂	N ₂ O	CH ₄	CO ₂	N ₂ O	CH ₄	CO ₂	N ₂ O	CH ₄	CO ₂	N ₂ O
Post-harvest (2017)	CO ₂	0.73**			-0.15			-0.28			nc		
	N ₂ O	0.29	0.28		0.25	-0.24		-0.35	-0.12		nc	0.00	
	Cond	-0.30	-0.43	0.03	0.10	-0.36	-0.26	-0.15	-0.12	0.38	nc	0.08	-0.32
	Temp	-0.12	-0.18	-0.13	-0.01	0.06	-0.23	0.05	0.30	-0.31	nc	0.31	0.08
	WL	-0.39	-0.57**	0.10	0.10	-0.50*	-0.23	nc	nc	nc	nc	nc	nc
Pre-growing (2018)	Eh	-0.15	0.23	0.03	0.03	0.14	-0.08	0.32	nc	-0.32	nc	0.89	0.92
	CO ₂	-0.15			-0.60*			0.56			0.84**		
	N ₂ O	0.07	0.22		-0.50	0.42		0.15	-0.62*		0.43	0.06	
	Cond	-0.16	-0.07	0.19	0.26	-0.32	0.01	0.60*	-0.02	0.44	-0.18	-0.58*	0.41
	Temp	0.31	-0.23	-0.21	-0.35	0.39	0.46	0.32	0.16	0.12	0.28	0.23	-0.01
Growing (2018)	WL	-0.14	-0.05	-0.42	0.27	-0.54	-0.23	nc	nc	nc	nc	nc	nc
	Eh	nc	0.90	0.07	nc	0.29	0.68	nc	nc	nc	nc	nc	nc
	CO ₂	0.28			0.63**			0.57**			0.55**		
	N ₂ O	-0.32	-0.34		-0.18	-0.49*		-0.41*	-0.49*	0.07	0.16	-0.03	
	Cond	-0.31	-0.14	-0.03	-0.01	0.05	-0.39	-0.59**	-0.17	0.07	-0.10	0.25	0.34
Post-harvest (2018)	Temp	0.49*	0.80**	-0.39	0.73**	0.90**	-0.45*	0.74**	0.76**	-0.31	0.77**	0.74**	0.08
	WL	0.39	0.88**	-0.50*	0.56**	0.81**	-0.32	0.71**	0.64**	-0.32	0.59**	0.61**	-0.03
	Eh	-0.40	0.15	0.20	-0.29	-0.14	-0.14	-0.36	-0.33	0.28	-0.72**	-0.36	0.06
	CO ₂	-0.23			-0.02			-0.03			0.35		
	N ₂ O	-0.12	0.11		0.65**	0.04		0.11	-0.04		-0.36	-0.22	
Post-harvest (2018)	Cond	-0.52*	0.09	-0.23	-0.13	0.19	0.01	-0.06	-0.30	-0.04	-0.16	-0.18	0.06
	Temp	-0.13	-0.15	-0.23	0.19	0.40	0.06	-0.03	0.11	-0.33	0.60**	0.20	-0.26
	WL	-0.04	-0.25	-0.34	0.27	0.25	0.18	nc	nc	nc	0.04	0.00	0.18
	Eh	-0.16	0.19	0.71*	-0.14	0.10	-0.22	-0.61*	-0.03	-0.31	0.22	0.59*	-0.33

Significant effects are highlighted in bold type. * Represents significant difference at $0.01 < P < 0.05$. ** Represents significant difference $P < 0.01$. nc represents no calculated. WFL-ESI, winter flooding and early straw incorporation; WFL-LSI, winter flooding and late straw incorporation; NWF-ESI, non-winter flooding and early straw incorporation; NWF-LSI, non-winter flooding and late straw incorporation

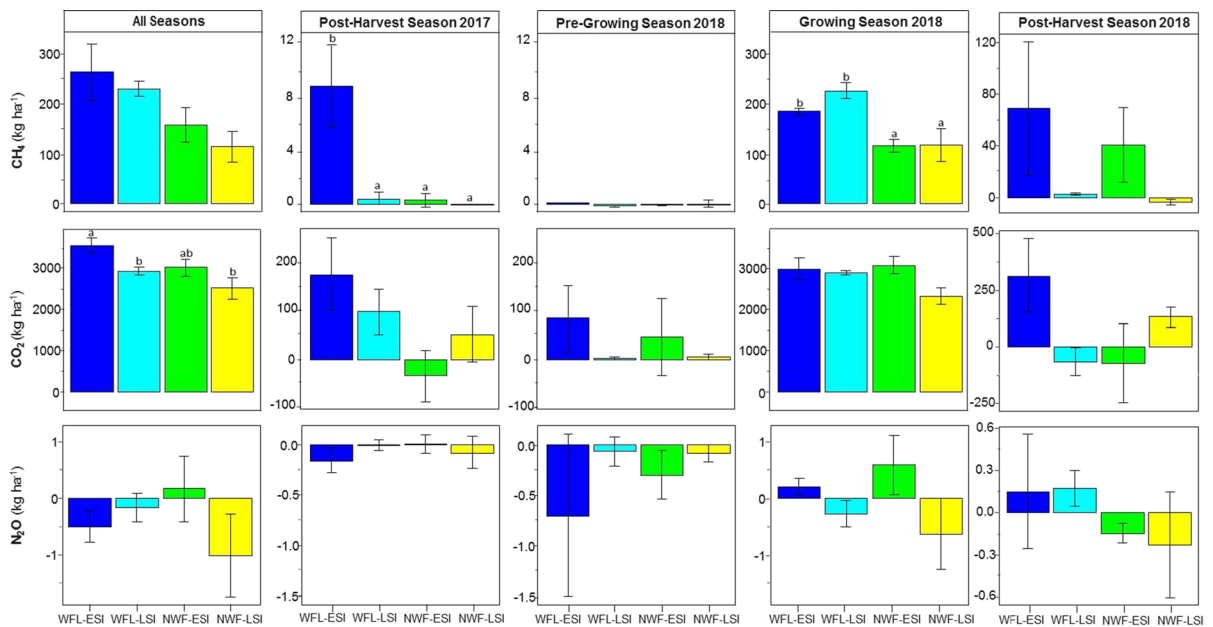


Fig. 3 GHG cumulated emission rates under different post-harvest managements by crop season (error bars are the mean SE; $n=3$). Different letters mean significant differences ($P < 0.05$) between treatments. Treatments are WFL-ESI, winter flooding and early straw incorporation; WFL-LSI, winter flooding and late straw incorporation; NWF-ESI, non-winter flooding and early straw incorporation; NWF-LSI, non-winter flooding and late straw incorporation. Note the different range of GHG emissions along the cropping seasons

flooding and late straw incorporation; NWF-ESI, non-winter flooding and early straw incorporation; NWF-LSI, non-winter flooding and late straw incorporation. Note the different range of GHG emissions along the cropping seasons

(4.3 ± 1.4 mg $\text{CO}_2\text{-C m}^{-2} \text{ h}^{-1}$) and pre-growing (0.79 ± 4.7 mg $\text{CO}_2\text{-C m}^{-2} \text{ h}^{-1}$) seasons, similarly as observed for CH_4 , and supported by the large size effect of this factor ($\eta^2=0.95$). The effect of winter flooding and timing of straw incorporation were significant only during the post-harvest in 2017 (Table 2).

In post-harvest seasons, CO_2 emission rates were consistently higher in WFL-ESI in both years (9.01 ± 11.7 and 9.5 ± 7.7 mg $\text{CO}_2\text{-C m}^{-2} \text{ h}^{-1}$ in 2017 and 2018, respectively (see Table S1; Fig. 2)) than in the rest of the treatments. Besides, WFL-LSI changed from emitting in 2017 (3.8 ± 4.7 $\text{CO}_2\text{-C m}^{-2} \text{ h}^{-1}$) to CO_2 uptake (-0.9 ± 4.4 $\text{CO}_2\text{-C m}^{-2} \text{ h}^{-1}$) in 2018. Emission rates in NWF-ESI were slightly lower than in NWF-LSI, but both treatments showed an increase in 2018 compared to 2017 (0.4 ± 6.3 vs 3.7 ± 9.4 in 2017 and 1.9 ± 18.0 vs 6.9 ± 19.3 $\text{CO}_2\text{-C m}^{-2} \text{ h}^{-1}$ in 2018 for NWF-ESI and NWF-LSI, respectively).

During the growing season, similar mean rates and trends across treatments were observed (Fig. 2). As

confirmed by the RM-ANOVA, CO_2 emission rates were significant for the time effect but not for any of the treatments. Emission rates were significantly positive correlated with temperature (Table 3).

Cumulative CO_2 emissions were larger in the growing season (range: 2319.5 – 3081.38 kg C ha^{-1}), than in the post-harvest (range: 73.06 – 313.75 kg ha^{-1}) and pre-growing seasons (range: 2.51 – 83.10 kg C ha^{-1}) (Fig. 3). Significant differences in cumulative CO_2 among treatments were only observed in the overall account. WFL-ESI was the treatment with the largest cumulative CO_2 emissions (3559.4 ± 171.1 kg C ha^{-1}) while both LSI treatments emitted significantly less (2921.3 ± 172.9 for WFL-LSI and 2507.7 ± 249.5 kg C ha^{-1} for NWF-LSI).

Compared to WFL-ESI, alternative managements reduced by 45 – 123% CO_2 emissions. During post-harvest and pre-growing seasons WFL-ESI and NWF-LSI tended to show more cumulative emissions than the rest of the treatments while NWF-ESI showed a consistent CO_2 net uptake in the two

Table 4 Characteristics of annual net ecosystem carbon budget (NECB) under different post-harvest managements

	WFL-ESI	WFL-LSI	NWF-ESI	NWF-LSI	Flooding (F)	Incorporation (I)	F x I
Yield 2018 (kg grain ha ⁻¹)	5158.2	5571.3	5370.1	4894.2	ns	ns	ns
C Input (kg C ha ⁻¹)	8455.5	8872.5	8669.3	8188.9	ns	ns	ns
NPP	5207.1	5624.1	5421.0	4940.5	ns	ns	ns
C grain	2011.7	2172.8	2094.3	1908.7	ns	ns	ns
C straw	1908.5	2061.4	1986.9	1810.8	ns	ns	ns
C roots	392.0	423.4	408.1	372.0	ns	ns	ns
C litter	215.6	232.9	224.5	204.6	ns	ns	ns
C Rhizodeposits	679.2	733.6	707.1	644.4	ns	ns	ns
Amendment	3248.4	3248.4	3248.4	3248.4			
C Output (kg C ha ⁻¹)	7360.0 b	7448.3 b	7292.3 b	6215.5 a	*	ns	*
Harvest	3920.3	4234.2	4081.3	3719.6	ns	ns	ns
CO ₂ -C	3245.6	2987.7	3093.2	2376.1	ns	ns	ns
CH ₄ -C	194.2 ab	226.4 b	117.9 a	119.8 a	*	ns	ns
NECB	1095.4	1424.2	1377.0	1973.4	ns	ns	ns

"*" Represents significant difference at $P < 0.05$. "ns" represents no significant. Different letters mean significant differences ($P < 0.05$) between treatments. WFL-ESI, winter flooding and early straw incorporation; WFL-LSI, winter flooding and late straw incorporation; NWF-ESI, non-winter flooding and early straw incorporation; NWF-LSI, non-winter flooding and late straw incorporation

post-harvest seasons (Fig. 3). Treatment WFL-LSI was the more variable across the year, turning from net CO₂ emissions in 2017 to CO₂ uptake in 2018. In the growing season, NWF-LSI emitted the less CO₂ emissions (2319.6 ± 205.8 kg C ha⁻¹), while the rest of the treatments emitted around 3000 kg ha⁻¹. Despite the observed trends across the treatments, differences were not statistically significant (Fig. 3).

N₂O emissions

Negative or close to zero N₂O emissions were detected in post-harvest and pre-growing seasons. During the growing season N₂O emission rates were slightly higher, but only a positive peak in NWF-ESI treatment was observed (Fig. 2) coinciding with a previous fertilizer application (Table 1; Fig. 1). Post-harvest managements did not cause any effect on N₂O emission rates (Table 2). The NWF-LSI treatment absorbed more N₂O (1.02 kg ha⁻¹) (Fig. 3), but differences between treatments were not statistically significant.

Emission rates were very low compared with CH₄ and CO₂ during the study period, with values ranging from emissions of 0.14 to uptakes of

-0.19 mg N₂O-N m⁻² h⁻¹ (Fig. 2) despite of the successive fertilizations (Table 1). Cumulative N₂O emissions ranged from -0.85 to 0.45 kg ha⁻¹ and did not show any significant seasonal pattern (Fig. 2).

Net ecosystem carbon balance

The NECB was positive for all treatments (Table 4) which indicates a net increase of soil organic carbon considering an entire year from post-harvest 2017 to growing season 2018. The estimated NECB ranged from 1095.4 to 1973.4 kg C ha⁻¹ and, while the mean across the treatments was statistically the same, some differentiated patterns were observed.

Compared to the conventional post-harvest management, i.e., WFL-ESI, the alternative treatments increased NECB by 25.7%, 30.0%, and 80.2% under NWF-ESI, WFL-LSI and NWF-LSI, respectively. The largest increase in NECB by NWF-LSI treatment was mostly explained by the significantly lower C output (Table 4). Avoiding winter flooding led significantly reduced C outputs mostly explained by the significant reductions in CH₄ emissions (Table 4).

Table 5 Annual characteristics of rice yield, GHG emissions, net GWP and GHG intensity (GHGI) under different post-harvest managements

Treatments	Grain yield (kg grain ha ⁻¹)	Annual Fluxes (kg ha ⁻¹)			GWPs (kg CO ₂ eq ha ⁻¹ yr ⁻¹)			Net GWP (kg CO ₂ eq ha ⁻¹ yr ⁻¹)	GHGI (kg CO ₂ eq yield ⁻¹)
		CH ₄	N ₂ O	NECB	CH ₄	N ₂ O	NECB		
WFL-ESI	5158.2 a	258.9 ab	-1.02 a	1095.4 a	7249.4 ab	-270.9 a	4016.5 a	2961.2 b	0.57 b
WFL-LSI	5571.3 a	294.3 b	-0.53 a	1424.2 a	8239.4 b	-140.5 a	5221.9 a	2876.9 b	0.52 b
NWF-ESI	5370.1 a	153.2 a	0.48 a	1377.0 a	4290.8 a	127.8 a	5048.9 a	-630.4 ab	-0.12 ab
NWF-LSI	4894.2 a	155.8 a	-1.25 a	1973.4 a	4361.1 a	-330.4 a	7235.7 a	-3204.4 a	-0.65 a
Flooding (F)	ns	*	ns	ns	*	ns	ns	*	*
Incorporation (I)	ns	ns	ns	ns	ns	ns	ns	ns	ns
F x I	ns	ns	ns	ns	ns	ns	ns	ns	ns

"*" Represents significant difference at $P < 0.05$. "ns" represents no significant. Different letters mean significant differences ($P < 0.05$) between treatments. WFL-ESI, winter flooding and early straw incorporation; WFL-LSI, winter flooding and late straw incorporation; NWF-ESI, non-winter flooding and early straw incorporation; NWF-LSI, non-winter flooding and late straw incorporation

Effects of post-harvest management on the net GWP

The net GWP was calculated to assess the effect of the post-harvest practices on the overall balance estimated from GHG fluxes (CH₄ and N₂O) and NECB (Table 5). Avoiding winter flooding significantly reduced the net GWP by 121 – 206%, showing negative GWP balance as compared to the positive balance under both WFL treatments.

The WFL treatments averaged 3025.1 ± 690.8 kg CO₂-eq ha⁻¹ of which 61% was attributed to CH₄ emissions whose warming effect was partially offset by NECB and N₂O emissions, accounting for 37% and ~2% for NECB and N₂O, respectively, of the net GWP. In contrast, NWF showed a negative GWP balance, -520.4 ± 639.4 and -3092.6 ± 890.3 kg CO₂-eq ha⁻¹ for NWF-ESI and NWF-LSI, respectively, being the last significantly lower to WFL treatments (Table 5). In particular, the lower CH₄ emissions in NWF treatments contributed to 37 – 45% to the GWP, which was 16 to 24 percentage points less than in WFL. Besides, N₂O emissions in NWF-ESI contributed positively by 1% to net GWP balance while in NWF-LSI, WFL-ESI and WFL-LSI contributed negatively by 2.8%.

Significant differences were also observed in GHGI between WFL and NWF treatments being 0.57, 0.52, -0.12 and -0.65 kg CO₂-eq yield⁻¹ for WFL-ESI, WFL-LSI, NWF-ESI and NWF-LSI, respectively. NWF-LSI treatment showed the lowest grain yield being reduced by 8% compared to

NWF-ESI and 5 – 12% respect to winter flooding treatments, but differences were not statistically different (Table 5).

Discussion

Effect of post-harvest management on CH₄ emissions

Winter flooding management and timing of straw incorporation influenced CH₄ emissions in both post-harvest and the following growing season. The studied post-harvest practices herein presented have important implications on GHG emissions in the paddy field: while the incorporation of the straw acts as an organic carbon supply, soil moisture and temperature modulates the mineralization processes (Devèvre & Horwath, 2000) which in this study were influenced by water management and straw incorporation timing.

In the post-harvest season, the largest emissions were found under flooded fields with early straw incorporation. Dry fields over the winter significantly reduced or even avoided post-harvest CH₄ emissions, because methanogenesis is strictly carried out under anaerobic conditions. Despite of this, CH₄ fluxes were observed in NWF-ESI in 2018 which were explained by the rainfall occurring in October that led the soil to saturated conditions with the necessary reductive soil environment for methanogenesis, i.e., Eh lower than -150 mV (Wang et al., 1993).

Postponing the straw incorporation from October to December very much reduced post-harvest CH₄ emissions presumably because soil temperature dropped to 9 °C (Fig. 1), which is lower than optimal 15 – 30 °C range for methanogenesis (Fey et al., 2004; Fey & Conrad, 2003). The large CH₄ reduction is explained by the exponential response of methane emissions to temperature (Camacho et al., 2017). The peak of CH₄ consistently observed five weeks after adding the straw in October in the two years of the study, is in line with the methanogenesis lag phase time described at 15 – 20 °C by Fey et al. (2004), which suggests that WFL-ESI management in our rice field provided the optimal conditions for methane formation. In their study, Fey et al. (2004) also reported an extended methanogenesis lag phase to 60 days under suboptimal temperature (10 °C). In our study, such an elongated methanogenic lag phase initiated after delayed straw input in late November, with temperature around 9 °C, would have overlapped with the drying conditions imposed in the pre-growing season, thus preventing the initiation of methanogenesis. Furthermore, the lack of CH₄ emissions during October in LSI, before the rice straw incorporation, indicates that straw addition is needed as a source to promote CH₄ emissions, either because readily available soil organic carbon content was insufficient (low soil organic matter content) or because was protected in organo-mineral complexes (Wang et al., 2003).

The mitigating effect of non-winter flooding was prolonged until the following growing season. Methane emissions during the growing season were reduced by 35 to 47% in comparison to WFL. These reductions are within the 35 to 52% range reported by Sander et al. (2014) and Zhang et al. (2010). Soil drainage during the post-harvest promotes the change to oxidized forms of soil metal elements, thus buffering the decrease in soil redox potential when the field is flooded in the following growing season (Cai et al., 2003), whereas flooding conditions maintain a low redox potential favorable for CH₄ formation (Wang et al., 1993). At the beginning of the rice-growing season, NWF fields showed higher soil Eh values explaining the lower methane emissions. After a few weeks, CH₄ rates under NWF remained low, despite the soil reached the critical Eh for methanogenesis in all treatments. This prolonged effect may be due

to changes in methanogenic populations mediated by drain conditions inhibiting their growth and subsequently, the production of CH₄ (K. Ma & Lu, 2011). Methanogenic populations can be restored after the soil is flooded but would need time to recover in biomass and activity (Pavlostathis & Giraldo-Gomez, 1991).

Contrasting with the persistent mitigation effect of dry fields beyond the post-harvest, the reduction of CH₄ emissions found under winter flooding and late straw incorporation was compensated during the subsequent growing season with a ca. 17% increase of CH₄ emissions in relation to WFL-ESI. Unfavorable conditions for straw decomposition during the fallow period can increase CH₄ emissions in the next cultivation period, because the pool of organic matter incorporated in the soil remains available with large labile fractions (Song et al., 2019; Tang et al., 2016). Additionally, winter flooding may also favor higher CH₄ emissions reinforcing soil conditions for methanogenesis, since comparing with late incorporation under unflooded fallow, the increase respect to early straw incorporation was less than 2%.

Effect of post-harvest management on CO₂ emissions

Both temperature and moisture are relevant in modulating aerobic decomposition of the straw (Devêvre & Horwath, 2000; Nakajima et al., 2015). Our field study corroborates that both factors influenced CO₂ emissions during the post-harvest season. Overall, late straw incorporation reduced significantly CO₂ emissions because the lower environmental temperatures slowing down microbial activity related with aerobic degradation (Nedwell, 1999). The 15 to 26% reduction found in our study is aligned with reductions found in incubated soils at 5 °C which emitted 20% and 63% less CO₂ than those at 15 and 25 °C, respectively (Devêvre & Horwath, 2000; Nakajima et al., 2015).

Emissions of CO₂ during post-harvest and pre-growing season is expected to occur under unflooded conditions due to aerobic decomposition of soil organic matter (Kudo et al., 2016). Conversely, we found less CO₂ emissions under unflooded than winter flooded fields (Fig. 2), contrasting with the hypothesis of a stimulatory effect on aerobic decomposition due to non-flooding conditions, promoted by

both the recently added organic matter (Devêvre & Horwath, 2000; Lee et al., 2020; Li et al., 2013) and the soil organic carbon oxidation (Haque et al., 2014; Kudo et al., 2016; Reba et al., 2019). However, the difference between both water treatments in the 2017 post-harvest was exacerbated, likely by the extreme soil drainage under non-winter flooding. Aerobic respiration is optimized with intermediate levels of soil moisture whereas it is reduced under extreme levels (Zhou et al., 2014) since soil water availability modulates carbon metabolism by limiting oxygen diffusion and substrate availability (Linn & Doran, 1984). The low rainfall and high temperatures recorded in 2017 post-harvest could have imposed severe drainage for C mineralization (Chow et al., 2006; Linn & Doran, 1984; Poblador et al., 2017) explaining the insignificant emissions rates in 2017 in the unflooded fields, which contrasts with those found in 2018, favoured by the abundant precipitation during this post-harvest (Fig. 2). Therefore, our results suggest that CO₂ emissions are larger under anaerobic than aerobic soil conditions. The CO₂ emissions found under anaerobic conditions would have been generated by the acetoclastic methanogenic pathway, in which the degradation of acetate, coming from the early stages of straw mineralisation, generates as by-products both CH₄ and CO₂ (Conrad, 2020). We observed CO₂ uptake in WFL-LSI and NWF-ESI. In paddy fields, hydrogenotrophic methanogenesis and chemolithotrophic acetogenesis have been described explaining CO₂ uptake in anoxic conditions. For the first, CO₂ is reduced to CH₄ in presence of H₂ (Liu & Conrad, 2011) while the second consists in the production of acetate from CO₂ (Rosencrantz et al., 1999). However, we cannot ascertain which of the pathways or if both of them were occurring. Under aerobic conditions, the Calvin-Benson-Bassham (CBB) inorganic carbon fixation pathway can also explain C consumption by chemolithoautotrophs in rice fields (Long et al., 2015).

Additionally, emission rates herein reported in either flooded or unflooded fields during fallow were very low ($-0.95 - 9.51 \text{ mg CO}_2\text{-C m}^{-2} \text{ h}^{-1}$) compared to either the $83 - 125 \text{ mg CO}_2\text{-C m}^{-2} \text{ h}^{-1}$ under flooded conditions or the close to $500 \text{ mg CO}_2\text{-C m}^{-2} \text{ h}^{-1}$ under non-flooded reported by Reba et al. (2019) and Kudo et al. (2016), respectively. Such differences may be explained by higher soil organic carbon content due to paddy cultivation in a reclaimed

peatland, and the edaphic conditions provided by a humic Andosol, respectively, both conditions being appropriate for large accumulation of organic matter (Saidy et al., 2020; Takahashi & Dahlgren, 2016) which contrasts with mineral soil and low organic carbon content (1.1%) of paddies of this study. Lower soil organic carbon means less substrate and therefore lower emission rates, which may also render the differences between flooding treatments the least obvious.

The dark chambers used in this study allowed the evaluation of post-harvest management on CO₂ emission balance which mostly relies on respiration by heterotrophs (growing and post-harvest seasons) and autotrophs (growing season), respectively. Our results showed a non-significant reduction in growing season CO₂ emissions under unflooded fields with late straw incorporation. A lack of effect of the post-harvest management on the subsequent growing season CO₂ emissions, which includes autotrophic respiration, is in line with Lee et al. (2020) and suggests the major contribution of autotrophic respiration in relation to heterotrophic respiration (Oliver et al., 2019), and therefore CO₂ emissions are mostly influenced by plant growth and temperature (Knox et al., 2016; Saito et al., 2005) and less by soil status, because flooding reduces soil respiration (Nay-Htoon et al., 2018).

Effect of post-harvest management on N₂O emissions

Emissions of N₂O were consistently low across the treatments and even negative rates were observed during the growing season. In line with previous studies, N₂O emissions are negligible from flooded soils (Wang et al., 2016). N₂O is produced by microbial processes including nitrification and denitrification, being the latter the major metabolic pathway. Denitrification is a dissimilatory process through which nitrogen oxidized forms, i.e., NO₃⁻, NO₂⁻ or NH₂OH, are progressively reduced to NO and N₂O being the last step, the reduction of N₂O to N₂ under anoxic conditions, which is common during the growing period. This last step is catalysed by N₂O reductase (Cheng-Fang et al., 2012). Therefore, N₂O can be the final or intermediate product of denitrification, being the composition of microbial community relevant to explain N₂O emissions (Wang et al., 2019).

Straw amendment for long time periods reduces N₂O emissions either by reducing the abundance of denitrifying bacteria or by increasing the abundance of N₂O reducing bacteria (Cheng-Fang et al., 2012; Wang et al., 2019). Therefore, the incorporation of the rice straw not only during the study period but also for long time ago, which is it is a common practice in the area, could explain the low N₂O emission rates.

Post-harvest management effect NECB and net GWP trade-off

Our study revealed that, regardless of the post-harvest treatments, paddies act as a carbon sink. This supports straw addition as a mitigation practice to shift the balance towards sequestration in paddy rice cultivations, as concluded by Lee et al. (2020) who reported net C losses of 0.24 – 1.24 Mg C ha⁻¹ with straw removal. Sequestration rates observed in our study (1.1 – 2.0 Mg C ha⁻¹) are in line with previous studies despite the differences in rice cultivation practices such as dry fields during the post-harvest (1.48 – 2.82 Mg C ha⁻¹; (Lee et al., 2020)) or double cropping (0.9 – 1.0 Mg C ha⁻¹; (Alberto et al., 2015)).

The effects of incorporation and flooding on GHG emissions reported here reflect C dynamics that correspond to monoculture systems and temperate climates. The results of such management have been reported in numerous studies; however, most are conducted in areas with tropical or subtropical climates with two or three harvests per year. The cropping system is the main driver of the carbon balance and budget due to the differences between inputs and outputs of C derived from the crop. Similar is the case for climate, since temperature modulates carbon metabolism.

Attention to residue management has increased towards controlling mineralisation processes to optimise net carbon balance (Liu et al., 2014; Smith et al., 2010b). Previous studies indicate that net C sequestration is mostly driven by the amount of C loss via gas emissions (Alberto et al., 2015) or harvest removal (Haque et al., 2020). Our study showed a larger, though non-significant, increased NECB under no winter flooding and late straw incorporation resulting from significantly less C outputs, from less CH₄ emission during the post-harvest and less

growing season CO₂ emissions (see Fig. 3, growing season), being the latter likely related to the lower NPP (5 - 12%). In contrast, C output through C emissions in the remaining three treatments was similar because the larger C losses from CH₄ emissions in the flooded treatments were offset by larger CO₂ emissions in unflooded fields with early straw incorporation treatment (Table 4).

While NECB estimates changes in soil C stock, whether the overall balance is an increase or depletion of soil carbon, the net GWP estimates the overall radiative forcing of the system by the net exchanges of CH₄ and N₂O and the NECB. Net GWP was mostly affected by winter flooding regime, with winter flooded rice fields performing as a source of GHG as opposed to unflooded fields which became a net sink. The influence of post-harvest water management on the net GWP is mainly explained by the reduction in CH₄ emissions, which consequently went from contributing ~61% of net GWP to 37 – 45% by avoiding winter flooding. Moreover, winter drainage did not promote N₂O emission, as observed when drainage is carried out during cultivation, which could have offset the benefits of mitigating CH₄ emission by N₂O (Cai et al., 1997; Zou et al., 2005).

The results presented here are in line with theoretical suggestions regarding the important role of straw and irrigation management, which propose a combined mitigation from both shortening flooding periods, thus reducing methane emission without being compensated by favoured N₂O emissions, and the carbon sequestration by incorporating straw that at least partially offsets C emissions (Hussain et al., 2015; Smith & Conen, 2004). Winter flooded fields showed positive net GWP values (2.9 – 3.0 Mg CO₂-eq ha⁻¹), which are within or in the lower range of other mono-crop paddy rice studies reporting intervals of 0.3 – 1.2 in Italy (Mejjide et al., 2017), 10.6 in South Korea (Hwang et al., 2017) and 3.5 – 13.4 in Japan (Lee et al., 2020). Non-winter flooded treatments became a sink of GHG, thus showing negative balances in terms of GWP (Table 5), in contrast to the positive balances commonly attributed to rice paddies (Alberto et al., 2015; Haque et al., 2016; Hwang et al., 2017; Lee et al., 2020; Mejjide et al., 2017). Besides, the net CO₂-C mitigation capacity of rice cultivation with straw incorporation has been previously estimated for upland rice fields, where

flooded conditions are scarce (Liu et al., 2014). We attribute the negative net GWP in non-winter flooded paddies to low CH₄ emissions in comparison to the other studies during the growing season: for instance, we report 117 – 119 kg ha⁻¹ which is substantially less than the 349 – 412 kg ha⁻¹ reported by Lee et al. (2020). In addition, contribution of N₂O to the GWP in our study was minimal or even negative across the treatments, i.e., we found was –2.8 – 1% which is substantially lower than the 4 –10% reported by Lee et al. (2020) or 13% given by Hwang et al. (2017). Finally, as far as net GWP was decided by CH₄ emissions, it is relevant that reductions of CH₄ in post-harvest season, where 30 – 70% can be emitted in this season (Cai et al., 2003; Fitzgerald et al., 2000; Knox et al., 2016; Martínez-Eixarch et al., 2018; Zhang et al., 2011), this have a strong mitigation effect on the net GWP of the crop.

Combination of both managements showed a strong influence on net GWP but not in NECB mostly due to avoiding CH₄ emissions in post-harvest and growing season. Since the amount of straw returned is the same, nutrient inputs are similar and production is not compromised, thus differences in GHGI between treatments are due to the effect of winter flooding in the net GWP (Table 5). This indicates that, when considering these alternative post-harvest managements, yield is not affected and could be a way to improve environmental benefits without detriment to economic ones.

Implications for mitigation options

Our study confirms that soil drainage in the post-harvest season is an efficient measure to decrease GWP by avoiding favourable conditions to CH₄ formation and not being compensated through aerobic decomposition of soil organic carbon; but a few considerations have to be taken into account. Regarding soil carbon preservation, drying organic soils promotes soil carbon oxidation (Deverel et al., 2010), hence flooding in agricultural soils is a recommended practice to prevent organic carbon oxidation and subsidence (Kirk et al., 2015). It is expected that subsoil composition of rice paddies in Ebro Delta are heterogeneous because land reclamation was done over different wetland habitats (lagoons, riverbanks, marshes or peats), according to the spatial variation of conditions in deltas (Benito et al., 2014). Therefore, prolonged winter drainage in paddies located over

organic soils could change soil carbon metabolisms (Morant et al., 2020) boosting oxidation of organic carbon. Another benefit of winter flooding is to lower soil conductivity as it has been shown in the Rhone Delta (Poumadère et al., 2008) preventing salt intrusion to protect rice production that is affected by salt stress (Hussain et al., 2017).

Furthermore, winter flooding has also been promoted to enhance biodiversity, especially for birds (Czech & Parsons, 2002; Ibáñez et al., 2010), and changes in water management may threaten some species (Toffoli & Rughetti, 2017). Site-specific decision-making should be taken to ensure the best mitigation measures (Belenguer-Manzanedo et al., 2021; Li et al., 2006). Long-term studies that consider both emissions and carbon sequestration adjusted to specific environmental-geographical conditions are needed in order to have greater efficiency and versatility in implementing mitigation measures in the coming decades of climate change.

Conclusions

This study demonstrates that post-harvest management affects net GWP of the paddy rice cultivation by modifying GHG emissions in post-harvest and next growing season without compromise sequestration C budget. Only preventing winter flooding during post-harvest and incorporating the straw in late November reduced efficiently the net GWP of rice crop by 206%, compared to winter flooding and straw incorporation in early October (WFL-ESI), the conventional post-harvest management. The main contribution to GWP reduction was due to avoiding winter flooding, which prevented CH₄ emissions and net GWP efficiently in the next growing season by increased soil Eh conditions. Regarding timing of the straw incorporation, late straw incorporation reduced both, CH₄ and CO₂ emissions, directly in the post-harvest period regardless flooding treatments, being temperature the main controlling factor. Our results suggest that when straw is incorporated in early October, the combination of higher temperatures and saturated soil conditions, either by irrigation or flooding rainfall, would promote emissions in the post-harvest season. Conversely, late straw incorporation increased CH₄ emission during the next growing season. Therefore, combined strategies of non-winter flooding and late straw

incorporation were more effective in reducing CH₄ and CO₂ emissions, due to avoiding favourable mineralization conditions during post-harvest and increasing soil Eh conditions at the following growing season. Finally, the post-harvest managements studied here show no effect on N₂O emissions either post-harvest or during growing season. In all treatments and during the whole study period the observed N₂O emission rates were low showing mainly N₂O fixation resulting in a low contribution to the GWP of the crop.

Acknowledgements This work was supported by the European Union through the Life + Environmental Policy and Governance, project entitled Pilot project for adaptation and mitigation measures for Climate Change in Ebre Delta (Life13 ENV/ES/001182); and by the Ministry of Economy and Competitiveness through the National Institute for Agricultural and Food Research and Technology (INIA) Spanish, project entitled Mitigation and adaptation to climate change in coastal rice fields (RTA2014-00058-C03); as well as by the project CLIMAWET-CONS (PID2019-104742RB-I00), funded by the Agencia Estatal de Investigación of the Spanish Ministry of Science and Innovation, granted to AC; and by the European Agricultural Fund for Rural Development (EAFRD) and the Agriculture, Livestock, Fishery and Alimentation Department of the Catalan Government (Demonstration activity 01.02.01), project entitled Rice straw management to fight against climate change. The support of the CERCA Programme / Generalitat de Catalunya is also acknowledged. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript. MB-M hold an FPI-INIA Predoctoral Scholarship by the Spanish Ministry of Science, Innovation and Universities (CPD2016-0059).

The authors would like to thank Lluís Jornet, Pep Cabanes and David Mateu (IRTA-Marine and continental waters), Andrea Bertomeu (IRTA- Extensive crops), and Joan Noguero (IRTA-GIRO) for technical support in analysis assessment. Also thanks to María Aranzazu Ciarso Corredor for English language editing.

Availability of data and material If requested

Code availability Not applicable

Authors' contributions Not applicable

Funding Open Access funding provided thanks to the CRUE-CSIC agreement with Springer Nature. European Union through the Life + Environmental Policy and Governance, project entitled Pilot project for adaptation and mitigation measures for Climate Change in Ebre Delta (Life13 ENV/ES/001182). CLIMAWET-CONS (PID2019-104742RB-I00), funded by the Agencia Estatal de Investigación of the Spanish Ministry of Science and Innovation, granted to AC.

Ministry of Economy and Competitiveness through the National Institute for Agricultural and Food Research and Technology (INIA) Spanish, project entitled

Mitigation and adaptation to climate change in coastal rice fields (RTA2014-00058-C03).

MB-M hold an FPI-INIA Predoctoral Scholarship by the Spanish Ministry of Science, Innovation and Universities (CPD2016-0059).

Declarations

Conflicts of interest/competing interests None

Ethics approval Not applicable

Consent to participate Not applicable

Consent for publication Not applicable

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Alberto MCR, Wassmann R, Gummert M, Buresh RJ, Quilty JR, Correa TQ et al (2015) Straw incorporated after mechanized harvesting of irrigated rice affects net emissions of CH₄ and CO₂ based on eddy covariance measurements. *Field Crop Res* 184:162–175. <https://doi.org/10.1016/j.fcr.2015.10.004>
- Altor AE, Mitsch WJ (2008) Pulsing hydrology, methane emissions and carbon dioxide fluxes in created marshes: a 2-year ecosystem study. *Wetlands* 28(2):423–438. <https://doi.org/10.1672/07-98.1>
- Belenguier-Manzanedo, M., Martínez-Eixarch, M., Fennessy, M. S., Ibáñez, C., Morant, D., Rochera, C., et al. (2021). Environmental and human drivers of carbon sequestration and GHG emissions in a Mediterranean Delta. In: *Wetland Carbon and Environmental Management. In press*
- Benito X, Trobajo R, Ibáñez C (2014) Modelling habitat distribution of Mediterranean coastal wetlands: the Ebro Delta as case study. *Wetlands* 34(4):775–785. <https://doi.org/10.1007/s13157-014-0541-2>
- Cai Z, Tsuruta H, Gao M, Xu H, Wei C (2003) Options for mitigating methane emission from a permanently flooded rice field. *Glob Chang Biol* 9(1):37–45. <https://doi.org/10.1046/j.1365-2486.2003.00562.x>

- Cai Z, Xing G, Yan X, Xu H, Tsuruta H, Yagi K, Minami K (1997) Methane and nitrous oxide emissions from rice paddy fields as affected by nitrogen fertilisers and water management. *Plant Soil* 196(1):7–14. <https://doi.org/10.1023/A:1004263405020>
- Camacho A, Picazo A, Rochera C, Santamans AC, Morant D, Miralles-Lorenzo J, Castillo-Escriba A (2017) Methane emissions in Spanish Saline Lakes: current rates, temperature and salinity responses, and evolution under different climate change scenarios. *Water* 9(9). <https://doi.org/10.3390/w9090659>
- Carlson K, Gerber J, Mueller N, Herrero M, MacDonald G, Brauman K et al (2016) Greenhouse gas emissions intensity of global croplands. *Net Clim Chang* 7. <https://doi.org/10.1038/NCLIMATE3158>
- Cheng-Fang L, Dan-Na Z, Zhi-Kui K, Zhi-Sheng Z, Jin-Ping W, Ming-Li C, Cou-Gui C (2012) Effects of tillage and nitrogen fertilizers on CH₄ and CO₂ emissions and soil organic carbon in paddy fields of Central China. *PLoS One* 7(5):e34642. <https://doi.org/10.1371/journal.pone.0034642>
- Chivenge P, Rubianes F, Van Chin D, Van Thach T, Khang VT, Romasanta RR et al (2020) Rice straw incorporation influences nutrient cycling and soil organic matter. In: Gummert M, Hung NV, Chivenge P, Douthwaite B (eds) *Sustainable Rice straw management*. Springer International Publishing, Cham, pp 131–144
- Chow A, Tanji K, Gao S, Dahlgren R (2006) Temperature, water content and wet–dry cycle effects on DOC production and carbon mineralization in agricultural peat soils. *Soil Biol Biochem* 38:477–488. <https://doi.org/10.1016/j.soilbio.2005.06.005>
- Conrad R (2020) Methane production in soil environments—anaerobic biogeochemistry and microbial life between flooding and desiccation. *Microorganisms* 8(6). <https://doi.org/10.3390/microorganisms8060881>
- Czech HA, Parsons KC (2002) Agricultural wetlands and Waterbirds: a review. *Waterbirds: The International Journal of Waterbird Biology* 25:56–65
- Deverel S, Hydrofocus I, Leighton D (2010) Historic, recent, and future subsidence, Sacramento-san Joaquin Delta, California, USA. *San Francisco Estuary and Watershed Science* 8. <https://doi.org/10.15447/sfews.2010v8iss2art1>
- Devèvre O, Horwath W (2000) Decomposition of rice straw and microbial carbon use efficiency under different soil temperatures and moistures. *Soil Biol Biochem* 32. [https://doi.org/10.1016/S0038-0717\(00\)00096-1](https://doi.org/10.1016/S0038-0717(00)00096-1)
- Fey A, Claus P, Conrad R (2004) Temporal change of ¹³C-isotope signatures and methanogenic pathways in rice field soil incubated anoxically at different temperatures. *Geochim Cosmochim Acta* 68(2):293–306. [https://doi.org/10.1016/s0016-7037\(03\)00426-5](https://doi.org/10.1016/s0016-7037(03)00426-5)
- Fey A, Conrad R (2003) Effect of temperature on the rate limiting step in the methanogenic degradation pathway in rice field soil. *Soil Biol Biochem* 35(1):1–8. [https://doi.org/10.1016/S0038-0717\(02\)00175-X](https://doi.org/10.1016/S0038-0717(02)00175-X)
- Fitzgerald GJ, Scow KM, Hill JE (2000) Fallow season straw and water management effects on methane emissions in California rice. *Glob Biogeochem Cycles* 14(3):767–776. <https://doi.org/10.1029/2000gb001259>
- Haque MM, Biswas JC, Hwang HY, Kim PJ (2020) Annual net carbon budget in rice soil. *Nutr Cycl Agroecosyst* 116(1):31–40. <https://doi.org/10.1007/s10705-019-10029-w>
- Haque MM, Kim GW, Kim PJ, Kim SY (2016) Comparison of net global warming potential between continuous flooding and midseason drainage in monsoon region paddy during rice cropping. *Field Crop Res* 193:133–142. <https://doi.org/10.1016/j.fcr.2016.04.007>
- Haque MM, Kim SY, Ali MA, Kim PJ (2014) Contribution of greenhouse gas emissions during cropping and fallow seasons on total global warming potential in mono-rice paddy soils. *Plant Soil* 387(1–2):251–264. <https://doi.org/10.1007/s11104-014-2287-2>
- Haque MM, Kim SY, Kim GW, Kim PJ (2015) Optimization of removal and recycling ratio of cover crop biomass using carbon balance to sustain soil organic carbon stocks in a mono-rice paddy system. *Agric Ecosyst Environ* 207:119–125. <https://doi.org/10.1016/j.agee.2015.03.022>
- Huang S, Sun Y, Yu X, Zhang W (2015) Interactive effects of temperature and moisture on CO₂ and CH₄ production in a paddy soil under long-term different fertilization regimes. *Biol Fertil Soils* 52(3):285–294. <https://doi.org/10.1007/s00374-015-1075-3>
- Huang S, Zeng Y, Wu J, Shi Q, Pan X (2013) Effect of crop residue retention on rice yield in China: a meta-analysis. *Field Crop Res* 154:188–194. <https://doi.org/10.1016/j.fcr.2013.08.013>
- Huang Y, Zhang W, Sun W, Zheng X (2007) Net primary production of CHINESE croplands from 1950 to 1999. *Ecol Appl* 17(3):692–701. <https://doi.org/10.1890/05-1792>
- Hussain S, Peng S, Fahad S, Khaliq A, Huang J, Cui K, Nie L (2015) Rice management interventions to mitigate greenhouse gas emissions: a review. *Environ Sci Pollut Res Int* 22(5):3342–3360. <https://doi.org/10.1007/s11356-014-3760-4>
- Hussain S, Zhang J-H, Zhong C, Zhu L-F, Cao X-C, Yu S-M et al (2017) Effects of salt stress on rice growth, development characteristics, and the regulating ways: a review. *J Integr Agric* 16(11):2357–2374. [https://doi.org/10.1016/S2095-3119\(16\)61608-8](https://doi.org/10.1016/S2095-3119(16)61608-8)
- Hwang HY, Kim GW, Kim SY, Mozammel Haque M, Khan MI, Kim PJ (2017) Effect of cover cropping on the net global warming potential of rice paddy soil. *Geoderma* 292:49–58. <https://doi.org/10.1016/j.geoderma.2017.01.001>
- Ibáñez C, Curcó A, Riera X, Ripoll I, Sánchez C (2010) Influence on birds of Rice field management practices during the growing season: a review and an experiment. *Waterbirds* 33(sp1):167–180, 114
- Kimura M, Murase J, Lu Y (2004) Carbon cycling in rice field ecosystems in the context of input, decomposition and translocation of organic materials and the fates of their end products (CO₂ and CH₄). *Soil Biol Biochem* 36(9):1399–1416. <https://doi.org/10.1016/j.soilbio.2004.03.006>
- Kirk ER, van Kessel C, Horwath WR, Linnquist BA (2015) Estimating annual soil carbon loss in agricultural peatland soils using a nitrogen budget approach. *PLoS One* 10(3):e0121432. <https://doi.org/10.1371/journal.pone.0121432>

- Knox SH, Matthes JH, Sturtevant C, Oikawa PY, Verfaillie J, Baldocchi D (2016) Biophysical controls on interannual variability in ecosystem-scale CO₂ and CH₄ exchange in a California rice paddy. *Journal of Geophysical Research: Biogeosciences* 121(3):978–1001. <https://doi.org/10.1002/2015JG003247>
- Kudo Y, Noborio K, Shimoozono N, Kurihara R, Minami H (2016) Greenhouse gases emission from paddy soil during the fallow season with and without winter flooding in Central Japan. *Paddy Water Environ* 15(1):217–220. <https://doi.org/10.1007/s10333-016-0523-5>
- Lee JH, Lee JG, Jeong ST, Gwon HS, Kim PJ, Kim GW (2020) Straw recycling in rice paddy: trade-off between greenhouse gas emission and soil carbon stock increase. *Soil Tillage Res* 199:104598. <https://doi.org/10.1016/j.still.2020.104598>
- Li C, Salas W, DeAngelo B, Rose S (2006) Assessing alternatives for mitigating net greenhouse gas emissions and increasing Yields from Rice production in China over the next twenty years. *J Environ Qual* 35(4):1554–1565. <https://doi.org/10.2134/jeq2005.0208>
- Li C, Zhang Z, Guo L, Cai M, Cao C (2013) Emissions of CH₄ and CO₂ from double rice cropping systems under varying tillage and seeding methods. *Atmos Environ* 80:438–444. <https://doi.org/10.1016/j.atmosenv.2013.08.027>
- Linn DM, Doran JW (1984) Effect of water-filled pore space on carbon dioxide and nitrous oxide production in tilled and nontilled Soils. *Soil Sci Soc Am J* 48:1267. <https://doi.org/10.2136/sssaj1984.03615995004800060013x>
- Linquist BA, van Groenigen KJ, Adviento-Borbe MA, Pittekkow C, van Kessel C (2012) An agronomic assessment of greenhouse gas emissions from major cereal crops. *Glob Chang Biol* 18(1):194–209. <https://doi.org/10.1111/j.1365-2486.2011.02502.x>
- Liu F, Conrad R (2011) Chemolithotrophic acetogenic H₂/CO₂ utilization in Italian rice field soil. *ISME J* 5(9):1526–1539. <https://doi.org/10.1038/ismej.2011.17>
- Liu C, Lu M, Cui J, Li B, Fang C (2014) Effects of straw carbon input on carbon dynamics in agricultural soils: a meta-analysis. *Glob Chang Biol* 20. <https://doi.org/10.1111/gcb.12517>
- Long X-E, Yao H, Wang J, Huang Y, Singh BK, Zhu Y-G (2015) Community structure and soil pH determine chemoautotrophic carbon dioxide fixation in drained Paddy soils. *Environ Sci Technol* 49(12):7152–7160. <https://doi.org/10.1021/acs.est.5b00506>
- Lu FEI, Wang X, Han B, Ouyang Z, Duan X, Zheng H, Miao H (2008) Soil carbon sequestrations by nitrogen fertilizer application, straw return and no-tillage in China's cropland. *Glob Chang Biol* 15:281–305. <https://doi.org/10.1111/j.1365-2486.2008.01743.x>
- Ma K, Lu Y (2011) Regulation of microbial methane production and oxidation by intermittent drainage in rice field soil. *FEMS Microbiol Ecol* 75:446–456. <https://doi.org/10.1111/j.1574-6941.2010.01018.x>
- Ma YC, Kong XW, Yang B, Zhang XL, Yan XY, Yang JC, Xiong ZQ (2013) Net global warming potential and greenhouse gas intensity of annual rice–wheat rotations with integrated soil–crop system management. *Agric Ecosyst Environ* 164:209–219. <https://doi.org/10.1016/j.agee.2012.11.003>
- Mandal B, Majumder B, Adhya TK, Bandyopadhyay PK, Gangopadhyay A, Sarkar D et al (2008) Potential of double-cropped rice ecology to conserve organic carbon under subtropical climate. *Glob Chang Biol* 14(9):2139–2151. <https://doi.org/10.1111/j.1365-2486.2008.01627.x>
- Martínez-Eixarch M, Alcaraz C, Viñas M, Noguerol J, Aranda X, Prenafeta-Boldú FX et al (2018) Neglecting the fallow season can significantly underestimate annual methane emissions in Mediterranean rice fields. *PLoS One* 13(5):e0198081. <https://doi.org/10.1371/journal.pone.0198081>
- Martínez-Eixarch M, Alcaraz C, Viñas M, Arias J, Aranda X, Prenafeta-Boldú F-X et al (2021) The main drivers of methane emissions differ in the growing and flooded fallow seasons in Mediterranean rice fields. *Plant Soil*. <https://doi.org/10.1007/s11104-020-04809-5>
- Matías J, Cruz V, García A, González D (2019) Evaluation of Rice straw yield, fibre composition and collection under Mediterranean conditions. *Acta Technologica Agriculturae* 22(2):43–47. <https://doi.org/10.2478/ata-2019-0008>
- Meijide A, Gruening C, Goded I, Seufert G, Cescatti A (2017) Water management reduces greenhouse gas emissions in a Mediterranean rice paddy field. *Agric Ecosyst Environ* 238:168–178. <https://doi.org/10.1016/j.agee.2016.08.017>
- Morant D, Picazo Mozo A, Rochera Cordellat C, Santamans A, Miralles-Lorenzo J, Camacho A (2020) Influence of the conservation status on carbon balances of semiarid coastal Mediterranean wetlands. *Inland Waters*. <https://doi.org/10.1080/20442041.2020.1772033>
- Mosier AR, Halvorson AD, Reule CA, Liu XJ (2006) Net global warming potential and greenhouse gas intensity in irrigated cropping Systems in Northeastern Colorado. *J Environ Qual* 35(4):1584–1598. <https://doi.org/10.2134/jeq2005.0232>
- Moyano FE, Manzoni S, Chenu C (2013) Responses of soil heterotrophic respiration to moisture availability: an exploration of processes and models. *Soil Biol Biochem* 59:72–85. <https://doi.org/10.1016/j.soilbio.2013.01.002>
- Nakajima M, Cheng W, Tang S, Hori Y, Yaginuma E, Hattori S et al (2015) Modeling aerobic decomposition of rice straw during the off-rice season in an Andisol paddy soil in a cold temperate region of Japan: effects of soil temperature and moisture. *Soil Science and Plant Nutrition* 62(1):90–98. <https://doi.org/10.1080/00380768.2015.1121116>
- Naser HM, Nagata O, Sultana S, Hatano R (2019) Carbon sequestration and contribution of CO₂, CH₄ and N₂O fluxes to global warming potential from Paddy-fallow fields on mineral soil beneath peat in Central Hokkaido, Japan. *Agriculture* 10(1):6
- Nay-Htoon B, Xue WE, Lindner S, Cuntz M, Ko J, Tenhunen J et al (2018) Quantifying differences in water and carbon cycling between paddy and rainfed rice (*Oryza sativa* L.) by flux partitioning. *PLoS One* 13. <https://doi.org/10.1371/journal.pone.0195238>
- Nedwell DB (1999) Effect of low temperature on microbial growth: lowered affinity for substrates limits growth at low temperature. *FEMS Microbiol Ecol* 30(2):101–111. <https://doi.org/10.1111/j.1574-6941.1999.tb00639.x>
- Neue HU, Wassmann R, Lantin RS, Alberto MCR, Aduna JB, Javellana AM (1996) Factors affecting methane emission

- from rice fields. *Atmos Environ* 30(10):1751–1754. [https://doi.org/10.1016/1352-2310\(95\)00375-4](https://doi.org/10.1016/1352-2310(95)00375-4)
- Oliver V, Cochrane N, Magnusson J, Brachi E, Monaco S, Volante A et al (2019) Effects of water management and cultivar on carbon dynamics, plant productivity and biomass allocation in European rice systems. *Sci Total Environ* 685:1139–1151. <https://doi.org/10.1016/j.scitotenv.2019.06.110>
- Pan G, Li L, Wu L, Zhang X (2004) Storage and sequestration potential of topsoil organic carbon in China's paddy soils. *Glob Chang Biol* 10(1):79–92. <https://doi.org/10.1111/j.1365-2486.2003.00717.x>
- Pavlostathis SG, Giraldo-Gomez E (1991) Kinetics of anaerobic treatment: a critical review. *Crit Rev Environ Control* 21(5-6):411–490. <https://doi.org/10.1080/10643389109388424>
- Poblador S, Lupon A, Sabaté S, Sabater F (2017) Soil water content drives spatiotemporal patterns of CO₂ and N₂O emissions from a Mediterranean riparian forest soil. *Bio-geosciences* 14(18):4195–4208. <https://doi.org/10.5194/bg-14-4195-2017>
- Poumadère M, Mays C, Pfeifle G, Vafeidis AT (2008) Worst case scenario as stakeholder decision support: a 5- to 6-m sea level rise in the Rhone delta, France. *Climatic Change* 91(1):123. <https://doi.org/10.1007/s10584-008-9446-5>
- Reba ML, Fong BN, Rijal I (2019) Fallow season CO₂ and CH₄ fluxes from US mid-south rice-waterfowl habitats. *Agric For Meteorol* 279:107709. <https://doi.org/10.1016/j.agrformet.2019.107709>
- Rosencrantz D, Rainey FA, Janssen PH (1999) Culturable populations of *Sporomusa* spp. and *Desulfobivrio* spp. in the anoxic bulk soil of flooded rice microcosms. *Appl Environ Microbiol* 65(8):3526–3533. <https://doi.org/10.1128/AEM.65.8.3526-3533.1999>
- Saidy AR, Razie F, Aidawati N, Hidayat T (2020) Increases in greenhouse gases following the use of peatlands for agricultural areas. IOP Conference Series: Earth and Environmental Science 499:012021. <https://doi.org/10.1088/1755-1315/499/1/012021>
- Saito M, Miyata A, Nagai H, Yamada T (2005) Seasonal variation of carbon dioxide exchange in rice paddy field in Japan. *Agric For Meteorol* 135(1):93–109. <https://doi.org/10.1016/j.agrformet.2005.10.007>
- Sander BO, Samson M, Buresh RJ (2014) Methane and nitrous oxide emissions from flooded rice fields as affected by water and straw management between rice crops. *Geoderma* 235-236:355–362. <https://doi.org/10.1016/j.geoderma.2014.07.020>
- Smith KA, Conen F (2004) Impacts of land management on fluxes of trace greenhouse gases. *Soil Use Manag* 20(2):255–263. <https://doi.org/10.1111/j.1475-2743.2004.tb00366.x>
- Smith, P., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsidig, E., et al. (2014). Chapter 11. Agriculture, forestry and other land use (AFOLU). In
- Smith P, Lanigan G, Kutsch WL, Buchmann N, Eugster W, Aubinet M et al (2010b) Measurements necessary for assessing the net ecosystem carbon budget of croplands. *Agric Ecosyst Environ* 139(3):302–315. <https://doi.org/10.1016/j.agee.2010.04.004>
- Smith WN, Grant BB, Desjardins RL, Worth D, Li C, Boles SH, Huffman EC (2010a) A tool to link agricultural activity data with the DNDC model to estimate GHG emission factors in Canada. *Agric Ecosyst Environ* 136(3):301–309. <https://doi.org/10.1016/j.agee.2009.12.008>
- Song HJ, Lee JH, Jeong H-C, Choi E-J, Oh T-K, Hong C-O, Kim PJ (2019) Effect of straw incorporation on methane emission in rice paddy: conversion factor and smart straw management. *Applied Biological Chemistry* 62(1):70. <https://doi.org/10.1186/s13765-019-0476-7>
- Takahashi T, Dahlgren RA (2016) Nature, properties and function of aluminum–humus complexes in volcanic soils. *Geoderma* 263:110–121. <https://doi.org/10.1016/j.geoderma.2015.08.032>
- Tang S, Cheng W, Hu R, Guigue J, Kimani SM, Tawaraya K, Xu X (2016) Simulating the effects of soil temperature and moisture in the off-rice season on rice straw decomposition and subsequent CH₄ production during the growth season in a paddy soil. *Biol Fertil Soils* 52(5):739–748. <https://doi.org/10.1007/s00374-016-1114-8>
- Toffoli R, Rughetti M (2017) Bat activity in rice paddies: organic and conventional farms compared to unmanaged habitat. *Agric Ecosyst Environ* 249:123–129. <https://doi.org/10.1016/j.agee.2017.08.022>
- von Lütow M, Kögel-Knabner I (2009) Temperature sensitivity of soil organic matter decomposition—what do we know? *Biol Fertil Soils* 46(1):1–15. <https://doi.org/10.1007/s00374-009-0413-8>
- Wang W, Chen C, Wu X, Xie K, Yin C, Hou H, Xie X (2019) Effects of reduced chemical fertilizer combined with straw retention on greenhouse gas budget and crop production in double rice fields. *Biol Fertil Soils* 55(1):89–96. <https://doi.org/10.1007/s00374-018-1330-5>
- Wang W, Wu X, Chen A, Xie X, Wang Y, Yin C (2016) Mitigating effects of ex situ application of rice straw on CH₄ and N₂O emissions from paddy-upland coexisting system. *Sci Rep* 6(1):37402. <https://doi.org/10.1038/srep37402>
- Wang WJ, Dalal RC, Moody PW, Smith CJ (2003) Relationships of soil respiration to microbial biomass, substrate availability and clay content. *Soil Biol Biochem* 35(2):273–284. [https://doi.org/10.1016/S0038-0717\(02\)00274-2](https://doi.org/10.1016/S0038-0717(02)00274-2)
- Wang ZP, DeLaune RD, Patrick WH Jr, Masscheleyn PH (1993) Soil redox and pH effects on methane production in a flooded Rice soil. *Soil Sci Soc Am J* 57(2):382–385. <https://doi.org/10.2136/sssaj1993.03615995005700020016x>
- Xu H, Cai Z, Li X, Tsuruta H (2000) Effect of antecedent soil water regime and rice straw application time on CH₄ emission from rice cultivation. *Australian Journal of Soil Research - AUST J SOIL RES* 38. <https://doi.org/10.1071/SR99026>
- Xu H, Hosen Y (2010) Effects of soil water content and rice straw incorporation in the fallow season on CH₄ emissions during fallow and the following rice-cropping seasons. *Plant and Soil - PLANT SOIL* 335:373–383. <https://doi.org/10.1007/s11104-010-0426-y>
- Zhang G, Zhang X, Ma J, Xu H, Cai Z (2010) Effect of drainage in the fallow season on reduction of CH₄ production and emission from permanently flooded rice fields. *Nutr*

- Cycl Agroecosyst 89:81–91. <https://doi.org/10.1007/s10705-010-9378-0>
- Zhang GB, Ji Y, Ma J, Xu H, Cai ZC (2011) Case study on effects of water management and rice straw incorporation in rice fields on production, oxidation, and emission of methane during fallow and following rice seasons. *Soil Research* 49(3):238–246. <https://doi.org/10.1071/SR10117>
- Zhou W, Hui D, Shen W (2014) Effects of soil moisture on the temperature sensitivity of soil heterotrophic respiration: a laboratory incubation study. *PLoS One* 9(3):e92531. <https://doi.org/10.1371/journal.pone.0092531>
- Zou J, Huang Y, Jiang J, Zheng X, Sass RL (2005) A 3-year field measurement of methane and nitrous oxide emissions from rice paddies in China: effects of water regime, crop residue, and fertilizer application. *Glob Biogeochem Cycles* 19(2). <https://doi.org/10.1029/2004GB002401>

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.